

Necessity and Satisfaction Conditions of the Maximum Fuel Temperature Design Limit in Research Reactors with Plate-Type Fuel

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1. Introduction

Plate-type dispersion fuels for high-performance research reactors exhibit a distinct change in irradiation behavior at elevated fuel temperature [1,2]. Post-irradiation examinations compiled by Hofman et al. [1] show that U_3Si_2 -Al dispersion fuel irradiated at fuel temperatures of 200 °C and higher behaves clearly differently from the large body of experience accumulated at 100–165 °C, and they conclude that a maximum fuel meat temperature of 200 °C, including realistic uncertainties, constitutes a main performance limit of such fuel designs. The temperature sensitivity itself has long been known: annealing tests of U_3Si_2 dispersion fuel reviewed by Nazaré [2] identified the temperature range in which the formation of the low-density fuel-matrix interaction layer, the driver of rapid swelling, remains negligible. On this basis, a fuel temperature design limit of 200 °C has been proposed for U-7Mo plate-type fuel to preclude rapid swelling caused by fuel-matrix interaction [3], and the fuel qualification program required the maximum fuel temperature to remain below this limit under enveloping irradiation conditions [4].

In this study, this fuel design limit is taken as the maximum fuel temperature criterion during normal operation of a representative open-pool research reactor with plate-type fuel, and its role in the core thermal-hydraulic (TH) design is examined. This choice of criterion is not universal: U.S. non-power reactor licensing practice protects plate-type fuel during normal operation primarily through departure-from-nucleate-boiling and flow-instability margins rather than through a fuel temperature limit, noting that the fuel temperature of plate-type elements is not a directly measurable quantity [5,6].

An earlier parametric study by Im et al. [7] examined the influence of fuel thermal conductivity, oxide layer, and engineering hot channel factors on the maximum temperature of plate-type fuel; the present work builds on that sensitivity structure and extends it to the level of design limit values and their practical management.

Two questions are addressed. First, how does the 200 °C criterion actually operate in the TH design space — is

it reached before the conventional thermal margins (onset of nucleate boiling, flow instability, critical heat flux)? Second, if it governs, what must be managed to satisfy it — that is, what are the 200 °C-equivalent limit values of the design and operating variables, and which of them carries the practical management burden?

2. Methods

2.1. Reference reactor and analysis conditions

A hypothetical reference reactor representative of modern open-pool multipurpose research reactors is defined: thermal power 20 MW with a fuel-plate power fraction of 0.95, core-average heat flux of 711 kW/m², inlet temperature 36 °C, a pool-side pressure of 1.8 bar at the core top (the pressure boundary of an open-pool core; the resulting channel-inlet pressure is about 3.4 bar), upward channel velocity 9 m/s, and a total power peaking factor (PPF) of 3.0 composed of a radial factor of 2.5 and a chopped-cosine axial shape with a peak of 1.2 (used for the TH analyses; the oxide-growth calculation of Section 2.3 uses a bounding outlet-peaked shape). The PPF is defined to include the core-calculation uncertainty. The end-of-life (EOL) peak cladding oxide thickness is treated as a design parameter with a reference value of 50 μm.

2.2. Thermal-hydraulic model

Steady-state single-channel analyses were performed with a one-dimensional TH code developed by the author. Single-phase convection is modeled by the Dittus-Boelter correlation and friction by the Blasius correlation; the onset of nucleate boiling (ONB) by the Bergles-Rohsenow correlation [8]; the onset of flow instability (OFI) by the Whittle-Forgan criterion [9] with the parameter $\eta = 32.5$ — the conservative value proposed in the later literature [10] rather than the best-fit value of 25 in the original work; and critical heat flux by the Sudo-Kaminaga correlation [11]. Water properties follow IAPWS-IF97. Thermal margins are reported as ratios. For ONB, the PLTEMP definition of the onset-of-nucleate-boiling ratio is adopted [12]: $ONBR = (T_{ONB} - T_{in}) / (T_{wall} - T_{in})$, evaluated on the hot channel with the hot

channel factors applied and with T_{ONB} computed at the locally increased heat flux. Because the wall temperature rise from the inlet scales approximately with power, this ratio can be read as the power multiple at which ONB would be reached; $\text{ONBR} = 1$ corresponds to the onset of nucleate boiling. For OFI, the PLTEMP channel-power definition is likewise adopted [12]: the Whittle–Forgar criterion places OFI at the channel power for which the bulk outlet temperature rise reaches the fraction $R = 1/(1 + \eta/(L/D_h))$ of the inlet-to-saturation rise, and OFIR is the ratio of that power to the operating channel power, evaluated on the hot channel with the hot channel factors applied. Engineering hot channel factors are combined following Appendix V of the PLTEMP/ANL manual [12] — random tolerances by root-sum-square and systematic ones multiplicatively — and are applied deterministically to the bulk, film, and conduction temperature rises of the hot channel. The core-calculation uncertainty is excluded from the factors because the PPF definition above already contains it; double counting would otherwise result. The factor values themselves are design-specific and are not reported.

The code was verified against the PLTEMP/ANL 4.4 code [12] on an equivalent single-channel problem: computed temperatures agreed within 0.5 °C, and the ONBR, OFIR, and DNBR within 1 %, the residuals being traceable to the different steam-table implementations.

The temperature rise across the oxide layer is computed with two thermal-conductivity models spanning the range of common practice — the oxide thermal conductivity being among the most influential parameters for the maximum fuel temperature [7]: a constant 2.25 W/m·K, and a thickness-dependent degradation model, $k(t) = 2.25 - 0.016(t - 25)$ W/m·K, where t is the oxide layer thickness in μm , for $t > 25 \mu\text{m}$ [13], referred to below as the " $k(t)$ model". The maximum fuel temperature is evaluated with the EOL oxide thickness imposed simultaneously with the peak power condition; the conservatism of this non-simultaneous superposition is discussed in Section 4.

2.3. Evaluation of end-of-life oxide thickness

To connect the oxide-thickness parameter to its practical management variable, EOL oxide thickness was additionally computed as a function of coolant pH using the revised Kim model [14], whose rate law and the underlying solubility formulation [13] make the growth kinetics an explicit function of oxide–water interface temperature, surface heat flux, coolant velocity, and pH. A physically bounding exposure history was adopted: the hot spot is held at the full PPF of 3.0 until the local burnup reaches 100 at.% (its physical ceiling), which bounds every achievable shuffling history because oxide growth increases monotonically with the time at high flux; the local burnup rate is evaluated from the local heat flux on an energy basis (200 MeV per fission, capture

included). In addition, the axial power shape for this calculation places its peak (1.2, with 0.8 at the inlet) at the channel outlet, bounding the axial-peak location where the local heat flux coincides with the warmest coolant; the resulting history is a deliberately conservative, bounding assumption adopted for the sensitivity calculations of this study. A model prediction uncertainty factor was applied to the growth rate constant. The oxide–water interface temperature was evaluated with the same hot-channel treatment as in Section 2.2.

3. Results

3.1. The 200 °C criterion at the reference point

Table I summarizes the reference case. With the constant-conductivity oxide model the maximum fuel temperature reaches 196.8 °C: the fuel-temperature margin is nearly exhausted, only 3.2 °C below the limit. The conventional thermal margins computed at the same time are: the minimum ONBR is 1.18, the minimum OFIR is 2.27, and the minimum DNBR is 2.79. The ONBR here is the PLTEMP-definition ratio of Section 2.2: the value of 1.18 means the reactor power would have to increase by roughly 18 % before ONB, even in the fully factored hot-channel state. Figure 1 shows the axial distributions. Under the TH inputs and hot-channel methodology adopted here, the 200 °C limit is reached before ONB, OFI, and DNB; compared with the conventional thermal margins, it is therefore a criterion that warrants full consideration in the core TH design.

With the thickness-dependent $k(t)$ oxide-conductivity model of Section 2.2 [13], the same reference case yields 209.3 °C, exceeding the limit by 9.3 °C. The choice of oxide thermal-conductivity model alone decides compliance — a first indication that the practical substance of this criterion lies in the oxide layer, developed quantitatively below.

Table I: Reference case results (20 MW, 9 m/s, PPF 3.0, EOL oxide 50 μm)

Quantity	$k = 2.25$ W/m·K	$k = k(t)$
Max. fuel temperature [°C]	196.8	209.3
Margin to 200 °C [°C]	+3.2	−9.3
Min. ONBR (PLTEMP definition) [–]	1.18	1.18
Min. OFIR [–]	2.27	2.27
Min. DNBR (Sudo–Kaminaga) [–]	2.79	2.79

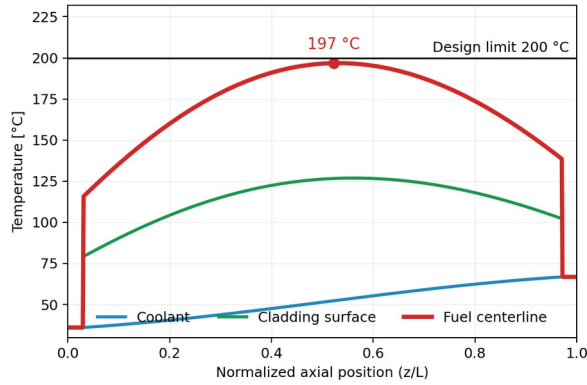


Fig. 1. Axial distributions of the hot-channel temperatures at the reference condition.

3.2. 200 °C-equivalent limit values and the heat-flux ceiling

Every design variable possesses a 200 °C-equivalent limit value, and Figure 2 collects them in a single map: the allowable core-average heat flux — the quantity that sets the neutron flux the core can host — as a function of the EOL oxide thickness, for 8–10 m/s and the two oxide-conductivity models (up to 25 μm the models coincide, since $k(t) = 2.25 \text{ W/m}\cdot\text{K}$ there). The open circle marks the reference design point, and the shaded areas below the 9 m/s curves mark the achievable region under both conductivity models (green) and under $k_{\text{ox}} = 2.25 \text{ W/m}\cdot\text{K}$ only (orange). Read horizontally at the installed flux of 711 kW/m^2 , the 9 m/s curves give the allowable EOL thickness: 52.8 μm with $k_{\text{ox}} = 2.25$ and 45.2 μm with the $k(t)$ model. For the former, the 8 and 10 m/s curves give 45.5 and 58.8 μm , so ± 1 m/s moves the allowable thickness only modestly. Read vertically at the reference thickness of 50 μm , the allowable flux is 726 kW/m^2 (672 kW/m^2 with $k(t)$) against 711 installed, and the minimum velocity holding 50 μm is 8.6 m/s (10.4 m/s with $k(t)$). Every limit value lies immediately adjacent to its reference, confirming that the design is pinned to the 200 °C surface; under the $k(t)$ model the reference point already sits above its curve — the verdict of compliance depends on the oxide property model before it depends on any TH variable.

The same map fixes the ceiling of the configuration. With no oxide the core could sustain 1.09–1.28 MW/m^2 at 8–10 m/s (1.18 at 9 m/s), so the 50 μm oxide layer consumes roughly 40 % of the thermally possible heat flux, while at 50 μm one m/s of velocity moves the allowable flux by only about 5 % (about 8 % with no oxide — the oxide conduction ΔT does not respond to velocity); at 100 μm and 9 m/s the allowable flux collapses to 0.33–0.53 MW/m^2 across the two conductivity models. For velocities and EOL oxide thicknesses near those of the reference design, the resulting ceiling is roughly 0.7–0.8 MW/m^2 core-average; both variables are design-specific, and the

ceiling shifts with them. Research reactors designed at average heat fluxes of about 1.8 MW/m^2 or higher belong to a different design regime: pressurized primary systems — core inlet pressures of about 1.5–3.3 MPa, adopted primarily for the boiling and CHF margins — and channel velocities of about 15–25 m/s [15–18]. Within the open-pool configuration considered here, a 200 °C-type criterion carries an intrinsic heat-flux ceiling, and the oxide layer sets how much of it is realizable.

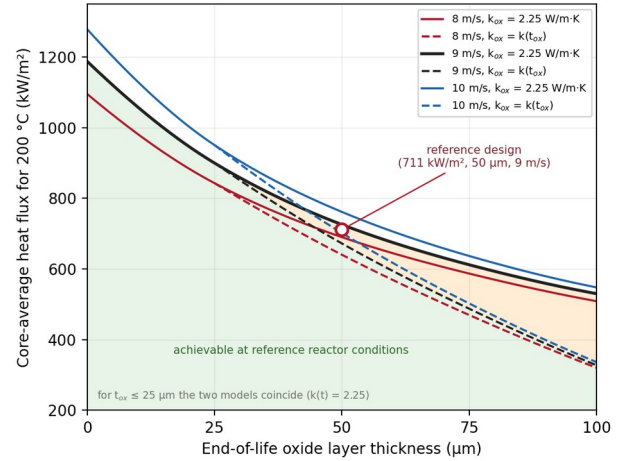


Fig. 2. Allowable core-average heat flux for the 200 °C limit versus EOL oxide thickness.

3.3. Operational levers for preserving the limit

The allowable EOL oxide thickness of 45–53 μm must be delivered over the fuel lifetime by the operational levers. Figure 3 shows EOL peak oxide thickness computed under the bounding exposure history of Section 2.3 as a function of coolant pH, for one-unit adjustments of velocity (± 1 m/s) and power (± 1 MW) about the reference condition — the same steps as the exchange rates of Fig. 4. The dependence on pH is exponential: raising pH from 5.7 to 6.2 multiplies the EOL thickness by about six. Because the allowable oxide thickness itself depends on the condition, the dot on each curve marks the point at which that condition reaches its own allowable value, computed with the TH model of Section 2.2 ($k_{\text{ox}} = 2.25$); each dot is therefore the maximum admissible pH of its condition. At the reference condition this limit lies at pH 5.94; one additional m/s relaxes it to 6.05 and one less tightens it to 5.79, while $-1/+1$ MW move it to 6.02/5.86. Under the $k(t)$ conductivity model each limit shifts lower by roughly 0.04 in pH. The strong pH dependence originates in the oxide solubility, which is minimal near pH 5 and increases with both pH and temperature [12,18]: beyond a solubility threshold the rate-law exponent of the growth kinetics collapses and the oxide switches from self-limiting to nearly linear growth. This mechanism also explains the wide adoption of $\text{pH} \approx 5.7$ as the normal water chemistry of open-pool research reactors [19].

Velocity influences the oxide in two opposing ways — a higher velocity augments growth through oxide-film degradation but reduces the interface temperature through improved heat transfer and reduced bulk heating — and the net effect is beneficial: a single m/s changes the EOL thickness by 30–50 % (Fig. 3).

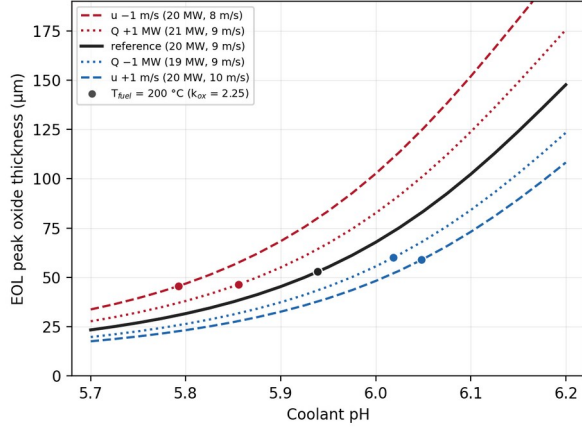


Fig. 3. EOL peak oxide thickness versus coolant pH.

Figure 4 condenses the sensitivity structure into exchange rates: the total reduction of maximum fuel temperature bought by one practical adjustment of each variable at the reference point. Each total is split into a direct thermal component at fixed oxide (dark bars) and a component acting through the EOL oxide thickness of Fig. 3 (light bars); the oxide-thickness bar itself is the master variable through which the operational levers act. The oxide-mediated component dominates every operational lever: 1 m/s of additional velocity is worth 31–48 °C in total, of which only 7.6 °C is direct convective improvement and the rest is thinner oxide; a pH reduction of 0.1 delivers 23–40 °C entirely through the oxide; 1 MW of derating, 19–28 °C (direct about 8 °C); 0.1 of PPF, 13–19 °C (direct about 5 °C); and the oxide conductivity-model choice alone is worth 12.5 °C. The oxide thickness is thus the master variable of the fuel temperature: velocity, pH, power, and PPF act mainly by changing oxide growth. The levers belong to different engineering domains — velocity to the hydraulic design (pumps, piping, pressure drop, and the critical-velocity limit), power and PPF to the core design (configuration, fuel management, and shuffling schemes), and pH to the water-chemistry and purification systems — so the choice among them is a multidisciplinary, design-specific one; the exchange rates of Fig. 4 are offered as the common currency in which it can be made.

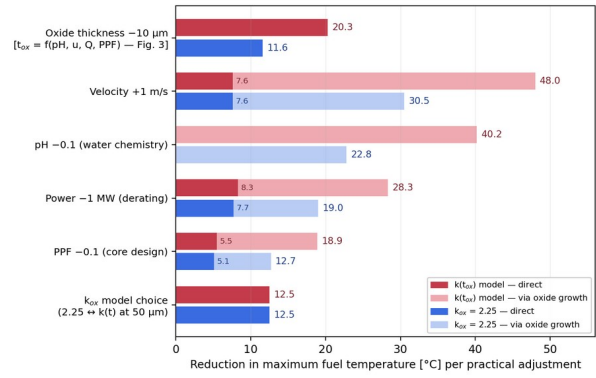


Fig. 4. Reduction of maximum fuel temperature per practical adjustment of each variable at the reference point.

4. Discussion

Four observations follow on the use of the criterion.

Conservatism of the compliance calculation. The demonstration stacks non-simultaneous worst conditions: the EOL peak oxide thickness is imposed together with the peak power condition (PPF 3.0), and deterministic hot-channel factors are applied in addition. Moreover, the fuel degradation behind the limit is a progressive process [1,2], while the criterion is verified as an instantaneous never-exceed limit. Both choices are defensible as bounding practice, but they convert margin that the fuel itself may possess into calculational conservatism.

Compliance is decided by the calculation method.

At the reference point the two accepted oxide-conductivity models return verdicts 12.5 °C apart — larger than the margins typically at stake (Table I). The TH calculation carries uncertainties of the same character: with a margin of only 3.2 °C, a few-percent change in the heat-transfer coefficient, or a different hot-channel-factor treatment, likewise moves the verdict. The oxide models, the TH correlations, and the uncertainty treatment are therefore not analysis details but part of the limit's effective definition. A stated 200 °C criterion is incomplete without them.

The management substance is the oxide layer.

Every result above converges on the same structure: the 200 °C criterion is closely approached at the reference point, its equivalent limit values are pinned to the design point, and the variable with the dominant leverage is the EOL oxide thickness. In practice, therefore, the fuel temperature design limit operates as an oxide-management requirement. How the oxide budget is delivered — by water chemistry, velocity, power, or peaking — is the design-specific choice discussed in Section 3.3.

The form of the criterion. What the limit ultimately protects is fuel integrity, and what is reported above 200 °C [1,2] is not an immediate loss of integrity, such as blistering or burnout, but a change of degradation regime — accelerated interaction-layer growth and swelling.

How far, and over what time, this degradation must proceed before integrity is challenged has not been established. The answer determines the proper form of the criterion. If the damage accumulates with time at temperature, a time-integrated limit is the natural form. More fundamentally, the degradation phenomena themselves could be modeled in the TH evaluation, so that fuel integrity is assessed directly; a separate temperature limit would then no longer be needed. Whether to carry this limit as a design limit is, in the end, an engineering, design, and regulatory judgment.

5. Conclusions

For a representative 20 MW open-pool research reactor with plate-type fuel, the 200 °C maximum fuel temperature design limit was shown, under the inputs and methodology adopted here, to be reached before ONB, OFI, and CHF; compared with the conventional thermal margins, it is a criterion that warrants full consideration in the core TH design. By sweeping the design variables — EOL oxide thickness, coolant velocity, core-average heat flux, power, peaking, and coolant pH — the limit was translated into its 200 °C-equivalent limit values, an intrinsic heat-flux ceiling of the open-pool configuration, and exchange rates among the variables. The practical management substance of the limit is the cladding oxide layer — compliance is decided by the oxide property and growth models, every operational lever acts chiefly through oxide growth, and the choice among the levers is a design-specific, multidisciplinary one. A re-examination of the form of the criterion — time-integrated, or based on explicit modeling of the degradation phenomena — and a formal uncertainty treatment of the oxide models are identified as directions for future work.

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