First Line:
US – LHC COLLABORATION

Second Line:
1.1.4 – IR ABSORBERS - TAS

Title:
TAS – IN-SITU BAKEOUT CALCULATIONS

MAG

"A" revision – 6/30/00 - Bakeout temperature increased to 200 C, calculations added.

SUMMARY

For in-situ bakeout of the TAS vacuum chamber, 4 heaters of 1500 watt capacity each are required to bring either the ATLAS TAS or CMS TAS to 200 C in 24 hours. If the heater input remains constant 10 additional hours are required to bring the TAS to 220 C.

For the ATLAS TAS, the surrounding shielding, fixed shielding and support tube, temperature will rise 15 C after a 24 hour warmup period to 200 C and a 24 hour bakeout bakeout at 200 C.

For the CMS TAS, the surrounding shielding, fixed iron nose and top insert, temperature will rise 55 C after a 24 hour warmup to 200 C and a 24 hour bakeout at 200 C. After the bakeout, with the thick rotating shielding removed, the surrounding shielding temperature will drop 25 C in the 1st day, 39 C in the 2 days and 50 C in 4 days.

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BAKEOUT REQUIREMENTS

- TAS vacuum chamber and copper absorber must be heated to 200 C and stay at temperature for several days.

- Heaters are to be sized so that the assembly will be brought to 200 C in 24 hours.

DESIGN CONSIDERATIONS FOR BAKEOUT

- The vacuum chamber and copper absorber will become too radioactive after physics operation has started – work there after on the TAS will have to be done remotely.

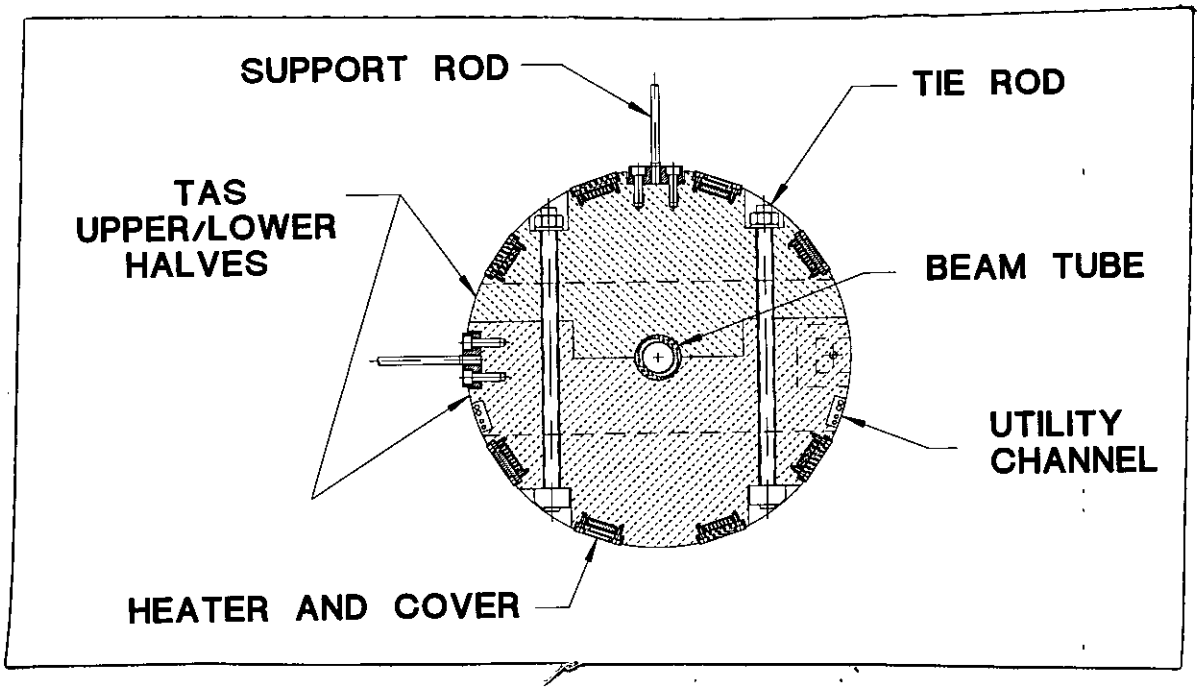
- Use the air space around the TAS as a thermal barrier. For the ATLAS configuration the air space is 35 mm; for the CMS configuration the air space is 20 mm.

- All the leads and instrumentation for the TAS are to come from the tunnel, not the cavern.

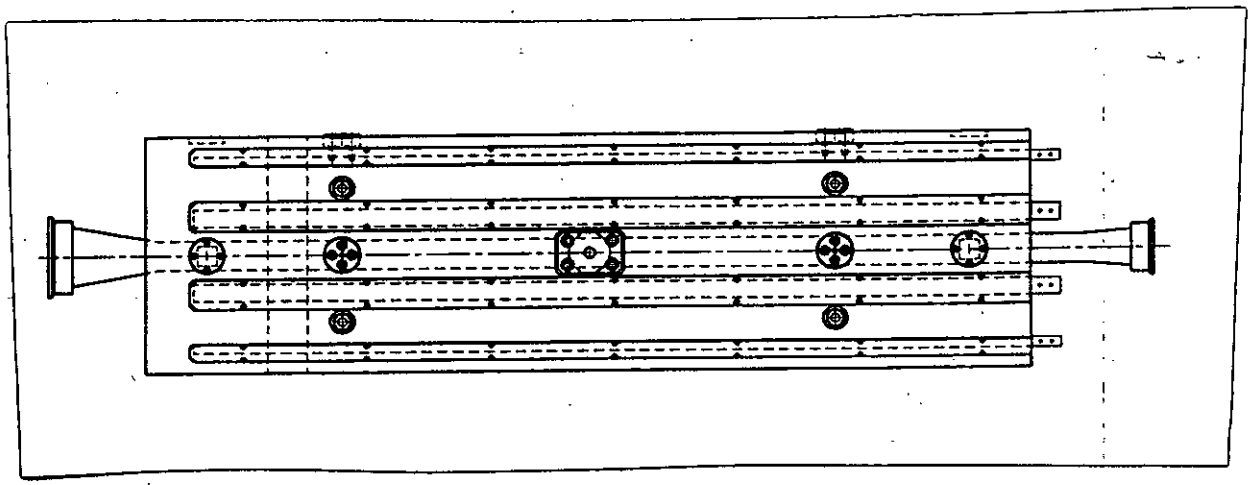
- Have redundant bakeout heaters.

TAS CONFIGURATION & WEIGHTS

TAS CROSS-SECTION:

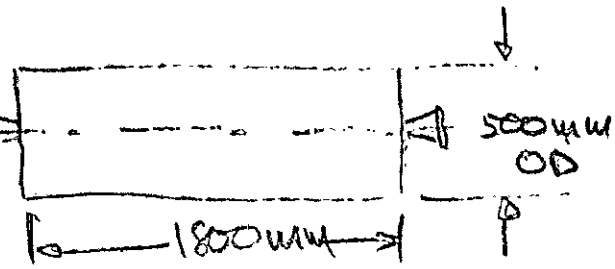


TAS SHOWING HEATER LAYOUT



WEIGHTS:

ABSORBER:



$$W_A = \left(8.96\frac{gm}{cm^3}\right)\left(\frac{\pi}{4}(50cm)^2\right)(180cm)\frac{kg}{10^3 gm}$$

$$= \underline{3166\ kg}$$

SURROUNDING ATLAS SHIELDING:

- TAS-CRADLE, FIXED SHIELDING & SUPPORT PIECE.

$$W_{T_{ATLAS}} = \left(\frac{7.84g}{cm^3}\right)(225cm)\left(\frac{\pi}{4}(300cm)^2 - 57.2cm^2\right)\frac{kg}{10^3 gm}$$

$$= \underline{120'157\ kg}$$

- RATIO OF ABSORBER WT. TO SURROUNDING STEEL WEIGHT:

$$\eta_{ATLAS} = \frac{3166}{120'157} = \underline{0.0263}$$

SURROUNDING CMS SHIELDING:

- NOSE PIECE, TOP INSERT:

$$W_{T_{CMS}} = \left(\frac{7.84g}{cm^3}\right)(250cm)\left(\frac{\pi}{4}\left(\frac{188+130}{2}\right)^2 cm^2 - 91.2cm^2\right)\frac{kg}{10^3 gm}$$

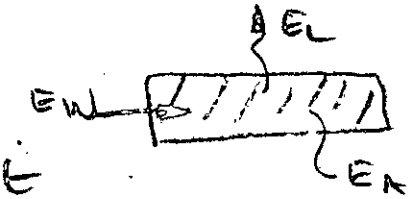
$$= \underline{32\,940\ kg}$$

- RATIO OF ABSORBER WT. TO SURROUNDING STEEL WEIGHT:

$$\eta_{CMS} = \frac{3166\ kg}{32\,940\ kg}$$

$$= \underline{0.0961}$$

HEATER CAPACITY FORMULA



$$E_{IN} = E_A + E_L$$

$$P_{IN}\,dt = W_A C_A\, d(T_A - T_0) + U_L(T_A - T_0)\,dt$$

$$\frac{d(T_A - T_0)}{P_{IN} - U_L(T_A - T_0)} = \frac{dt}{W_A C_A}$$

$$-\frac{1}{U_L}\ln\left(P_{IN} - U_L(T_A - T_0)\right) = \frac{t}{W_A C_A} + C_1$$

For $t = 0 \Rightarrow T_A = 0$

$$C_1 = -\frac{1}{U_L}\ln P_{IN}$$

$$\ln\left(P_{IN} - U_L(T_A - T_0)\right) - \ln P_{IN} = -\frac{U_L t}{W_A C_A}$$

$$\ln\left(\frac{P_{IN} - U_L(T_A - T_0)}{P_{IN}}\right) = -\frac{U_L t}{W_A C_A}$$

$$\frac{P_{IN} - U_L(T_A - T_0)}{P_{IN}} = e^{-\frac{U_L t}{W_A C_A}}$$

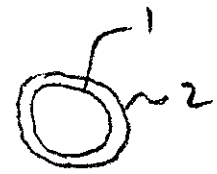
$$P_{IN} = \frac{U_L(T_A - T_0)}{\left(1 - e^{-\frac{t}{\tau_a}}\right)}$$

$$\tau_a = \frac{W_A C_A}{U_L}$$

$$T_A - T_0 = \frac{P_{IN}}{U_L}\left(1 - e^{-t/\tau_a}\right)$$

RADIATING HEAT TRANSFER FORMULA

$$Q = \sigma A_{TAS} \epsilon_{EFF} F \left(T_{TAS}^4 - T_0^4\right)$$



FOR CONCENTRIC CYLINDERS

$$\epsilon_{EFF} = \frac{1}{\frac{1-\epsilon_1}{\epsilon_1} + 1 + \frac{A_1}{A_2}\frac{(1-\epsilon_2)}{\epsilon_2}}$$

FOR OXIDIZED COPPER (1) & OXIDIZED STEEL (2) +

$\epsilon_1 = 0.85$, $\epsilon_2 = 0.65$ $\quad \frac{A_1}{A_2} = \frac{500}{542} = 0.9225$

+ KREITH, 4TH EDITION, PG 450

$$\epsilon_{EFF} = \frac{1}{\frac{\overset{(.4765)}{1-.85}}{.85} + 1 + .9225\,\frac{\overset{(.4967)}{(1-.65)}}{.65}}$$

$$= 0.5977 \rightarrow 0.600$$

$$Q_{RAD} = \left[5.67 \times 10^{-8} \frac{W}{m^2\,{}^\circ K^4}\right]\left[\overset{3.22}{(1.8m)(\pi)(.5m) + (2)(\pi)(.5m)^2}\right]\left[0.6\right]\left[1.0\right]\left[T_{TAS}^4 - T_0^4\right]$$

$$= 10.95 \times 10^{-8} \frac{W}{{}^\circ K^4}\left[T_{TAS}^4 - T_0^4\right]$$

OR

$$Q_{RAD} = 10.95 \times 10^{-8} \frac{W}{{}^\circ K^4}\, 4\left[\frac{T_{TAS}+T_0}{2}\right]^3 \left[T_{TAS} - T_0\right]$$

$$= \underbrace{43.8 \times 10^{-8} \frac{W}{{}^\circ K^4}\left(\frac{T_{TAS}+T_0}{2}\right)^3}_{U_R}\left(T_{TAS} - T_0\right)$$

ATLAS — TAS — SURROUNDING SHIELDING HEAT TRANSFER

ABSORBER HEAT UP:

TEMPERATURE RANGE: 20°C TO 200°C

AVERAGE TEMPERATURE DIFFERENTIAL DURING HEATUP: ASSUME 115°C

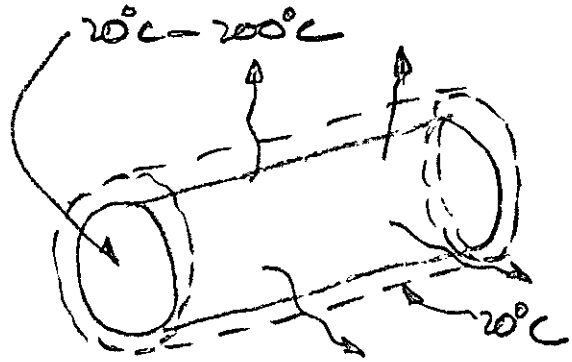
- RAYLEIGH NUMBER:

$Ra_{\nu} = Gr_{\nu} Pr$

$Gr_{\nu} = \frac{g\beta}{\nu^2} \Delta T \nu^3$

$= \left(\frac{0.782 \times 10^{8}}{°K\ m^3}\right)(115°C)(.035m)^3$

$= \underline{3.856 \times 10^5}$



$D_i = 0.50m$

$D_o = 0.57m$

$Pr = 0.71$

$Ra_{\nu} = (3.856 \times 10^5)(.71) = \underline{2.737 \times 10^5}$

AVERAGE HEAT LOSS FROM THE ABSORBER TO THE ADJACENT SHIELDING VIA NATURAL CONVECTION:

FOR CONCENTRIC CYLINDERS, KREIT, Pg 265

$$\frac{h_{eff}}{k} = .386 \underbrace{\left[\frac{\ln(D_o/D_i)}{\nu^{3/4}\left[\left(\frac{1}{D_i}\right)^{3/5} + \left(\frac{1}{D_o}\right)^{3/5}\right]^{5/4}}\right]}_{I} \left(\frac{Pr}{.861 + Pr}\right)^{1/4} Ra^{1/4}$$

$$I = \frac{\ln(.57/.50)}{(.035)^{3/4}\left[\frac{1}{.50}^{3/5} + \frac{1}{.57}^{3/5}\right]^{5/4}} = \underline{0.425}$$

EQUATION VALID FOR:

$0.70 \le Pr \le 600$ $\qquad$ $\underline{Pr = .71}$

$$10 \le [I]^4 Ra_{\nu} \le 10^7$$

$$[I]^4 Ra_{\nu} = [.425]^4 \, 2.737 \times 10^5 = \underline{8913} \quad \text{OK}$$

$$\frac{k_{eff}}{k} = (.386)(.425)\left(\frac{.71}{.861 + .71}\right)^{1/4}\left(2.737 \times 10^5\right)^{1/4}$$

$$= \underline{3.073}$$

FOR AIR @ ~68°C (60°C)

$$k_{eff} = \left(0.0279 \frac{W}{m\,°K}\right)(3.073) = \underline{0.08574 \, W/m\,°K}$$

$$Q_{HUL} = k_{eff} A \frac{(T_h - T_o)}{\nu}$$

$$= \left(.08574 \frac{W}{m\,°K}\right)\left[2\left[\frac{\pi}{4}(.5m)^2\right] + \overset{(3.22)}{(\pi)}(.50m)(1.60m)\right]\frac{115}{.035m}$$

$$= \underline{907} \; W \qquad \frac{k_{eff} A}{\nu} = \underline{7.888 \, W/°C}$$

AVERAGE HEAT LOSS DUE TO RADIATION:

$$Q_{HRAD} = 43.80 \, 10^{-8} \frac{W}{°K^4}\left[273 + \frac{135+20}{2}\right]^3 (135-20)$$

$$= \underline{2169} \; W \qquad U_R = 18.86 \; W/°C$$

AVERAGE TOTAL HEAT LOSS

$$E_{HL} = Q_{HUL} + Q_{HRAD}$$

$$= 907 + 2169 = \underline{3076} \; W$$

$$U_L = 7.89 \, W/°C + 18.86 \, W/°C = \underline{26.75 \; W/°C}$$

REQUIRED HEATER CAPACITY:

FOR: $t = 24$ HRS

$$T_R = \frac{3166\ \text{Kg}\left[\left(\frac{10^3\ \text{g}}{\text{Kg}}\right)\left(.092\ \frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}}\right)\left(4.185\ \frac{\text{W-sec}}{\text{cal}}\right)\frac{\text{Hr}}{3600\ \text{sec}}\right]}{26.75\ \text{W}/{}^\circ\text{C}}$$

$0.107\ \frac{\text{W-HR}}{\text{Kg}\cdot{}^\circ\text{C}}$

$$= \underline{12.66}\ \text{HR}$$

$$P_{IN} = \frac{(26.75\ \text{W}/{}^\circ\text{C})(200^\circ\text{C} - 20^\circ\text{C})}{\left(1 - e^{-\frac{24}{13.92}}\right)}$$

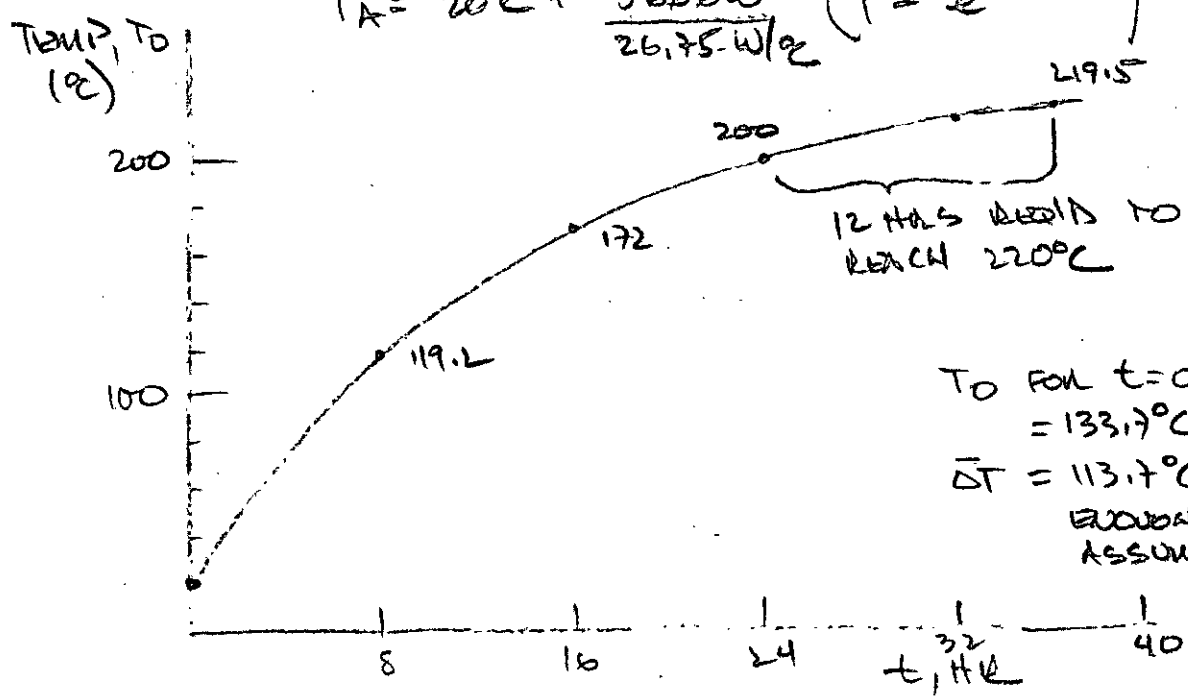
$$= \underline{5666}\ \text{W}$$

POWER PER HEATER (4):

$$P_H = \frac{P_{IN}}{4} = \underline{1416\ \text{W}}$$

TIME TEMPERATURE PROFILE:

$$T_A = 20^\circ\text{C} + \frac{5666\ \text{W}}{26.75\ \text{W}/{}^\circ\text{C}}\left(1 - e^{-t/12.66}\right)$$



T_O FOR $t = 0$ TO 24 HRS $= 133.7^\circ$C

$\bar{\Delta T} = 113.7^\circ$C – CLOSE ENOUGH TO ASSUMED 115°C

HEAT LOSS DURING BAKEOUT:

TEMPERATURE DIFFERENTIAL DURING BAKEOUT: 180°C

NATURAL CONVECTION LOSS:

$$Gr_{bdr} = \left(\frac{0.472 \times 10^{+8}}{°K\ m^3}\right)(180)(.035\ m)^3$$

$$= 3.643 \times 10^5$$

$$Ra_{bdr} = (3.643 \times 10^5)(.71) = 2.586 \times 10^5$$

$$h_{eff\ bdr} = \left(\frac{2.586}{2.737}\right)^{1/4}\left(.0852 \frac{W}{m°K}\right)$$

$$= 0.0845 \frac{W}{m°C}$$

$$Q_{NC} = \left(.0845\ W/m°C\right)(3.22\ m^2)\left(\frac{180°}{.035\ m}\right)$$

$$= 1399\ W$$

RADIATION LOSS:

$$Q_{bRAD} = \left[\frac{43.80 \times 10^{-8}\ W}{°K^4}\right]\left[273 + \frac{200+20}{2}\right]^3 (180°C)$$

$$= 4429\ W$$

TOTAL HEAT LOSS

$$Q_{bT} = Q_{bNC} + Q_{bRAD}$$

$$= 1399 + 4429 = 5828\ W$$

SINCE $Q_{bT} > P_{IN}$, THEN

P_{IN} 5828W P_h = 1457 W

TEMPERATURE RISE OF SURROUNDING SHIELDING:

$$W_{THLAS} C_S (T_S - T_D) = P_{IN}\, dt$$

$$T_S - T_D = \frac{P_{IN}\, dt}{W_{THLAS}\, C_S}$$

$$= \frac{(5828W)(48\,HR) - (3166Kg)\left(0.107\frac{W\text{-}HR}{Kg\,°C}\right)(160°C)}{(120157\,Kg)\left(0.1256\frac{W\text{-}HR}{Kg\,°C}\right)}$$

60977

$$= \underline{14.5°C}$$ FOR 24 HOUR BAKE OUT

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CMS — TAS — SURROUNDING SHIELDING HEAT TRANSFER

ABSORBER HEAT UP:

FROM PAGE 7

$$R_{12} = 2.737 \times 10^5 \left(\frac{.02}{.1035}\right)^3 = \underline{5.107 \times 10^4}$$

AVERAGE HEAT LOSS FROM THE ABSORBER TO THE ADJACENT SHIELDING VIA NATURAL CONVECTION:

FROM PAGE 7-B

$$I = \frac{\ln\left[.54/.50\right]}{(.02)^{3/4}\left(\left(\frac{1}{.50}\right)^{5/5} + \left(\frac{1}{.54}\right)^{3/5}\right)^{5/4}} = \underline{.391}$$

$$h_{eff} = \left(\frac{.057\ W}{m\,°K}\right)\left(\frac{.391}{.1425}\right)\left(\frac{5.107 \times 10^4}{2.737 \times 105}\right)^{1/4} = \underline{0.0518\ \frac{W}{m\,°K}}$$

$$\frac{h_{eff} A}{\Delta} = \frac{\left(.0518\ \frac{W}{m\,°K}\right)\left(8.22\ m^2\right)}{.02\ m} = \underline{8.343\ W/°K}$$

$$Q_{HAR\ CMS} = \left(8.343\ W/°K\right)\left(115°C\right) = \underline{959\ W}$$

$$Q_{RAD\ CMS} = \underline{2169\ W}$$

$$U_R = \underline{18.86\ W/°C}$$

$$E_{TL\ CMS} = 959 + 2169 = \underline{3128\ W}$$

$$U_L = 8.343 + 18.86 = \underline{27.20\ W/°C}$$

SINCE THE HEAT UP LOSSES ARE NEARLY IDENTICAL TO THE ATLAS, THE HEATER REQUIREMENTS ARE ESSENTIALLY THE SAME FOR BOTH THE CMS & ATLAS.

HEAT LOSS DURING BAKEOUT:

(FROM PG 10 + 12

$$Ra_{L_{CMS}} = (2.586 \times 10^5)\left(\frac{.02}{.0355}\right)^3 = \underline{4.825 \times 10^4}$$

$$h_{eff} = \left(.0845 \frac{W}{m°K}\right)\left(\frac{4.825}{25.86}\right)^{1/4} = \underline{0.0555 \frac{W}{m°K}}$$

$$\frac{h_{eff} A}{L} = \left(\frac{.0555 W}{m°K}\right)\left(\frac{.3177 m^2}{.02 m}\right) = \underline{8.94 \ W/°K}$$

$$Q_{wall_{CMS}} = (8.94 \ W/°K)(180°C) = \underline{1609 \ W}$$

$$Q_{bldg_{CMS}} = \underline{4429 W}$$

TOTAL HEAT LOSS:

$$Q_{TOT_{CMS}} = 1609 + 4429 = \underline{6038 \ W}$$

SINCE $Q_{TOT_{CMS}} > P_{IU}$, THEN

$$P_{IU} = \underline{6038 W}$$

$$P_h = \frac{6038}{4} = \underline{1510 W}$$

AGAIN, HEAT LOSS FROM THE CMS ABSORBER IS NEARLY THE SAME AS THE ATLAS ABSORBER WHEN AT BAKEOUT TEMPERATURE.

TEMPERATURE RISE OF THE SURROUNDING SHIELDING:

$$w_{T_{CMS}} C_S (T_S - T_0) = P_{IN}\, dt$$

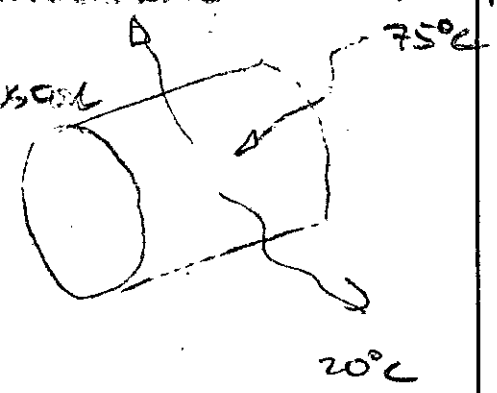
$$T_S - T_0 = \frac{P_{IN}\, dt}{w_{T_{CMS}} C_S}$$

$$= \frac{(5967\,W)(48\,HR) - 60977\ W\text{-}HR}{(32940\,KG)\left(.1256\ \frac{W\text{-}HR}{KG\text{-}°C}\right)}$$

$$= \underline{84.5}\ °C \quad \text{FOR 24 HOUR BAKE}$$

COOLDOWN TIME FOR THE SURROUNDING SHIELDING:

NATURAL CONVECTION HEAT TRANSFER



$$Gr = \frac{g\beta}{\nu^2} \Delta T\, L^3$$

USE $\overline{\Delta T} = \frac{55°C}{2} = 27.5°C$

$$L = \frac{1.3\,m + 1.8}{2}\ m = 1.55\,m$$

$$= \left(\frac{0.782 \times 10^8}{m^3\,°K}\right)(27.5°C)(1.55\,m)^3$$

$$= \underline{8.01 \times 10^9}$$

$$h_{NC} = \frac{k}{D}\, 0.53 (Gr_D\, Pr)^{0.25}$$

– KREITH, PAGE 276

VALID FOR $10^3 < Gr < 10^9$ – USE ANYWAY

$$= \frac{.0279\,W}{m\,K} \frac{1}{1.55\,m}\ .53 \left((8.01 \times 10^9)(.71)\right)^{1/4}$$

$$= \underline{2.620}\ W/m^2\,°C$$

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RADIATION HEAT TRANSFER

$$h_R = \left(\frac{5.67\times10^{-8}\,W}{m^2\,°K^4}\right)\epsilon F\ 4\left[\frac{T_{STEEL}+T_{AMB}}{2}\right]^3$$

$$= \left(\frac{5.67\times10^{-8}\,W}{m^2\,°K^4}\right)(.65)\ 4\left[273+\frac{75+20}{2}\right]^3$$

$$= \underline{4.85}\ \frac{W}{m^2\,°K}$$

$$Q_{STEEL} = (h_{NC}+h_R)\,A\,(\bar{T}_S - T_\infty)$$

$$= (2.62+4.85)(1.55\,m\ \pi)(3.7\,m)[27.5°C]$$

$$= \underline{3702}\ W$$

$$U_S = (h_{NC}+h_R)A$$

$$= \frac{3702\,W}{27.5°C} = \underline{134.6\ W/°C}$$

FROM M 7742A, pg 20

$$\frac{T_S - T_{AMB}}{T_{S0} - T_{AMB}} = e^{-t/\tau_S}$$

$$\tau_S = \frac{W_S C_S + W_A C_A\left(\frac{T_A - T_{AMB}}{T_{S0} - T_{AMB}}\right)}{U_S}$$

$$= \frac{(329.04\,kg)(.1256\,\frac{W\text{-}HR}{kg\text{-}°C}) + (316.64\,kg)(.107\,\frac{W\text{-}HR}{kg\text{-}°C})\left(\frac{180}{55}\right)}{134.6\ W/°C}$$

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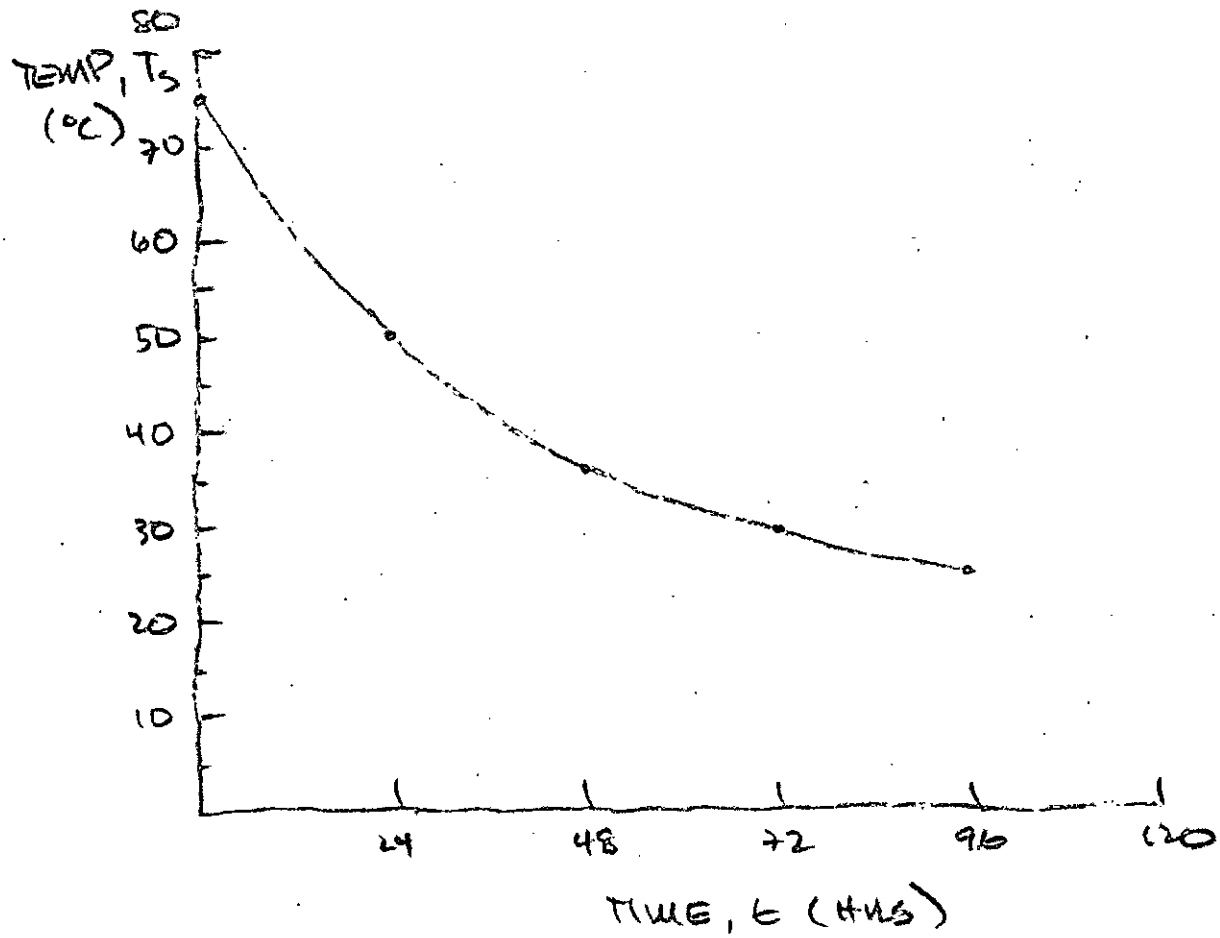
$= \underline{39.0}$ HR

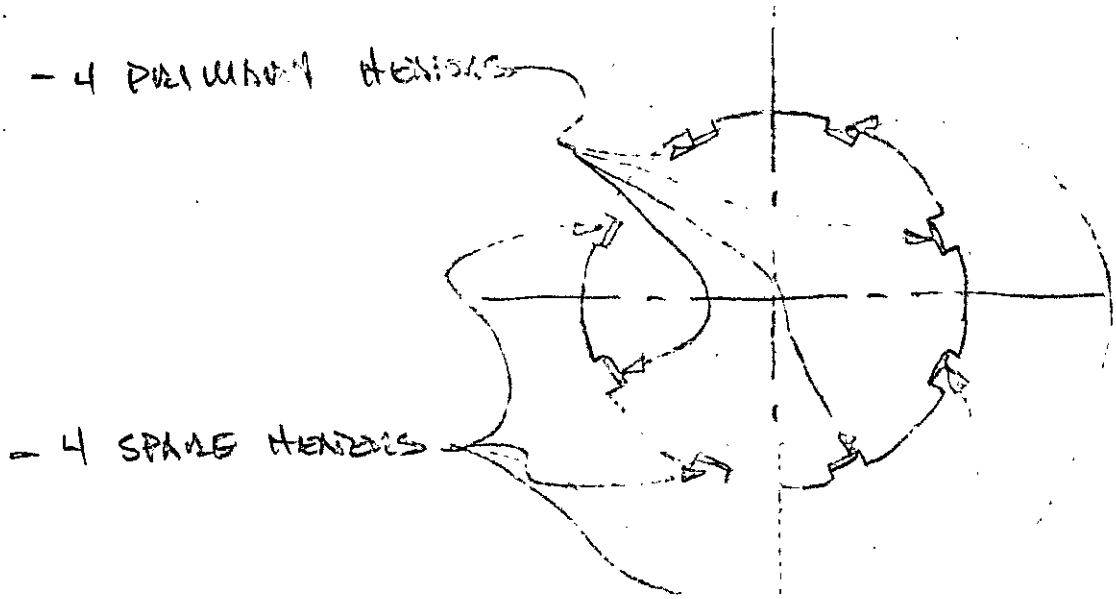
$$T_S = T_{AMB} + (T_{S0} - T_{AMB})\, e^{-t/\tau_S}$$

$$= 20 + 55\, e^{-t/39.0}$$

t (HR)	0	24	48	72	96
T_S (°C)	75	50	36	29	25



HEATER CONFIGURATION



- HEATER LENGTH ~ 1.7 - 1.8M (67" - 71")
- OPTIONS (CHROMALOX - 240V)

CATALOG NUMBER	ACTIVE LENGTH (IN)	WIDTH (IN)	RATED POWER DENSITY (W/IN²)	RATED POWER (W)	SHEATH MATERIAL
SE 72"	69 3/8	1 1/2	8	2000	CHROME STEEL
131 C35		(3.8 cm)	12	3000	
131 043					
142180	69 1/2	1 11/16 (4.3cm)	10	2550	MONEL

PICK THE NARROWER HEATER - EITHER OK - CAPACITY ADEQUATE

- LEADS TO EXIT REAR OF TAS.
- LEADS TO BE NICKEL PLATED COPPER THAT ARE INSULATED WITH CERAMIC BEADS.
- LEADS TO BE TERMINATED ON CERAMIC TERMINAL STRIPS INSIDE A METAL ENCLOSURE ATTACHED TO THE REAR OF THE TAS.