CC CRYOSTAT COOLDOWN TEST WARMUP

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INTRODUCTION:

This report discusses the warming up of the stainless steel inner vessel of the CC Cryostat back to room temperature after it has been cooled down by liquid nitrogen. It considers the sufficiency of a standard magnet warm-up 12KW heater in delivering enough heat to warm the Cryostat in a couple of days.

The concept of sufficiency will be answered by the following questions, and by an experimental test that was made of the heater in question.

QUESTIONS:

The concept of heater sufficiency and Cryostat warming are approached with three questions in mind:

- 1) How much time will it take for a 12Kw gas heater to deliver enough Joules of energy to warm the CC Cryostat back to room temperature?

For this calculation, the weight of the inner vessel is needed, and can be found from ref. 1. Also the change in enthalpy of the stainless steel Cryostat is needed between room temperature (300K) and liquid nitrogen temperature (77K). (see ref. 2)

RESULTS: Energetically speaking, it will take 18.5 hours to warm the Cryostat's inner vessel back to 300K (80.33°F) by delivering 8.00×10^8 J. This assumes that an average of 12KW are input and transferred to the vessel, i.e. a room temperature exhaust on average. (see calculations)

- 2) How does convection in the Cryostat's inner vessel affect the exhaust temperature of the air? ie. For a given inner vessel wall temperature, what exhaust temperature and power output can be expected if the input temperature and power from the heater remain constant? The real concern is that the heat that is being put in is being transferred to the walls of the vessel, and not just coming back out as warm air. Since the exact method of convection is uncertain, both forced and free convection will be considered.

Case 1: Forced convection at 100CFM from the top of the Cryostat, to the bottom while in crossflow to an exterior cylindrical surface. (see ref. 3 and attached calculations)

FORCED CONVECTION RESULTS:

All temperatures are in degrees Kelvin.

T_{wall}	T_{IN}	T_{OUT}	T_{AVE}	Q (KW)
100	463.7	370.3	417.0	5.50
200	463.7	396.3	430.1	3.97
300	463.7	422.3	443.1	2.44

CONCLUSION:

These results show that most of the heat that is put in is **not** being left behind because the exhaust temperature is very near the input temperature, and little progress is made in warming the inner vessel back to 300K. At this point, we must consider that perhaps we are in fact not dealing with a forced convection problem, but rather one of free convection. (See calculations) The results for free convection follow:

CASE 2: Free convection in the inner vessel. Modeled as a vertically oriented flat plate. (see ref. 3 and attached calculations)

FREE CONVECTION RESULTS:

All temperatures are in degrees Kelvin.

T_{wall}	T_{IN}	T_{OUT}	Q (KW)
100	463.7	134.5	18.45
200	463.7	224.5	13.41
300	463.7	314.5	8.37

CONCLUSION:

These results show that indeed the air is coming out very near the wall temperature. This implies that most of the heat in the air is being transferred to the vessel's walls. Note that over the range of 100K to 300K, the air is cooling near an average of 10KW (10,000 J/S). Since the velocity of the incoming air in the large vessel is very small, free convection dominates.

- 3) Will a 100 CFM air compressor satisfy 12KW and a temperature of 375°F?

100 CFM is the maximum available air compressor flow and 12KW is the maximum power output from the heater. 375°F (463.7K) is chosen as a safe upper operating temperature for the heater.

$$Q = \dot{M} * C_p * \Delta T$$

where: Q is the power in watts. (J/S).

ΔT is the temperature change involved. (Kelvin).

C_p is the specific heat of air at constant pressure. (J/(G-K))

$\dot{M}$ is the mass flow. (G/S).

RESULTS:

The calculations show that if the heater operates at 12KW, 153 SCFM at 120°F, or 132 SCFM at 80°F, (See heater test results note) is required to warm the air to 375°F. Since our compressor can only operate to 100 CFM, only 7.87KW (for 120°F input) or 9.10KW (for 80°F input) are required to achieve the 375°F temperature. The warmup time in either case for free convection is 16.75 hours.

HEATER TEST RESULTS:

In a recent test of the 12KW heater that is available for the CC Cryostat warmup, using an Ingersoll Rand air compressor the following data was observed, and collected:

Compressor Discharge Pressure	88 psig (Full flow)
Compressor Discharge Temperature	
without after cooler	180°F
(Operating in the Modulation Mode)	
Heater Set point	350°F, Heater Output 342°F

The heater was run for 1.0 hour, and the above stated output remained constant.

Note: No receiver was used with the air compressor, and no insulation was used on any of the lines. The line from the compressor to the heater was only 1/2" (I.D) where it needs to be 1" (I.D). The actual discharge temperature with the after cooler was not measured, but the line to the heater was considerably warm. For this report, it will be assumed that the input temperature be in the range from 80°F to 120°F. These test conditions will not exist during the actual warmup. (see ref. 4)

FINAL CONCLUSION:

It can be seen from the calculations that the heater in question will be fully sufficient for the warmup. The 12KW heater need only be run somewhere between a range of 7.87KW and 9.10KW, and a 375 °F output will be maintained for 16.75 hours to warm the CC Cryostat back to room temperature.

References

1. Wintercorn, S.J., "D-Zero Calorimeter Multiplan", D-Zero Engineering Note 3740.000-EN-40, May 26, 1987; Rev. N (see Row 8, Col 37).
2. Cryogenic Data, Cooldown Refrigeration Calculation Chart, Cryenco Co., Denver, Colorado.
3. Kreith, "Principles of Heat Transfer", International Textbook Co., Scranton, Pennsylvania, 1959.
4. Hentges, M., Results of a 12KW heater warmup test, 9/1987.
5. Barron, F. Randall, "Cryogenic Systems", Oxford University Press, New York, 1985.

Calculations

⑦

CC Cryostat Warmup Via Gas Heater

Weight of Inner Vessel

$$W = 11.38 \text{ Tons (From Multiplan)}$$

$$= 11.38 \text{ Tons} \times \frac{2000 \text{ lbs.}}{\text{TON}} = 22,760 \text{ lbs.}$$

$$= 22,760 \text{ lbs.} \times \frac{453.6 \text{ g}}{\text{lb}} = \boxed{1.03 \times 10^7 \text{ g}}$$

Δ Enthalpy of CC Cryostat (Inner Vessel)

Iron $\approx$ Stainless Steel

(From cryogenic Data sheet)

Room Temp $\rightarrow H_{300K} = 81.1 \frac{\text{J}}{\text{g}}$

$\rightarrow H_{77K} = 3.43 \frac{\text{J}}{\text{g}}$

$\Delta H = 77.67 \frac{\text{J}}{\text{g}}$ when cooled down,
so need same ΔH on Warmup to
get back to normal.

Joule Delivery Necessary to Warm Back to 300K

$$1.03 \times 10^7 \text{ g} \times 77.67 \frac{\text{J}}{\text{g}} = \boxed{8.00 \times 10^8 \text{ J} \approx 10^9 \text{ J}}$$

How Long? w/ 12KW Heater (Assuming 12KW in, 12KW out)

$$8.00 \times 10^8 \text{ J} / 12 \times 10^3 \frac{\text{J}}{\text{s}} = 6.66 \times 10^4 \text{ s} \times \frac{\text{DAY}}{(24)(3600) \text{ s}}$$

$$= \boxed{1.77 \text{ DAYS or } 18 \frac{1}{2} \text{ hrs.}}$$

Properties of Air (The Fluid) at 100 ATM, Room Temp

$$K = \text{Thermal Conductivity} = .01516 \frac{\text{Btu}}{\text{ft} \cdot \text{hr} \cdot ^\circ\text{F}}$$

$$P = \text{Density} = .0735 \frac{\text{lb}_m}{\text{ft}^3} \quad (\text{FROM REF. 5})$$

$$\mu = \text{Viscosity} = .0447 \frac{\text{lb}_m}{\text{ft} \cdot \text{hr}}$$

$$\begin{aligned} D = \text{"inner" cylinder Diameter} &= 64.375 + 2(.375) \\ &= 65.125 \text{ in} \\ &= \underline{5.43 \text{ ft}} \end{aligned}$$

π = whole exposed inside surface Area

$$= \pi(O.I.D.)L_0 + \pi(I.O.D.)L_1 + 2\pi(O.I.R.)^2 + 2\pi(I.O.R.)^2$$

$$\begin{aligned} &= \pi[(193.5 - 2(\frac{5}{8}))](117.25 - 2(\frac{3}{8})) + (64\frac{3}{8} + 2(\frac{3}{8}))(109)] \\ &\quad + 2\pi[(96.125)^2 - (82.86)^2] \end{aligned}$$

$$= 144,059.22 \text{ in}^2$$

$$= \underline{1000.41 \text{ ft}^2}$$

$$\frac{\mu_g}{P_f} = \frac{.0447 \frac{\text{lb}_m}{\text{ft} \cdot \text{hr}}}{.0735 \frac{\text{lb}_m}{\text{ft}^3}} = .6082 \frac{\text{ft}^2}{\text{hr}}$$

⑤

$$V = \text{velocity} = \frac{Q}{A}$$

⑨

$$\dot{V} = 100 \text{ GPM} = 55.55 \text{ ft}^3/\text{s}$$

$$2A_x = F_{0.0} = E.0 \times L_0$$

$$2A_x = \left[\left((193.5 - 2(7/8)) - (64/8 + 2(7/8)) \right) \right] (109)$$

$$= 13,911.125 \text{ in}^2$$

$$= \underline{\underline{96.60 \text{ ft}^2}}$$

$$V = \frac{100 \frac{\text{ft}^3}{\text{min}}}{96.60 \text{ ft}^2} = \underline{\underline{1.035 \frac{\text{ft}}{\text{min}}}}$$

⑥

$$RE = \text{Reynolds \#} = \frac{\rho V D}{\mu} = \frac{V D}{\nu}$$

$$= \left(.0735 \frac{\text{lb}_m}{\text{ft}^3} \right) \left(1.035 \frac{\text{ft}}{\text{min}} \right) \left(5.43 \text{ ft} \right)$$

$$\left(.0447 \frac{\text{lb}_m}{\text{ft} \cdot \text{hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \right)$$

$$RE = 554.46 \quad (\text{Laminar Flow}) (\leq 2100)$$

$$\therefore C = .615$$

$$\therefore \underline{\underline{n = .466}}$$

From Table 9-1

$$\textcircled{7} \text{ Nusselt} = C(Re)^n$$

$$\frac{h_c D}{K} = C(Re)^n$$

$$\frac{h_c (5.43 \text{ ft})}{(.01516 \frac{\text{Btu}}{\text{hr-ft-F}})} = (.615) (554.46)^{.466}$$

$$h_c = .0326 \frac{\text{Btu}}{\text{hr-ft}^2\text{-F}^\circ}$$

$$\textcircled{8} \text{ using: } \textcircled{1} Q = \dot{M}_{air} \Delta H = \dot{M}_{air} \Delta T c_p$$

$$\textcircled{2} Q = h_c A = (\bar{T}_{ave} - T_{wall})$$

$$\textcircled{3} \bar{T}_{ave} = \frac{T_{in} + T_{out}}{2} \quad \text{with } t_{in} = 375 \text{ F}^\circ$$

Determine Q & T_{out}

$$\text{From 1) } Q = (55.55 \frac{\text{g}}{\text{s}}) (463.7 \text{ K} - T_{out}) (1.00 \frac{\text{J}}{\text{g-K}})$$

or conventional units of:

$$Q = (55.55 \frac{\text{g}}{\text{s}}) (375 \text{ F}^\circ - T_{out}) (.2528 \frac{\text{Btu}}{\text{lb-F}^\circ}) \left(\frac{1 \text{ lb}}{4.535 \times 10^{-1} \text{ kg}} \right) \times \left(\frac{1 \text{ kg}}{1000 \text{ g}} \right) \times \frac{3600 \text{ s}}{1 \text{ hr.}}$$

$$Q = 111.48 (375 - T_{out})$$

$$Q = 41,804 - 111.48 T_{out}$$

$$\text{From 2) } Q = (.0326 \frac{\text{Btu}}{\text{hr-ft}^2\text{-F}^\circ}) (1000.41 \text{ ft}^2) \left(\frac{375 \text{ F}^\circ + T_{out}}{2} - T_{wall} \right)$$

$$Q = 32.61 \left(\frac{375}{2} + \frac{T_{out}}{2} - T_{wall} \right)$$

$$Q = 6115.01 + 16.30 T_{out} - 32.61 T_{wall}$$

⑨ solve simultaneously:

$$Q = 41,804 - 111.48 t_{out}$$

$$Q = 6115.01 + 16.30 t_{out} - 32.61 t_{wall}$$

$$41,804 - 111.48 t_{out} = 6115.01 + 16.30 t_{out} - 32.61 t_{wall}$$

$$t_{out} = \frac{35,689}{127.78} + \frac{32.61}{127.78} t_{wall}$$

$$\underline{t_{out} = 279.30 + .26 t_{wall}}$$

⑩ Results:

	t_{wall}	t_{in}	t_{out}	$\bar{T}_{ave}$	Q
Conventional or	$(-279.67F^\circ)$	$375F^\circ$	$206.58F^\circ$	$290.8F^\circ$	$19774 \frac{Btu}{hr}$
	$(-99.67F^\circ)$	$375F^\circ$	$253.38F^\circ$	$314.2F^\circ$	$13557 \frac{Btu}{hr}$
	$(80.33F^\circ)$	$375F^\circ$	$300.18F^\circ$	$337.6F^\circ$	$8340 \frac{Btu}{hr}$
SI units	100 K	463.9 K	370.3 K	417 K	5500 watts
	200 K	463.9 K	396.3 K	430.1 K	3972 watts
	300 K	463.9 K	422.3 K	443.1 K	2444 watts

CHECK Free convection Heat Transfer Coefficient

- ① Assume: That we only deal with Flow over a vertically oriented Flat plate. The "Flat" plate in this case is The inner cylinder.

* Also Assume Heat Transfer will be poor & use properties of air at 100K (near L_{m2} temp.)

END view of Cryostat

- ② Find Gr

$$Gr = \rho^2 B g (T_{air} - T_{wall}) L^3 / \mu^2$$

$$\frac{\rho^2 B g}{\mu^2} = \left(\frac{1.76 \times 10^6}{F \text{ ft}^3} \right) \text{ For air at } 100K$$

$L = 5.43 \text{ ft.}$ (Assume "Flat plate" has Length = Diameter of inner cylinder)

$$Gr = \left(\frac{1.76 \times 10^6}{F \text{ ft}^3} \right) (375 F - T_{wall}) (5.43 \text{ ft})^3$$

$$Gr = 2.82 \times 10^8 (375 F - T_{wall})$$

- ③ Find Gr Pr

$$Pr = .72 \text{ For air at } 100F$$

$$Gr Pr = (.72) (2.82 \times 10^8) (375 F - T_{wall})$$

$$Gr Pr = 2.03 \times 10^8 (375 F - T_{wall})$$

Results:

④

$T_{wall} (K)$	$T_{wall} (F)$	$Gr Pr$	$\overline{Nu}$	$\overline{h}_c$
100	-280	1.33×10^{10}	591	1.68
200	-100	9.64×10^{10}	520	1.47
300	80	5.99×10^{10}	430	1.22

calculate $\overline{Nu}$ via;

$$\overline{Nu} = .0210 (Gr Pr)^{1/5} \quad (\text{see Fig 7-4, Ref 3})$$

calculate $\overline{h}_c$ via:

$$\overline{h}_c = \frac{\overline{Nu} K}{L} = \frac{\overline{Nu} (.0154 \frac{Btu}{hr ft F})}{5.43 ft.}$$

$$\overline{h}_c = 2.836 \times 10^{-3} \overline{Nu}$$

- ⑤ Conclusion: Since The $\overline{h}_c$ is at least 1.00 for free convection & that is higher than the forced convection $\overline{h}_c$ of .0326., we will assume that $\overline{h}_c = 1.00$ for the rest of the calculations. (Note, to solve the problem exactly we would need to use some iterative process, but we'll just assume our assumptions are fairly valid.)

⑥ Solve simultaneously for Q & T_{out} (As in forced convection)

$$\textcircled{A} \quad Q = (55.55 \frac{J}{s}) (464 K - T_{out}) (1.00 \frac{J}{g \cdot K})$$

$$= (56 \frac{W}{K}) (464 K - T_{out})$$

$$\textcircled{B} \quad Q = (1.0 \frac{Btu}{hr \cdot ft^2 \cdot F}) (1000 ft^2) (\frac{464 K + t_{out}}{2} - t_{wall})$$

$$\times \frac{9 F}{5 K} \times \frac{1 W}{3.41 \frac{Btu}{hr}}$$

$$= (527.86 \frac{W}{K}) (\frac{464}{2} + \frac{t_{out}}{2} - T_{wall})$$

$$\text{Set : (A) = (B)} \Rightarrow 56(464 - T_{out}) = 527.86 (232 + \frac{t_{out}}{2} - t_{wall})$$

$$25984 - 56 t_{out} = 122463 + 263.93 t_{out} - 528 t_{wall}$$

$$-96479 + 528 T_{wall} = 320 T_{out}$$

$$\underline{T_{out} = 1.65 T_{wall} - 301.5}$$

Conclusion: There is a problem here. The problem is THAT because h_c is so large, (B) Gives A huge Q . The Avg. Temp. cannot be $\frac{T_{out} + T_{in}}{2}$.

Since The gas COOLS quickly, we will assume

T_{out} as The Average gas temp. for convection inside.

$$\textcircled{7} \quad \begin{aligned} \text{(B)} \quad Q &= (528 \text{ W/K}) (T_{\text{gas}} - T_{\text{wall}}) \\ \text{(A)} \quad Q &= (56 \text{ W/K}) (464 - T_{\text{out}}) \end{aligned}$$

Again, Assume $T_{\text{gas}} \cong T_{\text{out}}$ inside vessel if gas cools quickly.

$$528 T_{\text{out}} - 528 T_{\text{wall}} = (56)(464) - 56 T_{\text{out}}$$

$$584 T_{\text{out}} = 528 T_{\text{wall}} + 25984$$

$$\underline{T_{\text{out}} = .90 T_{\text{wall}} + 44.5}$$

Results:

$T_{\text{wall}} \text{ (K)}$	$T_{\text{out}} \text{ (K)}$	$T_{\text{out}} \text{ (F)}$	$Q \text{ (W)}$
100	134.5	-218	18,452
200	224.5	-56	13,412
300	314.5	106	8,372

Conclusion: In this consideration most of the heat is left behind since $T_{\text{out}} \approx T_{\text{wall}}$. ON AVERAGE, we have 10 KW of cooling.

⑫

WILL A 100 CFM Air compressor SATISFY 12 KW @ 375°F?

use: $\dot{M} c_p (T_{out} - T_{in}) = Q$

$$\dot{M} (1.00 \frac{J}{g \cdot K}) (463.9 K - 322.2 K) = 12 \times 10^3 \frac{J}{s}$$

↑
this is 100°F (see Heater Test Results)

$$\dot{M} = 84.7 \frac{g}{s}$$

1.00 g/s
(kg/s)

$$84.7 \frac{g}{s} \times \frac{1 \cancel{kg}}{1000 \cancel{g}} \times \frac{1 \cancel{hr}}{3600 \cancel{s}} \times \frac{60 \cancel{min}}{1 \cancel{hr}} \times \frac{1 \cancel{ft}^3}{0.0735 \cancel{m}^3} = 152.6 \approx \boxed{153 \text{ scfm}}$$

OR: IF $T_{in} = 300 K$ (Room Temp.) (See Heater Test Results)

$$\dot{M} (1.00) (464 - 300) = 12 \times 10^3$$

$$\dot{M} = 73.1 \frac{g}{s} = 131.7 = \boxed{132 \text{ scfm}}$$

Actual Temp. Necessary to Achieve 100 CFM at 375°F

$$\frac{100 \cancel{ft}^3}{\cancel{min}} \times \frac{1 \cancel{hr}}{60 \cancel{s}} \times \frac{4.535 \times 10^{-4} \cancel{kg}}{1 \cancel{lb}_m} \times \frac{0.0735 \cancel{ft}^3}{1 \cancel{m}^3} \times \frac{1000 \cancel{g}}{1 \cancel{kg}} = 55.55 \frac{g}{s}$$

$$= 55.55 \frac{g}{s} \Rightarrow (55.55 \frac{g}{s}) (1.00 \frac{J}{g \cdot K}) (T_{out} - 322.2 K) = 12 \times 10^3$$

$$\boxed{T_{out} = 538.2 K = 508.8 F^\circ}$$

OR: IF $T_{in} = 300 K \Rightarrow 55.55 (1.00) (T_{out} - 300) = 12 \times 10^3$

$$\boxed{T_{out} = 516.0 K = 468.8 F^\circ}$$

Conclusion: The Heater controls allow a MAXIMUM of 550°F. In either case of T_{in} , 100 cfm & 12KW CAN Be Achieved.

Actual Power Necessary To Achieve 375°F & 100 cfm

$$(55.55)(1.00)(463.9 - 322.2 K) = Q$$

$$Q = 7,871.4 \text{ watts} = 7.87 \text{ KW}$$

OR w/ T_{in} at 300K:

$$(55.55)(1.00)(463.9 - 300 K) = Q$$

$$Q = 9,104.6 \text{ watts} = 9.10 \text{ KW}$$

Actual Warmup Times At 7.87 KW OR 9.10 KW

$$T_{in} = 464 K (375 F)$$

$$T_{out} = 225 K$$

$$\text{use: } \dot{M} C_p \Delta T = Q$$

$$(55.5)(1.00)(464 - 225) = Q$$

$$Q = 13,264.5 \text{ watts } (\frac{5}{3})$$

$$\text{Necessary Delivery} = 8 \times 10^8 J$$

$$\begin{aligned} 8 \times 10^8 J / 13,264.5 \frac{J}{s} &= 60,311.3 \text{ sec} \\ &= 16.75 \text{ hrs.} \\ &= .69 \text{ DAYS} \end{aligned}$$

TABLE 9-1
COEFFICIENTS FOR CALCULATION OF AVERAGE HEAT-TRANSFER COEFFICIENT OF A CIRCULAR CYLINDER IN A GAS FLOWING NORMAL TO ITS AXIS, BY EQ. 9-3.

Re _D	C	n
0.4-4	0.891	0.330
4-40	0.821	0.385
40-4,000	0.615	0.466
4,000-40,000	0.174	0.618
40,000-400,000	0.0239	0.805

FIG. 7-4. Correlation of data for free-convection heat transfer from vertical plates and cylinders.