LIGO-E970009-01-V

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-096 PAGE 1 OF 15
REV.	DEO #	DATE	BY:	CHECK	TITLE: Regen. System Process Calculations	
0	130	4/19/96	D.Moore	D. McW		
1	416	1/16/97	D.Moore	D.McW		
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PROJECT: LIGO					PROJECT NO: V59049	

PURPOSE: Determine process requirements for the 80K pump regen. heaters, to estimate the warmup time(time to reach 150 C) for the pump under wintertime conditions in Washington, and to determine insulation thickness for personnel protection.

METHOD: Standard heat transfer manual calcs. and on spreadsheet format.

JAN 21 1997

ASSUMPTIONS: Used weather conditions for Kennewick, Washington: 15 deg. F dry bulb (Above this temperature 97.5% of the time.) For personnel protection, used summertime design temperature of 96 deg. F dry bulb (Below this temperature 97.5% of the time), and light (5 mph) breeze.

INPUTS: Max. regen. flowrate = 100 gm/sec. for long pump; 50 gm/sec. for short pump. N2 temperature from the vaporizer = -5 deg. F (20 deg. F approach temp. specified by mfg.)

REFERENCES:

CALCULATIONS: See attached.

CONCLUSIONS: Long pump heater size: 25 kw adequate. Short pump heater size: 12 kw adequate Estimated warmup times, including liquid vaporization: long pump = 16.75 hrs., short pump = 8.0 hrs. Max. surface temperature of insul. = 115 deg. F is acceptable for personnel protection.

NOTES:

REVISION HISTORY

Rev. 0	Original Issue -April 19, 1996
Rev. 1	Revised to determine insulation thickness for pesonnel protection

80K Pump Regeneration Process Calculations

Sizing of Regen Heaters:

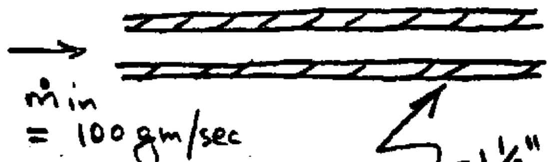
Heaters must be sized to deliver hot N_2 gas to the 80K pumps. The 80K pumps are to be heated to 302°F (150°C). Assuming a 20°F approach temperature, the gas temperature entering the cryopump should be about 325°F.

Wintertime Operation:

Using available design data, size the heater for 15°F dry bulb wintertime conditions (see Attachment 1). Assume a 10 m.p.h. wind blowing across the line supplying the regen. gas to the cryopump. ∴ Calculate the temperature exiting the heater in order to overcome heat losses from the supply line.

Heat Loss thru 60 ft. of regen pipe:

Long pump:

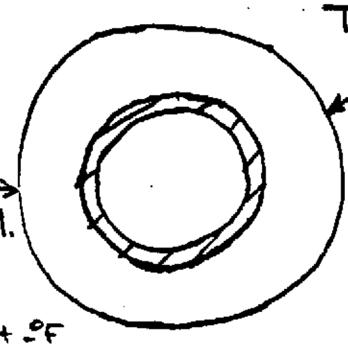


$T_{amb} = 15°F$

$T_{out} = 325°F$

$T_{in} = ?$

$T_o = ?$ $T_{amb} = 15°F$



$k = .04 \frac{Btu}{hr\text{-}ft\text{-}°F}$

$$q_{in} = q_{out}$$

$$kS(T_i - T_o) = hA(T_o - T_{amb})$$

$$S = \frac{2\pi L}{\ln(r_o/r_i)}$$

$$= \frac{2\pi(1.0)}{\ln(6.5/3.5)} = 10.15 \text{ ft}$$

Assume 10 mph wind

$$A = 2\pi r_o L$$

$$= 2\pi\left(\frac{3.25}{12}\right)(1.0)$$

$$= 1.70 \text{ ft}^2/\text{ft}$$

$$Re = \frac{D_o u_\infty}{\nu_f} = \frac{\rho_f D_o u_\infty}{\mu_f}$$

$$10\ \frac{mile}{hr}\left(\frac{5280\ ft}{mile}\right) = 52800\ \frac{ft}{hr}$$

$$Re = \frac{\left(\frac{6.5}{12}\right)(52800)(.084)}{.04} \qquad \mu_f = .04\ \frac{lb_m}{hr\text{-}ft}$$

$$= 60000$$

$$\frac{hD_o}{k_f} = 170 \quad \text{(see pg 7)}$$

$$h = \frac{170(.0135)}{(6.5/12)}$$

$$= 4.24\ \text{Btu/hr-ft}^2\text{-}^\circ F$$

To account for radiation, say $h = 4.5\ \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F}$

$$\therefore\ .04(10.15)(325 - T_o) = 4.5(1.70)(T_o - 15)$$

$$131.95 - .406T_o = 7.65T_o - 114.75$$

$$8.06T_o = 246.7$$

$$T_o = 30.6\ ^\circ F$$

$$\therefore\ q = kS(T_i - T_o)$$

$$= .04(10.15)(325 - 30.6)$$

$$= 119.5\ \frac{Btu}{hr\text{-}ft}$$

for 60 ft of pipe

$$q = 119.5(60) = 7172\ \text{Btu/hr}$$

∴ Calculate the temp drop of the N_2 inside the pipe

$$q = \dot{m} c_p \Delta T$$

$$7172 = .22(3600)(.25)\Delta T$$

$$\Delta T = 36°F$$

N_2 temp in needs to be

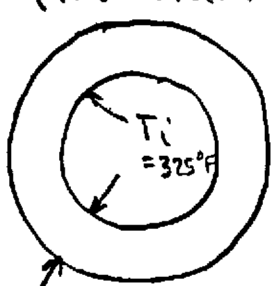
$$\begin{array}{r} 325 \\ +\ 36 \\ \hline 361\,°F \end{array} \quad \text{say } 360°F$$

—//—

Short pump

1½" ϕ pipe

(1.9" o.d.)



1½" insul

$$S = \frac{2\pi(1.0)}{\ln(4.9/1.9)} = 6.63 \text{ ft}$$

$$A = 2\pi\left(\frac{4.9}{2(12)}\right)(1.0)$$

$$= 1.28 \text{ ft}^2/\text{ft.}$$

10 m.p.h. wind

$$Re = \frac{\left(\frac{4.9}{12}\right)(52800)(.084)}{.04}$$

$$= 45300$$

.50 gm/sec

(.11 lbm/sec)

$$\frac{hD_o}{k_f} = 150$$ (see pg 7)

$$h = \frac{150\,(.0135)}{(4.9/12)}$$

$$= 4.96 \quad Btu/hr\text{-}ft^2\text{-}°F$$

say $5.5 \ Btu/hr\text{-}ft^2\text{-}°F$

$$kS(T_i - T_o) = hA(T_o - T_{amb})$$

$$.04(6.63)(325 - T_o)$$
$$= 5.5(1.28)(T_o - 15)$$
$$86.19 - .265T_o = 7.04T_o - 105.6$$
$$191.8 = 7.305T_o$$
$$T_o = 26.3°F$$

$$q = kS(T_i - T_o)$$
$$= .04(6.63)(325 - 26.3)$$
$$= 79.21 \quad Btu/hr\text{-}ft$$

for 60 ft of pipe

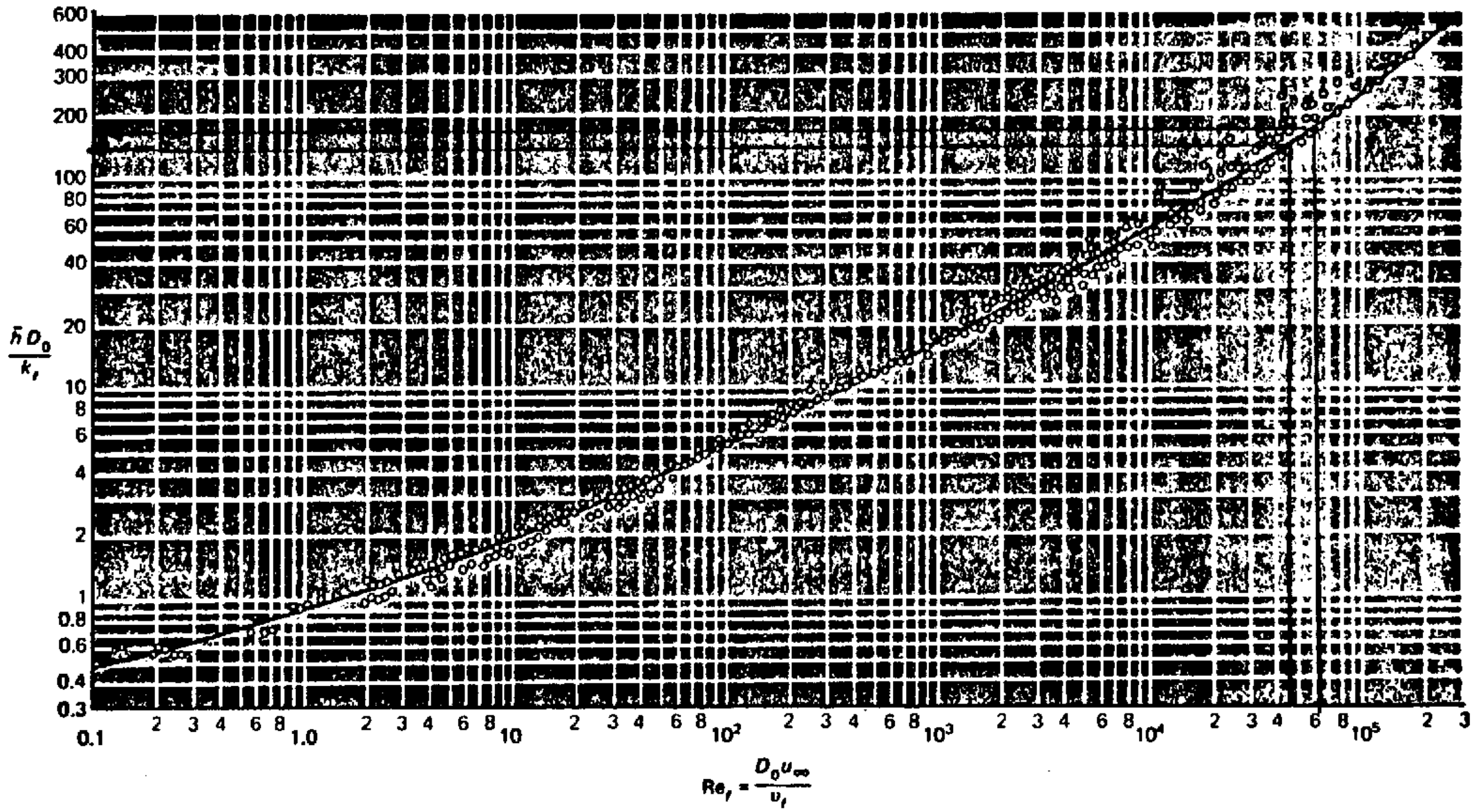
$$q = 60(79.21) = 4753 \ Btu/hr$$

∴ Temp drop of N_2:

$$q = \dot{m}c_p\Delta T$$
$$4753 = .11(3600)(.25)\Delta T$$
$$\Delta T = 48°F$$

∴ T_{in} must be 325 + 48 = 373 (say 375°F)

Fig. 6-9 Data for heating and cooling of air flowing normal to single cylinders, from McAdams [10].



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Regen Heater Sizes:

Vaporizer design is based on 20°F approach temp. ∴ the N_2 gas out of the vaporizer will be 15°F - 20°F = -5°F (253 K)

Long pump:

100 gm/sec. flowrate at 253K raised to 455K (360°F)

$$Q = \left(100 \frac{gm}{sec}\right)(472.8 - 262) \frac{j}{gm}$$

$= 21080$ watts

(Heater size approx 25 kW)

100 gm/sec ⟶ 10572 SCFH (say 10600 SCFH)

Short pump:

50 gm/sec. flowrate at 253K raised to 464 K (375°F)

$$Q = 50 \frac{gm}{sec} (482.3 - 262) j/gm$$

$= 11015$ watts (Heater size approx 12 kW)

50 gm/sec → say: 5300 SCFH

Time to Vaporize LN_2:

Long pump: ~1700 lbm of LN_2 (772,700 gm)
Purge gas flow = 100 gm/sec. @ 253K

$$(\dot{m}\Delta h)_{N_2\,gas} = \dot{m}\, h_{fg}$$

$$\dot{m}_{vaporized} = \frac{(\dot{m}\Delta h)_{N_2\,gas}}{h_{fg}}$$

$$= \frac{(100\ \text{gm/sec})(262 - 79.6)\ \text{j/gm}}{(78.4 + 118.1)\ \text{j/gm}}$$

$$= 92.8\ \text{gm/sec.}\ (.204\ \text{lbm/sec})$$

∴ Time to vaporize is:

$$t = \frac{1702\ \text{lbm}}{.204\ \text{lbm/sec}}$$

$$= 8324\ \text{sec}\ (2.3\ \text{hr.})$$

Short pump: ~550 lbm of N_2
Purge gas flow = 50 gm/sec.

$$\dot{m}_{vaporized} = \frac{(50)(262-79.6)}{(78.4+118.1)}$$

$$= 46.4\ \text{gm/sec}\ (.102\ \text{lbm/sec})$$

∴ Time to vaporize is:

$$t = \frac{550}{.102} = 5392\ \text{sec}\ (1.5\ \text{hr.})$$

Long Pump Regen.
Warmup Time
Winter Conditions

N2 flow (gm/sec)	Cp of N2 (j/gm-K)	N2 in (K)	N2 out (K)	Cp alum. (j/gm-K)	Initial alum. temp (K)	Final alum. temp. (K)	Alum. mass (gm.)	Elapsed time (sec)
50	1.05	253	80	0.357	80	100	1341000	1054.2
50	1.05	253	100	0.481	100	120	1341000	2660.22
50	1.05	253	120	0.58	120	140	1341000	4888.02
50	1.05	253	140	0.654	140	160	1341000	7844.66
50	1.05	253	160	0.713	160	180	1341000	11761.2
50	1.05	253	180	0.76	180	200	1341000	17079.7
50	1.05	253	200	0.797	200	220	1341000	24761.9
100	1.05	436	220	0.826	220	240	1341000	25738.7
100	1.05	436	240	0.849	240	260	1341000	26845.1
100	1.05	436	260	0.869	260	280	1341000	28106.3
100	1.05	436	280	0.886	280	300	1341000	29557
100	1.05	436	300	0.902	300	320	1341000	31251.1
100	1.05	436	320	0.918	320	340	1341000	33272.5
100	1.05	436	340	0.934	340	360	1341000	35757.6
100	1.05	436	360	0.934	360	380	1341000	38896.7
100	1.05	436	380	0.934	380	400	1341000	43156.8
100	1.05	436	400	0.934	400	420	1341000	49783.8
100	1.05	436	420	0.934	420	423	1341000	52020.4

Time to vaporize LN2 = 2.3 hours
Total warmup time = 16.75 hours

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Short Pump Regen.
Warmup Time
Winter Conditions

N2 flow (gm/sec)	Cp of N2 (j/gm-K)	N2 in (K)	N2 out (K)	Cp alum. (j/gm-K)	Initial alum. temp (K)	Final alum. temp. (K)	Alum. mass (gm.)	Elapsed time (sec)
50	1.05	253	80	0.357	80	100	398000	312.879
50	1.05	253	100	0.481	100	120	398000	789.537
50	1.05	253	120	0.58	120	140	398000	1450.73
50	1.05	253	140	0.654	140	160	398000	2328.25
50	1.05	253	160	0.713	160	180	398000	3490.66
50	1.05	253	180	0.76	180	200	398000	5069.16
50	1.05	253	200	0.797	200	220	398000	7349.16
50	1.05	436	220	0.826	220	240	398000	7928.97
50	1.05	436	240	0.849	240	260	398000	8585.73
50	1.05	436	260	0.869	260	280	398000	9334.34
50	1.05	436	280	0.886	280	300	398000	10195.5
50	1.05	436	300	0.902	300	320	398000	11201.1
50	1.05	436	320	0.918	320	340	398000	12400.9
50	1.05	436	340	0.934	340	360	398000	13876.1
50	1.05	436	360	0.934	360	380	398000	15739.4
50	1.05	436	380	0.934	380	400	398000	18268.2
50	1.05	436	400	0.934	400	420	398000	22201.8
50	1.05	436	420	0.934	420	423	398000	23529.5

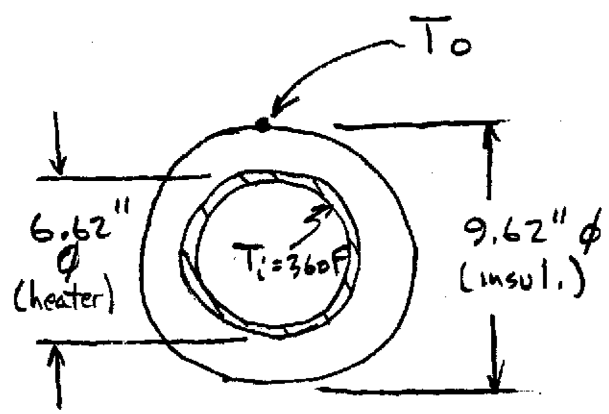
Time to vaporize LN2 = 1.5 hours
Total warmup time = 8.036 hours

Personnel Protection:

Calculate heater insulation outside surface temperature under extreme conditions.

Outside ambient = 96 °F dry bulb

Assume light breeze (5 m.p.h.) and heater has been powered up beyond normal requirements. (Heater will need to operate slightly above 150 C (302F) for pump regeneration.) Assume 360 F heater temp.



Tamb. = 96°F

Heater Cross-section

$k_{insul} = .04 \frac{Btu}{hr\text{-}ft\text{-}°F}$

(fiberglass)

$\varepsilon \approx 0.8$

Energy in = energy out

$$kS(T_i - T_o) = hA(T_o - T_a) + \sigma A \varepsilon (T_o^4 - T_{amb}^4)$$

$$S = \frac{2\pi L}{\ln (d_o/d_i)}$$

$$= \frac{2\pi(1.0)}{\ln(9.62/6.62)} = 16.81 \text{ ft.}$$ (per unit ft. of length)

$$A = \pi d_o L$$

$$= \pi\left(\frac{9.62}{12}\right)(1.0) = 2.52 \text{ ft}^2/\text{ft.}$$

For 5 mph wind

$$5 \text{ mph } (5280) = 26400 \text{ ft/hr.}$$

$$Re = \frac{\rho_f D u_\infty}{\mu_f}$$

$$= \frac{.07\,(9.62/12)(26400)}{.046}$$

$$= 32000$$

From pg 7, $\frac{h D_o}{k_f} = 125$

$$h = \frac{125\,(.0154)}{(9.62/12)}$$

$$h = 2.4 \text{ Btu/hr-ft}^2\text{-°F}$$

$$\therefore \; .04(16.81)(360 - T_o)$$

$$= 2.4(2.52)(T_o - T_{amb}) +$$

$$(.1714 \times 10^{-8})(2.52)(0.8)\left((T_o+460)^4 - 554^4\right)$$

$$.672(360 - T_o) = 6.05(T_o - 96) + 3.46 \times 10^{-9}\left((T_o+460)^4 - 554^4\right)$$

Solution by trial & error

T_o (°F)	L.H.S. (Btu/hr)	R.H.S. (Btu/hr)	
110	168	124	
115	164.6	167.2	← close

∴ Surface of insulation will be approx 115 °F & 1½" thick insulation is adequate for personnel protection.

Attachment 1.

Table C-1 (Cont.)

STATE AND STATION	WINTER Latitude	WINTER DB 97½%	SUMMER DB 2½%	SUMMER WB 2½%	SUMMER Outdoor Daily Range
Lubbock AP	33	15	97	72	26
Lufkin AP	31	28	96	80	20
McAllen	26	38	100	79	21
Midland AP	32	23	98	73	26
Mineral Wells AP	32	22	100	77	22
Palestine CO	31	25	97	79	20
Pampa	35	11	98	72	26
Pecos	31	19	100	71	27
Plainview	34	14	98	72	26
Port Arthur AP	30	33	92	80	19
San Angelo, *Goodfellow* AFB	31	25	99	75	24
San Antonio AP	29	30	97	77	19
Sherman-Perrin AFB	33	23	99	78	22
Snyder	32	19	100	74	26
Temple	31	27	99	78	22
Tyler AP	32	24	97	79	21
Vernon	34	18	101	76	24
Victoria AP	28	32	96	79	18
Waco AP	31	26	99	78	22
Wichita Falls AP	34	19	100	76	24
UTAH					
Cedar City AP	37	6	91	64	32
Logan	41	7	91	65	33
Moab	38	16	98	65	30
Ogden CO	41	11	92	65	33
Price	39	7	91	64	33
Provo	40	6	93	66	32
Richfield	38	3	92	65	34
St. George CO	37	26	102	70	33
Salt Lake City AP	40	9	94	66	32
Vernal AP	40	−6	88	63	32
VERMONT					
Barre	44	−13	84	72	23
Burlington AP	44	−7	85	73	23
Rutland	43	−8	85	73	23
VIRGINIA					
Charlottsville	38	15	90	77	23
Danville AP	36	17	92	77	21
Fredericksburg	38	14	92	78	21
Harrisonburg	38	9	90	77	23
Lynchburg AP	37	19	92	76	21
Norfolk AP	36	23	91	78	18
Petersburg	37	18	94	79	20
Richmond AP	37	18	93	78	21
Roanoke AP	37	18	91	75	23
Staunton	38	12	90	77	23
Winchester	39	10	92	76	21
WASHINGTON					
Aberdeen	47	27	80	61	16
Bellingham AP	48	18	74	65	19
Bremerton	47	29	81	66	20
Ellensburg AP	47	6	89	65	34
Everett-Paine AFB	47	24	78	65	20
Kennewick	46	15	96	68	30
Longview	46	24	86	66	30
Moses Lake, Larson AFB	47	−1	93	66	32
Olympia AP	47	25	83	65	32
Port Angeles	48	29	73	58	18
Seattle-Boeing Fld.	47	27	80	65	24
Seattle CO	47	32	79	65	19
Seattle-Tacoma AP	47	24	81	64	22
Spokane AP	47	4	90	64	28
Tacoma-McChord AFB	47	24	81	66	22
Walla Walla AP	46	16	96	68	27
Wenatchee	47	9	92	66	32
Yakima AP	46	10	92	67	36
WEST VIRGINIA					
Beckley	37	6	88	73	22
Bluefield AP	37	10	86	73	22
Charleston AP	38	14	90	75	20
Clarksburg	39	7	90	75	21
Elkins AP	38	5	84	73	22
Huntington CO	38	14	93	76	22
Martinsburg AP	39	10	94	77	21
Morgantown AP	39	7	88	74	22
Parkersburg CO	39	12	91	76	21
Wheeling	40	9	89	75	21
WISCONSIN					
Appleton	44	−6	87	74	23
Ashland	46	−17	83	71	23
Beloit	42	−3	90	76	24
Eau Claire AP	44	−11	88	74	23
Fond du Lac	43	−7	87	74	23
Green Bay AP	44	−7	85	73	23
La Crosse AP	43	−8	88	76	22
Madison AP	43	−5	88	75	22
Manitowoc	44	−1	86	74	21
Marinette	45	−4	86	72	20
Milwaukee AP	43	−2	87	75	21
Racine	42	0	88	75	21
Sheboygan	43	0	87	74	20
Stevens Point	44	−12	87	73	23
Waukesha	43	−2	89	75	22
Wausau AP	44	−14	86	72	23
WYOMING					
Casper AP	42	−5	90	62	31
Cheyenne AP	41	−2	86	62	30
Cody AP	44	−9	87	60	32
Evanston	41	−8	82	57	32
Lander AP	42	−12	90	62	32
Laramie AP	41	−2	80	59	28
Newcastle	43	−5	89	67	30
Rawlins	41	−11	84	61	40
Rock Springs AP	41	−1	84	57	32
Sheridan AP	44	−7	92	65	32
Torrington	42	−7	92	67	30

EXPLANATION OF DESIGN CONDITIONS:

WINTER – 97½% indicates that the temperature will be at or above the design temperature shown 97½% of the time.

SUMMER – 2½% indicates that the temperature will exceed the design temperature shown only 2½% of the time.

OUTDOOR DAILY RANGE – The outdoor daily range of DB temperatures is the difference between the average maximum and average minimum temperatures during the warmest month at each location. Refer to page 39 when outdoor daily range is other than 20°.

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