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AND DESIGN ANALYSIS BY FINITE DIFFERENCE TECHNIQUES

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ABSTRACT

Investigation of the combined thermal performance of the stacks and vapor-cooled leads for the Mirror Fusion Test Facility-"B" (MFTF-B) (Figure 1) demonstrates considerable interdependency. For instance, the heat transfer to the vapor-cooled lead (VCL) from warm bus heaters, environmental enclosure, and stack is a significant additional heat load to the joule heating in the leads, proportionately higher for the lower current leads that have fewer current-carrying, counter flow coolant copper tubes. Consequently, the specific coolant flow (G/sec-kA-lead pair) increases as the lead current decreases. The definition of this interdependency and the definition of necessary thermal management has required an integrated thermal model for the entire stack/VCL assemblies.

Computer simulations based on finite difference thermal analyses computed all the heat interchanges of the six different stack/VCL configurations. These computer simulations verified that the heat load of the stacks beneficially alters the lead temperature profile to provide added stability against thermal runaway. Significant energy is transferred through low density foam filler in the stack from warm ambient sources to the vapor-cooled leads.

Stack-contributed heat transfer has such a significant influence on lead performance that grossly erroneous conclusions may evolve if vapor-cooled leads are analyzed independent of their stack assemblies.

INTRODUCTION

The stack is a tunnel through which current is introduced to the coil utilizing vapor-cooled counter flow leads. The stack assembly also includes various accessories to assure adequate operation of these major components as well as a transfer space for other services to the interior of the magnet such as instrumentation leads. Thermally, the stack is operating at liquid helium temperature at one end and ambient temperature at the other end and along the outside; and, therefore, the components in the stack assembly experience strong temperature gradients. Thus, the stack design requires thermal analysis to ensure minimum heat loads to the cryogen and also the thermal and structural integrity of those components involved.

The stack assembly consists of two subassemblies: The current lead subassembly and the stack subassembly as illustrated in Figure 2. The current lead duct is installed between the coil case and the penetration in the vacuum vessel. The duct serves to enclose the conductor leads in the helium coolant, to provide support for the conductor leads, and to provide a return for the helium coolant. As shown in Figure 2, a helium return pipe stub is provided near the duct attachment to the case. Subsequent connection to this stub provides for the main helium return to the facility system.

The stack subassembly consists of basically everything from the vacuum vessel mating flange upward. The primary constituents of the stack, as shown in Figure 3, are the vapor-cooled leads (VCL). The stack itself consists of two concentric pressure vessels: the inner a helium vessel, the outer a vacuum vessel. The design utilized for all of the magnet stacks is consistent throughout the MFTF-B magnet configuration. The vapor-cooled leads illustrated in Figure 4 will vary only in size to match the current requirements of the different type magnets. The current-carrying component of the lead consists of a cluster of 1/4-inch, 0.025-inch wall thickness, RRR = 35 copper tubes each sheathed in 5/16-inch, 0.020-inch wall stainless steel tubes for heat capacity during uncooled operation. Geometry and sizes of the VCL's are summarized in Table 1.

The primary elements of the current lead subassembly (depicted in Figure 5) are the lead bus bars, the current lead pipe, G-10CR divider planks, support guides, brackets, two concentric reducers, a helium return line, and a helium bypass (or liquid level control) line.

The current leads and buses must be capable of uncooled operation for 10 minutes. The 1-inch diameter helium liquid level control line is located considerably below the optimum location which would require passage through the port wall and web of a vacuum vessel. This line is located inside the vacuum vessel to avoid this external routing and places an added burden on design of the buses to maintain their superconducting performance.

G-10CR divider planks provide support for the lead buses and, with the application of Kapton film laminated in the plank, provide electrical isolation between the entering and exiting leads. G-10CR brackets secure the current leads to the divider planks. Clearance is provided between the brackets and the leads to prevent binding during differential contraction and expansion.

The solenoid stack (which was the basic design concept for thermal analysis) and important thermal control features are depicted in Figure 3. The vapor-cooled leads previously analyzed as a separate entity, were included in the stack thermal performance analyses. The conduction heat leak through the inner pipe cryostat wall is reduced with an LN₂ intercept installed at 24 inches from the top of the G-10 cover plate. The radiation between the two pipes is reduced with six layers of stainless steel foil radiation shield around G-10 support rings and slotted 2 x 0.1875-inch stranchions in eight locations. The helium ullage volume inside the inner pipe is filled with low density open cell foam (polyimide insulation) to attenuate helium circulation and downward radiation in the space.

DESCRIPTION OF THERMAL MODEL ANALYSES

The definition of the interdependency of heat transfer between stack and VCL's and the definition of the necessary thermal management for the entire lead/stack/VCL assemblies required an integrated thermal model for the entire stack/VCL assembly. This model was a node-resistance network of the stack, VCL's and helium coolant consisting of approximately 143 heat capacitance nodes with heat generation as applicable. The nodes were interconnected by approximately 349 resistances simulating the flow, conduction, radiation, and free and forced convection modes of heat transfer coupling the nodes.

Boundary thermal environment conditions could be varied and both transient and steady-state simulations run.

The MFT-B stack/VCL thermal model allows multi-dimensional heat flow with combined heat transfer mechanisms. The VCL's have a vapor-cooled temperature profile and act as a thermal sink to the remaining components of the stack which have a conduction temperature profile. The radiation shield causes a transverse temperature gradient and acts as a radiation fin attached to two points along the stack wall. Convection by percolation through the foam insulation further alters the temperature profiles of the stack components. Simple one-dimensional hand calculations are inadequate to determine the true degradation of performance of the VCL due to lateral transfer of heat into the lead. To confidently estimate the heat leaks and temperature profiles of the MFT-B stacks, a P4560E Thermal Analyzer² model was built and solved. The model treats the stacks as an essentially axisymmetric two-dimensional heat transfer problem. Initially the model was only of the stack components surrounding the vapor-cooled leads treated as predetermined heat sinks from an isolated VCL analysis.^{3,4} This later evolved into a model of the complete stack and thermally responding lead as insight into the interdependence of the VCL performance and the surrounding thermal environment became understood.

INTEGRAL STACK/LEADS THERMAL DESIGN ANALYSES

During the course of the analysis, it became evident that stack heating greatly influenced VCL performance, with the common-size stacks having increasing influence as the leads decreased in current as shown in Figure 6 and the number of tubes accordingly decreased as noted in Table 1. The leads were then remodeled to completely respond to the combined stack heat inputs, joule heating, and coolant flows.

The stack assembly plus lead components (Figure 7) are intimately and complexly related in their common performance and transfer of heat. Stack heating increases the cooling requirements for the leads and the heat into the liquid helium. Other aspects of the design that increase the cooling requirements and heating of helium are the room temperature bus heaters to provide environmental control at the top of the lead.

Figure 8 illustrates and quantifies the typical heat load schematic and balance of the MFTF-B stack assemblies. A major conclusion from the figure and tabulation is that the environment created by the stack puts nominally 100 watts into the leads independent of the size of the leads. The common size stack then contributes external heating disproportionately higher than the joule heat in the leads as the leads decrease in current rating.

Also for the design flow rates, the warm buses contribute for warm and minimum ambient temperatures, respectively, 30 to 150 watts and 60 to 250 watts of heat to the VCL cooling lead, depending on lead size when the warm bus heaters are operating at levels to maintain 300K box environment temperature. These external heat inputs to the leads cause the specific coolant flow rate to increase as the lead size decreases. Table 2 shows this higher specific flow rate required by each type of lead/stack. The aggregate flow rate increase for the total magnet set of leads excluding the Yin-Yang leads is 14 percent greater than if all the leads could be cooled by the originally specified 0.11 G/sec-kA-lead pair rate.

Also evident in Figure 8 is the relative small amount of stack heating that is intercepted by the LN_2 intercept. Most of the stack environmental heating is shunted into the colder leads at any axial station along the stack. Also, some heat flows longitudinally through the foam filler bypassing to the inside of the LN_2 intercept.

Another somewhat unusual interchange of energy occurs in the helium ullage between the vapor-cooled leads and the liquid level. A considerable amount of energy is convected from the upper, warmer zones of the lead duct wall, transition bus, and bottom of the foam to the lower, cooler zones of the lead duct wall and transition bus, which then conduct it into the liquid helium.

The six-layer radiation shield is an integral part of the stack thermal design synthesis. Because of the energy interactions, tuning of this shield component design required using the integrated analysis model. From design and fabrication considerations, the G-LOCK supports for the radiation shield became larger and more numerous. Several computer runs were made to define improvements and to tune the shield design.

Improvements to the supports were made by cutouts in the support stanchions to decouple the shields from the stack wall except at the end support rings. To permit closer approach to radiation shield performance, the shield radiation equilibrium temperatures were decoupled from the supports by threading them through the G-10 stanchions without bonding (point or line contact on only one interface) and by reducing transverse conduction in the shields by making them thin (0.002- to 0.005-inch) stainless steel foils instead of aluminum foils. The computer runs showed the reduced conduction made them more effective radiation shields in spite of the higher emittance of the stainless steel over the aluminum foil.

The G-10 support rings were covered with the low emittance foil on the outside to reduce radiation input to the G-10 which would subsequently conduct into the stack. The lead duct LN₂-cooled liner must close over the six-layer shield with an anti-shine-through shield to reduce radiation shorting into this crucial ullage zone of the lead duct. Temperature profiles illustrating the shield effectiveness as well as other inner stack components are depicted in Figure 9.

The six-layer shields were extended as high on the stack inner tube as possible. The optimum location for the upper G-10CR ring support would be where its equilibrium temperature equals the tube temperature profile. The approach to this condition is also seen on Figure 9.

While Figure 6 shows that stack heat input to the leads increases the specific coolant flow rate, an important stabilizing benefit is also evident. At 300K, the rate of change of temperature with flow rate is lower for lead performance with the stack heat input. That is, the tendency to run away to higher temperatures with decrease in flow rate is less pronounced than for thermally isolated leads. This reflects conclusions in the literature that heat transfer between and to the counter flow current tubes tends to stabilize them.⁵

Stack heat input in the tubes tends to reduce the gradient (temperature change with distance) in the tubes which is a stabilization influence. Coupling the tubes together is achieved by ventilating the lead enclosing tube and allowing circulation of helium around and along the outside of the tubes. This ventilation is supplied by two 5/8-inch holes in the structural tube just under the G-10 top plate (Figure 4). Single station ventilation precludes excessive energy transport by helium flowing into the lead at the top and out of the lead at the bottom as driven by the cooling influence of the current tubes.

CONCLUSIONS

- 1) All MFTF-B Axicell configuration magnet stack assemblies operate for 10 minutes of uncooled operation margin before the transition buses become normal. (This response was also predicted and buses configured with transient solutions of the thermal model).

- 2) The heat load of the stacks stabilizes the vapor-cooled leads. Significant energy is transferred through the low density foam filler from the warm ambient sources longitudinally and radially to the vapor-cooled leads and longitudinally bypassing the LN_2 intercept on the stack wall.
- 3) Aggregate mass flow has increased 14 percent from previous thermally isolated vapor-cooled lead analyses.^{3,4} Stack-contributed heat has a significant influence on VCL performance.

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Table 1. Major Design Parameters for the Different Magnet Stacks/VCLs/Buses

DESIGN PARAMETER	SOLENOID STACKS S1 - S6	BARRIER STACKS A1/A20	INSERT STACK A2I	TRANSITION STACK T1	TRANSITION STACK T2
Geometry	Vertical Stack	Vertical Stack	Vertical With 23.0" Offset	Stack 45° Slope to Horizontal	Stack 51° Slope to Horizontal
Current (A)	2866	4208/4648	1517	5266	6278
Outside Diameter of VCL Outer Tube - Inches	2.25	3.25	2.25	3.25	3.25
Number of .25 O.D. VCL Copper Tubes	26	42	14	48	57
Non-Wet Bus Length - Inches	41.0	42.0	46.8	21.9	34.0
Size of Copper Bus Leads - Inches	3.50 x .75	4.00 x 1.375	3.50 x .75	4.00 x .75	4.00 x .75 4.00 x 1.375
Size & Material of Superconductor - Inches	.200x.067 Nb ₃ Sn	.436x.214 Nb ₃ Sn	.256x.256 NbTi .272x.083 Nb ₃ Sn	.438x.214 Nb ₃ Sn	.256x.256 NbTi .436x.214 Nb ₃ Sn

Table 2. Summary of Stack/VCL Liquefaction and Refrigeration Heat Rates

MAGNET	CURRENT KA	PREVIOUS DESIGN REVIEWS (TARGET) REFRIG. LOAD (1) WATTS	CURRENT STACK FINAL DESIGN ANALYSIS (2)				
			EXCESS HEAT TO LHe ABOVE BOILING 0.11 G/S/KA/PR WATTS	MINIMUM SPECIFIC FLOW ROT G/S/KA/PAIR	MAXIMUM STACK REFRIG. WATTS	RECOMMENDED SPECIFIC FLOW (3) (4) G/S/KA/PAIR	STACK REFRIG. LOAD FOR REC. FLOW WATTS
A2I	1.52	11.4	16.0	0.130	12.0	0.14	11.0
S1-S6	2.87	9.7	13.5	0.1225	10.0	0.13	8.0
A1	4.21	15.4	14.0	0.110	14.0	0.12	10.0
A20	4.65	15.4	13.5	0.115	11.0	0.12	9.0
T1	5.27	15.4	14.5	0.1125	13.0	0.12	9.5
T2	6.28	15.4	16.0	0.110	16.0	0.12	10.5

- (1) ALL DESIGN REVIEW MAGNET HEAT LOAD TABULATIONS GAVE EXCESS STACK/VCL REFRIGERATION LOAD ABOVE THE HEAT TRANSFERRED TO BOIL OFF SPECIFIC COOLANT OF 0.11 G/S/KA/PR.
- (2) WITH CURRENT DESIGN SIZE BUSES.
- (3) YIELDS SIMILAR SAFETY MARGINS ($\Delta T = 35K$ OR $\Delta \dot{W} = 0.015$ G/S/KA/PR) AGAINST RUN AWAY AS BEFORE, CONSIDERING STABILIZING INFLUENCE OF STACK HEATING OF VCL AND MAINTENANCE OF VCL TOP TEMPERATURE TO NOMINAL OF 315K BY HEATERS.
- (4) AGGREGATE TOTAL FLOW INCREASE TO THESE MAGNETS OF 14 PERCENT.

Figure 1. MFTF-B Axicell Configuration Magnet System

Figure 2. Solenoid Stack Assembly

Figure 3. MFTF-B Stack Subassembly Depicting the Thermal Control Elements
Featured in Each Stack

Figure 4. Typical Vapor-Cooled Lead (VCL) Assembly

Figure 5. Central Cell Solenoid S1-S6 Current Lead Subassembly

Figure 6. Stack Heating of VCL Induces Higher Required Specific Flow Rates As Lead/Current Becomes Smaller

Figure 7. Heat and Flow Balance Schematic of a Typical Stack Assembly

LEADS	JOULE HEATING Q_G Watts	STACK HEAT TO VCL* Q_S Watts	$\frac{Q_S}{Q_G}$ %	MIN. SPECIFIC FLOW RATE G/SEG-KA-PR
T2 6300 Amp	912	115	13	0.11
SOL 2900 Amp	445	105	24	0.1225
A2I 1500 Amp	244	90	37	0.13

*Not including heated bus conduction
which varies with lead and ambient
temperature.

Figure 8. Typical Distribution of Heat Load Components of Stack
Assembly Flowing into VCL's and Magnet

Figure 9. Temperature Profiles from LHe Level Through Solenoid Stack Components to Top of Stack at a Specific Flow Rate of 0.12 G/Sec-kA-Lead Pair