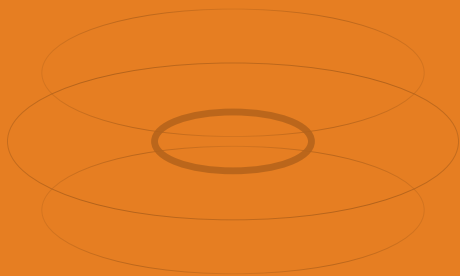


OWNER

Joule-Thomson Cooling, Hydrate and Dewpoint

Calculation



Document No.: [REDACTED] PRO-CAL-003

Rev. A, Issued for Review

Date: September 29, 2026

Project: [REDACTED] [REDACTED]



TORUS

[REDACTED], [REDACTED] County, [REDACTED]

ISSUE SUMMARY AND APPROVAL

This page records each issue of PRO-CAL-003. The preparer, reviewer and approver sign for each revision.

Rev.	Date	Issue purpose	Description
A	2026-09-29	Issued for Review	First issue

Contributors

Rev.	Discipline	Prepared by	Reviewed by	Approved by
A	Process			

CONTENTS

1.	OBJECTIVE.....	1
2.	METHODOLOGY	1
3.	DESIGN INPUTS.....	2
4.	ASSUMPTIONS.....	2
5.	REFERENCES	3
6.	CALCULATION.....	3
6.1.	COOLING ACROSS THE CONTROL VALVES	3
6.2.	WATER CONTENT AND WATER DEWPOINT	4
6.3.	HYDRATE FORMATION WITH FREE WATER	4
6.4.	HYDRATE DEWPOINT OF TARIFF GAS	5
6.5.	HYDROCARBON PHASE ENVELOPE.....	7
6.6.	REQUIRED VALVE OUTLET TEMPERATURE	8
6.7.	CASES THAT NEED THE HEATER.....	9
6.8.	HEATER BYPASS LIMIT	10
7.	RESULTS AND CONCLUSIONS	10

FIGURES AND TABLES

Figure 6-1. Hydrate, Water and Hydrocarbon Dewpoint Curves, Design Gas.....	7
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Figure 6-2. Required Control Valve Outlet Temperature against Outlet Pressure	9
Table 3-1: Design Inputs.....	2
Table 6-1: Control Valve Outlet Temperature, Heater Bypassed	4
Table 6-2: Water Content of Sweet Natural Gas, lb/MMscf	4
Table 6-3: Hydrate Formation Temperature with Free Water, °F	5
Table 6-4: Water and Hydrate Dewpoints, °F	6
Table 6-5: Hydrocarbon Phase Envelope Summary	7
Table 6-6: Hydrocarbon Dew Temperature, °F	7
Table 6-7: Heater Setpoint Characterizer	8
Table 6-8: Heater Requirement by Case	10
Table 6-9: Minimum Station Inlet Temperature for Heater Bypass, °F.....	10



1. OBJECTIVE

This calculation determines how cold the gas becomes when it is throttled across flow control valves FCV-131 and FCV-132, and at what temperature that gas can form hydrates or drop hydrocarbon liquid. From these results it sets the temperature that line heater H-101 must hold downstream of the control valves, and confirms which operating cases need the heater.

2. METHODOLOGY

The pressure cut across the control valves is a throttling process at constant enthalpy. TORUS took the valve inlet and outlet pressures for each basis case from the station hydraulic model of PRO-CAL-002, and solved for the outlet temperature with the GERG-2008 equation of state (AGA Report No. 8 Part 2), implemented in CoolProp 8.0. Heat exchange with ambient over the short station runs was neglected, which slightly understates the winter cooling seen at the pipe wall but not the gas temperature that the controller measures.

Water content was calculated with the Bukacek correlation, which reproduces the McKetta-Wehe chart of the GPSA Engineering Data Book within a few percent for sweet gas. Below 32 °F the equilibrium liquid is supercooled water, as on the McKetta-Wehe chart. The hydrate formation temperature with free water present was calculated with the Towler-Mokhatab and Motiee fits of the Katz gas-gravity chart, and the higher of the two was used.

Tariff-quality gas carries no free water, so the governing hydrate condition is the hydrate dewpoint: the temperature at which gas holding 7 lb/MMscf of water is in equilibrium with hydrate. TORUS anchored this curve at the three-phase point on the free-water hydrate curve and extended it to lower temperature with a Clausius-Clapeyron slope, using an effective enthalpy of 51 kJ/mol for the transfer of water from hydrate to vapor. This is the ice sublimation value; the sensitivity to it is reported. A hydrate program using a CPA or van der Waals-Platteeuw model should confirm the result once the extended gas analysis is available.

The hydrocarbon phase envelopes of the design and rich gas were traced with GERG-2008. The same tracer did not converge for the lean gas above about 500 psia, so the lean dew curve, and a cross-check of the other two, was calculated with a Peng-Robinson equation of state and a Michelsen tangent-plane stability test.

The required valve outlet temperature is the largest of the 40 °F delivery minimum, the hydrate dewpoint plus 10 °F, and the hydrocarbon dewpoint plus 10 °F. The 10 °F margin is the one stated in the Basis of Design for hydrates, applied to hydrocarbon dewpoint in the same way.

3. DESIGN INPUTS

The inputs in Table 3-1 govern the calculation.

Table 3-1: Design Inputs

Input	Value	Source
Gas compositions	Lean, design and rich (mol %)	GEN-DB-001, Section 5.1 (HOLD H-12)
Specific gravity (ideal gas, air = 1)	Lean 0.593, design 0.638, rich 0.680	Calculated from composition
Tariff water content	7 lb/MMscf maximum	GEN-DB-001, Section 5.2 (HOLD H-13)
Tariff hydrocarbon dewpoint	15 °F cricondenthem maximum	GEN-DB-001, Section 5.2
Delivery temperature	40 °F minimum, 120 °F maximum	GEN-DB-001, Section 5.2
Operating cases	C1 to C7	GEN-DB-001, Section 6
Control valve inlet and outlet pressures	Per case	PRO-CAL-002, Line Sizing and Station Hydraulics
Minimum design metal temperature	-20 °F	GEN-DB-001, Section 7
Local atmospheric pressure	14.1 psia	GEN-DB-001, Section 3

4. ASSUMPTIONS

1. The gas is sweet (H₂S not above 4 ppmv) and dehydrated to the tariff water content, and no hydrate inhibitor is injected.
2. Station piping is adiabatic. The controller measures gas temperature downstream of the valves and acts on the measured value, so heat loss to ambient does not change the setpoint.
3. The hydrate dewpoint is an engineering estimate with an uncertainty of about ± 3 °F. *Verification required with a hydrate program once the extended analysis is received (HOLD H-12).*
4. The heavy end of the gas is lumped as n-hexane. A real C₆⁺ fraction containing C₇ to C₁₀ raises the cricondenthem, typically by 10 to 30 °F for 0.1 mol % C₆⁺, so the dewpoints reported here are lower bounds. *Verification required (HOLD H-12).*
5. The acid-gas correction to water content is not applied, since CO₂ is below 1 mol % and H₂S below 4 ppmv, and the gravity correction factor at a specific gravity of 0.64 is about 1.0.

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6. CALCULATION

6.1. COOLING ACROSS THE CONTROL VALVES

The largest pressure cut occurs in cases C1 and C6: the station receives gas at 1,150 psig and 45 °F and delivers it at 750 psig. C6 is the same condition with the heater out of service. The control valve inlet is at 1,144.8 psig and 44.7 °F, where GERG-2008 gives an enthalpy of 297.68 Btu/lb. Holding that enthalpy constant at the outlet pressure:

GERG-2008, isenthalpic throttling

$$h(P_2, T_2) = h(P_1, T_1) = 297.68 \text{ Btu/lb} \Rightarrow T_2 = 18.2 \text{ °F at } P_2 = 751.6 \text{ psig}$$

The gas cools by 26.5 °F over 393 psi, an average of 6.7 °F per 100 psi. Table 6-1 gives the result for every case with the heater bypassed.

Table 6-1: Control Valve Outlet Temperature, Heater Bypassed

Case	Gas	Inlet, psig	Inlet, °F	Outlet, psig	Pressure drop, psi	Outlet, °F	Cooling, °F per 100 psi
C1	Design	1,145	44.7	752	393	18.2	6.7
C2	Design	1,046	69.8	951	96	64.3	5.7
C3	Design	1,000	60.0	950	50	57.0	6.0
C4	Design	1,093	119.7	1,002	91	115.5	4.6
C5	Design	893	59.5	752	141	50.7	6.3
C6	Design	1,145	44.7	752	393	18.2	6.7
C7	Rich	1,094	59.6	852	242	43.3	6.8

6.2. WATER CONTENT AND WATER DEWPOINT

The Bukacek correlation gives the water content of sweet gas in equilibrium with liquid water:

Bukacek (1955); GPSA Section 20

$$W = 47,484 \frac{P_v}{P} + B, \quad \log_{10} B = \frac{-3083.87}{T + 459.6} + 6.69449$$

with W in lb/MMscf, P and the water vapor pressure P_v in psia and T in °F. Table 6-2 tabulates it, and Table 6-4 gives the water dewpoint of gas at the tariff limit of 7 lb/MMscf and at a typical dehydrated content of 4 lb/MMscf.

Table 6-2: Water Content of Sweet Natural Gas, lb/MMscf

Temperature, °F	Water vapor pressure, psia	300 psig	750 psig	950 psig	1,150 psig	1,440 psig
0	0.0220	4.3	2.3	2.0	1.9	1.7
20	0.0539	10.0	5.2	4.5	4.0	3.6
32	0.0886	16.0	8.1	7.0	6.3	5.5
40	0.1217	21.7	10.9	9.3	8.3	7.3
50	0.1781	31.3	15.5	13.2	11.7	10.2
60	0.2564	44.5	21.7	18.4	16.2	14.1
80	0.5075	86.3	41.1	34.5	30.2	26.1
100	0.9504	158.9	74.3	62.1	54.0	46.3
120	1.6950	279.9	129.0	107.1	92.8	79.0

6.3. HYDRATE FORMATION WITH FREE WATER

With free water present, hydrates form at the temperatures in Table 6-3. The fits used are:

Towler and Mokhatab (2005), Katz gravity chart



$$T_h = 13.47 \ln P + 34.27 \ln \gamma - 1.675 \ln P \ln \gamma - 20.35$$

Motiee (1991), Katz gravity chart

$$T_h = -238.24 + 79.00 \log P - 5.353 (\log P)^2 + 349.47 \gamma - 150.85 \gamma^2 - 27.60 \gamma \log P$$

with T_h in °F, P in psia and γ the gas specific gravity. The last column of Table 6-3 shows the water content of gas at the free-water hydrate point, 18 to 39 lb/MMscf. Gas at the 7 lb/MMscf tariff limit therefore cannot drop free water anywhere in the station. Free water appears only after an upset: hydrotest water not removed, a dehydration failure upstream, or water carried in with a pig.

Table 6-3: Hydrate Formation Temperature with Free Water, °F

Pressure, psig	Design gas, Towler-Mokhatab	Design gas, Motiee	Lean gas, Towler-Mokhatab	Rich gas, Towler-Mokhatab	Hammerschmidt	Water content at hydrate point, lb/MMscf
100	31.6	26.9	29.7	33.3	34.3	38.9
300	46.0	43.2	44.2	47.6	45.8	27.1
500	53.0	50.4	51.3	54.5	52.7	23.2
750	58.7	55.8	57.0	60.1	59.0	20.7
850	60.4	57.4	58.7	61.9	61.1	20.1
950	62.0	58.8	60.3	63.4	63.1	19.6
1,050	63.4	60.0	61.7	64.8	64.9	19.2
1,150	64.6	61.2	63.0	66.1	66.6	18.8
1,250	65.8	62.2	64.2	67.2	68.1	18.5
1,440	67.8	63.9	66.2	69.2	70.9	18.0

Note 1: Hammerschmidt is shown for comparison only; it does not account for gas gravity.

6.4. HYDRATE DEWPOINT OF TARIFF GAS

The governing case is the 750 psig valve outlet of cases C1 and C6, at $P = 765.7$ psia and $\gamma = 0.6375$. The free-water hydrate temperature is 58.7 °F by Towler-Mokhatab and 55.8 °F by Motiee, so $T_h = 58.7$ °F (287.97 K). At that temperature $P_v = 0.2446$ psia and $B = 5.550$, so the water content at the three-phase point is:

Bukacek (1955)

$$W_{sat} = 47,484 \times \frac{0.2446}{765.7} + 5.550 = 20.72 \text{ lb/MMscf}$$

Below T_h , the water content in equilibrium with hydrate falls with temperature. Gas holding 7 lb/MMscf reaches hydrate equilibrium at:

Clausius-Clapeyron, anchored at the three-phase point



$$\frac{1}{T_{hd}} = \frac{1}{T_h} - \frac{R}{\Delta H} \ln \frac{W}{W_{sat}} = \frac{1}{287.97} - \frac{8.3145}{51,000} \ln \frac{7}{20.72} \Rightarrow T_{hd} = 274.01 \text{ K} = 33.6 \text{ } ^\circ\text{F}$$

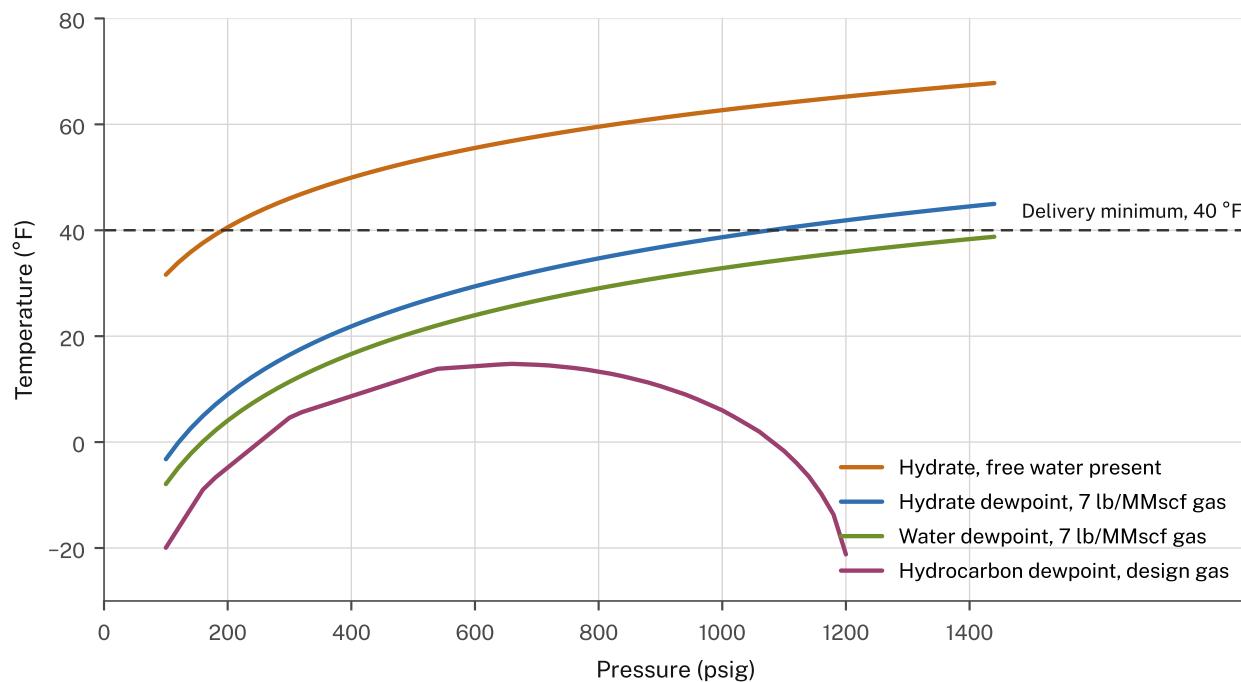
The metastable water dewpoint of the same gas is 27.9 °F. Below T_h hydrate, not water, is the stable phase, so the hydrate dewpoint of 33.6 °F governs. With an effective enthalpy of 45 or 57 kJ/mol it would be 30.4 or 36.1 °F. Table 6-4 extends the result over the station pressure range, and Figure 6-1 plots it with the free-water hydrate curve and the hydrocarbon dewpoint.

Table 6-4: Water and Hydrate Dewpoints, °F

Pressure, psig	Water dewpoint, 7 lb/ MMscf	Water dewpoint, 4 lb/ MMscf	Hydrate dewpoint, 7 lb, 45 kJ/mol	Hydrate dewpoint, 7 lb, 51 kJ/ mol	Hydrate dewpoint, 7 lb, 57 kJ/mol	Hydrate dewpoint, 4 lb	Hydrate dewpoint, 7 lb, rich gas
100	-7.9	-19.4	-7.5	-3.2	0.2	-13.6	-3.0
300	11.4	-1.6	12.8	16.5	19.4	5.3	16.7
500	20.7	6.9	22.6	26.0	28.7	14.4	26.3
750	27.9	13.3	30.3	33.5	36.0	21.5	33.8
850	30.1	15.3	32.7	35.8	38.3	23.6	36.0
950	32.0	17.0	34.7	37.8	40.2	25.5	38.0
1,050	33.7	18.4	36.5	39.5	42.0	27.2	39.8
1,150	35.2	19.8	38.2	41.1	43.5	28.7	41.4
1,250	36.5	21.0	39.6	42.6	44.9	30.1	42.9
1,440	38.8	22.9	42.1	45.0	47.3	32.4	45.3

Note 1: The 51 kJ/mol column is the basis value. The other two show the sensitivity to the effective enthalpy.

Figure 6-1. Hydrate, Water and Hydrocarbon Dewpoint Curves, Design Gas



6.5. HYDROCARBON PHASE ENVELOPE

Table 6-5 summarizes the phase envelopes. The design gas meets the 15 °F tariff cricondenthem by GERG-2008 with essentially no margin. The rich gas, which the Basis of Design treats as an off-specification upset case, exceeds it by a wide margin. Table 6-6 gives the dew temperature on the upper dew branch; the Peng-Robinson results run 3 to 5 °F below GERG-2008, and GERG-2008 is used for design.

Table 6-5: Hydrocarbon Phase Envelope Summary

Gas	Cricondenthem, GERG-2008	Cricondenbar, GERG-2008	Cricondenthem, Peng-Robinson	15 °F tariff limit
Lean	Not converged	Not converged	-45.4 °F at 425 psia	Meets
Design	14.8 °F at 669 psia	1,217 psia at -26.0 °F	11.9 °F at 607 psia	Meets
Rich	42.5 °F at 786 psia	1,371 psia at -1.9 °F	39.0 °F at 716 psia	Exceeds

Table 6-6: Hydrocarbon Dew Temperature, °F

Pressure, psia	Lean, GERG-2008	Lean, Peng-Robinson	Design, GERG-2008	Design, Peng-Robinson	Rich, GERG-2008	Rich, Peng-Robinson
100	-	-63.7	-22.5	-22.1	-6.4	-5.6
300	-	-47.2	3.3	3.4	24.1	25.0

Pressure, psia	Lean, GERG-2008	Lean, Peng-Robinson	Design, GERG-2008	Design, Peng-Robinson	Rich, GERG-2008	Rich, Peng-Robinson
500	-	-46.0	11.9	11.0	36.0	35.8
700	-	-52.9	14.7	11.3	42.0	39.0
800	-	-61.0	13.6	9.3	42.5	38.6
900	-	-	11.1	5.9	41.7	36.9
1,000	-	-	6.7	0.6	39.6	33.9
1,100	-	-	-0.4	-7.7	35.9	29.4
1,200	-	-	-15.7	-	30.1	22.4

Note 1: A dash means the pressure is above the cricondenbar, where no liquid forms at any temperature, or the method did not converge.

6.6. REQUIRED VALVE OUTLET TEMPERATURE

At the governing 750 psig outlet the required temperature is:

$$T_{SP} = \max (40, 33.6 + 10, 14.1 + 10) = 43.6 \text{ } ^\circ\text{F}$$

The Basis of Design sets a flat 40 °F and states that it is at least 10 °F above the hydrate formation temperature. This calculation shows the hydrate dewpoint is 33.5 °F at 750 psig and 41.1 °F at 1,150 psig, so a flat 40 °F would leave 6.5 °F of margin at 750 psig and would sit 1.1 °F below the hydrate dewpoint at 1,150 psig. The heater control will therefore use a pressure-compensated setpoint. A single fixed setpoint of 52 °F was considered; it was rejected because it would burn fuel to heat gas beyond the requirement at the low outlet pressures that dominate winter operation.

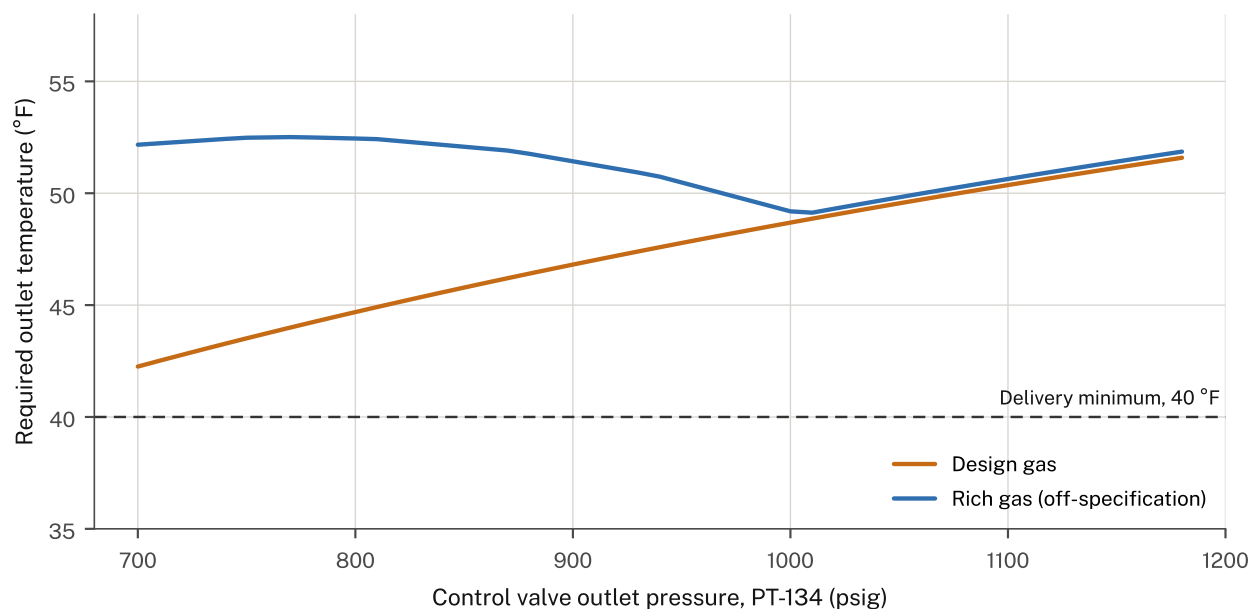
Table 6-7 gives the setpoint characterizer that the control system will apply to outlet pressure transmitter PT-134, feeding the heater temperature controller. Between the 50 psi points, linear interpolation is within 0.01 °F of the calculated curve. A straight line between the 750 and 1,150 psig values was also considered and rejected: because the hydrate curve is concave, it under-predicts the requirement by up to 0.4 °F in the middle of the range. Figure 6-2 shows the characterizer. The rich-gas column applies while the high heating value alarm is active, because the rich gas has a hydrocarbon dewpoint near 42 °F.

Table 6-7: Heater Setpoint Characterizer

PT-134, psig	Setpoint, design gas, °F	Setpoint, rich gas, °F	Envelope, °F	Straight line, °F	Calculated minus straight line, °F
700	42.3	52.2	52.2	-	-
750	43.5	52.5	52.5	43.5	+0.0
800	44.7	52.4	52.4	44.5	+0.2
850	45.8	52.1	52.1	45.4	+0.4

PT-134, psig	Setpoint, design gas, °F	Setpoint, rich gas, °F	Envelope, °F	Straight line, °F	Calculated minus straight line, °F
900	46.8	51.4	51.4	46.4	+0.4
950	47.8	50.5	50.5	47.3	+0.4
1,000	48.7	49.2	49.2	48.3	+0.4
1,050	49.5	49.8	49.8	49.2	+0.3
1,100	50.4	50.6	50.6	50.2	+0.2
1,150	51.1	51.4	51.4	51.1	+0.0
1,180	51.6	51.9	51.9	-	-

Figure 6-2. Required Control Valve Outlet Temperature against Outlet Pressure



6.7. CASES THAT NEED THE HEATER

Table 6-8 compares each case with its requirement. Heat is needed in C1, C6 and C7. Case C5, which the Basis of Design runs with the heater on, meets the requirement with the heater bypassed (50.7 °F against 43.6 °F) because its pressure cut is small; the heater may stay in service at low fire but is not needed. C1 governs the heater duty. C6 falls to 18.2 °F, below the hydrate dewpoint and the delivery minimum but above the -20 °F minimum design metal temperature, so a heater outage is an operating upset rather than a metal temperature hazard.

Table 6-8: Heater Requirement by Case

Case	Heater per basis	Hydrate dewpoint, °F	HC dewpoint, °F	Required outlet, °F	Outlet bypassed, °F	Heat needed	Absorbed duty, MMBtu/h
C1	On	33.6	14.1	43.6	18.2	Yes	3.96
C2	Bypassed	37.8	8.5	47.8	64.3	No	0
C3	Bypassed	37.8	8.6	47.8	57.0	No	0
C4	Bypassed	38.7	5.9	48.7	115.5	No	0
C5	On	33.6	14.1	43.6	50.7	No	0
C6	Bypassed	33.6	14.1	43.6	18.2	Yes	3.96
C7	On	36.1	42.1	52.1	43.3	Yes	1.52

Note 1: The absorbed duty is the heat needed to meet the requirement. It is sized in PRO-CAL-004.

6.8. HEATER BYPASS LIMIT

Table 6-9 gives the lowest station inlet temperature at which the valve outlet meets the setpoint with H-101 bypassed. It allows 15 psi of station losses upstream of the valves and 2 psi downstream. Operations will use it to decide when the heater can be taken out of service in summer.

Table 6-9: Minimum Station Inlet Temperature for Heater Bypass, °F

Station inlet, psig	Outlet 750 psig	Outlet 850 psig	Outlet 950 psig	Outlet 1,050 psig
900	52	48	-	-
1,000	58	54	50	-
1,050	61	57	53	-
1,100	64	60	56	52
1,150	67	63	59	54

Note 1: A dash means the outlet pressure is too close to the inlet pressure for the case to apply.

7. RESULTS AND CONCLUSIONS

TORUS draws the following conclusions:

1. The heater will hold the control valve outlet at the pressure-compensated setpoint of Table 6-7, 43.5 °F at 750 psig rising to 51.1 °F at 1,150 psig, in place of the flat 40 °F of the Basis of Design. The low-temperature alarm on TT-135 should be set 3 °F below the setpoint, with a low-low alarm at 40 °F.
2. Heat is required in cases C1, C6 and C7. Case C1 governs the heater duty at 3.96 MMBtu/h absorbed.

3. The heater-out upset C6 produces 18.2 °F at the valve outlet. This is a hydrate and delivery temperature risk that operations must correct by reducing the pressure cut or the rate, not a metal temperature hazard.
4. The design gas meets the 15 °F cricondenthem (14.8 °F) with essentially no margin, and a real C6+ fraction will raise it. The analyzer scope should include a C9+ chromatograph or a chilled-mirror dewpoint check.
5. Gas at the 7 lb/MMscf limit is 3.9 °F above its hydrate dewpoint at the station inlet in winter (45 °F, 1,150 psig). Typical dehydrated gas at 4 lb/MMscf has 16 °F of margin. The water analyzer alarm should be set at 5 lb/MMscf, with the 7 lb/MMscf limit starting the gas quality shut-in timer (HOLD H-13).

The following items remain open: the extended gas analysis for dewpoint and hydrate confirmation (HOLD H-12) and the receiving pipeline operator's water, dewpoint and temperature specifications (HOLD H-13).