KOREAN NUCLEAR SOCIETY · AUTUMN MEETING 2026

Evaluation of Off-Design Safety Margins for the ESW–CCW Cooling System

Seawater-temperature response and relative plate augmentation

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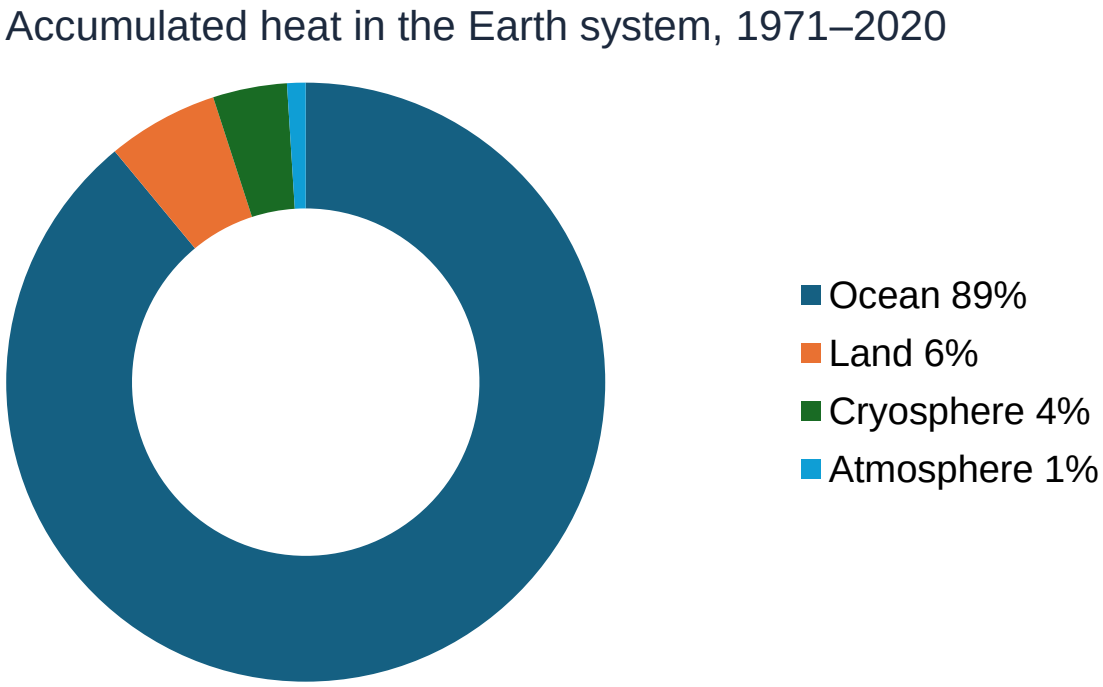
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Seawater warming and cooling requirements



The ocean stores most of the accumulated heat. Coastal cooling systems therefore need evaluation beyond a single seawater design condition.

Seawater as the heat sink

Warmer seawater reduces the temperature difference available for heat rejection through the ESW–CCW heat exchangers.

Cooling performance away from design

We vary the ESW inlet temperature and calculate the resulting CCW outlet temperature to assess the remaining cooling margin.

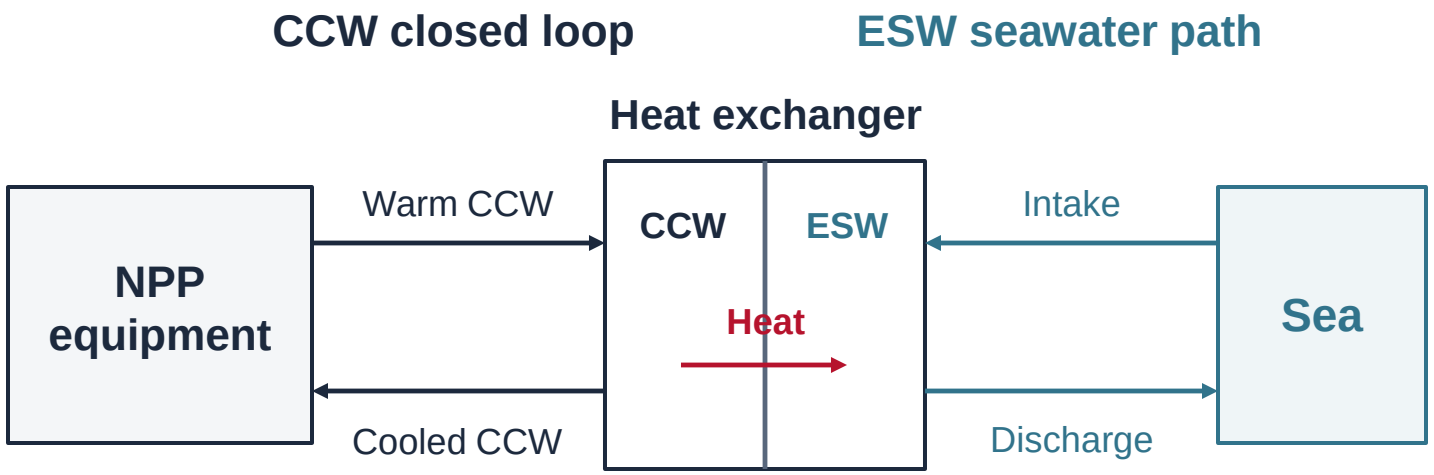
Ocean warming and cooling-water temperature limits

The ocean stores most of the excess heat accumulated in the climate system. Warmer seawater reduces the temperature difference available for heat rejection, affecting nuclear plants that use seawater to remove internal heat.

Plant	Previous criterion	Revised criterion / status	Basis for review or improvement
Millstone 2	23.9°C	26.7°C	Equipment operability at higher UHS temperature
Turkey Point 3 & 4	37.8°C	40.0°C	UHS surveillance, CCW performance and accident conditions
Braidwood 1 & 2	37.8°C	38.9°C	Safety-function capability at higher UHS temperature
Hanul 5 & 6	**30.0°C**	**32.4°C (2009)**	**Reassessment of existing heat-exchanger cooling margin**
Shin-Wolsong 1 & 2	31.5°C	+1.37°C proposed (as of Aug 2025)	Plate augmentation before a proposed design-temperature increase

The five cases cover UHS and design cooling-water criteria. Plant-specific temperature criteria and review bases differ.

NPP–CCW–ESW cooling system



Separate water paths; heat transfer only

CCW removes equipment heat

A closed water loop carries heat from plant equipment to the heat exchangers, then returns cooled water to the equipment.

ESW rejects heat to the sea

Seawater takes heat from CCW across the exchanger plates. CCW and seawater remain physically separate.

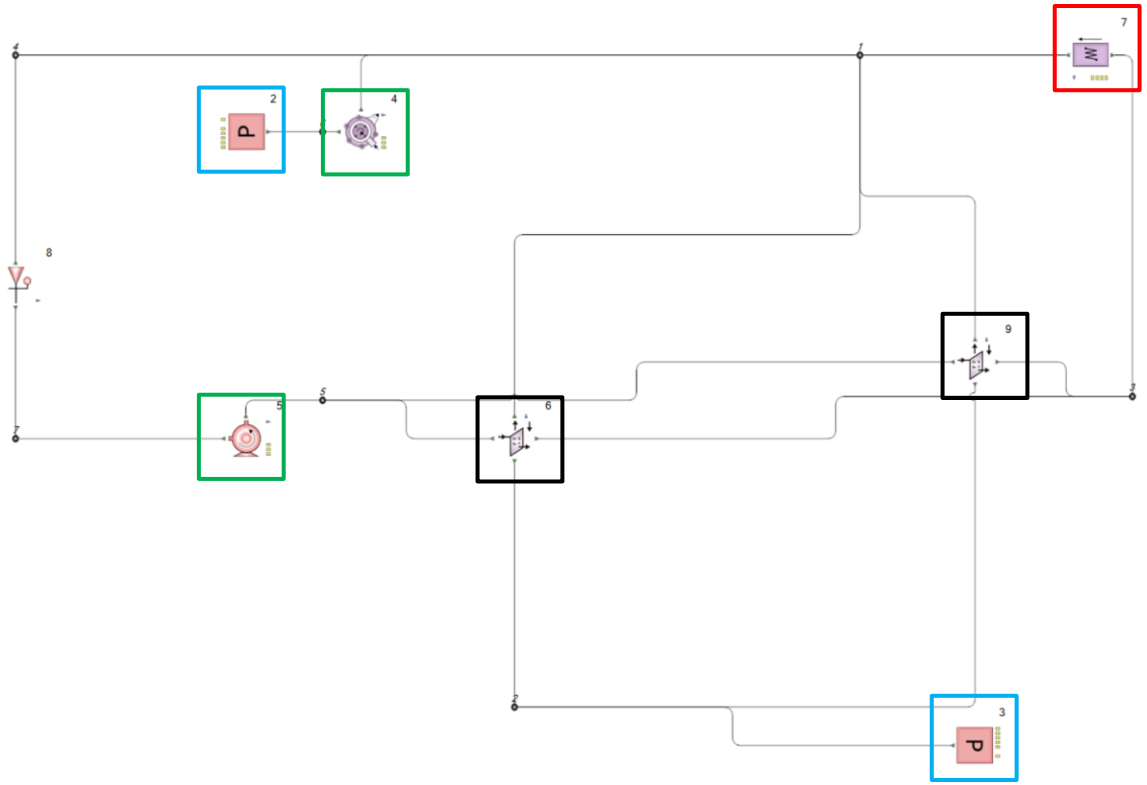
The single-train model represents the coupled heat-transfer and flow response of these two paths.

Operational and safety temperature margins

Reference / definition	Normal Operation	DBA / Post-Accident
CCW supply-temperature reference	35.0°C	43.3°C
ESW design-temperature reference	27.5°C	32.4°C
Temperature margin	Operational margin 35.0 − CCW outlet temperature (°C)	Safety margin 43.3 − CCW outlet temperature (°C)
Operating conditions	Normal	CSAS / SIAS / Recirculation

Each margin uses the CCW outlet temperature from the matching operating condition.
Positive margin means the outlet is below the selected reference.

Single-train Flomaster model



Network configuration

One train contains two parallel hea t exchangers. The model couples t he ESW and CCW flow paths throu gh heat transfer.

Common pump condition

One CCW pump operates in every case. Pump inputs and other factor settings remain unchanged across the comparisons.

Each operating mode uses its single-train heat load without further division. The same network then resolves the thermal and flow response for each condition.

Heat-load conditions

Mode	Single-train heat load (kW)
Normal operation	23,454
SIAS(Safety Injection Actuation Signal)	13,194
CSAS(Containment Spray Actuation Signal)	11,245
Recirculation	58,049

Separate steady-state, single-train load cases. Heat loads are not divided again.

Simulation Matrix

Variable	Evaluated range
ESW inlet temperature	20–40°C · 23 points
Relative plate augmentation	0%, 10%, 20%, 30%, 40%, 50%
Heat-load conditions	4 modes

ESW: 27.5°C Normal / 32.4°C DBA

CCW: 35.0°C Normal / 43.3°C DBA

The temperature and plate-augmentation sweep is repeated for each of the four modes.

Heat balance and heat transfer

Steady-state energy balance

$$\dot{Q} = \dot{m}_{\mathrm{CCW}} c_{p,\,\mathrm{CCW}} (T_{\mathrm{CCW,\,in}} - T_{\mathrm{CCW,\,out}}) = \dot{m}_{\mathrm{ESW}} c_{p,\,\mathrm{ESW}} (T_{\mathrm{ESW,\,out}} - T_{\mathrm{ESW,\,in}}) \tag{1}$$

Overall heat-transfer relation

$$\dot{Q} = UA\Delta T_{\mathrm{m}} \tag{2}$$

in/out refer to heat-exchanger ports. ΔT_{m} is the effective mean temperature difference.
The coupled network solution accounts for both heat transfer and flow.

Temperature margins and criterion crossing

Normal Operation

$$M_{op}(T_{ESW,in}, r) = 35.0 - T_{CCW,out,Normal}(T_{ESW,in}, r) \quad (3a)$$

DBA / Post-Accident

$$M_{s}(T_{ESW,in}, r) = 43.3 - T_{CCW,out,mode}(T_{ESW,in}, r) \quad (3b)$$

Positive margin: modeled CCW outlet is below the applicable reference.

Recirculation criterion crossing

$$T^{*}_{\mathrm{ESW,\,in}} = T_{\mathrm{ESW,\,in},\,i} + \frac{43.3 - T_{\mathrm{CCW,\,out},\,i}}{T_{\mathrm{CCW,\,out},\,i+1} - T_{\mathrm{CCW,\,out},\,i}}\left(T_{\mathrm{ESW,\,in},\,i+1} - T_{\mathrm{ESW,\,in},\,i}\right) \quad (4)$$

r: relative plate augmentation. Adjacent ESW inlet points bracket CCW 43.3°C at fixed r.

Interpolation gives the modeled criterion crossing. Licensed operating limits are outside this analysis.

Sensitivity and flow-change measures

$$\bar{S}(r) = \frac{T_{\mathrm{CCW,\,out}}(40, r) - T_{\mathrm{CCW,\,out}}(20, r)}{(40 - 20)\,^{\circ}\mathrm{C}} \tag{5}$$

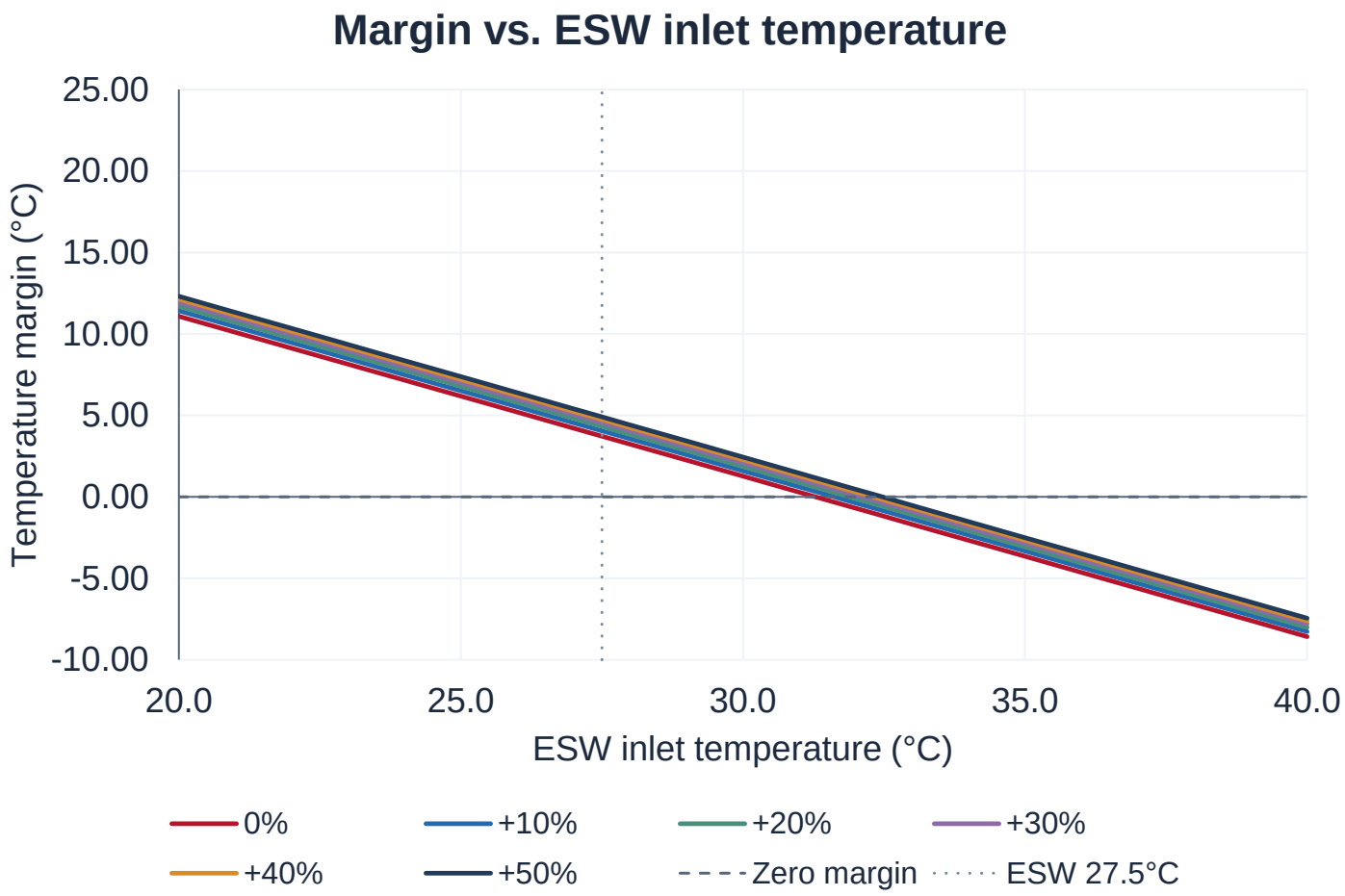
$$S_i(r) = \frac{T_{\mathrm{CCW,\,out}}(T_{\mathrm{ESW,\,in},\,i+1}, r) - T_{\mathrm{CCW,\,out}}(T_{\mathrm{ESW,\,in},\,i}, r)}{T_{\mathrm{ESW,\,in},\,i+1} - T_{\mathrm{ESW,\,in},\,i}} \tag{6}$$

$$G(r) = T_{\mathrm{CCW,\,out}}(32.4, r) - T_{\mathrm{CCW,\,out}}(32.4, r + \Delta r) \tag{7}$$

$$\delta \dot{V}_j(r) = \left[\frac{\dot{V}_j(r)}{\dot{V}_j(0\%)} - 1\right] \times 100\% \tag{8}$$

Each mode is evaluated separately. r = 0%, 10%, …, 50%. Δr = 10 percentage points.
Reported gains and flow changes use ESW inlet 32.4°C. j: ESW or CCW flow path.

Normal Operation: operational margin

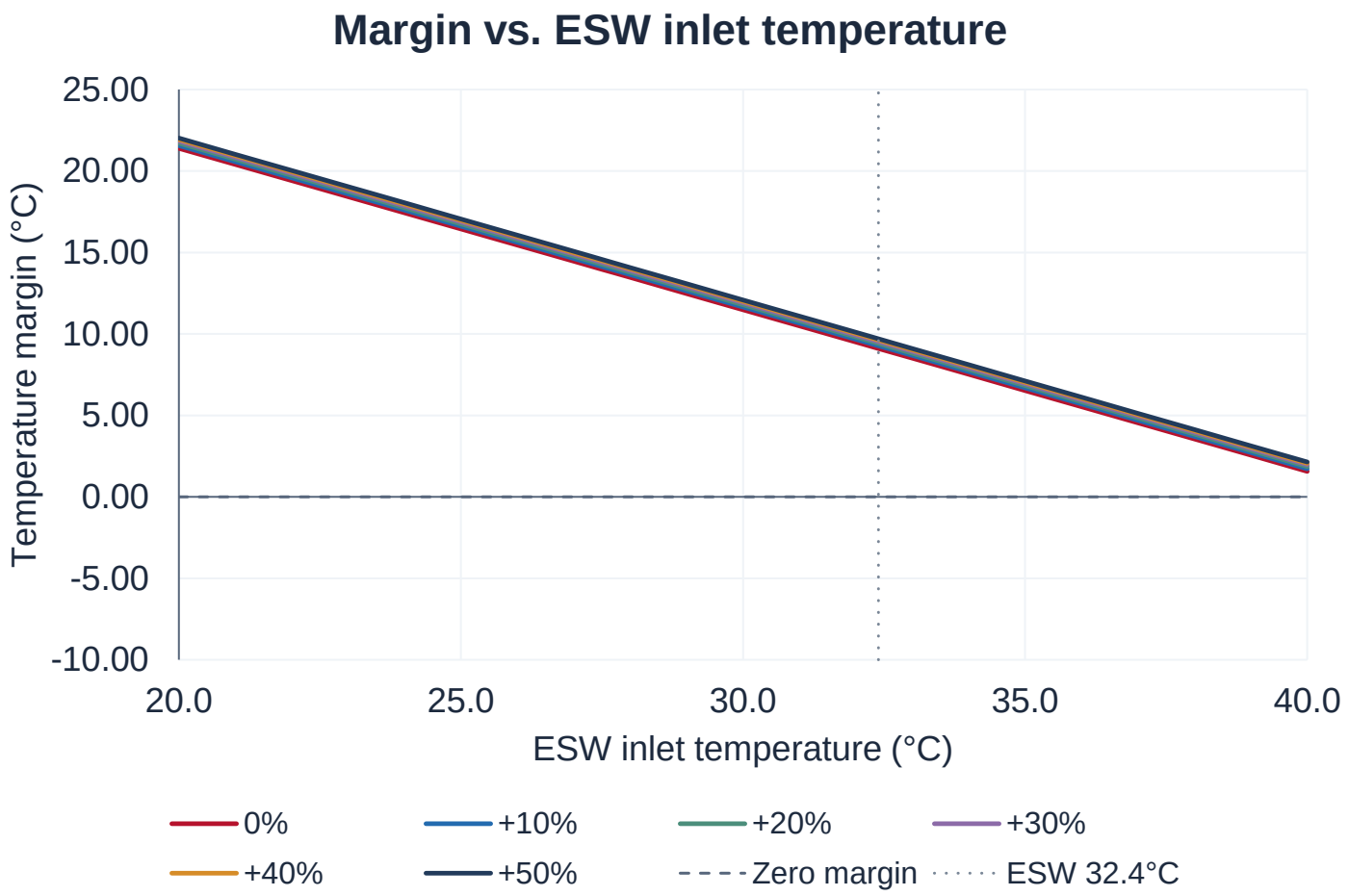


At ESW 27.5°C

Margin = 35.0°C − CCW outlet

Augmentation	CCW outlet (°C)	Margin (°C)
0%	31.28	3.72
+10%	30.95	4.05
+20%	30.67	4.33
+30%	30.45	4.55
+40%	30.25	4.75
+50%	30.09	4.91

DBA / Post-Accident: CSAS safety margin

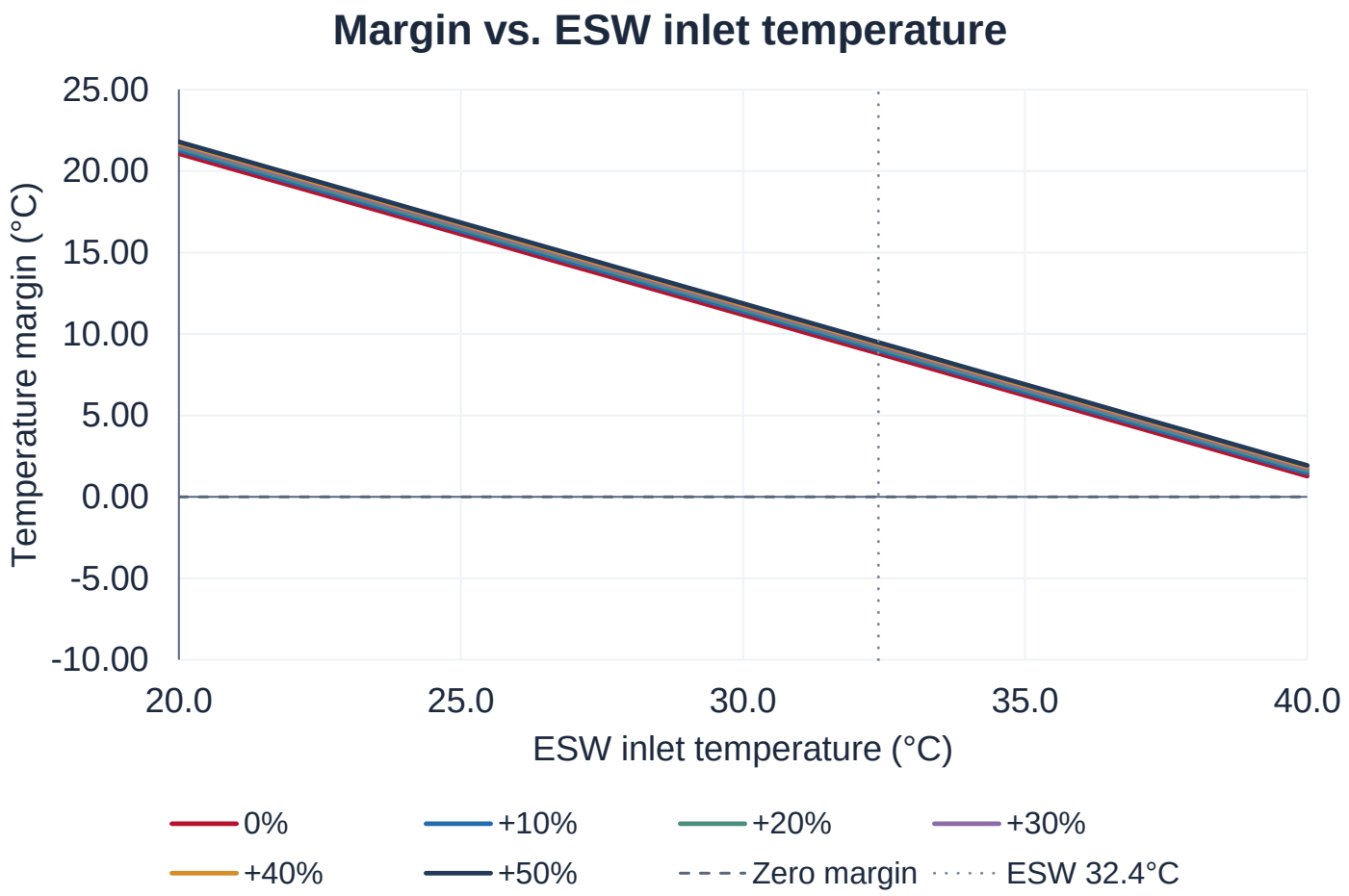


At ESW 32.4°C

Margin = 43.3°C − CCW outlet

Augmentation	CCW outlet (°C)	Margin (°C)
0%	34.20	9.10
+10%	34.03	9.27
+20%	33.89	9.41
+30%	33.78	9.52
+40%	33.68	9.62
+50%	33.60	9.70

DBA / Post-Accident: SIAS safety margin

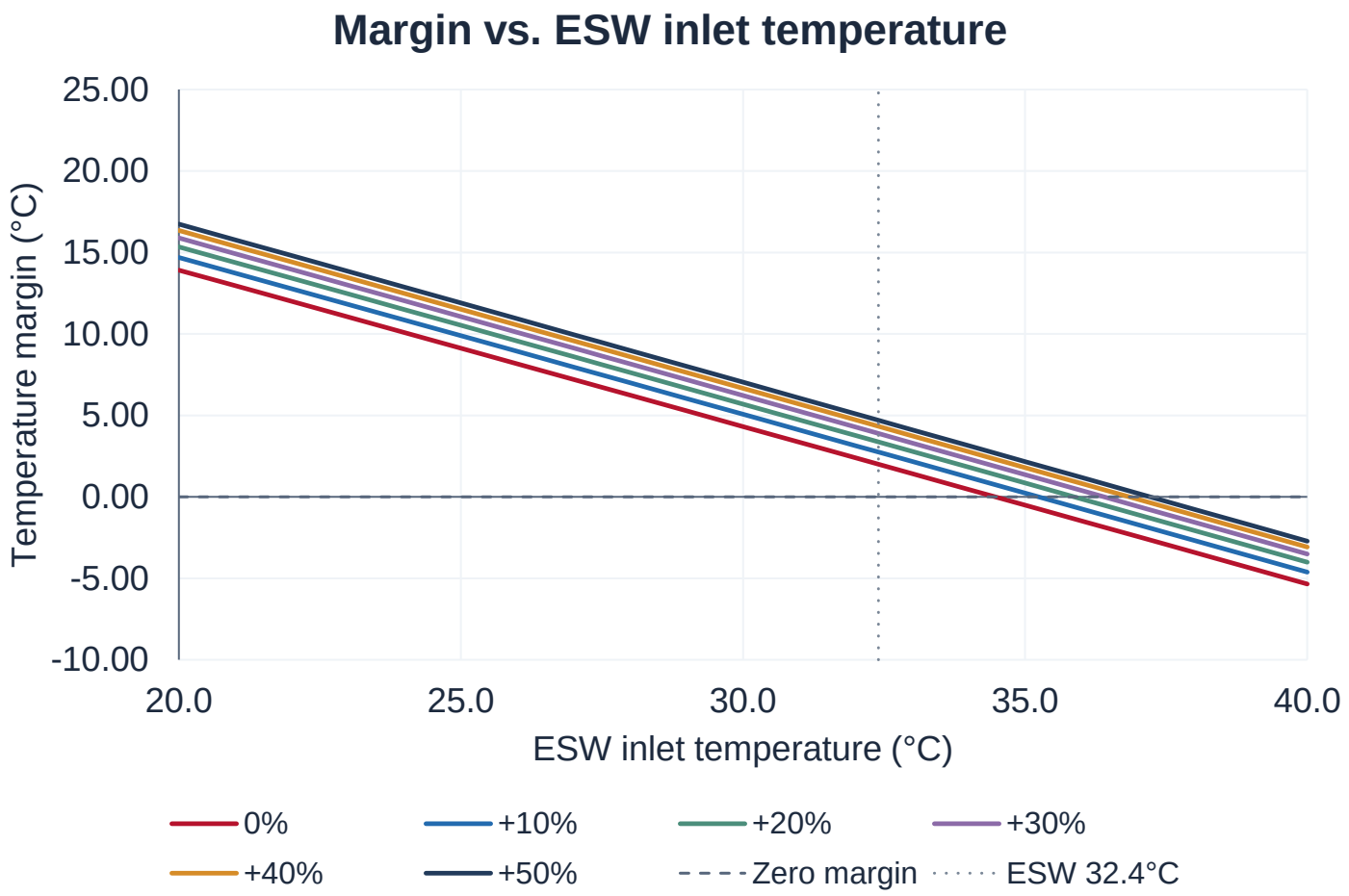


At ESW 32.4°C

Margin = 43.3°C − CCW outlet

Augmentation	CCW outlet (°C)	Margin (°C)
0%	34.50	8.80
+10%	34.31	8.99
+20%	34.15	9.15
+30%	34.02	9.28
+40%	33.91	9.39
+50%	33.82	9.48

DBA / Post-Accident: Recirculation safety margin

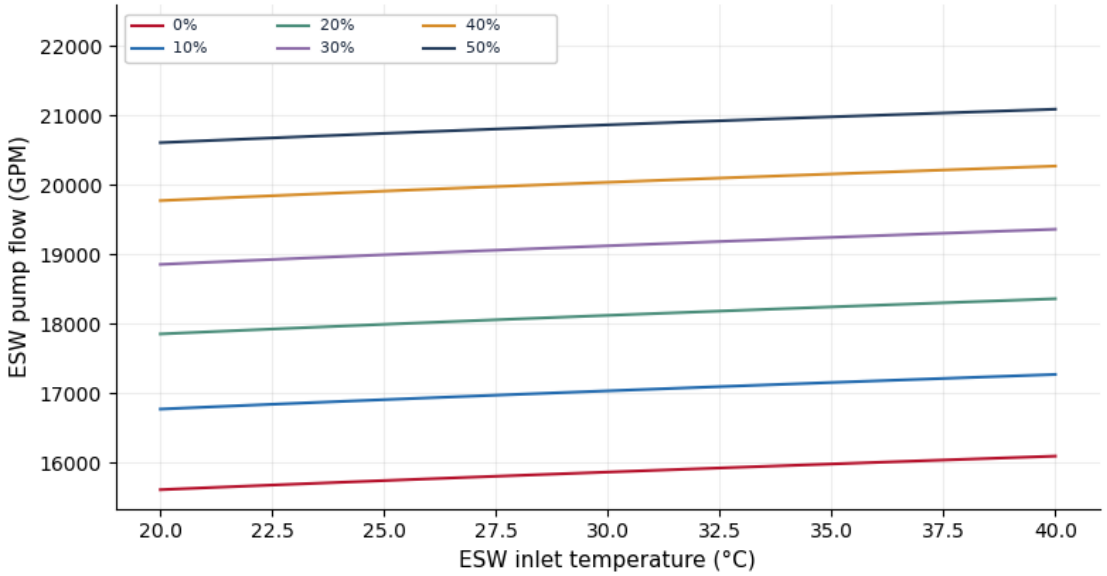


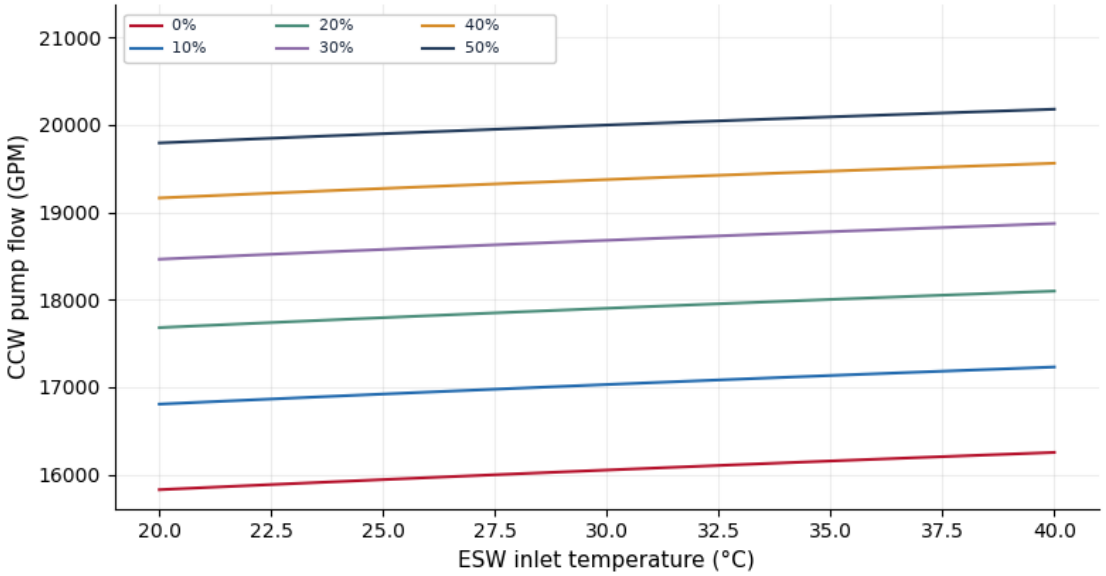
At ESW 32.4°C

Margin = 43.3°C − CCW outlet

Augmentation	CCW outlet (°C)	Margin (°C)
0%	41.30	2.00
+10%	40.55	2.75
+20%	39.93	3.37
+30%	39.41	3.89
+40%	38.97	4.33
+50%	38.60	4.70

Recirculation: ESW and CCW flow response



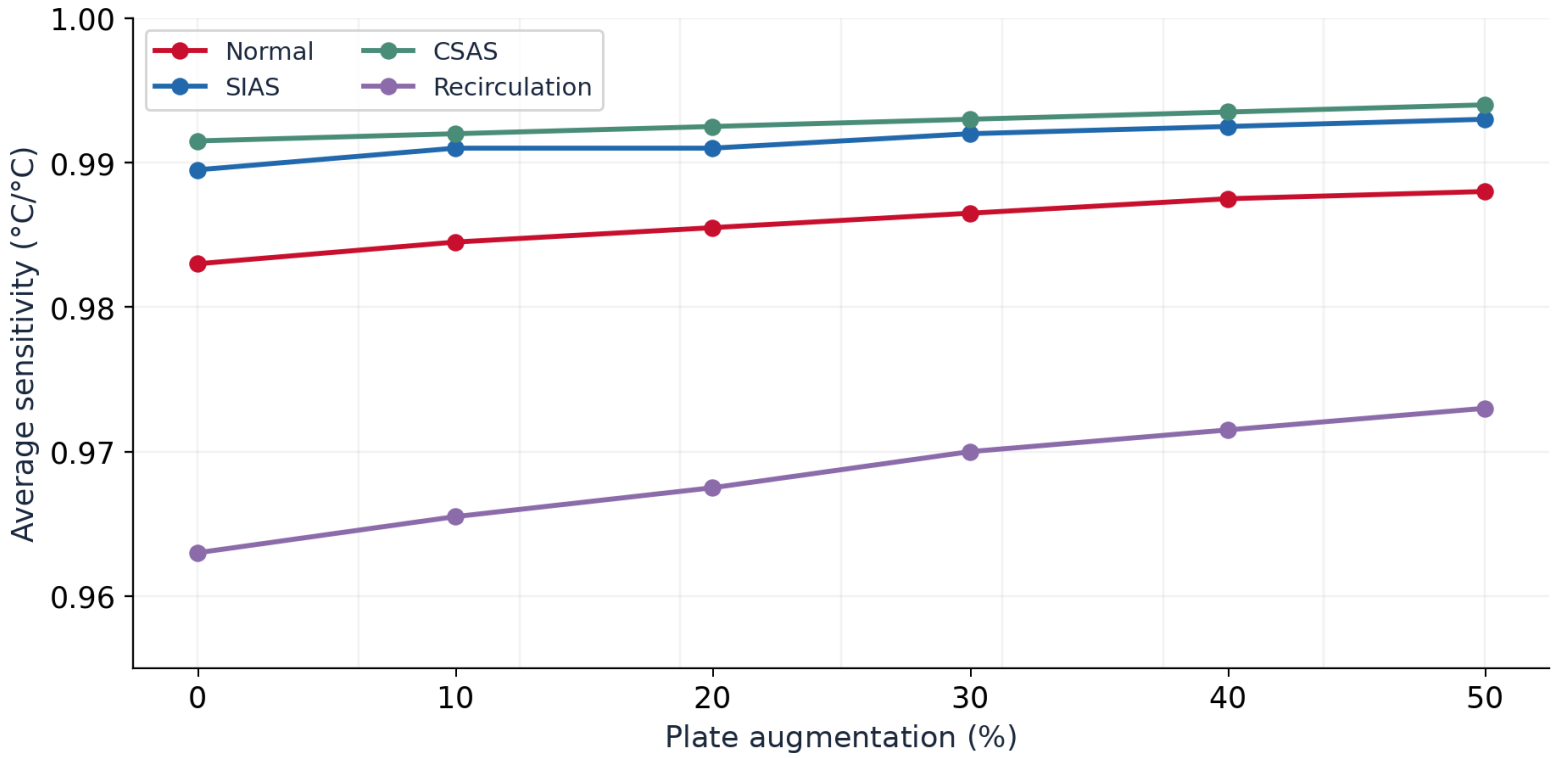


ESW: +31.41%

CCW: +24.47%

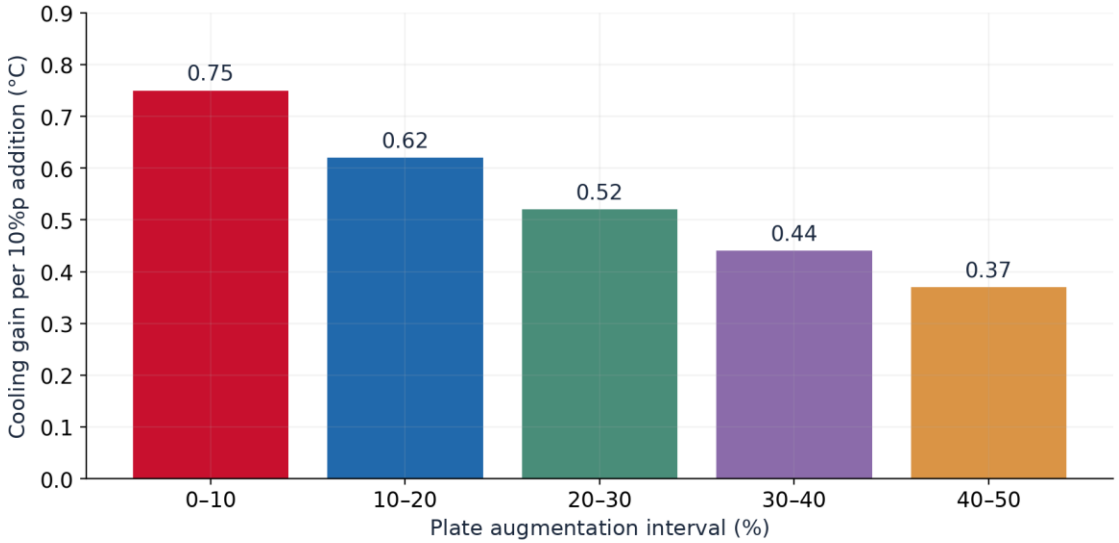
Flow changes are evaluated at ESW 32.4°C, from baseline to +50% augmentation, with pump inputs unchanged.

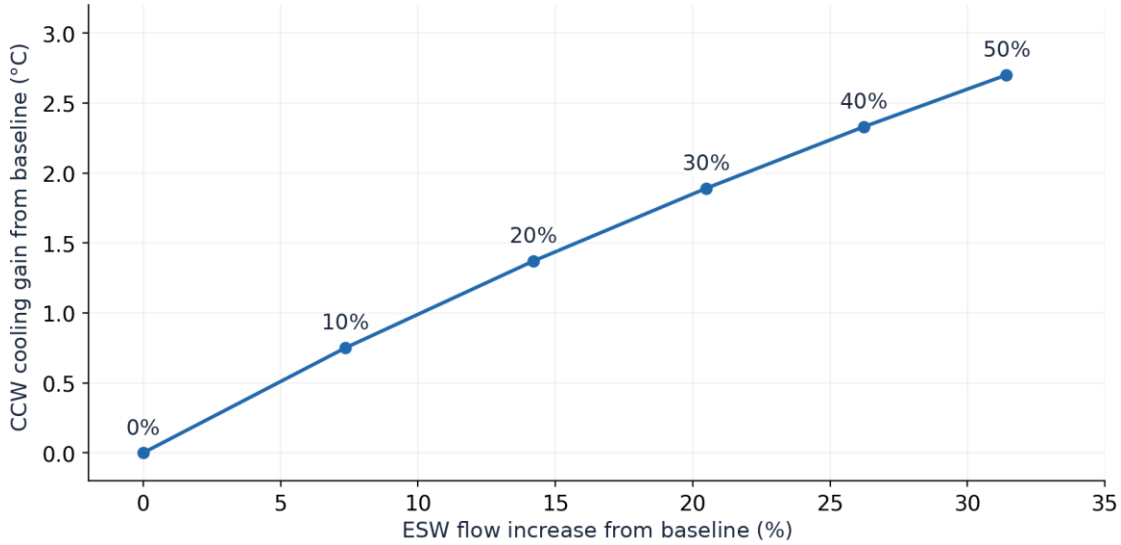
Temperature sensitivity across Normal and DBA conditions



Average CCW-outlet response to ESW-inlet temperature over 20–40°C.
Recirculation: 0.963 → 0.973°C/°C as augmentation increases from 0% to 50%.

Recirculation: incremental cooling gain and flow change at ESW inlet 32.4°C



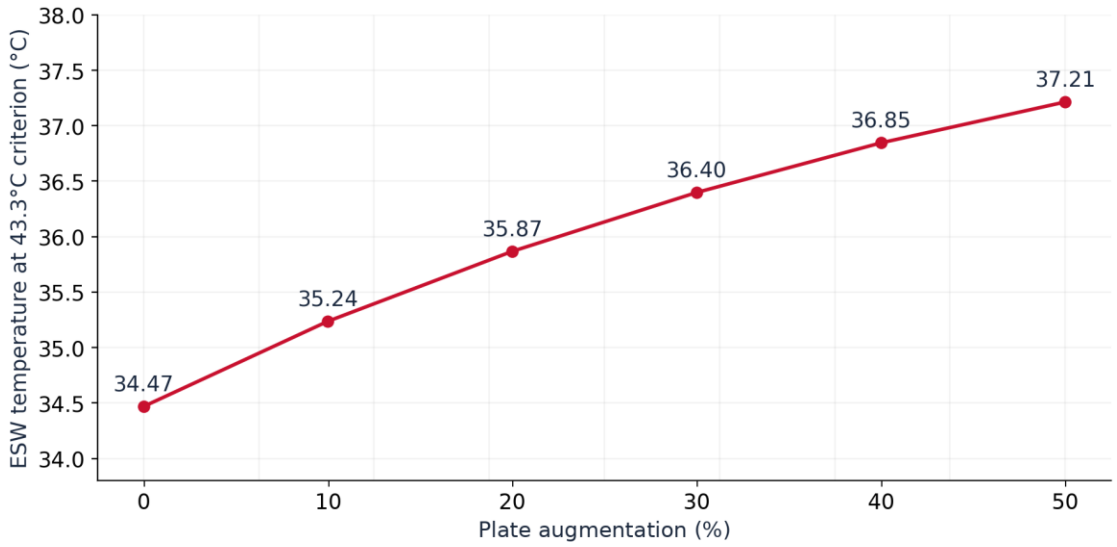


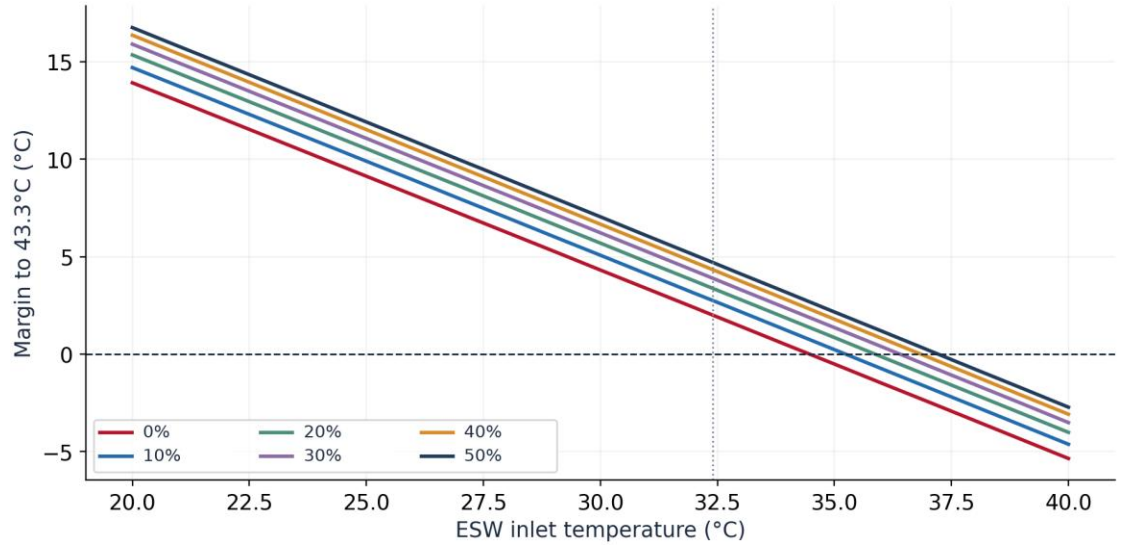
0.75 → 0.37°C per +10%p

2.70°C gain · +31.41% ESW flow

Each +10%p step adds 10 percentage points. The final cooling gain is 50.7% smaller than the first.

Recirculation: criterion crossing and remaining margin





ESW crossing: 34.47 → 37.21°C

At ESW 40°C: −2.72°C margin

The ESW criterion-crossing temperature shifts by 2.75°C at +50% augmentation.
The CCW safety margin at ESW inlet 40°C remains −2.72°C.

Conclusions

3.72 → 4.91°C

Operational margin
Normal at ESW 27.5°C

2.00 → 4.70°C

Safety margin
Recirculation at ESW 32.4°C

+2.75°C

Recirculation crossing shift
at +50% augmentation

Margin values compare 0% and +50% relative plate augmentation.

Plate additions give diminishing cooling gains and increase flow.

Selection requires plant-specific and manufacturer validation.

These results describe a single-train model with fixed pump inputs.

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Thank you for listening