An Experimental Investigation of a Liquid Cooling Scheme for the Low Dropout Voltage Regulators of the Multiplicity and Vertex Detector

by

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Abstract

This report presents a summary of an experimental investigation of a liquid cooling system for the low dropout voltage regulators in the multiplicity and vertex detector (MVD), a device used to determine and characterize the collision location of two accelerated heavy ions. The coolant temperatures and flow rates as well as the voltage regulator operating temperatures were used to assess and optimize the performance of the proposed cooling system, identify potential assembly problems and system limitations, and provide the necessary information for designing and sizing the final MVD cooling system components.

NOMENCLATURE

Symbol	Description
c_p	Specific heat (J/kg K)
D	tube diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
Nu	dimensionless Nusselt number
n	number of LDOs
Pr	dimensionless Prandtl number
Q	Volumetric flow rate (m^3/s)
q_{LDO}	Power dissipation of an individual low dropout voltage regulator (LDO) (W)
Re	dimensionless Reynolds number

T	Temperature (°C)
u	velocity (m/s)
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)

Subscript	Description
f	Property corresponding to the liquid
i	inlet
LDO	Property corresponding to an LDO
o	outlet

INTRODUCTION

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is being developed to detect and investigate a phase of matter, the quark-gluon plasma. This will be achieved by accelerating heavy ions to 100 GeV/nucleon and allowing them to collide. To determine the collision point and characterize the event, PHENIX will employ the multiplicity and vertex detector (MVD). Highly detailed information concerning all aspects of the MVD is available on the web at *http://p2hp2.lanl.gov/phenix/mvd*, and in [1], so only relevant and brief introductory information is provided here.

The MVD resides in an enclosure which opens in a “clam-shell” fashion to allow for installation around the beam pipe in which the ion collisions will occur, as shown in Figure 1. Each clam-shell-like half of the MVD houses twelve “C-shaped” cages which each contain silicon strip detectors used to detect charged particles emitted during heavy ion collisions. Each silicon detector is connected by a Kapton cable to its own front-end electronics circuit board, also referred to as a multichip module or MCM. The disk-

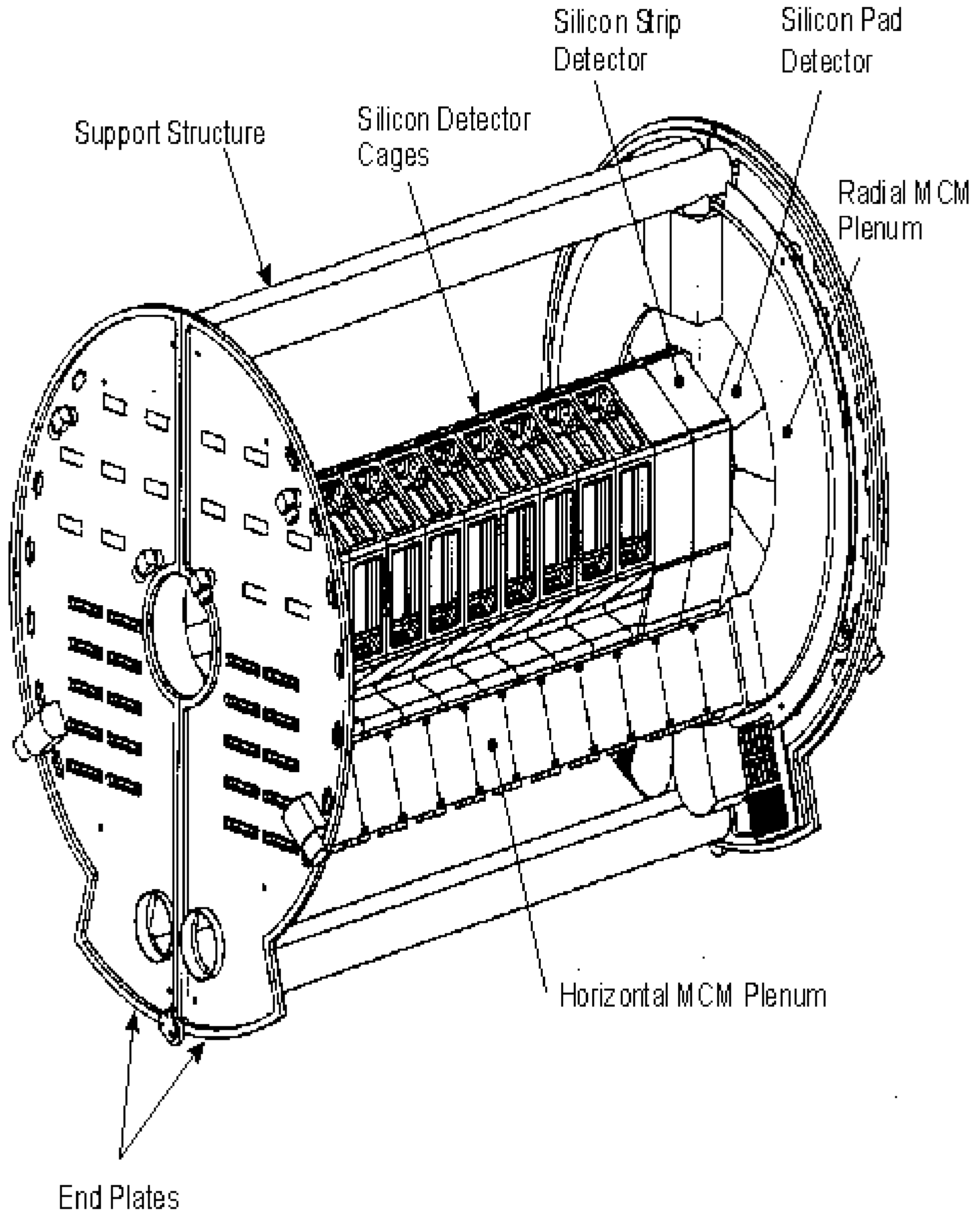


Figure 1. Schematic diagram of the MVD showing the full set of silicon detector cage assemblies, horizontal MCM plenum, support structure, and end plates including motherboards, pad detectors, and radial MCM plenums.

shaped endplates located on either end of the MVD each contain a total of twelve silicon pad detectors and twelve corresponding MCMs.

Within each of the four MVD endplates is a motherboard which contains the electronics necessary to supply power and transmit information to and from the MCMs. Mounted on each motherboard are thirty-five low dropout voltage regulators (LDOs) which control the voltage to various MCM analog and digital components. For each set of six MCMs, there is a corresponding set of five LDOs, of which only three dissipate significant amounts of waste heat. This waste heat, estimated to be at most 1 W (watt) per LDO, must be effectively dissipated to ensure reliable operation of the LDOs.

Figure 2 shows the proposed LDO cooling scheme including the relative placement of the LDOs and coolant tubing with respect to the motherboard.

Convection air cooling, which was found to provide satisfactory cooling of the MCM electronics of the MVD [1, 2, 3], was determined to be an inadequate means of cooling the LDOs. Because the LDOs must dissipate a relatively large amount of heat (on the order of 1 W) over a small surface area, a realistic forced convection air system would not be able to provide the necessary heat transfer rate needed to allow the LDOs to operate at a reasonable temperature. Consequently, the present study investigated the feasibility of using a forced convection liquid cooling system to provide a large enough heat transfer coefficient to maintain safe LDO operating temperatures.

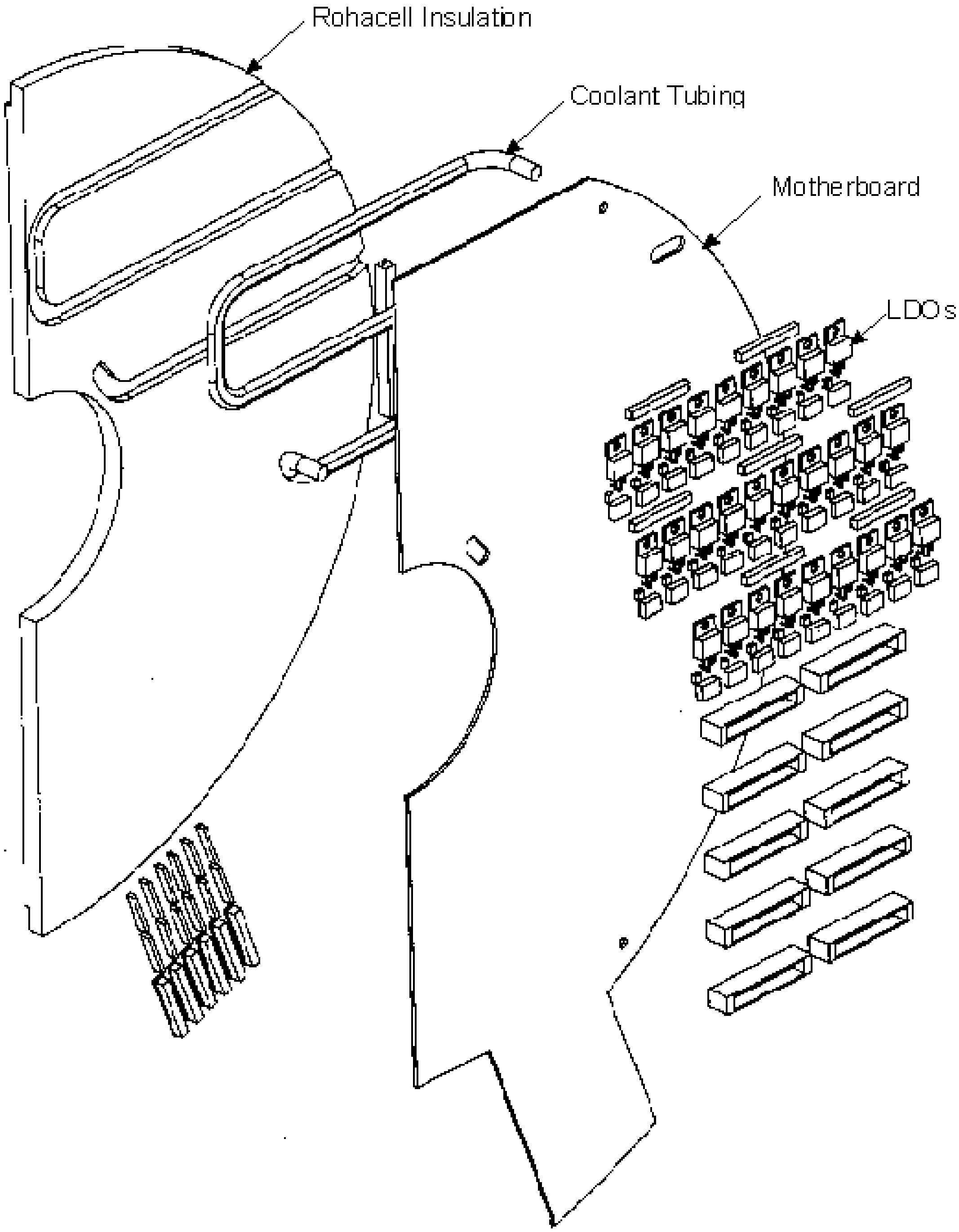


Figure 2. Exploded view schematic of the proposed liquid cooling scheme for the LDOs, showing the relative placement of the various components with respect to the motherboard

The following design criteria were specified for the LDOs and associated liquid cooling system:

- Cooling system design goal for maximum LDO operating temperature ----- 40°C
- Maximum power dissipation of a single LDO--------------------------------- 1.0 W
- Cooling liquid supply temperature--------------------------------------5°C to 10°C
- Dimensions of LDO main body---------9.0 mm (H) * 10.4 mm (L) * 4.5 mm (T)

While the maximum operating temperature of the LDOs intended for the final design (Micrel MI29 Series high-current low dropout regulators) is specified as 125°C, a limiting temperature of 40°C was imposed to prevent heat leakage to other components within the motherboard. In addition, the power dissipation by the actual LDOs will range from nearly 0 up to 1 W. Hence the 1 W heat generation rate used in this study corresponds to a worst-case scenario.

The purpose of this study was to determine the performance of the proposed liquid cooling system in a realistic geometry, identify potential problems and limitations, define assembly and system integration issues, and provide the necessary information for designing and optimizing the final MVD cooling system.

EXPERIMENTAL METHODS

A schematic of the experimental apparatus used in the present study is shown in Figure 3. The cooling of the simulated LDOs was provided by a closed-loop liquid

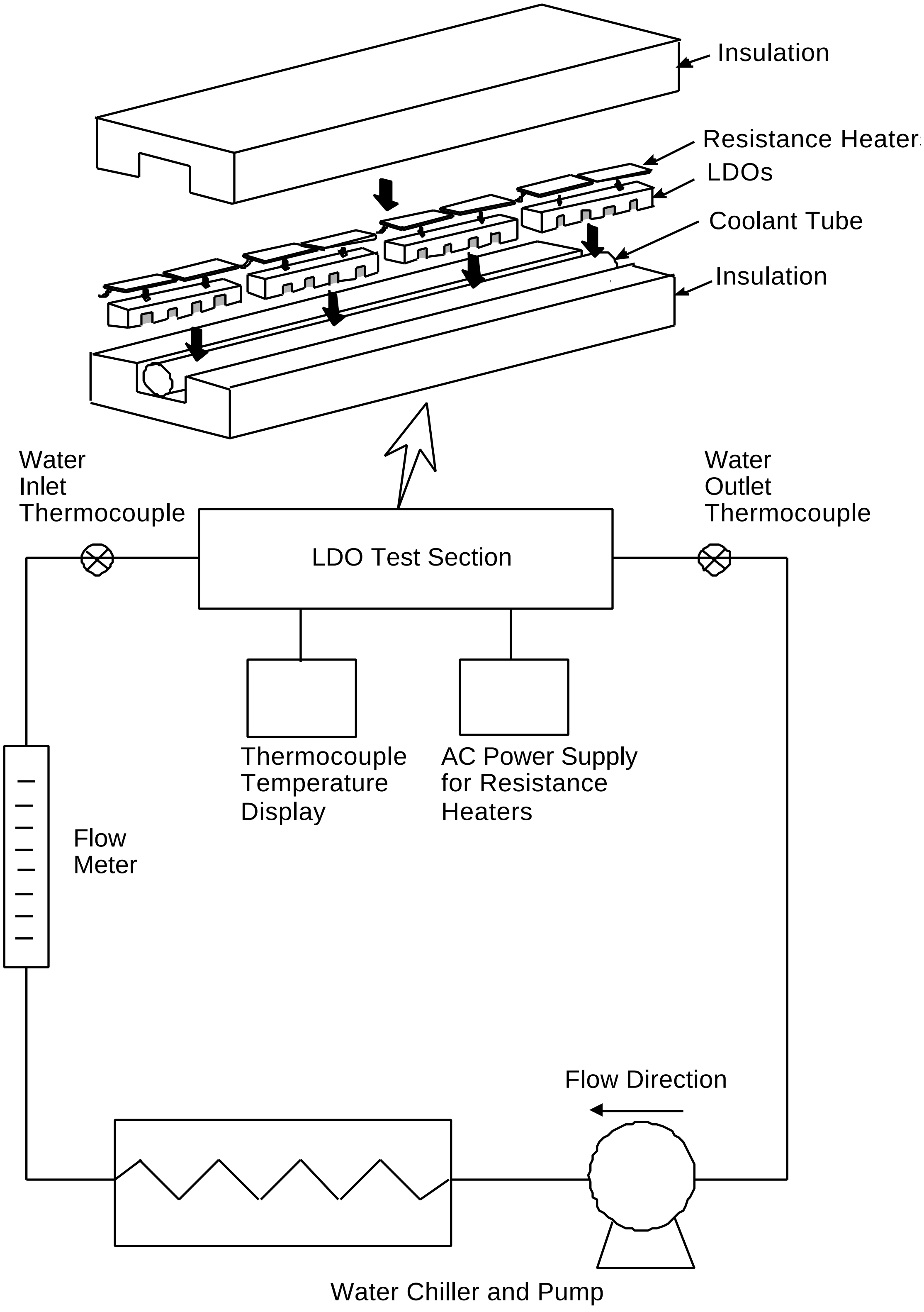
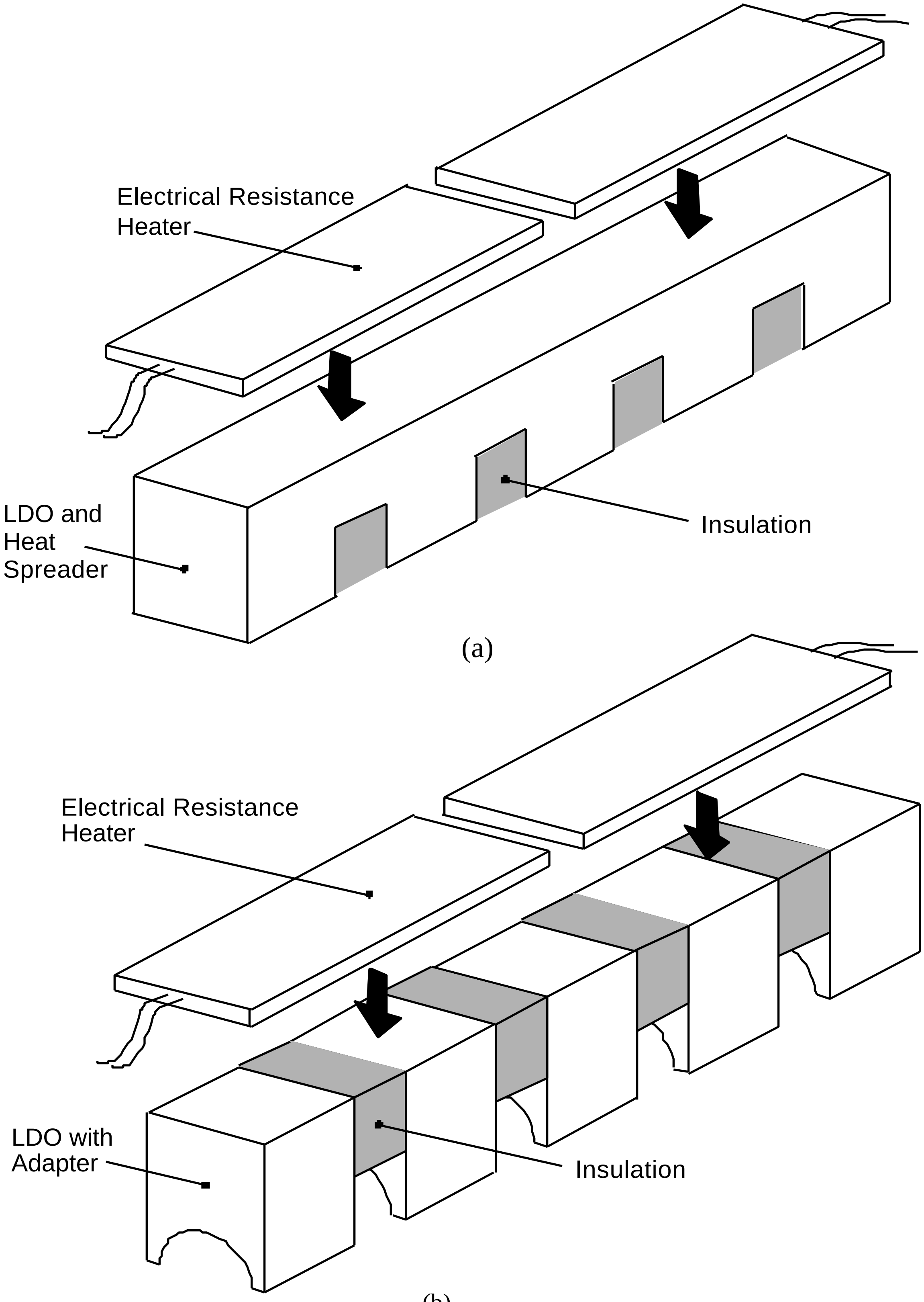


Figure 3. Schematic diagram of the experimental liquid cooling system for the low dropout voltage regulators in the MVD.

system. In particular, refrigeration and pumping of the liquid coolant (water in this study) were provided by a Neslab Endocal liquid chiller. Water flow rates were measured with a rotameter flow rate gauge which was calibrated over a flow rate range of 0 to 250 cm^3/min. Preliminary test results indicated that the LDO operating temperatures were insensitive to flow rate for water flow rates greater than 200 cm^3/min. Consequently, a single water flow rate of 220 cm^3/min was used throughout this study. Water temperatures at the inlet and outlet of the test section were measured with type T thermocouples. Insulated, flexible tygon tubing was used to connect the flow loop components to the test section. Two different test sections, a general concept and a motherboard prototype, were used in this study.

General Concept Test Section

The general concept test section allowed the typical performance characteristics of the proposed cooling system to be studied and quantified. This test section, shown as an exploded view in Figure 3, was made up of twenty simulated LDOs, eight electrical resistance heaters, a coolant tube fabricated from Al-6061-T6, and an insulation shell. The twenty simulated LDOs were fabricated from aluminum in two different configurations shown in Figure 4. The simulated LDOs are of the same geometrical dimensions as the LDOs chosen for the final MVD design. The first configuration, displayed in Figure 4(a), consisted of four LDO sections, each containing a set of five LDOs with their upper surfaces connected to an aluminum heat spreader on which were attached two Minco electrical resistance heaters. A single type T thermocouple was inserted into the fifth LDO in each of the four sections. Thermal insulation was inserted



(a)

(b)

Figure 4. Schematic diagram of the simulated low dropout voltage regulators for the (a) inline nonadapter and (b) individual adapter configurations.

between each LDO. The second LDO configuration, shown in Figure 4(b), possessed tubing adapters on the bottom surface of each LDO. Each LDO/adapter of this configuration was machined from a single piece of aluminum and was separated completely from the other adapters by insulation. Four sections of five LDOs were each connected to two electrical heaters and insulated as shown in Figure 4(b). As with the first configuration, every fifth LDO in the second configuration was supplied with a type T thermocouple.

For both LDO configurations, the general concept test section fabrication was completed by attaching the LDOs to an aluminum coolant tube with electrical tape. Three different configurations of the first test section, comprised of different LDO or coolant tube geometries, were used in the experiments. Cross-sectional views of these configurations are shown in Figure 5. In the first configuration, the LDOs (without the tubing adapter) were attached to a round, 6.35 mm O.D. (0.25 in.) coolant tube. The second configuration again used the flat LDO geometry, but employed a 6.35 mm O.D. coolant tube which had been pressed nearly flat to permit enhanced thermal contact between the LDOs and the tubing wall. Finally, the third configuration used adapters to connect the flat LDOs to the round coolant tube.

Motherboard Prototype Test Section

After satisfactorily completing the general concept tests, a more realistic geometry test section or prototype of the current motherboard design was constructed. The motherboard prototype, shown in Figure 6(a), was fabricated from a 1.59 mm (1/16 in.)

thick piece of G-10, a phenolic material which is thermally and electrically insulating. To

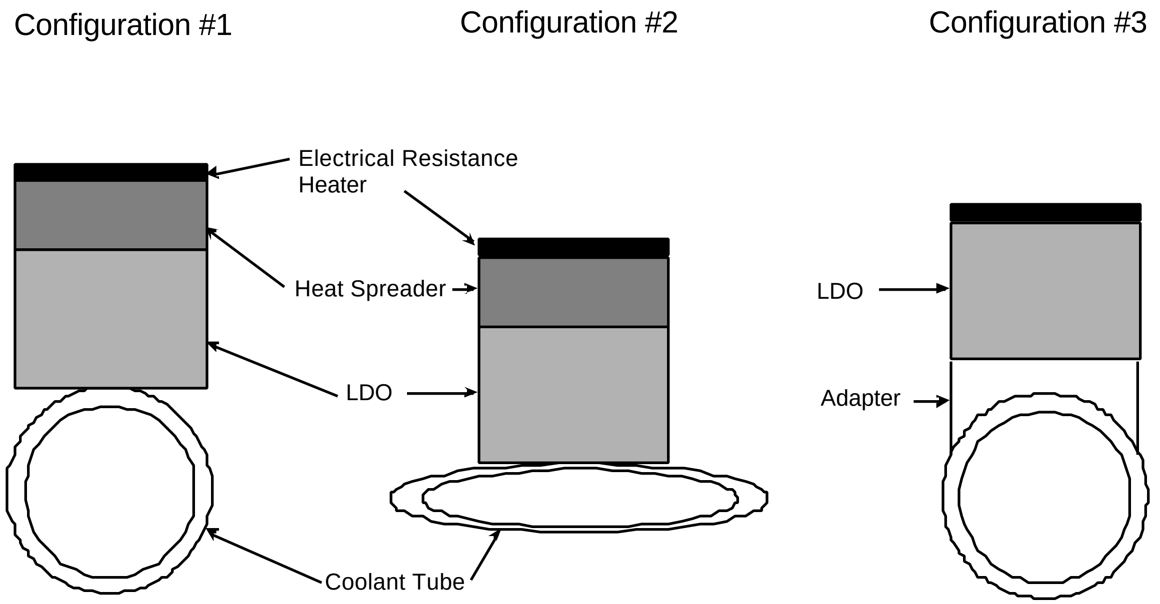
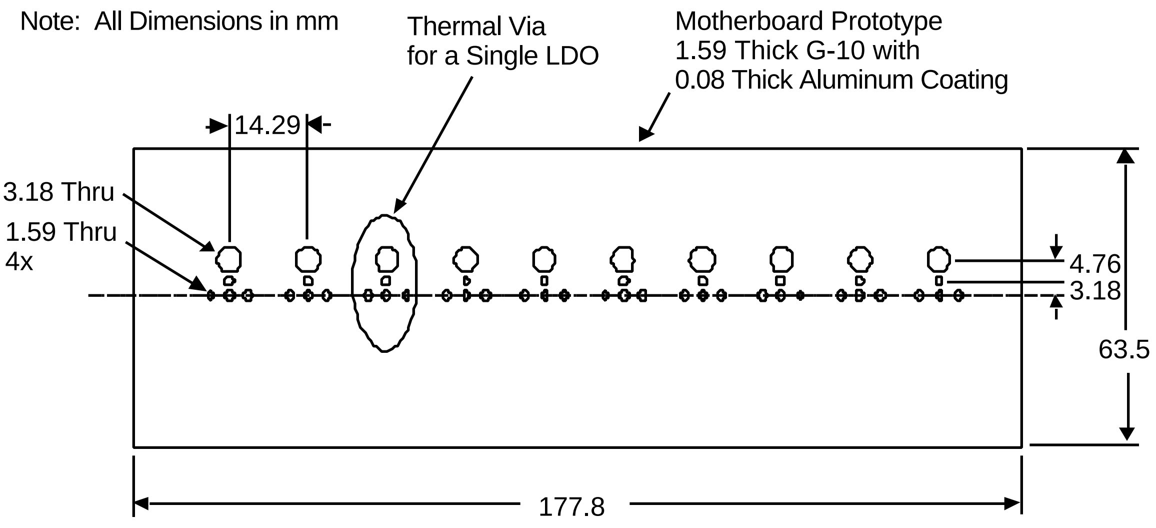
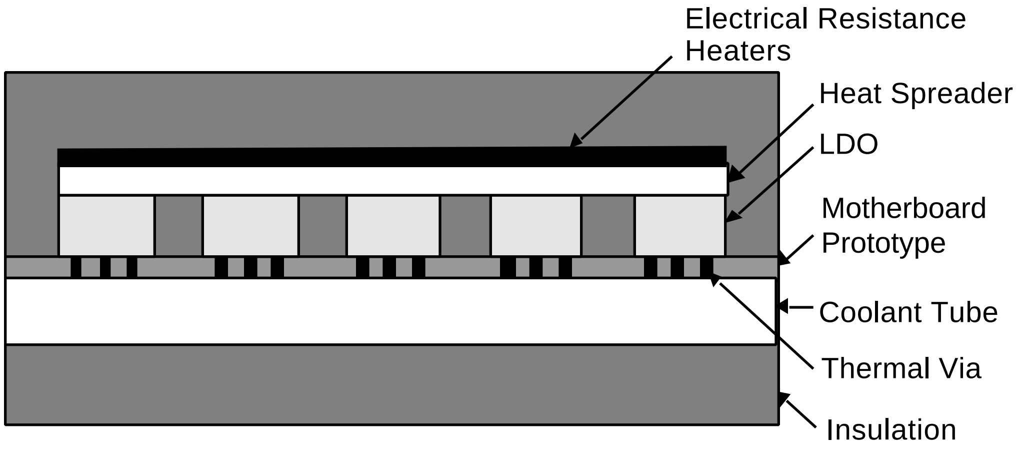


Figure 5. Cross-sections of the three different configurations of the general concept test section.



(a)



(b)

Figure 6. Schematic diagram of a portion of the second test section, showing the thermal vias in the prototype motherboard.

enhance heat transfer from the LDOs, attached on one side of the prototype, to the coolant tube mounted on the opposite side, a large number of thermal vias were placed in the motherboard. The thermal vias are simply holes in the G-10 that are coated with a 0.08 mm (0.003 in.) thick coating of aluminum to efficiently conduct heat from one side of the motherboard to the other. The motherboard prototype test section, shown in Figure 6(b) consisted of the motherboard with five simulated LDOs attached with a thermally conducting paste on one side, and a flat aluminum coolant tube attached to the other. Two electrical resistance heaters were attached to the back of the 5 LDOs and the entire test section was surrounded with insulation.

For each of the test sections, power was supplied to the electrical resistance heaters by a 120 V ac power supply. Type T thermocouples with an accuracy of ±0.5°C were used to monitor the test section inlet and outlet water temperatures, the operating temperatures of the fifth, tenth, fifteenth, and twentieth downstream LDOs in the general concept test section, and the first, third, and fifth downstream LDOs in the motherboard prototype test section. The thermocouples were found to agree with a mercury thermometer to within 0.5°C at a temperature of 23°C.

Experimental Procedure

The experiments were initiated by precooling the circulating liquid with the chiller to the desired test section inlet temperature for a specified flow rate. The liquid volumetric flow rate was monitored with a flow meter and adjusted with a throttle valve.

Next, the ac power supplies were set to provide the desired power dissipation of the LDOs. During the LDO heat-up phase, the water chillers had to be fine-tuned to account for the extra heat load of the LDOs in order to maintain the proper liquid inlet temperature. The temperatures of the cooling liquid and LDOs were continuously monitored through an Omega DP462 six channel thermocouple display. Once equilibrium was established, the power setting, liquid volumetric flow rate, and water and LDO temperatures were recorded. This procedure was conducted for an individual LDO power rate of 1.0 W, a liquid volumetric flow rate of 220 cm^3/min, liquid inlet temperatures of 5°C and 10°C, and two different test sections. Several runs were repeated for a single set of operating conditions to ensure reproducibility.

RESULTS

First (General Concept) Test Section

The results presented below show the effects of the coolant tube geometry and coolant temperature on the LDO steady-state operating temperatures for the various configurations of the first test section. Table 1 displays the experimental heat transfer data for an individual LDO power dissipation of 1 W and a water flow rate of 220 cm^3/min. Included in the data of Table 1 are the water inlet and outlet temperatures, various LDO temperatures, and the percent difference in the energy balance between the heat loss of the LDOs and the heat gain of the coolant for different LDO/coolant tube configurations.

Table 1. Summary of experimental heat transfer data and energy balance checks using Equation (1) for an individual LDO power dissipation of 1 W and a water flow rate of 220 cm^3/min for the general test section.

LDO/ Coolant Tube Config.	Inlet Water Temp. (°C)	Outlet Water Temp. (°C)	Fifth downstream LDO Temp. (°C)	Tenth downstream LDO Temp. (°C)	Fifteenth downstream LDO Temp. (°C)	Twentieth downstream LDO Temp. (°C)	% Diff. In Energy Balance of Eqn. (1) (%)
1*	6.6	> 10.0	> 70.0	> 70.0	> 70.0	> 70.0	
2**	6.6	8.1	40.0	40.9	47.6	48.3	15.4
3***	5.1	6.4	32.7	27.2	32.0	30.0	> 0.1
3***	6.4	7.9	32.6	27.1	34.8	29.6	15.4
3***	9.9	11.1	36.3	31.4	36.5	33.8	7.6

* 1. Round tubing, no LDO adapter
** 2. Flat tubing, no LDO adapter
*** 3. Round tubing, LDO adapter

The first LDO/coolant tube configuration (shown previously in Figure 5) allowed only a point contact for heat transfer. The poor thermal performance of this configuration resulted in LDO temperatures in excess of 70°C. The second configuration used a flat tubing geometry which allowed surface contact between the LDO and the coolant tube. This configuration greatly enhanced the heat transfer process and reduced the LDO operating temperatures into a range of 40.0°C to 48.3°C. Unfortunately, the forming process used to generate the flat tubing from round stock did not provide a sufficiently flat surface for mounting the LDOs. The resulting thermal contact resistance prevented achieving lower and more acceptable LDO operating temperatures. By using an adapter to serve as an effective thermal bridge between the LDOs and the coolant tube (shown in Figure 5), the design goal of LDO operating temperature of less than 40°C was met. As the data of Table 1 indicate, a coolant supply temperature in the range of 5°C to 10°C was used to meet the LDO temperature design goal.

To ensure reproducibility of the experimental data, several tests were repeated and found to provide nearly consistent LDO operating temperatures (within 1°C). In addition, an energy balance was performed for each test to check measurement accuracies. In the following energy balance equation, the left-hand side represents the energy supplied to the coolant by the n LDOs, $n\,q_{LDO}$, and the right-hand side represents the total enthalpy gained by the water with a volumetric flow rate Q.

$$nq_{LDO} = \rho_f\, Q c_{p,f}\,(T_{f,o} - T_{f,i}) \qquad (1)$$

For the tests listed in Table 1, the left- and right-hand sides of Equation (1) were found to agree to within 15.4%, thus indicating that the measurement techniques were supplying acceptable results. Differences may be attributed to environmental heat losses/gains and measurement uncertainties.

Second (Motherboard Prototype) Test Section

The techniques used to produce the results in the previous section tested 'proof-of-principle concepts. However, space limitations and assembly issues associated with the MVD motherboard required that these LDO/coolant tube configurations be further optimized to provide a compact and efficient heat removal system. Consequently, the thermal via motherboard prototype, presented previously in Figure 6, was designed to satisfy this need.

The results presented in this section reveal the thermal performance of the thermal via motherboard prototype in transferring heat from the LDOs to the liquid coolant. As indicated previously, the tests on this more realistic geometry were conducted after the proof-of-principle experiments were completed satisfactorily with the general concept test section. Table 2 displays the experimental heat transfer data for an individual LDO power dissipation of 1 W and a water flow rate of 220 cm^3/min. As was done in Table 1, the data presented in Table 2 contain the water inlet and outlet temperatures, various LDO temperatures, and the percent difference in the energy balance between the heat loss of the LDOs and the heat gain of the coolant.

Table 2. Summary of experimental heat transfer data and energy balance checks using Equation (1) for an individual LDO power dissipation of 1 W and a water flow rate of 220 cm^3/min for the motherboard prototype test section.

Inlet Water Temp. (°C)	Outlet Water Temp. (°C)	First downstream LDO Temp. (°C)	Third downstream LDO Temp. (°C)	Fifth downstream LDO Temp. (°C)	% Diff. In Energy Balance of Eqn. (1) (%)
5.0	5.4	37.6	38.4	38.6	22.0
10.2	10.5	40.6	41.6	41.9	8.5

The data of Table 2 indicate that the thermal vias, in combination with the thermally conducting paste, act as an effective thermal bridge for transferring heat from the LDOs to the liquid coolant. The LDO design temperature limit of 40°C was satisfied with a coolant inlet temperature of 5°C, and just slightly exceeded with the 10°C coolant.

Consequently, using this thermal bridge configuration and a coolant supply temperature of less than 10°C in the final MVD design will provide adequate cooling of the LDOs.

The data of Table 2 indicate that the LDO operating temperatures are very close to the design limit of 40°C. However, it should be noted that this temperature design limit and the 1 W LDO power dissipation used in this study were very conservative and do provide a significant safety margin.

General

For all cases studied, the coolant flow rate was sufficiently high to prevent less than a 2°C increase in the coolant temperature from the inlet to the outlet of the test sections. For an ideal coolant system with a isothermal heat sink, the LDOs would be expected to have the same operating temperature. The differences in the LDO temperatures in Tables 1 and 2 are due to heating of the coolant, contact resistance differences between the LDOs and coolant tube, as well as nonuniform heat distributions from the resistance heaters.

CONCLUSIONS AND DESIGN RECOMMENDATIONS

This study investigated the performance of a proposed forced convection liquid cooling system for the MVD's low dropout voltage regulators. From the experimental results of this study, the following key conclusions can be drawn:

1. The operating temperatures of the LDOs were found to be highly dependent on the thermal contact with the coolant supply tubing. By increasing the contact surface area between the LDOs and coolant tubing, the LDO operating temperatures were decreased.
2. The general concept study showed that using a water flow rate of 220 cm^3/min, an inlet water coolant temperature in the range of 5°C to 10°C, and a thermal bridge between the LDOs and coolant tube with sufficiently low thermal contact resistance (the LDO/coolant tube adapter configuration), the operating temperature design goal (< 40°C) of the LDOs was met.
3. The thermal via motherboard prototype, which represents the intended design of the LDO cooling system, maintained LDO operating temperatures below the 40°C design limit when a coolant supply temperature of 5°C was used. Consequently, for the current motherboard design, the thermal vias in combination with a thermally conducting paste, will act satisfactorily as a thermal bridge between the LDOs and the coolant tubing.

The results of this study add further support to finalizing the design of the MVD cooling systems. In particular, the following issues should be considered in the final design of the LDO cooling system:

1. A single large capacity (100 W) coolant supply system is recommended for the LDO cooling system of the MVD. The unit must be able to supply a coolant temperature

of 5°C or less to the inlets of the motherboards at a water flow rate of at least 300 cm^3/min (assuming the four endplate cooling lines are connected in parallel). At this temperature, all coolant lines should be well insulated to prevent unwanted heat gains and condensation build-up.

2. The use of water as the coolant poses a potential danger to surrounding electrical components in the MVD should a leak in the cooling system develop. To reduce this threat in the final design, it is recommended that the water coolant be replaced with FC-75, a fluorinert liquid with a low dielectric constant produced by the 3M Corporation. To maintain the same level of cooling performance as the water system, the flow rate of the FC-75 system will have to be modified slightly from that given in this report for water. These calculations are detailed in the appendix.
3. To ensure proper thermal performance of the final cooling system, thermal contact resistance between the LDOs and coolant must be minimized. This can be achieved by using a thermally conducting paste or epoxy to attach the LDOs and coolant tubing.

ACKNOWLEDGMENTS

The authors wish to thank Jan Boissevain of P-25 division for his technical input on the LDO electronics and Gary Smith and Gary Richardson of NIS division for their thermal via motherboard prototype design.

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APPENDIX

Dimensional Analysis for Replacing Water with FC-75 as the Coolant for the LDOs.

Problem: Determine the required flow rate of FC-75 that will provide the same heat dissipation rate as water flowing through the LDO coolant tubing.

The heat transfer coefficient for internal turbulent flow is given by the following empirical Nusselt correlation [4]:

$$Nu_D = 0.023\, Re_D^{0.8}\, Pr^{0.3}, \qquad \text{(A.1)}$$

where $Nu_D = h\,D/k$, $Re_D = u\,D\,\rho/\mu$, and $Pr = c_p\,\mu/k$.

After manipulating Equation (A.1), the following expression for the heat transfer coefficient is obtained:

$$h \propto \frac{k^{0.7}\, u^{0.8}\, c_p^{0.3}\, \rho^{0.8}}{\mu^{0.5}}. \qquad \text{(A.2)}$$

Using the properties in Table A.1 for water and FC-75 at 295 K, Equation (A.2) was solved for the heat transfer coefficient in terms of velocity for both fluids. Setting the heat transfer coefficients equal to one another for both fluids, the ratio of the velocities for the two different fluids to provide the same heat transfer coefficient was determined to be

$$u_{H2O}/u_{FC\text{-}75} = 0.124, \tag{A.3}$$

or in terms of flow rate,

$$Q_{FC\text{-}75} = 8\ Q_{H2O} \tag{A.4}$$

Consequently, to maintain the same heat transfer coefficient using FC-75 instead of water, the volumetric flow rate must be eight times greater than that of the water.

Table A.1. Thermophysical properties of liquid water and FC-75 at 295 K.

Property	Water	FC-75
Density (kg/m^3)	1000	1770
Specific heat at constant pressure (J/kg K)	4184	1047
Thermal conductivity (W/m K)	0.598	0.063
Dynamic viscosity (N s/m^2)	0.00108	0.00142