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Statewide CASE Team 2028 Title 24 Transcritical CO2 Refrigeration Modeling Memo

Additional submitted attachment is included below.

CALIFORNIA ENERGY CODES & STANDARDS
A STATEWIDE UTILITY PROGRAM

2028 TITLE 24 TRANSCRITICAL CO2 REFRIGERATION MODELING MEMO

November 5, 2026

California Energy Commission

Docket No. 25-BSTD-03

On June 25, 2026, the Statewide CASE Team docketed a comment letter (comment 271012) recommending adjustments to the code language for refrigerated warehouses and commercial refrigeration. This memo presents the results of subsequent modeling of transcritical CO_2 gas coolers conducted by the Statewide CASE Team and modifies the comment letter's gas cooler recommendations accordingly to allow air-cooled gas coolers as an additional compliance option in climate zones (CZs) 9 through 14.

The analysis investigated to what extent air-cooled gas coolers can achieve annual energy use effectively equivalent to that of adiabatic gas coolers in CZs 9 through 15, which represent the hottest areas of California. It evaluated minimally code-compliant air-cooled gas coolers, as well as air-cooled gas coolers with various design approach temperatures (design TDs), air-cooled systems with parallel compression, and air-cooled gas coolers with higher specific efficiency. The analysis is approximate, and the results are intended to be directional.

The California Statewide Codes and Standards Enhancement (CASE) initiative presents recommendations to support California Energy Commission (CEC) efforts to update California's Energy Code (Title 24, Part 6), including revisions to simplify and clarify existing code requirements. Three California Investor-Owned Utilities (IOUs)—Pacific Gas & Electric, San Diego Gas & Electric, and Southern California Edison—sponsored this effort.

Pacific Gas and Electric Company
SOUTHERN CALIFORNIA EDISON Energy for What's Ahead
SDGE

1. Proposal

1.1 Allow air-cooled gas coolers in more climate zones

1.1.1 Context

Air-cooled transcritical CO_2 gas coolers are prohibited for refrigerated warehouses in CZs 9 through 15 and for commercial refrigeration systems in CZs 10 through 15 (2025 Title 24, Part 6, Sections 901.1.8.1 [120.6(a)8A] and 902.1.5.1 [120.6(b)5A]). This is effectively a requirement to use adiabatic gas coolers in these climate zones. As documented in the Statewide CASE Team's Covered Process Refrigeration Comment Letter docketed on June 25, 2026, stakeholders have indicated that this requirement is problematic for multiple reasons, including increased water use in water-scarce areas, increased maintenance costs, questionable operational efficiency, and lack of design flexibility.[1] This requirement is also assumed to apply to CO_2 condensing units with integral gas coolers, which are a new product.

1.1.2 Proposal

Refrigerated warehouses:

> Remove the prohibition of air-cooled gas coolers in CZs 9-14 (Section 901.1.8.1 [120.6(a)8A]).

Commercial refrigeration:

> Remove the prohibition of air-cooled gas coolers in CZs 10-14 (Section 902.1.5.1 [120.6(b)5A]).

1.1.3 Rationale

The custom modeling described in this memo evaluated transcritical CO_2 systems with minimally code-compliant air-cooled and adiabatic gas coolers. The results suggest that air-cooled and adiabatic systems in CZs 9-12 have effectively equivalent annual energy use when modeling and operational uncertainties are considered. In CZs 13 and 14, effective equivalence can be reached when additional derating is also applied to

[1] See the original Statewide CASE Team comment letter for stakeholder interview summaries: California Statewide Utility Codes and Standards Enhancement (CASE) Team, "Covered Process Refrigeration Final CASE Team Comment Letter," June 25, 2026, California Energy Commission Docket No. 25-BSTD-03, TN 271012, https://efiling.energy.ca.gov/GetDocument.aspx?tn=271012&DocumentContentId=108579.

adiabatic gas coolers. This additional derating reflects stakeholder feedback suggesting that relative to air-cooled gas coolers, adiabatic gas coolers are more susceptible to fouling and degraded performance.

2. Modeling

2.1 Overview

The Statewide CASE Team developed annual hourly simulations of a two-stage transcritical CO_2 refrigeration system to compare a system with adiabatic gas coolers (baseline) to a system with air-cooled gas coolers (proposed) for California's hottest climate zones (CZs 9-15). Load profiles were developed in DOE-2.2R, and high-stage compressors and gas coolers were modeled with a custom model programmed in Python using NIST REFPROP. The sections below address key considerations of the analysis.

2.1.1 Analysis uncertainty & effective equivalency

Given the inherent modeling and operational uncertainties, the results of this analysis are intended to be directional, and interpretation would be improved if cross-checked with an empirical study of real systems in one or more of the relevant climate zones. In this memo, "effectively equivalent" means the annual energy of the air-cooled and adiabatic systems differs by less than the modeling uncertainty of ±3.7 percentage points. This uncertainty band was determined via an uncertainty analysis which is described in Section 3.1.

2.1.2 Modeled prototype

The modeled prototype is a transcritical CO_2 refrigerated warehouse system. The results are assumed to also apply to transcritical CO_2 commercial refrigeration because for the purpose of comparing gas cooler types, the Statewide CASE Team, based on its engineering judgment and experience, considers both to have sufficiently similar technology and system configurations. This is consistent with the 2022 CASE analysis, which applied the same transcritical CO_2 requirements to both building types and found comparable energy impacts for the two prototypes,[2] and with the growing use of

[2] California Statewide Utility Codes and Standards Enhancement (CASE) Team, "Refrigeration System Opportunities, Final CASE Report 2022-NR-COV-PROC2-F," prepared by Trevor Bellon and Doug Scott (VaCom Technologies), October 2020. https://title24stakeholders.com/measures/cycle-2022/refrigeration-system-opportunities/.

transcritical CO_2 technology developed for commercial refrigeration in industrial applications.[3] Though the load shapes may differ modestly between the two building types, each comparison applies the same load to both gas cooler types, so these differences are expected to have little effect on the comparative results.

2.1.3 DOE-2.2R limitations

In the 2022 Title 24 code cycle, analysis was performed for transcritical CO_2 systems using DOE-2.2R software for all modeling.[4] In this code cycle (2028 Title 24), the Statewide CASE Team adopted a combined modeling approach. DOE-2.2R was used to estimate evaporator loads and low-stage compressor power profiles, while a custom model simulated the high-stage compressors, gas coolers, and flash vessel.

This was done due to known DOE-2.2R limitations:

1) DOE-2.2R allows only one reset method for the gas cooler supercritical pressure setpoint, which is based on drybulb temperature and does not reflect stakeholder input that systems typically control the supercritical pressure as a function of the leaving gas temperature.
2) DOE-2.2R does not publish its methodology for gas cooler capacity calculation, which limits analysis of gas cooler performance.

2.1.4 Differences from 2022 CASE analysis

Apart from using a custom model to better assess changes in gas cooler characteristics on total system performance, the Statewide CASE Team also selected different values for two key input assumptions:

1) The 2022 CASE analysis used an adiabatic system wetmode setpoint of 60°F ambient drybulb—i.e., the wetmode is activated when the outside air temperature is above 60°F. Based on conversations with stakeholders, the Statewide CASE Team has learned that installers and operators commonly put adiabatic systems into a “water savings mode” that sets the wetmode setpoint to around 75°F or

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[3] A. Silva, "Intelligent CO2 Compressors and Ejectors for Enhanced System Efficiency and Reliability in Industrial Applications," Technical Paper #9, IIAR Natural Refrigeration Conference & Heavy Equipment Expo, Orlando, FL, March 24–27, 2024.

A. Silva, "CO2 Systems," ASHRAE Refrigeration Seminar, Atlanta, GA, May 20, 2025.

[4] California Statewide Utility Codes and Standards Enhancement (CASE) Team, “Refrigeration System Opportunities, Final CASE Report 2022-NR-COV-PROC2-F,” prepared by Trevor Bellon and Doug Scott (VaCom Technologies), October 2020. https://title24stakeholders.com/measures/cycle-2022/refrigeration-system-opportunities/

80°F, which saves water at the expense of using more energy. For this code cycle, the Statewide CASE Team conservatively assumed a wetmode setpoint of 75°F as the baseline condition and also evaluated setpoints of 70°F and 80°F to assess the impact of wetmode control uncertainty.

2) The 2022 CASE analysis used identical derate factors of 0.85 for the air-cooled and adiabatic systems—i.e., the systems, once installed, are assumed to operate at 85% of manufacturer-published capacities. Based on stakeholder feedback, the precooling pads of adiabatic gas coolers are easily fouled and often lack proper maintenance, leading to degraded system performance. The Statewide CASE Team therefore selected adiabatic system derate values of 0.75, 0.80, and 0.85 to better assess uncertainty associated with fouling and maintenance.

In the appendix of this memo, Section 3.2 further compares the input assumptions of the present analysis with those of the 2022 CASE analysis.

2.1.5 Limitations & future work

The analysis did not consider the following areas, which are recommended for future work:

1) Energy embedded in water use[5]
2) Additional alternatives for improving performance of air-cooled systems in hot climates, such as use of ejectors

2.2 Methods

Figure 1 shows a system schematic and the modeling boundaries.

[5] For more information on estimation of embedded energy in California water use, see SBW Consulting, Inc., in association with Pacific Institute, *Water-Energy Calculator 2.0 Project Report*, Report Group D – D14.01 (San Francisco: California Public Utilities Commission, February 22, 2022), https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/water-energy-nexus/we-calc20-project-report.pdf.

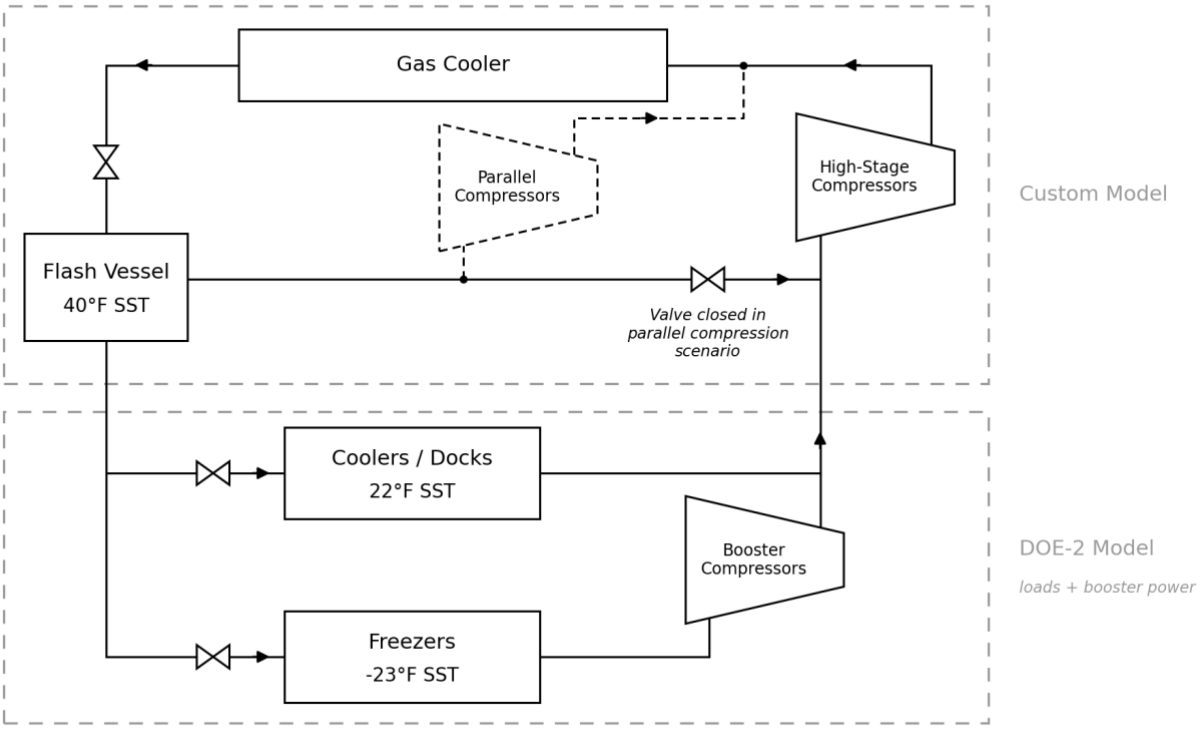


Figure 1. System schematic and modeling boundaries

DOE-2.2R provided hourly simulations of evaporator loads and low-stage (booster) compressor power. The custom model ingested the DOE-2.2R outputs and added hourly simulations of the high-stage compressors, parallel-compression compressors, gas coolers, and flash vessel, with the following principal features:

1) Gas coolers sized by climate zone to Title 24 requirements and variations thereof
2) Gas cooler selections modeled via regressions of manufacturer data, with transcritical operation modeled by one manufacturer and subcritical operation modeled by another manufacturer due to selection software limitations
3) High-stage compressors and parallel compression compressors modeled via manufacturer-published performance regression coefficients, corrected for hourly suction superheat conditions, with constant efficiency assumed at part-load
4) Gas cooler fans controlled to an annually optimal approach temperature setpoint in subcritical mode and set to 100% speed in transcritical mode
5) Adiabatic wetmode active when ambient drybulb is at or above the wetmode setpoint

6) Consideration of hourly load and weather conditions in the thermodynamic calculations for determining the gas cooler condensing temperature in subcritical mode and the leaving CO_2 temperature in transcritical mode
7) Iteratively solved heat balances between the system heat rejection load (evaporator loads and compressor work, including compression of flash gas) and the gas cooler capacity at the given operating conditions
8) Parallel compression, where modeled, compresses all flash gas with dedicated compressors, with gas coolers resized accordingly

Key modeling assumptions are given in Section 3.2.

2.3 Results

Figure 2 shows air-cooled gas cooler energy use relative to adiabatic gas cooler energy use, on a percentage difference basis, for minimally Title 24 compliant selections. The shaded region is the modeling uncertainty band, which represents the range within which the analysis cannot distinguish a difference in energy use between the adiabatic and air-cooled scenarios. The dot-and-line ranges show the adiabatic wetmode uncertainty band.

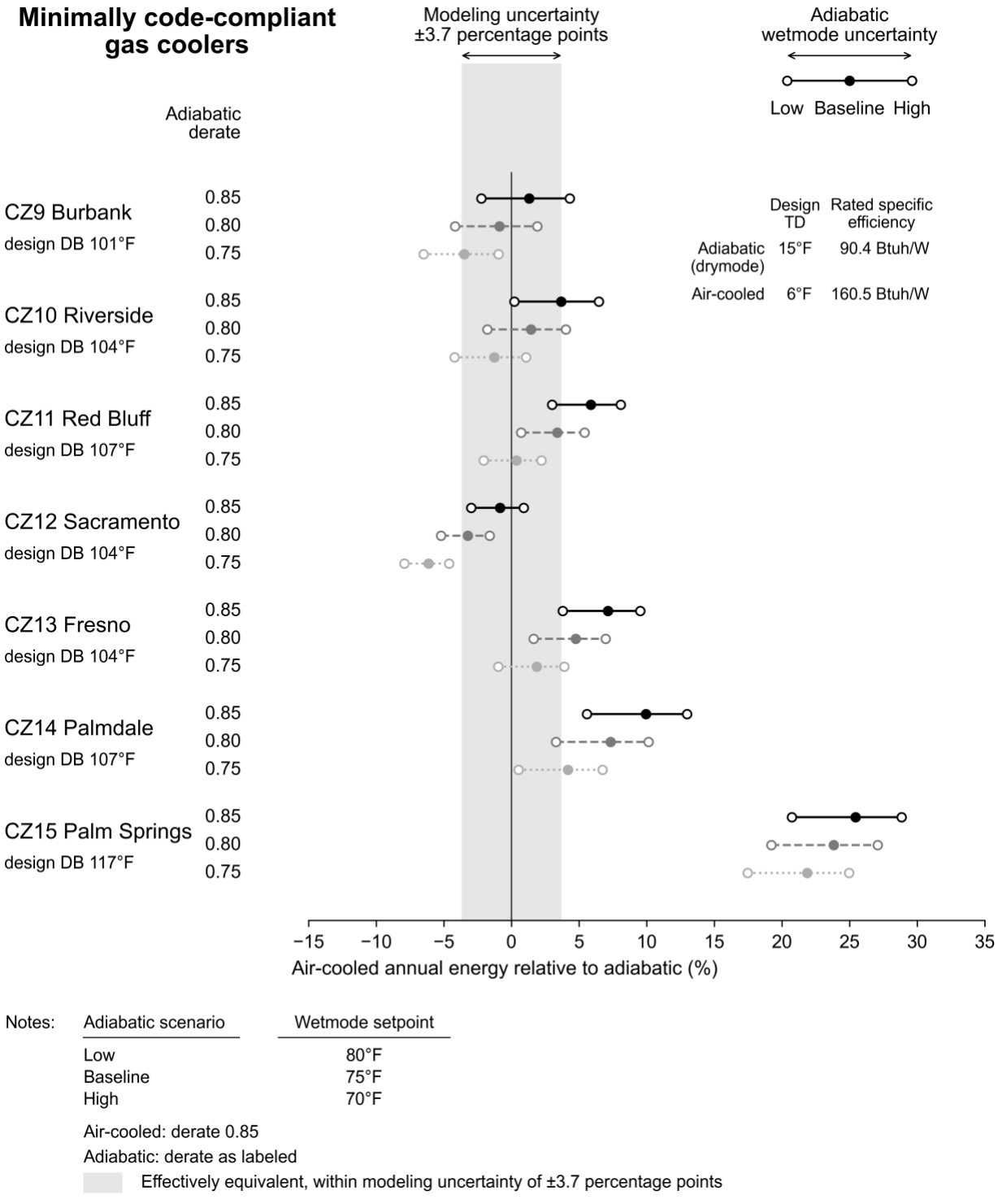


Figure 2. Results for minimally code-compliant gas coolers

Table 1 shows air-cooled gas cooler energy use relative to adiabatic gas cooler energy use for the same coil selections shown in Figure 2, with various air-cooled design TDs. Shaded areas of the table show where air-cooled is effectively equivalent to, or better than, adiabatic. Note that the 2025 Title 24 maximum design TD for air-cooled gas coolers is 6°F in most climate zones where air-cooled gas coolers are allowed. The adiabatic wetmode uncertainty band is not shown. If a wetmode setpoint of 80°F is assumed, then CZs 9-14 all would achieve effectively equivalent annual energy use for air-cooled gas coolers at a 6°F design TD.

Table 1. Annual energy of air-cooled relative to adiabatic (%)

Climate zone	Design DB	Air-Cooled Design TD				
		2°F	4°F	6°F	8°F	10°F
CZ9 Burbank	101°F	−3.7	−4.3	−3.5	−2.1	−0.3
CZ10 Riverside	104°F	−1.6	−2.1	−1.3	+0.1	+1.9
CZ11 Red Bluff	107°F	−0.6	−0.7	+0.4	+2.0	+3.9
CZ12 Sacramento	104°F	−7.8	−7.5	−6.1	−4.3	−2.2
CZ13 Fresno	104°F	+2.0	+1.2	+1.9	+3.2	+4.8
CZ14 Palmdale	107°F	+4.1	+3.4	+4.2	+5.6	+7.2
CZ15 Palm Springs	117°F	+22.8	+21.7	+21.9	+22.4	+22.9

Notes:

Adiabatic wetmode setpoint: 75°F

Derate factor: air-cooled 0.85, adiabatic 0.75

Shaded: air-cooled effectively equivalent or better, within modeling uncertainty of ±3.7 percentage points

Note the following:

1) In general, air-cooled uses less energy when its design TD is decreased, as the increased heat rejection capacity allows the gas cooler to operate at lower temperatures/pressures and lower rates of flash gas generation, which reduces high-stage compressor energy use.
2) When going from an air-cooled design TD of 4°F to 2°F, energy use in CZ11 remains almost constant, and energy use increases in all other CZs, except for CZ12. This is due to the greater fan motor power of the larger gas coolers causing an increasing fan energy penalty largely driven by the control assumption that the fans operate at 100% speed in transcritical mode.

Figure 3, on the following page, shows air-cooled gas cooler energy use relative to adiabatic for minimally Title 24 compliant selections with use of parallel compression in the air-cooled system. With this change, the air-cooled system performs effectively equivalent to, or better than, the adiabatic system in six of the seven climate zones (CZs

9-14). The prototype is a simplified model that assumes all generated flash gas is routed through the parallel compressors throughout the year and is intended to show the approximate magnitude of the benefit of parallel compression.

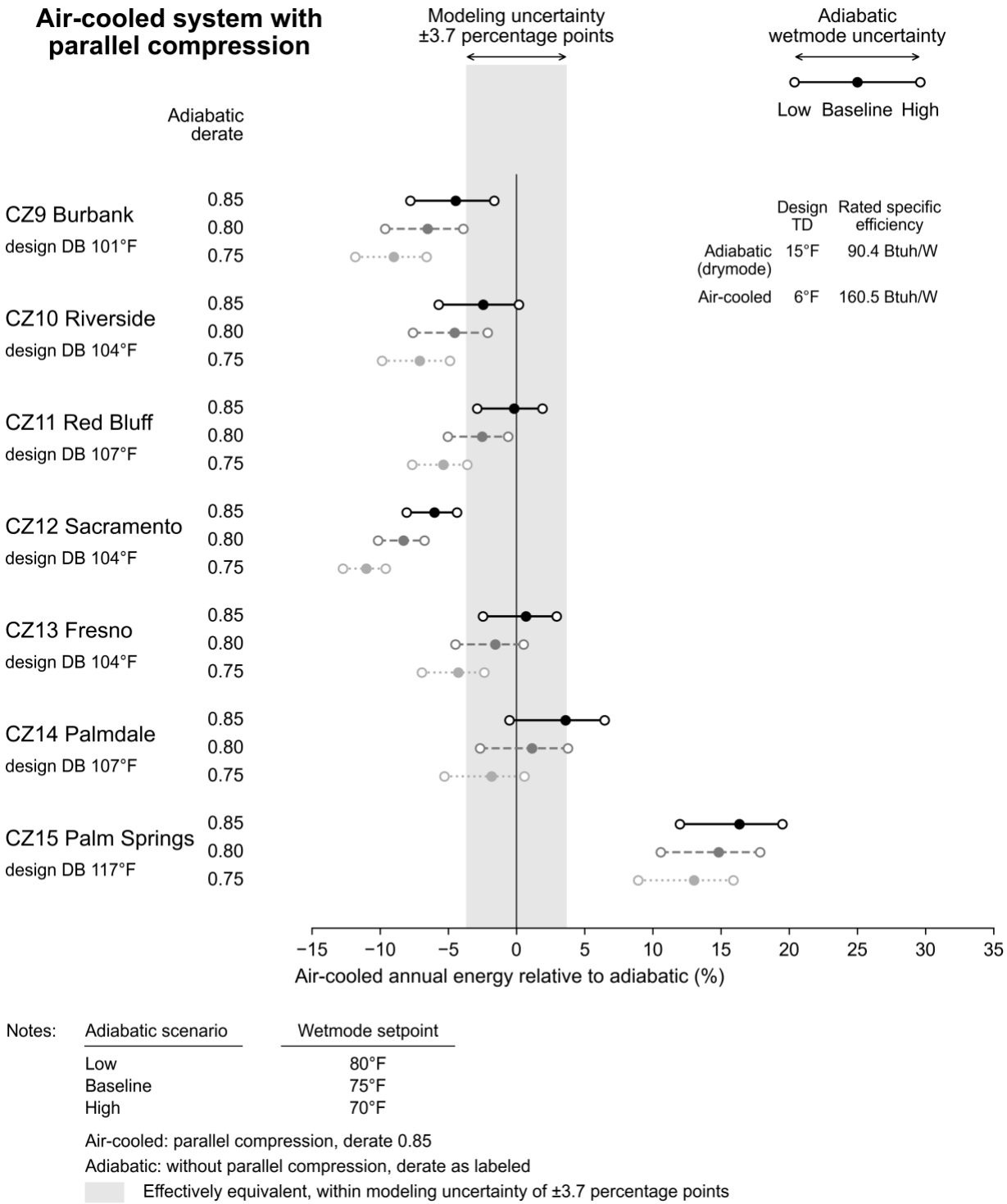
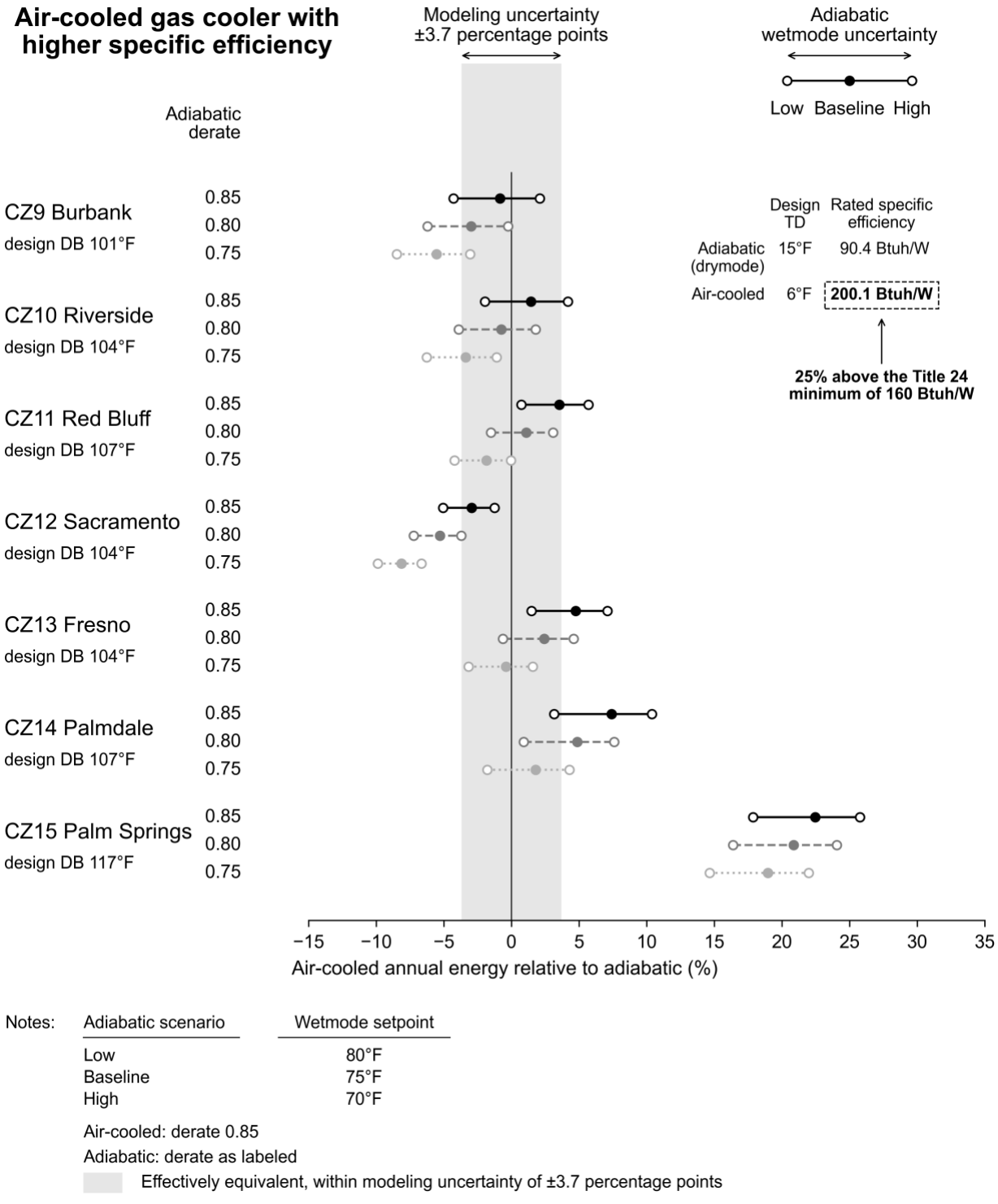


Figure 3. Results for air-cooled system with parallel compression

The Statewide CASE Team also evaluated the impact of increasing the air-cooled gas cooler specific efficiency to a value 25% above the 2025 Title 24 code minimum of 160 Btuh/W, as shown in Figure 4. This better reflects a gas cooler design that increases surface area without increasing fan power and moves air-cooled closer to adiabatic in every climate zone by about 2 to 3 percentage points. This prototype did not include parallel compression.



Notes:

Adiabatic scenario	Wetmode setpoint
Low	80°F
Baseline	75°F
High	70°F

Air-cooled: derate 0.85

Adiabatic: derate as labeled

Effectively equivalent, within modeling uncertainty of ±3.7 percentage points

Figure 4. Results for air-cooled gas cooler with higher specific efficiency

2.4 Conclusions

2.4.1 Summary observations

The modeling results suggest the following:

1) In CZs 9-12, minimally code-compliant air-cooled gas coolers have annual energy use effectively equivalent to adiabatic gas coolers when modeling and operational uncertainties are considered and when identical derate factors are applied to each gas cooler type.
2) In CZs 13 and 14, effective equivalence can be reached when additional derating is also applied to adiabatic gas coolers to reflect the potential for increased fouling and performance degradation due to the adiabatic media.
3) In CZ15, air-cooled gas coolers clearly use more energy than adiabatic gas coolers in every scenario evaluated.
4) An air-cooled design TD of 6°F is sufficient to achieve effectively equivalent annual energy use in CZs 9-14 when the aforementioned uncertainties and additional derating are considered.
5) The results are sensitive to how adiabatic gas coolers operate in the field. Changes in both the adiabatic derate and wetmode setpoint shift the results by an amount comparable to, or larger than, the modeling uncertainty.
6) With parallel compression, air-cooled systems reach effective equivalence in CZs 9-14 without additional adiabatic derating.
7) Increasing air-cooled gas cooler specific efficiency moves air-cooled closer to adiabatic by about 2 to 3 percentage points in every climate zone.

2.4.2 Modified recommendations based on modeling results

Based on the above, the Statewide CASE Team modifies the recommendations of its Covered Process Refrigeration Comment Letter, docketed on June 25, 2026, as follows:

1) Remove the prohibition of air-cooled gas coolers in CZs 9-14 for refrigerated warehouses and CZs 10-14 for commercial refrigeration.
2) Require air-cooled gas coolers in these climate zones to have a design TD of no more than 6°F, consistent with the 2025 Title 24 requirement for air-cooled gas coolers in most other climate zones.

The Statewide CASE Team maintains its recommendation to exempt gas coolers serving smaller systems based on size of total heat of rejection (freezers ≤ 20 tons, coolers ≤ 40 tons).

3. Appendix

3.1 Uncertainty Analysis

The Statewide CASE Team estimated the modeling uncertainty by changing one model input at a time and recording the shift in the result. All ranges for input adjustment were determined based on the engineering judgment of the Statewide CASE Team. Table 2 shows the model inputs tested.

Table 2. Model inputs tested

Input	Baseline	Test range	Average shift (± percentage points)
Design load safety factor	1.15	1.00 to 1.30	2.0
Adiabatic capacity, transcritical	Manufacturer data regression	±5%	0.2
Adiabatic capacity, subcritical	Reference coil, scaled	±5%	1.6
Air-cooled capacity, transcritical	Manufacturer data regression	±5%	0.3
Air-cooled capacity, subcritical	Reference coil, scaled	±5%	0.6
Adiabatic fan power	4.04 kW per fan	±5%	0.6
Air-cooled fan power	3.79 kW per fan	±5%	0.5
Compressor power	Manufacturer-published regressions	±5%	0.1
Fan-speed-to-coil-capacity exponent	0.75	0.65 to 0.85	0.4
Fan-speed-to-power exponent	2.7	2.5 to 2.9	0.2
Subcritical subcooling	3°F	2 to 4°F	0.2
Equipment representation, subcritical	Regression on reference coil subcritical ratings	Single rating at 10°F TD (linear relation of UA·TD)	2.4
Combined (root-sum-square)			**3.7**

Input	Baseline	Test range	Average shift (± percentage points)
Notes:			
Average shift is the average of the absolute value of the shifts at the low and high ends of the range, averaged over all climate zones.			
Test ranges are based on engineering judgment.			
Equipment representation, subcritical: the reference coil's UA value regression is replaced by a UA·TD relation with the UA value fixed for a single representative subcritical operating condition.			

Because independent sources of error are unlikely to all act in the same direction, a conventional method in uncertainty analysis is to calculate the root-sum-square of the error contributed from each source, treating the sources as independent, as follows:

$$u_c = \sqrt{(u_1^2 + u_2^2 + \ldots + u_12^2)}$$

where u_i is the average shift produced by changes in each input i.[6]

Using this methodology, the combined uncertainty, u_c, across all climate zones ranged between 3.7 and 3.8 percentage points for the different scenarios assessed. The Statewide CASE Team applied an overall modeling uncertainty band of ±3.7 percentage points to all results presented in this memo.

[6] Joint Committee for Guides in Metrology (JCGM), *Evaluation of Measurement Data: Guide to the Expression of Uncertainty in Measurement*, JCGM 100:2008 (JCGM, 2008).

American Society of Mechanical Engineers (ASME), *Test Uncertainty*, ASME PTC 19.1-2005, Revision of ASME PTC 19.1-1998 (New York: ASME, 2006).

3.2 Model & Assumptions

3.2.1 States & energy flows

Figure 5 shows the states and energy flows considered in the analysis.

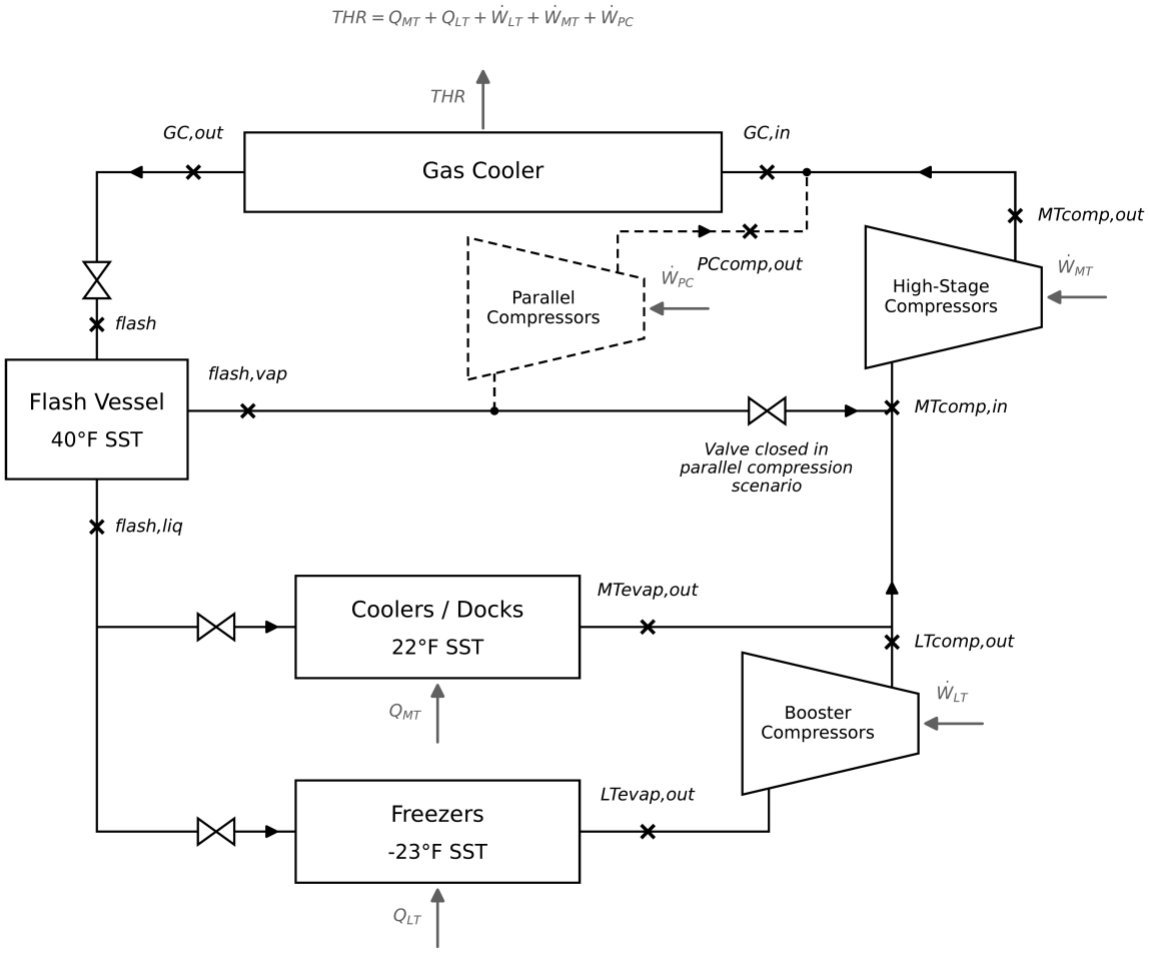


Figure 5. States and energy flows on the system schematic

3.2.2 Input assumptions

Table 3 shows a comparison of select modeling inputs from the analysis done for this memo and the 2022 CASE analysis.

Table 3. Comparison with the 2022 CASE analysis

Parameter	2022 CASE analysis	This analysis
Prototype and loads	– Refrigerated warehouse, 92,000 ft² (freezer, cooler, dock), and large supermarket – 1.15 safety factor	– Freezer, cooler and dock loads calculated for CZ12 (Sacramento) – Scaled to the other CZs based on annual DOE-2.2R load ratios – 1.15 safety factor
Climate zones	– All 16 CZs	– CZs 9-15
Design drybulb	– 0.1% by representative city	– Same
Design TD	– Air-cooled 8°F baseline – Adiabatic 15°F drymode	– Air-cooled 6°F (2-10°F tested) – Adiabatic 15°F drymode
Capacity representation	– DOE-2.2R gas cooler curves, with multipliers for other design TDs and for subcritical	– Transcritical capacity regressions on the manufacturer performance data of the selected gas coolers – Subcritical regression on a reference coil for which manufacturer subcritical data were available, scaled to the selected gas coolers
Specific efficiency at Title 24 rating condition	– Air-cooled 160 Btuh/W – Adiabatic 90 Btuh/W	– Air-cooled 160.5 Btuh/W – Adiabatic 90.4 Btuh/W
Fan control	– Subcritical: condensing reset with drybulb, 60°F minimum, control approach not stated, fans modulate in unison – Transcritical: fans at 100%	– Subcritical: setpoint drybulb + 10°F air-cooled, + 14°F adiabatic, 60°F minimum, fans modulate in unison – Transcritical: fans at 100%
Transcritical pressure	– P (Pa) = 2.3083×10^5 × DBT (°C) + 1.19×10^6, at DBT of 80°F and above	– Manufacturer formula: P (psia) = 19.66 × leaving gas (°F) - 614.6
Fan power and capacity at reduced speed	– Not stated	– Power ∝ speed$^{2.7}$ – Capacity ∝ speed$^{0.75}$
Gas cooler subcooling	– Not stated	– 3°F in subcritical operation – (2-4°F tested)
Flash vessel	– 40°F saturated – Flash gas to the high stage	– 40°F saturated

Parameter	2022 CASE analysis	This analysis
	– Parallel compression assessed as option for CZ10	– Flash gas to high-stage compressor suction – Parallel compression option available for all CZs
Compressors	– 8 booster and 8 high-stage reciprocating – Booster & high-stage compressor power from DOE-2.2R	– High-stage reciprocating compressor manufacturer-published regression coefficients for subcritical and transcritical operation – Booster compressor power from DOE-2.2R hourly data – Full-load efficiency assumed at part-load conditions
Adiabatic precooling	– Wetmode above 60°F ambient drybulb – Effectiveness 0.80	– Wetmode at and above 75°F ambient drybulb (70-80°F tested) – Effectiveness 0.80
Capacity derate factors	– 0.85 for both systems	– 0.85 for air-cooled – 0.75-0.85 range for adiabatic
Elevation	– Not considered	– Not considered

3.2.3 P-h diagrams for hourly operating conditions

Figure 6 shows a pressure-enthalpy diagram for an example subcritical hour with gas cooler fans modulating speed to maintain a 10°F approach to drybulb.

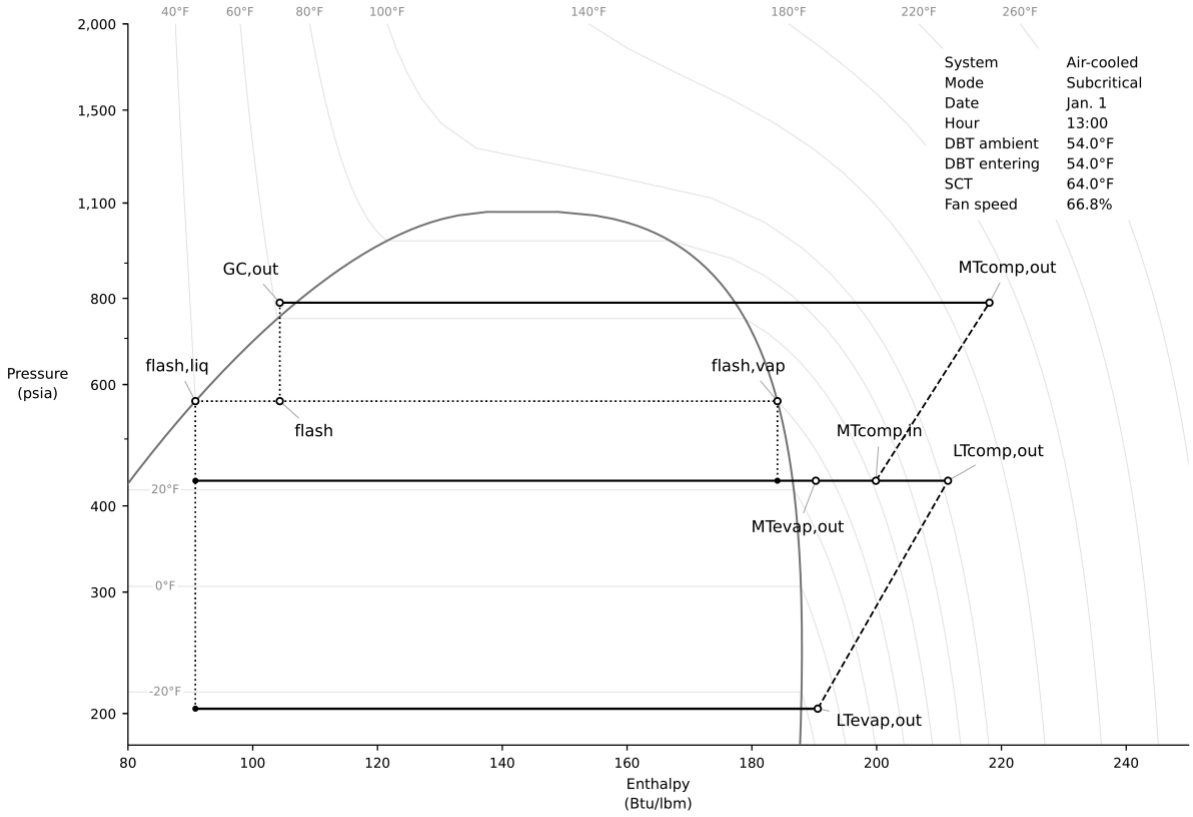


Figure 6. States on a pressure-enthalpy diagram, subcritical hour example

Figure 7 shows a pressure-enthalpy diagram for an example transcritical hour with the fans set to 100% speed.

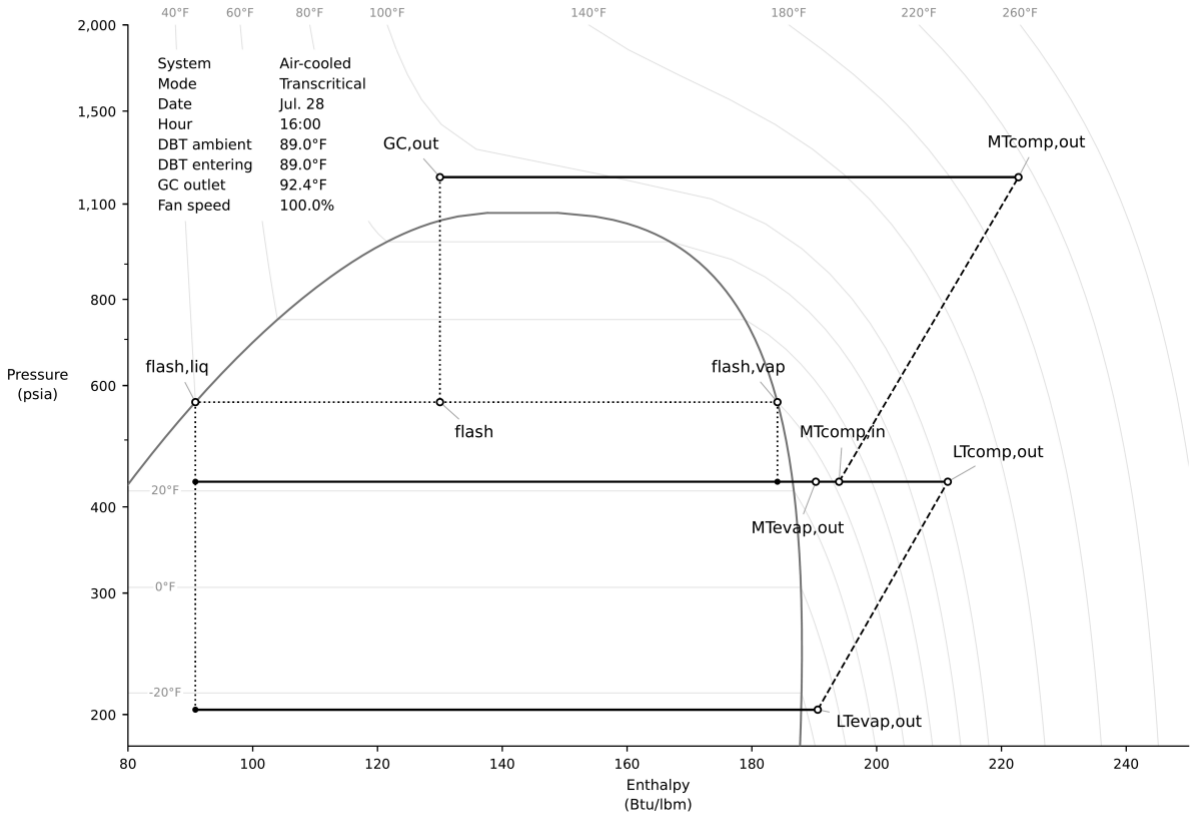


Figure 7. States on a pressure-enthalpy diagram, transcritical hour example

3.2.4 Thermodynamic properties

Based on NIST REFPROP data, Figure 8 shows the high variability of the specific heat of CO2 at supercritical pressures, especially when near the critical pressure (1,070 psia) and helps to illustrate why gas cooler modeling can have increased uncertainty near the critical point.

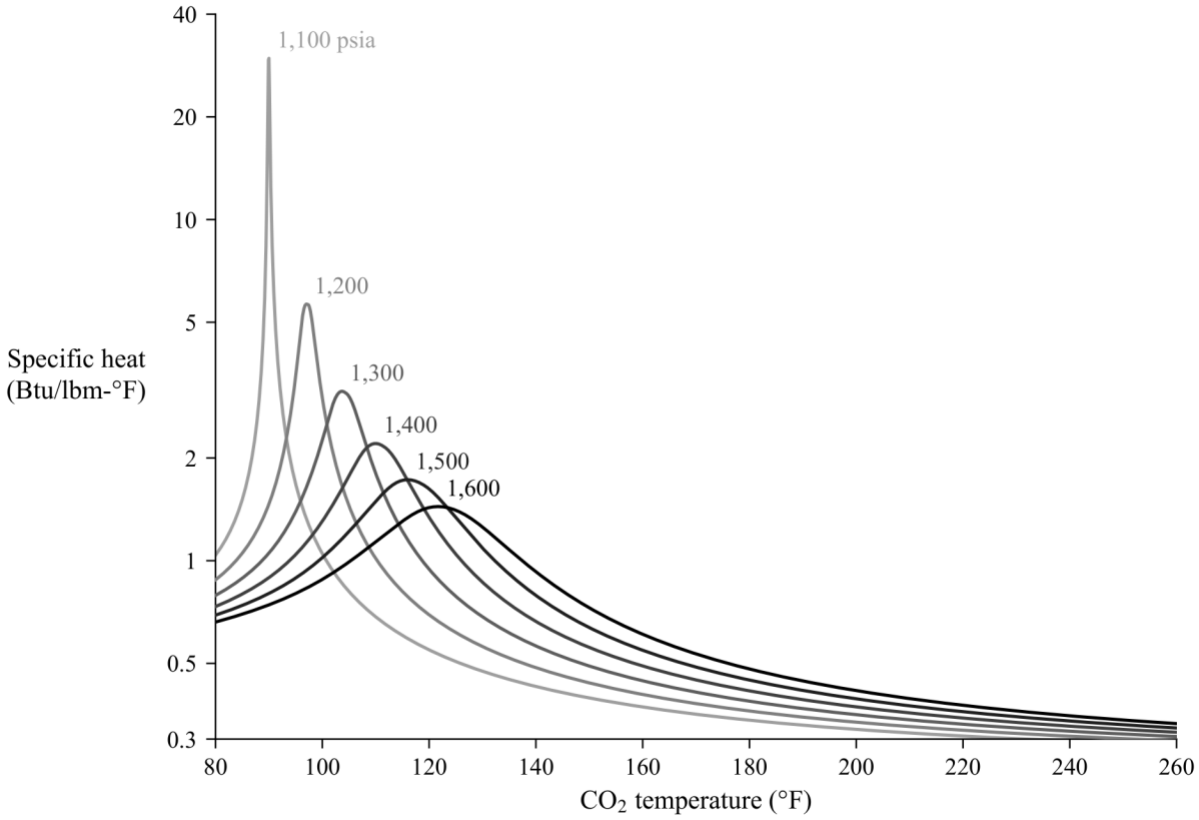


Figure 8. CO_2 specific heat at supercritical pressures as a function of temperature

4. Proposed Code Language

4.1 Guide to Markup Language

The proposed changes to the standards are provided below. Proposed changes to the 2025 documents are marked with dark blue underlining (new language) and ~~strikethroughs~~ (deletions).

4.1.1 Energy Code (Title 24, Part 6)

901.1.8.1 [Section 120.6(a)8A] **Air-cooled gas cooler prohibition.**
Air-cooled gas coolers are prohibited in Climate Zone~~s 9 through~~ 15.

902.1.5.1 [Section 120.6(b)5A] **Air-cooled gas cooler prohibition.**
Air-cooled gas coolers are prohibited in Climate Zone~~s 10 through~~ 15.