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THE EFFECT OF VACUUM GAS PRESSURES AND SPECIES ON INTERNAL HEAT LEAK IN THE SSCL MAGNET DESIGN

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INTRODUCTION

This work describes a procedure for calculating the heat transfer into the cryogens inside a 50-mm Collider Dipole Magnet (CDM) for the Superconducting Super Collider (SSC) during its operation in a Collider Ring Half Cell vacuum. Figure 1 is a schematic cross-section of the CDM showing various major components and their temperatures. Described here is the use of a species gas model for assessing the heat transfer due to conduction through the residual gases in the cryostat insulating vacuum. Residual gas heating is a major source of heat to the helium-cooled regimes in the magnet. It is a function of several variables that include the gas(es) involved, and it is found to decrease linearly with vacuum pressure and exponentially with gas temperature. Thermal radiation, in contrast, varies with temperature and diminishes as temperatures decrease on the T^4 curve.

The gas model used here is based on results from a Residual Gas Analyzer (RGA) measurement of the vacuum in the Fermi National Accelerator Laboratory (FNAL) ER 40-mm Dipole Magnet String Test (ST). At present, no vacuum tests have been conducted on 50-mm CDMs.

The work was done to analyze the effect on residual gas heat conduction of presumed gas species in the vacuum total pressure. It is seen to be a significant improvement over using a "single gas" model. Results would indicate that unless the species gas model is used, the residual gas heating can be significantly overestimated depending on the vacuum and gases involved.

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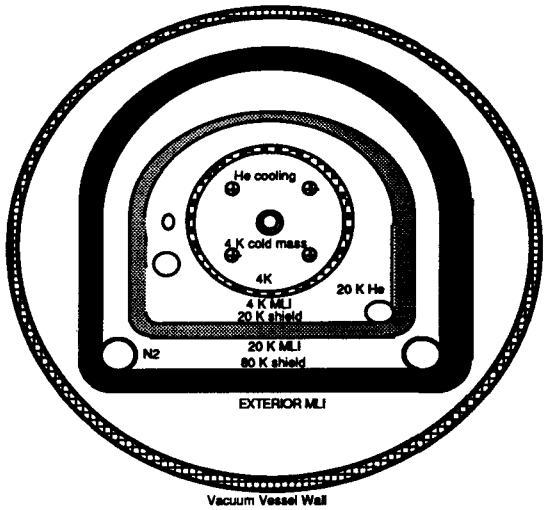

Figure 1. Schematic cross-section of the CDM showing components and temperatures.

GAS SPECIES MODEL

The 50-mm CDM Prime Item Development Specification states that the normal operating vacuum for the magnets in the Collider Ring Half Cell is not to exceed 1.0 E-06 Torr total pressure at the vacuum vessel wall.

Dalton's Law states that the total pressure of a gas is the sum of its component species. It is not defined above what the gas species components involved will be.

The gas species model used here was based on the gases identified in the FNAL ER ST RGA measurement on 9/6/91 of the vacuum for the 40-mm Dipole ST Magnets. Results of the gases and their partial pressures are shown in Figure 2. Total pressure was slightly over 2.0 E-08 Torr.

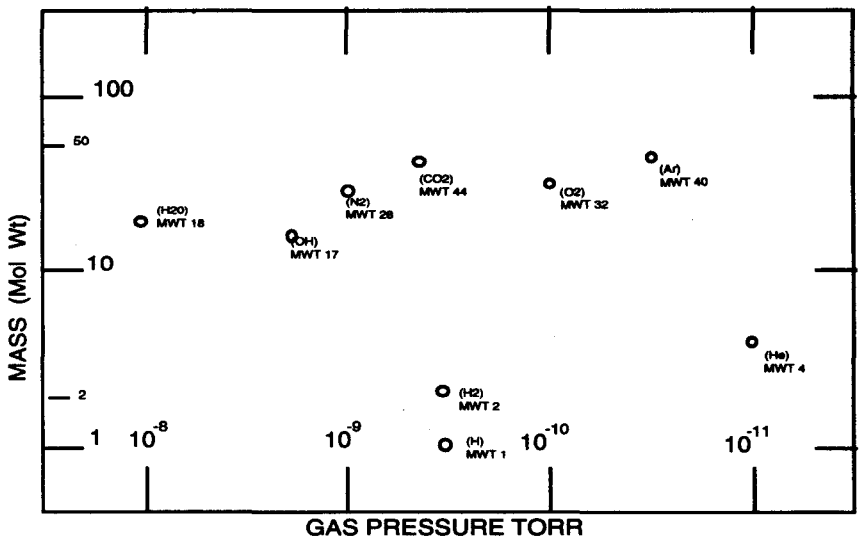

Figure 2. Species of Gases, Molecular Weight, and Partial Pressures from 9/6/91 RGA Data at FNAL ER.

At the time of the 9/6/91 RGA measurement the ST magnets had been under vacuum for over a month, and it was felt that outgassing should be seen. The water vapor and the H_2 in the data appear to be examples of this. Glassford[1] shows data for multi-layer insulation (MLI) such as is used in SSCL magnets. Clark[2] identifies outgassing rates for a series of materials, including H_2 from steel such as the vacuum vessel wall.

Certain of the RGA data also exist in air, including He, H_2 and CO_2. A choice here of the FNAL species seemed appropriate in that the 50-mm CDM design is similar to that of the 40-mm Dipoles.

In particular, the gases selected for this analysis are shown in Table 1.

Table 1. Analysis gas species.

H_2O	Water Vapor
H_2	Hydrogen
N_2	Nitrogen
CO_2	Carbon Dioxide
He	Helium

The gases are a mix of those with the highest partial pressures and those that will contribute heating to the Collider Ring helium refrigeration system.

The helium gas species above is noted to be here in a "trace" amount only. Again, it is included because it is a component of the gas mixture for air. As such, it probably could not be removed by N_2 purging.

ANALYSIS

The analysis began by determining values of expected gas species pressure due to their cooling as they move inward from the vacuum vessel wall. The temperature gradient involved is extreme. It ranges from the 300-K vessel wall to the 4-K cold mass surface.

The "Thermal Transpiration" theory of Welch[3] describes this pressure calculation. It is based on the relationship that

$$\frac{P}{\sqrt{T}} = \text{Constant}$$

where P = Pressure and
T = Temperature.

Starting P and T for the gas species components are the measured "room" conditions (P by RGA). T is the room air temperature at the pressure gauge.

From this

$$P_{cold} = P_{room} \bullet \sqrt{\frac{T_{cold}}{T_{room}}}$$

P_{cold} can be calculated for any assumed T_{cold}. This holds true until the species curve intersects its vapor pressure curve. This intersection, if it occurs, is where the gas cryocondenses ("freezes out"). Below this temperature value it no longer contributes to the gas conduction.

Figure 3 shows a plot of the analysis gases and where they intersect their cryocondensation curves for their FNAL RGA starting conditions. Assumed room temperature was 300 K. The "common gases" vapor curves are found in various works.[3,4,5]

For comparison, the situation of N_2 as a "single gas" was included here. Room pressure for it then is the 1.0 E-06 Torr maximum allowable Half Cell vacuum pressure.

Water vapor is projected to "freeze out" at about 150-K, CO_2 at around 70 K, and N_2 slightly above 20 K. H_2 and He will remain gases at and below the 20-K and the 4-K surfaces.

Also, from Figure 3 data it would appear that N_2 would not exist for gas conduction to the 4-K surface. For the Figure 2 room pressure of 1.0 E-09 Torr, it was calculated to freeze out at about 23 K. For the higher initial pressure of 1.0 E-06 Torr it was calculated to freeze out at around 27 K. This is due to the N_2 vapor pressure curve increasing. As such, for either case, the N_2 would probably freeze out somewhere in the 20-K MLI.

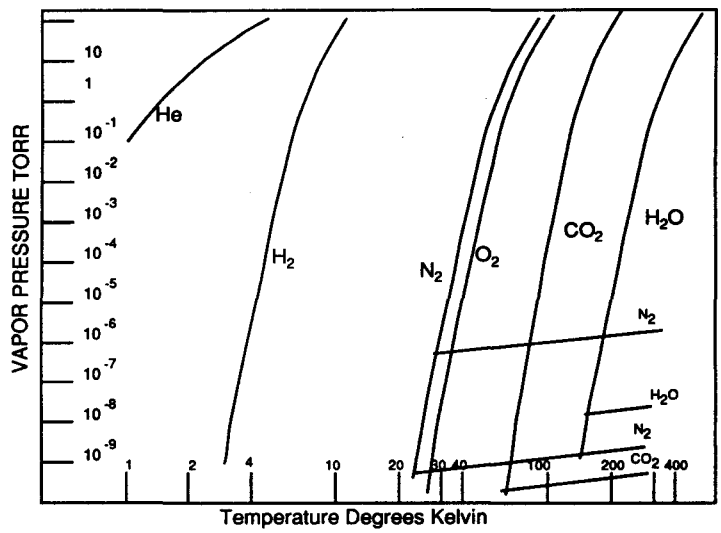

Figure 3. Vapor Pressure of Several Gases.

The method of analysis from here was to input the *P* versus *T* data for the five gas species into the gas conduction subroutine of the 50-mm CDM thermal math model.

The model used, developed by Randy Pletzer of the Magnet Systems Division Cryostat Design Section, is of the full magnet and its Interconnect.

The computer code used for the solution of heat flows in the model was the General Dynamics "Convair Thermal Analyzer" (CTA) Code. The routine is proprietary to General Dynamics. Results determined here are for "steady-state" solutions.

The thermal model describes the surfaces in the vessel experiencing heat transfer and the "paths" to be expected that connect them. The comprehensive model is solved for heat flows resulting from and into various "fixed" temperature locations such as the ambient air outside and the cryogens inside.

In that the CTA Code is based on the "Electrical Analogy" to heat transfer, these paths are defined as thermal "resistances," *R*. They are for such effects as solid conduction, radiation, and gas conduction between the surfaces involved.

Each pair of nodes in the thermal model that could exchange heat by the mechanism of residual gas conduction was connected by five gas conduction resistors—one for each gas involved. Figure 4 shows this arrangement for heat flow from the vacuum vessel wall through the MLI and into the cold mass.

An equivalent situation exists for heat flow through the support posts, except it included the solid conduction resistors.

The gas conduction equation solved for the Figure 4 resistors is that of Corruccini.[6] Barron[7] presents a similar theory. In these calculations the gas P versus T was calculated by the previously described thermal transpiration theory down to its cryocondensation value. Below this, its pressure was input as that of the "solidified" form, which is substantially below that of the vapor. This lower value effectively dropped its contribution out of the calculation.

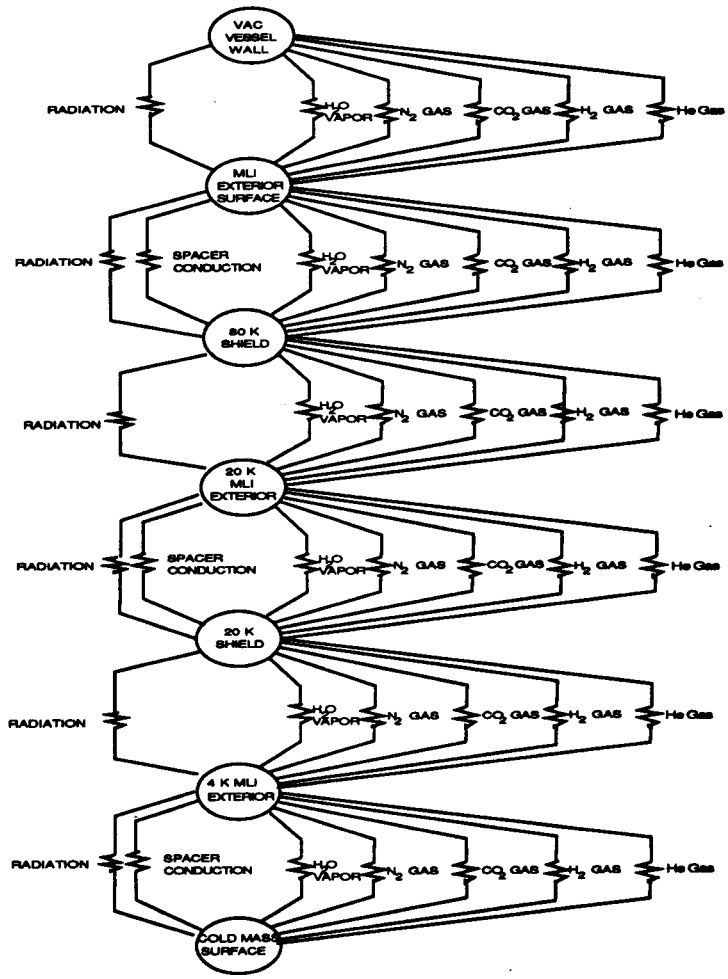

Figure 4. Thermal "resistance" path for heat flow from the vacuum vessel wall through the MLI blankets and into the cold mass.

This modeling approach has the effect of letting the code and the model determine where each species can exist in the gaseous form.

In contrast to the above, the previous procedure was to use a "single gas" model.

RESULTS

Four analysis cases for the gas model species partial pressures were analyzed here. These are shown in Table 2.

Table 2. Analysis cases and description.

Case	Description
# 1	Species gases at the Figure 2 "room" values.
# 2	Gases at 10X higher pressures than Case 1.
# 3	Gases at 100X higher pressures than Case 1. Case 3 is approximately the 50-mm vacuum total pressure operating condition. Case 1 was for a total pressure of E-08 Torr.
# 4	N_2 as a "single gas" model with a room pressure of 1.0 E-06 Torr. The CTA Code logic is such that it does not consider the freezing out of a gas. Instead, it "extends" gas property data.

Table 3 shows the pressure versus temperature values used for H_2 in Case 3. This shows the low gas pressures to be expected in the 4-K and the 20-K regimes in the magnet.

Table 3. Pressure versus temperature data for Case 3 H_2.

Temperature (K)	300	250	194	83	3
Pressure (Torr)	3.9 E-08	3.6 E-08	3.14 E-08	2.06 E-08	4.1 E-09

Results from the four analysis cases were summarized and are presented here as predicted heat loads to the three cryogens in the cryostat. They are compared to the "budget" heat leaks for these cryogens. The budget values[8] to the Collider Ring various refrigeration systems are shown in Table 4.

Table 4. Budget heat loads for CDM and Interconnect to various Collider Ring refrigeration systems.

	4 K	20 K	80 K
IR (W)	0.0530	2.335	18.40
Post (W)	0.160	2.400	17.34
Interconnect (W)	0.1500	0.320	2.100
Total (W)	0.363	5.055	37.84

Table 5 shows the results from the four analysis cases in comparison to the above. Results for Cases 1, 2, and 3 show the effect of decreasing initial ("room") pressure for the species gas model. Theory shows that the residual gas conduction heat transfer effect becomes less prominent as the vacuum pressure decreases. This effect is seen in the above results for the 4-K and 20-K regions. In the 80-K region, thermal radiation is the dominant mechanism. It largely dwarfs gas conduction.

Table 5. Comparison of 4-K,20-K and 80-K Refrigeration System Budget Heat Loads with Predicted Loads for Each and % Margin.

		Analysis Case			
		#1	#2	#3	#4
	4 K Budget (W)	0.363	0.363	0.363	0.363
–	4 K Predicted Load (W)	0.119	0.120	0.136	0.1805
=	Margin (W)	0.244	0.243	0.227	0.1825
	%	67.2%	66.9%	62.5%	50.3%
	Difference	Under	Under	Under	Under
	20 K Budget (W)	5.055	5.055	5.055	5.055
–	20 K Predicted Load(W)	2.937	2.891	2.989	3.062
=	Margin (W)	2.118	2.164	2.066	1.993
	%	41.9%	42.8%	40.9%	39.4%
	Difference	Under	Under	Under	Under
	80 K Budget (W)	37.84	37.84	37.84	37.84
–	80 K Predicted Load (W)	36.83	36.84	36.82	35.25
=	Margin (W)	1.252	1.20	1.13	2.59
	%	2.7%	3.22%	3.0%	6.8%
	Difference	Under	Under	Under	Under

Also, it is to be noted that the predicted loads above are totals of the described budget components of solid conduction through the support posts plus gas conduction and thermal radiation through the MLI. These latter two effects are the "IR" term used in SSCL data.

To get the needed modeling accuracy the thermal model involved here has a total of 2,471 surfaces ("nodes") and 7,669 resistors.

Due to space limitations and formatting problems with heat load results, the individual contribution of gas conduction could not be separately presented. As such, the effect is inferred between the various cases above. Changes in total heat load in the above cases are due entirely to the change in gas conduction. Essentially only the vacuum pressure changes between the cases. Internal temperatures remain fixed for radiation and solid conduction.

Comparing the results for Case 4 for the 20-K and especially for the 4-K predicted heat loads to those of Case 3 gives some ideas of the results of using a "single gas" model. It is seen that heat load is overpredicted. Again, the true residual gas conduction effect is somewhat masked by the format necessitated here.

CONCLUSIONS

A series of conclusions can be drawn regarding the preceding results. The first is that there are no test data yet for the gas species to be experienced in the 50-mm CDM insulating vacuum when it is in operation in the Collider Ring Half Cell. What was analyzed here is conjecture based on FNAL ER ST RGA data.

However, if it does turn out that the Half Cell vacuum makeup is in keeping with the Case 3 model used here, then it would be expected that heat loads to the helium refrigeration system would be well below budget values. If the vacuum makeup were to improve to the Case 2 or Case 1 conditions, the improvement would be even more noticeable.

From discussion with various vacuum system personnel it would seem that a good case can be made for the Case 3 gas mix.

It can be expected that the "dry" N_2 used for the purge will be somewhat readily removed during the pump down after purging because of its low "sticking" affinity for materials in the cryostat. Consequently, this would fit the FNAL data.

Also, the species with the highest partial pressure in the vacuum total pressure will probably be water vapor. Reference data show it will slowly outgas from the MLI. This is due to the MLI design. As such, not all of it will be removable during pump down and purge. Again, this fits the FNAL data.

The water vapor will be expected to freeze out, though, inside the 80-K MLI. Consequently, it will not contribute to gas conduction below the 80-K shield.

The final conclusion drawn here is that it should be noted that the total vacuum pressure will be a mix of species, each with its various partial pressures. Consequently, it is not descriptive to use the "room measured" total pressure as the starting condition for thermal transpiration calculations of gas pressure versus temperature. This would overestimate the gas pressure actually occurring in the gas conduction regime and consequently overpredict the effect of gas conduction there.

If possible an RGA reading is called for. This would establish the species involved and their partial pressures at room temperature. These pressures would be the correct values to use for the needed thermal transpiration calculations. Subsequent gas modeling would be based on what was done here.

It will be of interest to get an RGA reading of the Collider Ring Half Cell vacuum when possible. This would assess its makeup versus what is assumed here. If comparable, the predicted reduction in heat loads to the helium system would be expected.

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