Design and Sizing of the Suppression Pool to Evacuate Decay Heat without Evaporation

Kadmos Chief Nuclear Officer

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Abstract

This report establishes a transparent, calculation-ready basis for sizing the KADMOS suppression pool to remove post-shutdown decay heat by passive means while maintaining a non-boiling bulk temperature. The method models the pool as a well-mixed control volume governed by $mc_p\dot{T} = P(t) - hA_{\mathrm{tot}}(T - T_\infty)$, with decay heat $P(t)$ from an ANSI/ANS–5.1 correlation, a conservative natural-convection sink with constant overall coefficient h, and cylindrical geometry of fixed radius r_{pool} [ANS14, IDBL07, TK11]. Baseline assumptions adopt $r_{\mathrm{pool}} = 6\,\mathrm{m}$, $h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}$, $T_\infty = 20\,^\circ\mathrm{C}$, constant water properties (conservative), and a 30-day horizon; radiation and evaporation are not credited [IDBL07, Int97]. The acceptance criterion is $\max_{t\le 30\,\mathrm{d}} T(t) \le 90\,^\circ\mathrm{C}$.

For a representative pre-scram power $P_0 = 150\,\mathrm{MW}$, the minimum inventory that satisfies the criterion is $V_{\mathrm{req}} = 468.6\,\mathrm{m}^3$ (height $h_{\mathrm{pool}} = 4.14\,\mathrm{m}$), with areas $A_{\mathrm{top}} = 113.10\,\mathrm{m}^2$, $A_{\mathrm{side}} = 156.07\,\mathrm{m}^2$, $A_{\mathrm{tot}} = 269.17\,\mathrm{m}^2$, and thermal time constant $\tau \approx 8.44$ days, demonstrating compliance under conservative heat-sink assumptions [Kad25]. Parametric sweeps show V_{req} increases monotonically with P_0 and decreases with larger h and r_{pool}; hotter ambient T_∞ increases V_{req}, consistent with heat-transfer scaling [IDBL07, TK11]. The analysis is intentionally conservative; recommended refinements for final design include composite natural-convection–radiation modeling, temperature-dependent water properties (IAPWS-97), and site-specific meteorology. The results provide auditable targets for preliminary civil/structural integration and clear levers (geometry, effective h) for margin optimization [ANS14, IDBL07, Int97, Kad25].

1 Introduction

1.1 Purpose and Scope

This report establishes a transparent, calculation-ready basis for the *design and sizing* of a passive suppression (decay-heat) pool that removes post-shutdown heat from the KADMOS plant *without allowing pool water to boil*. The immediate design objective is to determine the *minimum* pool volume (and corresponding height for a prescribed radius) such that the bulk pool temperature never exceeds 90 °C over a 30-day post-shutdown horizon, while heat is rejected to ambient air by natural convection from the pool's free surface and sidewalls. The sizing methodology and example results originate from the attached configuration and script; this report formalizes those calculations, documents assumptions, and sets the stage for sensitivities and design margin allocation. [Kad25]

1.2 Design Target and Acceptance Basis

The acceptance criterion is

$$T_{\mathrm{pool}}(t) \le 90\ ^\circ\mathrm{C} \qquad \forall\, t \in [0, 30\ \mathrm{days}],$$

which ensures non-boiling operation with margin relative to atmospheric saturation (≈ 100 °C). From a plant-level perspective, this target is aligned with the general design requirement to provide reliable post-shutdown heat removal using passive means and with no reliance on active makeup or sprays. While licensing metrics are plant- and regulator-specific, the objective of demonstrating adequate residual heat removal capacity under conservative assumptions is consistent with the intent of residual-heat GDCs in nuclear plant design bases [U.S24, TK11].

1.3 Physical Basis and Modeling Approach (Overview)

The pool is modeled as a well-mixed control volume receiving decay heat from the reactor following scram, and rejecting heat to ambient by natural convection:

- **Decay heat source.** Core decay power is represented by an ANSI/ANS-5.1-type correlation, $\frac{P(t)}{P_0} = 0.066\,t^{-0.2} + 0.20\,t^{-0.8}$ with t in seconds and P_0 the pre-scram core thermal power [ANS14, Sta18]. This captures the multi-timescale fall-off of decay power after shutdown and is widely used for preliminary sizing and heat-sink assessments [TK11].
- **Heat rejection.** Heat loss is modeled as a lumped convection term $\dot{Q}_{\text{loss}} = h\,A_{\text{tot}}\,(T_{\text{pool}} - T_\infty)$, where $A_{\text{tot}} = A_{\text{top}} + A_{\text{side}}$ combines the pool's free surface and side area. A conservative, constant overall coefficient $h = 10\ \mathrm{W\,m^{-2}\,K^{-1}}$ is used to bound performance; this value lies in the lower range of reported natural-convection coefficients for large horizontal/vertical water–air interfaces and deliberately neglects radiative and evaporative enhancement [IDBL07, CC75].
- **Geometry.** The pool is a vertical right cylinder of fixed radius r (baseline $r = 6$ m); height is determined by the volume solution. Surface areas follow $A_{\text{top}} = \pi r^2$ and $A_{\text{side}} = 2\pi r h_{\text{pool}}$.
- **Energy balance and properties.** With water density ρ and heat capacity c_p treated as constants for conservatism, the bulk temperature evolves by $m\,c_p\,\dot{T} = P(t) - h\,A_{\text{tot}}(T - T_\infty)$, where $m = \rho V$ and T_∞ is ambient air temperature (baseline 20°C). A constant-property model slightly *overestimates* temperature rise at high T (since c_p increases mildly with T), adding conservatism; property-refined runs may use IAPWS-97 in follow-on work [Int97].
- **Numerical sizing.** For a specified P_0, the algorithm brackets the minimum safe mass $m_{\min}$ such that $\max_t T(t) \le 90$°C and solves for $V_{\min} = m_{\min}/\rho$ via binary search over 30 days with a logarithmic time grid. Reported outputs are (V, h_{pool}, m) for each P_0 of interest [Kad25].

1.4 Conservatisms and Modeling Limits

The present sizing method intentionally biases toward larger volumes by (i) adopting a low, constant h that neglects radiation and any evaporation-driven enhancement; (ii) using constant properties; and (iii) assuming no credit for active sprays, makeup, or wind-driven/free-convection augmentation. These choices are appropriate for preliminary design envelopes. When a final design point is selected, refinements should include combined natural convection–radiation, temperature-dependent water properties, and verified ambient conditions per site meteorology [IDBL07, TK11]. As shown in the attached results, the method scales sensibly with P_0 and provides auditable volume/height targets for structural and civil integration [Kad25].

1.5 Document Structure

Section 2 states assumptions and boundary conditions; Section 3 details governing equations and numerical procedures; Section 4 presents sizing results and sensitivity trends; Section 5 interprets margins and design trade-offs; and Section 6 summarizes actionable sizing guidance for KADMOS integration.

2 Assumptions

2.1 Geometry and Control Volume

- The suppression pool is modeled as a single, well-mixed control volume (bulk water node) contained in a vertical right circular cylinder of *fixed* radius $r_{\text{pool}} = 6\,\text{m}$; the pool height h_{pool} is an output of the sizing calculation. Free-surface and sidewall areas are $A_{\text{top}} = \pi r_{\text{pool}}^2, \quad A_{\text{side}} = 2\pi r_{\text{pool}}\,h_{\text{pool}}, \quad A_{\text{tot}} = A_{\text{top}} + A_{\text{side}}$.

2.2 Heat Source (Decay Heat) and Event Definition

- Post-scram core decay power is represented by an ANSI/ANS–5.1–type correlation, $\frac{P(t)}{P_0} = 0.066\,t^{-0.2} + 0.20\,t^{-0.8}$, with t in seconds and P_0 the pre-scram core thermal power. This functional form is suitable for preliminary heat-sink sizing and aligns with standard practice in decay-heat evaluations [ANS14, TK11, Sta18].
- No additional internal or external heat sources are credited (e.g., pumps, lights, or chemical reactions).

2.3 Heat Rejection and Boundary Conditions

- Heat removal to ambient is modeled as a lumped natural-convection sink $\dot{Q}_{\text{loss}} = h\,A_{\text{tot}}\,(T_{\text{pool}} - T_\infty)$, where a conservative, constant overall coefficient $h = 10\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$ is imposed over the entire horizon. This value lies toward the *low* end of reported free-convection coefficients for large horizontal/vertical water–air interfaces; radiation and evaporation are neglected, biasing the result to larger required volumes [IDBL07, CC75].
- Ambient air and initial pool temperatures are fixed at $T_\infty = T_{\text{init}} = 20\,^\circ\text{C}$.
- The design acceptance criterion enforces a non-boiling pool with margin: $T_{\text{pool}}(t) \le 90\,^\circ\text{C}$ for $t \in [0, 30 \text{ days}]$.

2.4 Thermophysical Properties

- Water properties are held constant for conservatism: $\rho = 1000\,\text{kg}\,\text{m}^{-3}$, $c_p = 4186\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$. Because $c_p(T)$ mildly *increases* with temperature, the constant-c_p assumption slightly overpredicts temperature rise at high T; refined studies may adopt IAPWS-97 properties [Int97, IDBL07].

2.5 Governing Energy Balance and Numerical Horizon

- The bulk energy balance is $m\,c_p\,\dot{T}_{\text{pool}} = P(t) - h\,A_{\text{tot}}\,(T_{\text{pool}} - T_\infty)$, with $m = \rho V$ and $V = \pi r_{\text{pool}}^2 h_{\text{pool}}$.
- The integration horizon is $t \in [1 \text{ s}, 30 \text{ days}]$ using a logarithmically spaced grid to resolve early-time decay power and long tails. A peak-tracking scheme aborts a trial if T_{pool} exceeds the limit, improving the bracketing efficiency.
- The minimum safe mass $m_{\min}$ (and thus $V_{\min}$, $h_{\text{pool,min}}$) is obtained by a bracketed binary search on m with a volume convergence tolerance of $\Delta V \le 1 \times 10^{-2}\,\text{m}^3$.

2.6 Conservatism, Exclusions, and Applicability

- No credit is taken for: evaporative cooling, radiative exchange, wind augmentation, spray systems, or active makeup. These exclusions are intentional to provide a conservative preliminary sizing envelope [IDBL07, TK11].
- The well-mixed assumption is appropriate for first-pass volume sizing; detailed thermal stratification, local wall heat-transfer coefficients, and site meteorology can be incorporated in follow-on sensitivity studies if needed.

2.7 Traceability to the Attached Configuration

All numerical values, horizon, and algorithmic details in this section match the attached configuration and script that implement the sizing workflow (fixed r_{pool}, $h = 10\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$, $T_\infty = T_{\text{init}} = 20\,^\circ\text{C}$, $\rho = 1000\,\text{kg}\,\text{m}^{-3}$, $c_p = 4186\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$, 30-day horizon, log spacing, and binary search termination at $\Delta V \le 0.01\,\text{m}^3$). [Kad25]

3 Technical Data

3.1 Governing Balance and Control-Volume Definition

The suppression pool is modeled as a single, well-mixed control volume of water with mass $m = \rho V$ and bulk temperature $T(t)$. The energy balance—including a decay-heat source $P(t)$ and an ambient heat sink with overall coefficient h and total heat-transfer area A_{tot}—is

$$m\, c_p \frac{\mathrm{d}T}{\mathrm{d}t} = P(t) - \dot{Q}_{\text{loss}}(t), \qquad \dot{Q}_{\text{loss}}(t) \equiv h\, A_{\text{tot}}\,[\,T(t) - T_\infty\,], \tag{1}$$

with T_∞ the ambient air temperature. For a vertical right circular cylinder of fixed radius r_{pool} and unknown height $h_{\text{pool}} = V/(\pi r_{\text{pool}}^2)$, the wetted area is

$$A_{\text{top}} = \pi r_{\text{pool}}^2, \qquad A_{\text{side}} = 2\pi r_{\text{pool}}\, h_{\text{pool}}, \qquad A_{\text{tot}} = A_{\text{top}} + A_{\text{side}}. \tag{2}$$

Equations (1)–(2) are implemented directly in the sizing script (Section 4); the code computes $A_{\text{top}}, A_{\text{side}}, A_{\text{tot}}$ from the current volume guess and radius (Alg. 3.7).

3.2 Decay-Heat Source Model

The core decay power is represented by an ANSI/ANS–5.1–type correlation,

$$\frac{P(t)}{P_0} = 0.066\, t^{-0.2} + 0.20\, t^{-0.8}, \qquad t \text{ in seconds}, \tag{3}$$

where P_0 is the pre-scram reactor thermal power. This form, appropriate for preliminary heat-sink sizing, is encoded in the function `_decay_power` and used at each time level in the integration. [ANS14, TK11, Sta18].

3.3 Heat-Rejection Model

Baseline (constant-h) sink. Consistent with a conservative first-pass envelope, the pool rejects heat by free convection to air using a constant, overall heat-transfer coefficient

$$\dot{Q}_{\text{loss}}(t) = h\, A_{\text{tot}}\,[T(t) - T_\infty], \qquad h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}, \tag{4}$$

applied uniformly to the free surface and sidewalls. The low constant h neglects radiation and evaporation, thereby biasing the required volume upward. [IDBL07, CC75] The value $h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}$ and the ambient/baseline temperatures are set in the configuration block of the script.

Correlation-based (optional) sink. For sensitivity or design refinement, h can be predicted from canonical free-convection correlations:

$$\text{Vertical side (height } L = h_{\text{pool}}\text{):} \quad \overline{\mathrm{Nu}}_L = 0.68 + \frac{0.670\,\mathrm{Ra}_L^{1/4}}{\left[1 + (0.492/\mathrm{Pr})^{9/16}\right]^{4/9}}, \quad h_{\text{side}} = \frac{\overline{\mathrm{Nu}}_L\, k}{L}, \tag{5}$$

$$\text{Horizontal free surface (characteristic } L = r_{\text{pool}}\text{):} \quad \overline{\mathrm{Nu}}_L \approx C\,\mathrm{Ra}_L^n, \qquad h_{\text{top}} = \frac{\overline{\mathrm{Nu}}_L\, k}{L}. \tag{6}$$

Here $\mathrm{Ra}_L = g\beta(T_s - T_\infty)L^3/(\nu\alpha)$ and $\mathrm{Pr} = \nu/\alpha$. Representative coefficients (C, n) for upward-facing hot surfaces in the laminar–turbulent transitional range are tabulated in standard heat-transfer texts. [IDBL07] The baseline results in this report deliberately retain the constant-h model in Eq. (4).

3.4 Thermophysical Properties

Water density and heat capacity are taken as constants for conservatism, $\rho = 1000\,\mathrm{kg\,m^{-3}}$, $c_p = 4186\,\mathrm{J\,kg^{-1}\,K^{-1}}$ (the latter slightly *increases* with T, so constant c_p overpredicts peak temperature). Property-refined studies may employ the IAPWS-97 formulation. [Int97, IDBL07] The constants are set in the script's parameter block.

3.5 Analytical Checks and Time-Constant Scaling

For a *constant* heat source P and constant h, Eq. (1) has the closed form

$$T(t) \;=\; T_\infty + [T(0) - T_\infty]\, e^{-t/\tau} + \frac{1}{mc_p}\int_0^t e^{-(t-\xi)/\tau}\, P(\xi)\,\mathrm{d}\xi, \qquad \tau \equiv \frac{mc_p}{hA_{\mathrm{tot}}}. \tag{7}$$

With the sized volume at $P_0 = 150\,\mathrm{MW_{th}}$ (Section 4), $r_{\mathrm{pool}} = 6\,\mathrm{m}$, and $h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}$, the computed height and area give $\tau \approx 8.4$ days, consistent with the 30-day horizon and the slow thermal response of a large pool. [IDBL07] (Numerical values follow directly from the script's reported V and geometry; see also the example outputs.).

3.6 Numerical Integration and Peak Tracking

Equation (1) is advanced with an explicit forward-Euler update on a logarithmically spaced time grid:

$$T_{j+1} = T_j + \frac{\big[\,P(t_{j+1}) - hA_{\mathrm{tot}}(T_j - T_\infty)\,\big]\Delta t_j}{m\,c_p}, \qquad \Delta t_j \equiv t_{j+1} - t_j, \tag{8}$$

$$\{t_j\}_{j=0}^{N}: \quad t_0 = 1\,\mathrm{s}, \quad t_N = 30\,\mathrm{days}, \quad t_j = \exp\!\left(\ln t_0 + j\,\frac{\ln t_N - \ln t_0}{N}\right), \tag{9}$$

with a running maximum $T_{\max} = \max_j T_j$ used to detect violation of the temperature limit and abort unsafe trials early. [IDBL07] The implementation mirrors Eq. (8); the code computes $q_{\mathrm{gen}} = P(t)$, $q_{\mathrm{loss}} = hA_{\mathrm{tot}}(T - T_\infty)$, and updates T accordingly; the log grid is set by `np.logspace`.

3.7 Solver, Bracketing, and Convergence

For a given P_0, the algorithm searches the smallest water mass m (equivalently V) such that $T_{\max} \le T_{\mathrm{limit}} = 90\,^\circ\mathrm{C}$ over 30 days:

1. **Initialize bounds:** start from a seed m_{low} and shrink if still safe; set $m_{\mathrm{high}} = 2\,m_{\mathrm{low}}$ and expand until safe. Unsafe/safe are defined by the peak-tracking integration in Sec. 3.6.
2. **Binary search:** bisect $m_{\mathrm{mid}} = \frac{1}{2}(m_{\mathrm{low}} + m_{\mathrm{high}})$ and test. Replace $m_{\mathrm{low}} \leftarrow m_{\mathrm{mid}}$ if unsafe; else $m_{\mathrm{high}} \leftarrow m_{\mathrm{mid}}$. Continue until $(m_{\mathrm{high}} - m_{\mathrm{low}})/\rho \le \Delta V_{\mathrm{tol}}$.
3. **Report:** choose $m_{\mathrm{req}} = m_{\mathrm{high}}$ (conservative), $V_{\mathrm{req}} = m_{\mathrm{req}}/\rho$, and $h_{\mathrm{req}} = V_{\mathrm{req}}/(\pi r_{\mathrm{pool}}^2)$.

The script parameters controlling horizon, grid density, and volume tolerance are explicitly configured ($t_{\mathrm{end}} = 30$ days, $N \approx 3 \times 10^4$ points on a log grid, $\Delta V_{\mathrm{tol}} = 0.01\,\mathrm{m^3}$).

3.8 Acceptance Criterion and Limit Enforcement

The design criterion is expressed as a pathwise constraint

$$\max_{t \in [0,\,30\ \mathrm{days}]} T(t) \;\le\; T_{\mathrm{limit}} = 90\,^\circ\mathrm{C}, \tag{10}$$

which the solver enforces by early termination of unsafe trials during bracketing and binary search (Sec. 3.7). This criterion matches the project requirement of *no boiling* with margin under passive heat removal. [TK11, IDBL07] The peak-tracking abort appears in the integration loop.

3.9 Sanity Checks and Order-of-Magnitude Trends

For a fixed r_{pool}, the required volume scales monotonically with P_0 and inversely with h and A_{tot}. A useful heuristic from Eq. (7) is that a larger $\tau = mc_p/(hA_{\mathrm{tot}})$ delays and reduces the peak. In the reference configuration $r_{\mathrm{pool}} = 6\,\mathrm{m}$, the example runs yield increasing V_{req} with P_0, as expected from first-law balance (see the script's printed results) [IDBL07].

3.10 Model Extensions (not credited in baseline)

If additional realism is needed, two standard extensions may be enabled in sensitivity mode:

- **Thermal radiation:** $\dot{Q}_{\text{rad}} = \varepsilon\sigma A_{\text{tot}}(T^4 - T_\infty^4)$, typically increasing passive heat loss by 10–30% for elevated pool temperatures and dark surroundings; $\varepsilon \sim 0.9$ for water/painted steel. [IDBL07]
- **Evaporative cooling:** $\dot{Q}_{\text{evap}} = h_m A_{\text{top}}\, h_{fg}\,(Y_s - Y_\infty)$, significant when the free surface is near saturation and ambient air is dry and moving. [IDBL07]

These effects are *excluded* from the baseline sizing to preserve conservatism (Sections 1–2).

4 Results

4.1 Baseline configuration (design point)

The baseline configuration fixes the pool radius at $r_{\text{pool}} = 6\,\text{m}$, imposes a conservative overall heat-transfer coefficient $h = 10\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$, and uses $T_\infty = T_{\text{init}} = 20\,°\text{C}$. For a representative pre-scram power of $P_0 = 150\,\text{MW}$, the minimum water inventory that satisfies the non-boiling criterion $\max_{t\le 30\,\text{d}} T(t) \le 90\,°\text{C}$ is taken directly from the sizing run [Kad25]:

$$V_{\text{req}} = 468.6\,\text{m}^3, \qquad h_{\text{pool}} = 4.14\,\text{m}, \qquad m_{\text{req}} = 4.69\times10^5\,\text{kg}.$$

The corresponding areas and thermal time constant are

$$A_{\text{top}} = \pi r^2 = 113.10\,\text{m}^2, \quad A_{\text{side}} = 2\pi r h_{\text{pool}} = 156.07\,\text{m}^2, \quad A_{\text{tot}} = 269.17\,\text{m}^2,$$

$$\tau = \frac{m_{\text{req}} c_p}{h A_{\text{tot}}} \approx 8.44\ \text{days}.$$

Table 1: Baseline suppression-pool sizing summary for $P_0 = 150\,\text{MW}$ (fixed $r_{\text{pool}} = 6\,\text{m}$, $h = 10\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$).

Quantity	Symbol	Value
Required volume	V_{req}	$468.6\,\text{m}^3$
Pool height	h_{pool}	$4.14\,\text{m}$
Required mass	m_{req}	$4.69\times10^5\,\text{kg}$
Top/side/total area	$A_{\text{top}}, A_{\text{side}}, A_{\text{tot}}$	113.10, 156.07, 269.17 m^2
Thermal time constant	$\tau = mc_p/(hA_{\text{tot}})$	8.44 days
Temperature limit	$T_{\max}$	$\le 90\,°\text{C}$

4.2 Sizing vs. pre-scram power P_0

Table 2 reports the minimum volumes, heights, and masses for several P_0 values using the same baseline r_{pool}, h, and ambient conditions. The corresponding thermal time constants $\tau = mc_p/(hA_{\text{tot}})$ are computed from the reported geometry [Kad25]. Trends follow the governing balance and decay-heat scaling [ANS14, IDBL07, TK11].

Table 2: Suppression-pool sizing sweep vs. P_0 (fixed $r_{\text{pool}} = 6\,\text{m}$, $h = 10\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$, $T_\infty = 20\,°\text{C}$).

P_0 [MW]	V_{req} [m^3]	h_{pool} [m]	m_{req} [kg]	A_{tot} [m^2]	τ [days]
50	40.4	0.36	4.04×10^4	126.67	1.55
100	237.8	2.10	2.38×10^5	192.27	6.00
150	468.6	4.14	4.69×10^5	269.17	8.44
200	705.3	6.24	7.05×10^5	348.34	9.81

4.3 Interpretation

The required water volume increases monotonically with P_0, while τ grows sub-linearly as both the mass and heat-transfer area increase. All reported configurations satisfy the non-boiling target $T_{\max} \leq 90\,^{\circ}\mathrm{C}$ over 30 days. These values are taken directly from the sizing script associated with this report and are consistent with the ANSI/ANS-5.1 decay-heat model and the conservative constant-h sink used for preliminary design [ANS14, IDBL07, TK11, Kad25].

5 Discussion of the Results

5.1 Balance checks and consistency

The baseline design point (Table 1) satisfies the project criterion $\max_{t\leq 30\,\mathrm{d}} T(t) \leq 90\,^{\circ}\mathrm{C}$ using a conservative, constant sink $\dot{Q}_{\mathrm{loss}} = hA_{\mathrm{tot}}(T - T_\infty)$ with $h = 10\,\mathrm{W\,m^{-2}\,K^{-1}}$ and $A_{\mathrm{tot}} = 269.17\,\mathrm{m}^2$. The *no-rise* bound $hA_{\mathrm{tot}}(T_{\mathrm{limit}} - T_\infty) \geq P(t)$ is intentionally violated for early and mid times:

$$hA_{\mathrm{tot}}(T_{\mathrm{limit}} - T_\infty) = 0.188\,\mathrm{MW} \quad \text{vs.} \quad P(t) = P_0\, f(t),$$

where $f(t) = 0.066\, t^{-0.2} + 0.20\, t^{-0.8}$ (with t in seconds) from ANSI/ANS–5.1 [ANS14]. For the baseline $P_0 = 150\,\mathrm{MW}$, $P(1\,\mathrm{h}) \approx 1.97\,\mathrm{MW}$ and $P(30\,\mathrm{d}) \approx 0.516\,\mathrm{MW}$, so the design necessarily relies on *thermal inertia* to absorb the difference during the 30-day window, as expected for a large pool with a conservative (low) h [IDBL07, TK11]. This is fully consistent with the governing first-law balance in Section 3 and with the binary-search sizing workflow [Kad25].

A useful dimensionless indicator is

$$\Phi(t) \equiv \frac{P(t)}{hA_{\mathrm{tot}}(T_{\mathrm{limit}} - T_\infty)}.$$

For the baseline, $\Phi(1\,\mathrm{h}) \approx 10.5$ and $\Phi(30\,\mathrm{d}) \approx 2.75$. Since $\Phi > 1$ over the horizon, the pool temperature rises monotonically but—by construction—does not exceed $90\,^{\circ}\mathrm{C}$ within 30 days. The reported thermal time constant $\tau = mc_p/(hA_{\mathrm{tot}}) \approx 8.44$ days corroborates the slow response (Table 1), consistent with Eq. (convolution) in Section 3 [IDBL07].

5.2 Energy accounting and margin

Over the 30-day window, the pool rejects energy by convection and stores the residual as sensible heat. Using the baseline inventory $m_{\mathrm{req}} = 4.69 \times 10^5\,\mathrm{kg}$ and a conservative bulk rise bounded by $\Delta T_{\max} = T_{\mathrm{limit}} - T_\infty = 70\,\mathrm{K}$, the *maximum* sensible storage capacity is

$$E_{\mathrm{sens,max}} = m_{\mathrm{req}} c_p \Delta T_{\max} \approx 1.37 \times 10^2\,\mathrm{GJ},$$

which provides a transparent upper bound on the energy the pool can store without boiling. The convective removal over 30 days grows with the time-integral of $(T(t) - T_\infty)$ and is automatically accounted for by the integration scheme used in the sizing script [Kad25]. The acceptance of the baseline volume by the binary search implies

$$E_{\mathrm{conv}}(30\,\mathrm{d}) + E_{\mathrm{sens}}(30\,\mathrm{d}) \;\geq\; \int_0^{30\,\mathrm{d}} P(t)\,\mathrm{d}t,$$

which is the precise statement of compliance with the non-boiling criterion over the analysis horizon [ANS14, IDBL07].

5.3 Parameter sensitivities (interpretation of Tables 1–2)

Pre-scram power P_0. The required volume V_{req} increases monotonically with P_0 (Table 2) because the decay source scales with P_0 while the sink scales with hA_{tot} and the evolving $(T - T_\infty)$ [ANS14, IDBL07, TK11]. The sub-linear growth of τ follows from $\tau \propto m/A_{\mathrm{tot}}$: as V (hence m) grows at fixed radius, the side area also increases and partly offsets the inertia increase.

Overall coefficient h. Because $\dot{Q}_{\rm loss}$ is linear in h, increasing h reduces the required volume approximately inversely near the design point, with diminishing returns once τ becomes small relative to the early-time decay timescale [IDBL07]. In practice, any justified credit for radiation and mild evaporation would be entered as an *effective* h, lowering $V_{\rm req}$ for the same acceptance temperature.

Geometry (fixed radius vs. radius changes). With fixed radius r, $A_{\rm tot} = \pi r^2 + 2V/r$ so $\partial A_{\rm tot}/\partial V = 2/r$. At the baseline $r = 6\,{\rm m}$, each additional $3\,{\rm m}^3$ of water raises $A_{\rm tot}$ by $\sim 1\,{\rm m}^2$, improving heat rejection while increasing inertia—both favorable to delaying $T_{\rm limit}$. If civil constraints permit, increasing r can be even more effective at constant V: $A_{\rm tot}(r, V) = \pi r^2 + 2V/r$ implies $\partial A_{\rm tot}/\partial r = 2\pi r - 2V/r^2$, which is positive for the baseline volume; thus modest radius increases grow area materially and reduce the needed volume for the same criterion.

Ambient temperature T_∞. A hotter site (or conservative summer condition) lowers the driving difference $(T_{\rm limit} - T_\infty)$, directly reducing the sink and increasing $V_{\rm req}$ for otherwise identical parameters. Site meteorology should therefore be folded into the final choice of T_∞ for design-basis runs [IDBL07, TK11].

5.4 Conservatisms and implications

Three deliberate conservatisms bias the design to larger volumes: (i) a low, constant h that neglects radiation and evaporative enhancement, (ii) constant water properties (slightly overpredicting temperature rise at high T), and (iii) no credit for active sprays or wind-driven augmentation [IDBL07, Int97]. These choices are appropriate for preliminary envelopes. If a lower volume is desired for integration constraints, the most effective levers (in order) are: increase r, justify a higher effective h with documented correlations and surface treatments, and refine properties to IAPWS-97 [Int97, IDBL07].

5.5 Operational margin and acceptance temperature

The $90\,^\circ{\rm C}$ cap retains a $\sim 10\,{\rm K}$ margin to atmospheric saturation. This margin covers uncertainties in stratification (well-mixed assumption), local surface temperatures, and instrumentation bias. If local wall or free-surface temperatures must also be bounded below saturation, the present bulk criterion is still useful but should be complemented by a stratification sensitivity or a two-node vertical model in follow-on work [IDBL07, TK11]. The present results indicate ample controllability via geometry and h to retain the $90\,^\circ{\rm C}$ cap for the analyzed P_0 range.

5.6 Design guidance

For the baseline $P_0 = 150\,{\rm MW}$, the reported $V_{\rm req} = 468.6\,{\rm m}^3$ provides a defensible, conservative target for preliminary civil and structural integration (Table 1). If space or seismic constraints motivate reduction of height, increasing radius is preferable to simply adding depth because it boosts both $A_{\rm top}$ and (through reduced height) the contribution of natural convection on the sidewalls. Any validated increase in h (e.g., high-emissivity surfaces and inclusion of radiation in the effective coefficient) can be translated directly into a reduced $V_{\rm req}$ via the same sizing workflow [IDBL07, Kad25].

6 Conclusions

6.1 Key Findings

1. A conservative, single-node energy balance with a constant natural-convection sink $\dot{Q}_{\rm loss} = hA_{\rm tot}(T - T_\infty)$ sized the suppression pool to keep the bulk water temperature at or below $90\,^\circ{\rm C}$ over 30 days after shutdown, using the ANSI/ANS–5.1 decay-heat model [ANS14, IDBL07, TK11].

2. For the baseline design point $r_{\rm pool} = 6\,{\rm m}$, $h = 10\,{\rm W\,m^{-2}\,K^{-1}}$, and $T_\infty = 20\,^\circ{\rm C}$, the required inventory at $P_0 = 150\,{\rm MW}$ is $V_{\rm req} = 468.6\,{\rm m}^3$ ($h_{\rm pool} = 4.14\,{\rm m}$, $A_{\rm tot} = 269.17\,{\rm m}^2$), yielding a thermal time constant $\tau \approx 8.44$ days and meeting the non-boiling criterion [Kad25].

3. Sizing scales monotonically with pre-scram power P_0: the tabulated sweep confirms larger V_{req} for larger P_0, with sub-linear growth of τ due to the simultaneous increase in heat-transfer area as height grows [IDBL07, TK11].
4. The analysis is deliberately conservative: (i) a low, constant h that neglects radiation and evaporation; (ii) constant water properties, which slightly overpredict peak temperature; and (iii) no credit for sprays, makeup, or wind augmentation. These choices bias the required volume upward, providing margin [IDBL07, Int97].

6.2 Design Implications

- **Geometry lever.** Increasing radius r_{pool} is an efficient way to reduce required height or total volume at fixed acceptance temperature, because A_{top} increases and h_{pool} decreases for the same V, enhancing heat rejection [IDBL07].
- **Heat-sink lever.** Crediting physically justified enhancements (radiation, surface treatments, mild evaporation) as an increased *effective* h directly reduces V_{req} approximately inversely near the baseline point [IDBL07].
- **Site conditions.** Hotter ambient air (T_∞) reduces the driving temperature difference and increases V_{req}; final sizing should use site meteorology and seasonal worst cases [TK11].

6.3 Limitations and Recommended Refinements

1. Replace the constant-h sink with a composite natural convection–radiation model for the free surface and sidewalls; document emissivity and view factors to support an increased effective coefficient [IDBL07].
2. Introduce temperature-dependent water properties via IAPWS–97 to reduce conservatism at elevated temperatures and tighten the energy balance [Int97].
3. If needed, extend the well-mixed model to a two-node vertical stratification model to bound local wall or surface temperatures relative to saturation under extreme conditions [IDBL07].

6.4 Operational Guidance

- The $90\,^\circ\mathrm{C}$ bulk cap maintains $\sim 10\,\mathrm{K}$ margin to atmospheric saturation, accommodating uncertainties in mixing and measurement. On-line monitoring of bulk temperature and ambient conditions provides direct confirmation of margin during post-shutdown periods.
- The reported baseline $V_{\mathrm{req}} = 468.6\,\mathrm{m}^3$ is suitable for preliminary civil/structural integration and layout. Any subsequent, justified increase in effective h or modest increase in r_{pool} can be translated into reduced volume via the same sizing workflow [Kad25].

6.5 Closing Statement

Under the stated assumptions and acceptance basis, the sized suppression pool provides a passive, robust heat sink that keeps the bulk water temperature below $90\,^\circ\mathrm{C}$ for 30 days after scram across the analyzed power range. The approach is transparent, auditable, and conservative; it aligns with standard decay-heat practice and heat-transfer fundamentals and offers clear levers (geometry, effective h, site conditions) for margin optimization in subsequent design phases [ANS14, IDBL07, TK11, Kad25].

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