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Thermal Control Subsystem Design for the Avionics of a Space Station Payload

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Prepared for the
International Mechanical Engineering Congress and Exposition
sponsored by the American Society of Mechanical Engineers
Atlanta, Georgia, November 17-22, 1996



National Aeronautics and
Space Administration

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ABSTRACT

A case study of the thermal control subsystem development for a space based payload is presented from the concept stage through preliminary design. This payload, the Space Acceleration Measurement System II (SAMS-II), will measure the acceleration environment at select locations within the International Space Station. Its thermal control subsystem must maintain component temperatures within an acceptable range over a 10 year life span, while restricting accessible surfaces to touch temperature limits and insuring fail safe conditions in the event of loss of cooling. In addition to these primary design objectives, system level requirements and constraints are imposed on the payload, many of which are driven by multidisciplinary issues. Blending these issues into the overall system design required concurrent design sessions with the project team, iterative conceptual design layouts, thermal analysis and modeling, and hardware testing. Multiple tradeoff studies were also performed to investigate the many options which surfaced during the development cycle.

NOMENCLATURE

A/D	Analog to Digital
CPS	Control Panel Subsystem
CU	Control Unit
DC	Direct Current
DIB	Drawer Interconnect Box
DSP	Digital Signal Processing
ECS	Electronic Control Subsystem
EMI	Electromagnetic Interference
EXPRESS	EXpedite the PRocessing of Experiments to Space Station
I/O	Input/Output
ISS	International Space Station
MSP	Mass Storage Power Subsystem

MSS	Mass Storage Subsystem
MTBF	Mean Time Between Failure
MTL	Moderate Temperature Loop (ISS cooling water)
PC/104	A standard form factor for electronic boards
RTS (-SE, -EE)	Remote Triaxial Sensor (-Sensor Enclosure, -Electronics Enclosure)
SAMS-II	Space Acceleration Measurement System II
TBD	To Be Decided

INTRODUCTION

Accurate measurement of the microgravity environment¹ which exists on the International Space Station (ISS) is critical to the experimental research payloads onboard. The Space Acceleration Measurement System II (SAMS-II) is tasked with measuring this acceleration environment at select locations within the ISS. Acceleration data from SAMS-II will be recorded and stored for subsequent retrieval, and will also be available in near-real time.

The planned ISS has separate sections, or modules, large enough for human-tended experimentation. The U.S. Lab module is a "shirt sleeve" environment (Vaden, 1994) with an air temperature of 18.3 to 26.7°C (65 to 80°F); air pressure of 97.9 to 102.7 kPa (14.2 to 14.9 psia); and an average ventilation air velocity of 0.076 to 0.203 m/s (15 to 40 ft/min). Contamination of the cabin air during normal operations is less than an average of 100,000 particles per cubic foot for particles greater than 0.5 microns.

Within the modules are racks which integrate several experimental payloads and provide an infrastructure for accessing ISS power, water cooling, network connections, and other avail-

¹ The term microgravity is used to describe the acceleration environment onboard the shuttle and space station which is nominally 10^{-6} g, where "g" denotes the gravitational acceleration value at sea level.

able utilities. Initial manifest location for SAMS-II was in an EXPRESS (EXpedite the PROcessing of Experiments to Space Station) rack within the U.S. Lab module.

Payload Overview

SAMS-II is composed of two discrete subsystems - the Control Unit (CU), and the Remote Triaxial Sensor (RTS). The CU design utilizes a two drawer structure occupying the volume of two middeck lockers² within an EXPRESS rack; and contains hardware for overall control, data storage, and display functions. Figure 1 shows the CU enclosure, and Fig. 2 illustrates SAMS-II installed in the ISS racks. Heat generating assemblies within the CU include: the Electronic Control Subsystem (ECS), the Mass Storage Subsystem (MSS), the Mass Storage Power subsystem (MSP), the Control Panel Subsystem (CPS), and various cables and connectors.

The RTS is comprised of the Sensor Enclosure (RTS-SE) and the Electronics Enclosure (RTS-EE). The RTS-SE contains the accelerometers and associated electronics, and is intended to be mounted in a location where acceleration data is desired. Power and data lines connect the RTS-SE to the RTS-EE, which contains electronics required for control and power distribution for up to two RTS-SE's. The RTS-EE is mounted in a convenient location to support the RTS-SE's connected to it. In turn, multiple RTS-EE's can be connected to the CU. An exploded view of the RTS-EE assembly is shown in Fig. 3. Figure 4 is a photograph of the RTS-SE prototype with A/D and I/O boards displayed outside of the enclosure.

Cooling Environment

For the CU, two resources are available for dissipation of heat generated within the payload electronics: water and avionics air. Both resources are ultimately tied into the ISS water loop which rejects the heat to space. Cooling water from the Moderate Temperature Loop (MTL) is available to the racks at 16.7 to 18.3°C (62 to 65°F) (Vaden, 1994). Water flowrate ranges from 0.0063 to 0.0378 kg/s (50 to 300 lbm/hr), at a maximum water pressure is 834.3 kPa (121 psia). No net heat dissipation to the EXPRESS rack structure is permitted. Although some low speed air circulation is present in the ISS modules, use of this cabin air for heat dissipation is generally not reliable due to the configuration of the racks, and is highly discouraged in any case.

Cooling for the RTS components is dependent on the mounting location and configuration of the RTS-EE and RTS-SE enclosures since both assemblies are primarily conduction optimized designs. SAMS-II has required that the maximum equivalent mounting and radiant temperature for the RTS subsystems does not exceed a predetermined value in order to maintain acceptable component temperatures. In most cases the RTS-EE will be mounted to a water-cooled coldplate to achieve adequate interface temperatures. Assembly conditions (e.g. surface finish and flatness, fastener

torque, etc.) are critical to effectively dissipate heat from both RTS assemblies.

A crucial heat dissipation mode that cannot be utilized in the microgravity environment of ISS is natural convection. This limitation has significant impacts on the thermal control design. In addition to making traditional finned heat sinks of little use, the lack of natural convection also allows hot spots to develop in stagnant air regions. Although these hot spots can also develop in a normal ground environments, natural convection limits component temperatures to a lower value than would be achieved by conduction through the air alone. No such contingency exists in a low gravity environment, making verified air flow across all heat dissipating surfaces critical for convection cooled components. Of course, conduction and radiation heat transfer techniques become more vital in a microgravity environment.

APPROACH

Development of a thermal control system for SAMS-II required a concurrent engineering approach to insure that multidisciplinary design goals were met without creating the long design cycle times inherent to sequential design approaches. A design team was created with members representing the following disciplines and areas: design/drafting, electrical, manufacturing, mechanical/structural, project management, reliability & safety, software, system integration, testing/assembly, and thermal control. The design team held weekly working meetings to report design status, assign new action items, and address complicated design issues as a group. These meetings were supplemented by discussions and testing in smaller groups (i.e. two to four people) to complete subsystem development tasks. This concurrent approach also minimized organizational barriers resulting from team members employed by two government and three contractor/subcontractor organizations.

Quarterly "table-top" reviews were also held for each subsystem to present the project accomplishments, status, and future plans to program management. A networked computer based project infrastructure provided an environment for generating, reviewing and tracking of procurements, project milestones, and required documents. A listserver feature was also created which allowed instantaneous posting of information to all project members simultaneously for dissemination and feedback.

Objectives and Constraints

There are four primary objectives which must be met by the SAMS-II thermal control system: 1) Maintenance of component temperatures within an acceptable range; 2) Operation over a 10 year life span on the ISS; 3) Restriction of accessible surfaces to touch temperature limits; and 4) Insurance of fail safe conditions in the event of loss of cooling. Objectives 1 & 2 are driven by the reliability of the system as a function of operating temperature. This system reliability is derived from the subsystems and components within the system, and is based on a empirical data and theoretical relationships. Prediction of system reliability is an art and science of its own, and the subject of debate regarding appropriate methods and analysis (Pecht, 1996). Although beyond

² Middeck lockers are used on the space shuttle for housing space experiments. This nomenclature, and the volume it represents, has become a standard manifest specification.

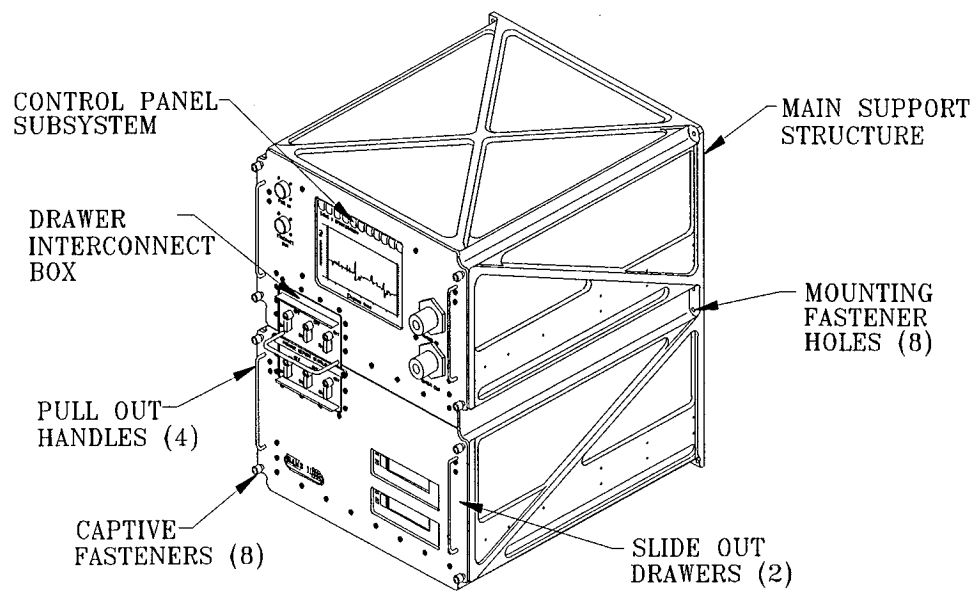


Figure 1: Control Unit enclosure

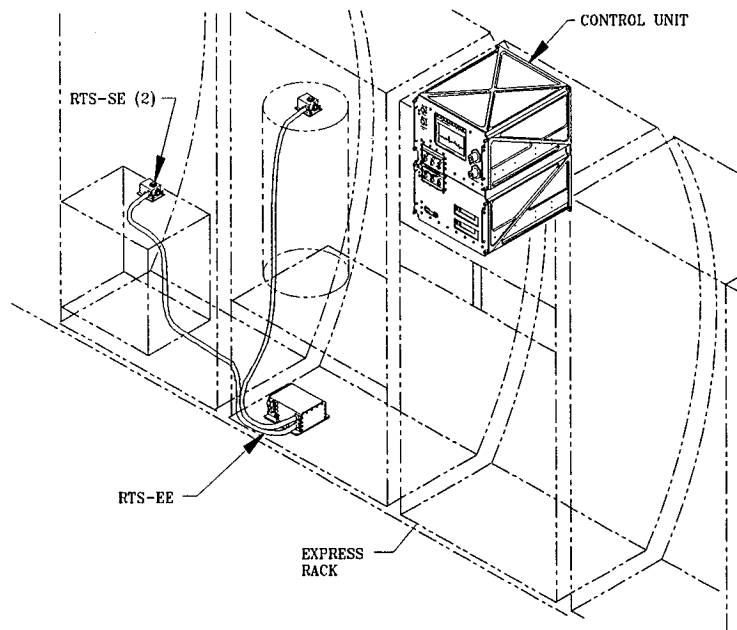


Figure 2: SAMS-II installed in the ISS racks

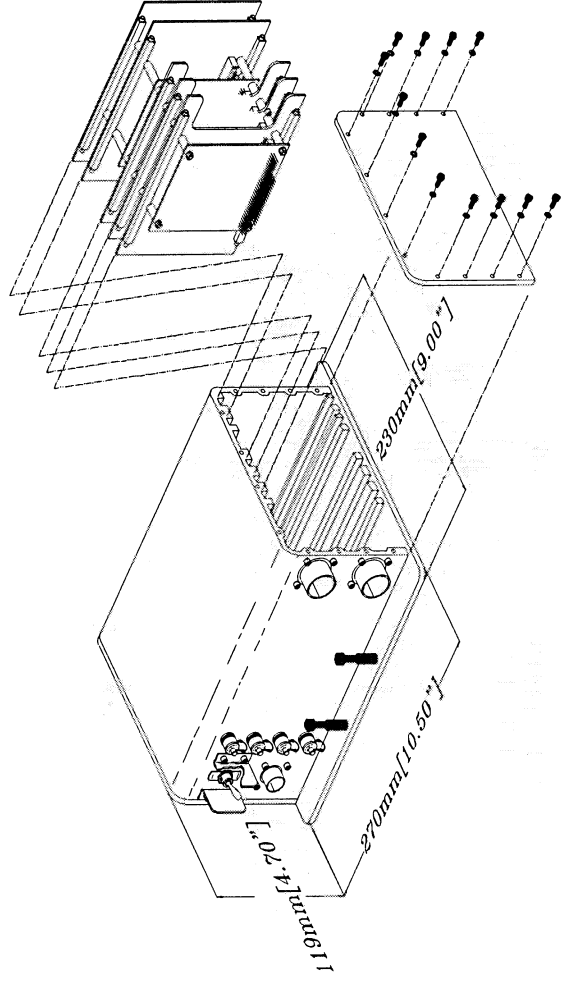


Figure 3: RTS-EE exploded view

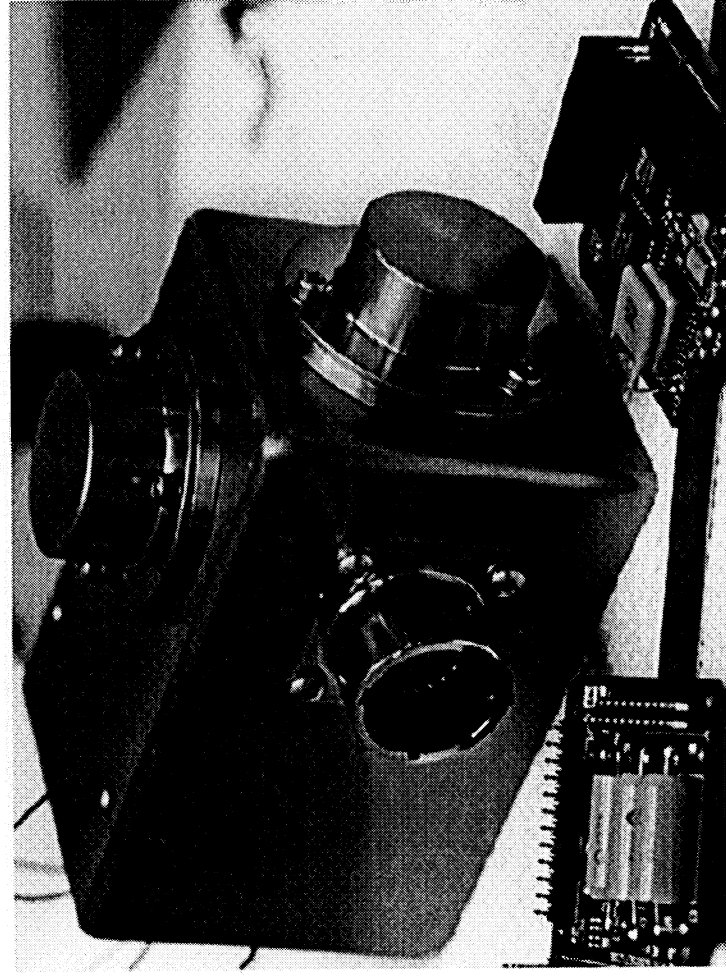


Figure 4: RTS-SE prototype

the scope of this paper, it is important to note that system reliability is at the core of electronics thermal control goals.

In addition to the primary objectives, there are other secondary objectives which are highly desirable but not absolutely essential. The ability to identify, detect, diagnose, and correct temperature conditions outside of acceptable limits is one such secondary objective. Another important secondary goal is the use of commercial "off-the-shelf" components wherever possible to reduce costs. This goal often requires making tradeoffs among factors such as higher reliability military grade components, verification testing required, nonrecurring costs associated with small volume procurements, etc. Other secondary objectives which affect the thermal control subsystem design include: maintainability, redundancy, and minimum acoustic noise.

A variety of thermal design constraints exist, and fall into one of three categories depending on which entity is imposing the constraint: ISS, EXPRESS rack, or SAMS-II. Table 1 summarizes the thermal related constraints (Vaden, 1994; Kittredge, 1995; and Golden, 1994). The purpose of thermal analysis and testing is to insure that the design objectives have been accomplished within these imposed constraints.

Conflicting Design Drivers

If design of the thermal control subsystem were driven solely by the objectives and constraints summarized above, the development task could be accomplished with only moderate interaction with other engineering disciplines. However, a multitude of interdisciplinary issues arise resulting in conflicting design drivers which must be resolved together by the design team, usually by compromise among the team members. This scenario necessitates frequent technical interaction of the design team.

For example, concerns about susceptibility to spurious EMI, as well as control of emitted EMI, dictates shielding of electronic components and enclosures. Many of these shielding techniques (i.e. sealing of enclosures, conductive gaskets, screens, etc.) compound electronic cooling problems by increasing pressure drop in forced air systems; increasing interface resistance in conduction applications; or otherwise limiting heat transfer mechanisms.

Another conflicting design driver is mass and center-of-gravity constraints. In order to minimize mass impacts, optimization of conduction structures and active cooling components is necessary. Placement of thermal control components is likewise critical to center-of-gravity constraints for the payload.

Maintainability is yet another design goal which can have negative ramifications on the cooling subsystem. Components and subsystems must be serviceable on-orbit, with as much modularity as practicable. This objective impacts the use of ducts, fans, and other components which must be designed for easy disassembly.

DEVELOPMENT CYCLE

The initial concept design for SAMS-II was developed primarily from a mechanical packaging and electronics functioning standpoint, with limited input in terms of thermal

Table 1: Thermal Control Related Constraints

<i>Requirement</i>	<i>Source</i>	<i>Compliance</i>
1. Maximum MTL water return temperature of 48.9°C (120°F)	ISS	Calculated maximum water outlet temperature is 28.7°C (83.6°F)
2. Payload water pressure drop of 22.4±1.0 kPa (3.25±0.15 psid) at required flowrate	EX-PRESS	To be verified by analysis and test
3. Capable of operating with a maximum water pressure of 834.3 kPa (121 psia)	ISS	Designed with appropriate safety factors, and pressure tested
4. Material and cleanliness compatibility with deionized MTL water	ISS	All wetted surfaces are stainless steel; cleaning to be performed
5. Equipment using MTL delivered on orbit charged with water	ISS	SAMS-II water loop will be charged with specified water
6. Maximum water leakage not to exceed TBD (scc/hr)	ISS	Leak tests will be performed on the water loop system
7. Water connections compatible with EXPRESS rack equipment	EX-PRESS	EXPRESS compatible quick disconnects to be used at front panel
8. Safe condition maintained in the event of loss of cooling	ISS	SAMS-II will be powered down if water or air cooling is lost
9. Touch temperature in the range 3.9 to 45.0°C (39 to 113°F) for contin. contact; 3.9 to 48.9°C (39 to 120°F) for momentary contact	ISS	Will be verified by analysis and test; warning labels/indicators/guards will be used if needed
10. Surfaces exposed to cabin air must be above 15.6°C (60°F) to prevent condensation	ISS	Coldest payload temperature is inlet water at 16.7 C (62°F) or above
11. Cannot rely on conductive cooling to the EXPRESS rack structure	EX-PRESS	All heat generated within the CU is transferred to the water loop
12. Max sound pressure level cannot exceed NC-40 curve in any octave band 83 Hz to 8 kHz @ 0.61 m (2 ft) from the equipment surface	ISS	Selection and mounting of fans will minimize generated noise; verification by test is planned
13. Max radiant, ambient air, and baseplate temp of 45°C (113°F) for the RTS	SAMS-II	RTS has been analytically verified at a b.c. of 45°C; testing is planned
14. RTS mounting surface finish of TBD and flatness of TBD; fastener torque of TBD	SAMS-II	Performance to be verified by test at given specifications

engineering. Figure 5 illustrates the top and bottom drawer layout of this early concept. The cooling method for this design utilized fans drawing air across water tubes at the side of the top drawer. Forced air cooling was used in both drawers, along with a water-cooled coldplate along the floor of the bottom drawer to supply additional conduction cooling. Difficulties with this thermal control design included:

- Low efficiency three-pass bare tube heat exchanger (without extended surfaces/fins)
- Blocked fan entrance region; insufficient exhaust/return paths
- Lack of controlled air circulation loop
- Ineffective coldplate performance under the drives which are designed for forced air cooling, and are thermally isolated from the coldplate
- Water cooling in both drawers requires flexible tubing design between top and bottom drawers

It was recognized shortly after the conceptual design was completed that thermal control was a significant driver in the overall design. As the preliminary design was started, thermal engineering support was added to the design team to address this need. Early integration of thermal control into the development cycle was crucial to an effective avionics design, and allowed the design team to focus on an approach which involved thermal control from the start. The alternative is often a retrofitted, expensive, and sometimes inefficient cooling subsystem which is designed in haste to address a temperature problem discovered late in the development cycle.

Some parameters that influenced the design direction early on for the thermal control subsystem included: desire to be thermally self-contained except for water connections (i.e. avoid reliance on rack avionics air); use of commercial drives designed for forced air cooling; and avoidance of vibration inducing components on RTS assemblies due to acceleration environment sensitivity.

Design Iterations

In order to work towards a preliminary design and the production of an engineering model, an iterative development process was employed by the design team. This iterative process was used to converge on a payload design which met the objectives for the entire system without compromising key subsystem performance parameters. Although the process was continuous, there were several discrete design iterations for the CU that represented intermediate solutions to the developmental goals. One of the early iterations is shown in Fig. 6.

This design made use of a compact finned-tube water-to-air heat exchanger mounted over an opening in the floor of the top drawer. A fan mounted to the card cage assembly draws air through the heat exchanger, and exhausts the conditioned air between the electronic cards. Two additional fans behind each set of drives brings the air exiting the card cage down to the bottom drawer to cool the drives. The loop is completed as return air enters the heat exchanger in the top drawer. Ducting is used in the top drawer to minimize pressure drop and bypass air flow. Elevated drive assemblies reduce blockage at the inlet of bottom drawer fans. Also, the water-cooled coldplate is eliminated from the bottom drawer along with the required water connections. Analysis showed acceptable

component temperatures within the card cage could be achieved with an air flow of 24 l/s (50 cfm).

Some unresolved issues raised with this early design iteration included:

- Upstream placement of Power Control Box raises air temp before reaching the drives
- Maintainability of subsystems is complicated by the use of ducts
- Insufficient contingency volume for connectors and other miscellaneous items
- Mass and center-of-gravity constraints are violated
- EMI concerns with an open card cage
- Payload power draw is high

An intermediate design iteration which addressed these issues utilized conduction cooled military grade electronics cards in a sealed card cage. This configuration minimizes EMI problems, and improves the overall reliability with the use of mil-grade cards. Power control is split into a distributed system with some of the components in the new Electronics Control Subsystem (ECS), and the remainder in the bottom drawer in a reduced Mass Storage Power (MSP) enclosure. A water-cooled cold plate was designed with sufficient tube length and appropriate heat transfer characteristics to keep the Electronics Control Subsystem at desired temperature levels, while the MSP conducts its heat to the bottom drawer floor to be dissipated to the circulating air.

Since the forced convection heat load is reduced by using the coldplate, a heat exchanger that is half the original size can be used. Coupled to a fan in the top drawer, the heat exchanger provides conditioned air cooling to the drives. Air forced through the heat exchanger to the bottom drawer is directed by two fans in series through the in-line mounted drive assemblies. Air is returned to the top drawer through a slot in the floor to complete the loop. In the interest of maintainability, no ducting is used in this design. Finally, the overall payload weight and volume is reduced to an acceptable level; and relocation of the components brings the center-of-gravity within tolerance. In a subsequent iteration one of the bottom drawer fans is eliminated resulting in lower overall power draw and increased reliability.

Many other design modifications and related tradeoffs/analyses were performed during the CU development cycle, including: optimization of the ECS structure for conduction; investigation of the use of sidewall water tubing for cooling the ECS; mounting configurations for reduced interface resistance; coldplate construction and assembly techniques; and enhanced surface heat transfer within the coldplate tubing.

Both RTS assemblies went through a similar iterative process, with the focus on passive cooling techniques to avoid induced vibrations. Since the RTS is an acceleration measurement device, the use of active components which could contaminate the measurement (e.g. fans) is undesirable. Analysis of the RTS structures, mounting techniques, and component heat dissipation was used to optimize cooling through conduction and radiation methods. Internal gaps were minimized wherever possible to enhance conduction through the air.

The processor board in the RTS-EE was found to dissipate sufficient heat to require additional passive cooling techniques to maintain the processor junction temperature below an acceptable

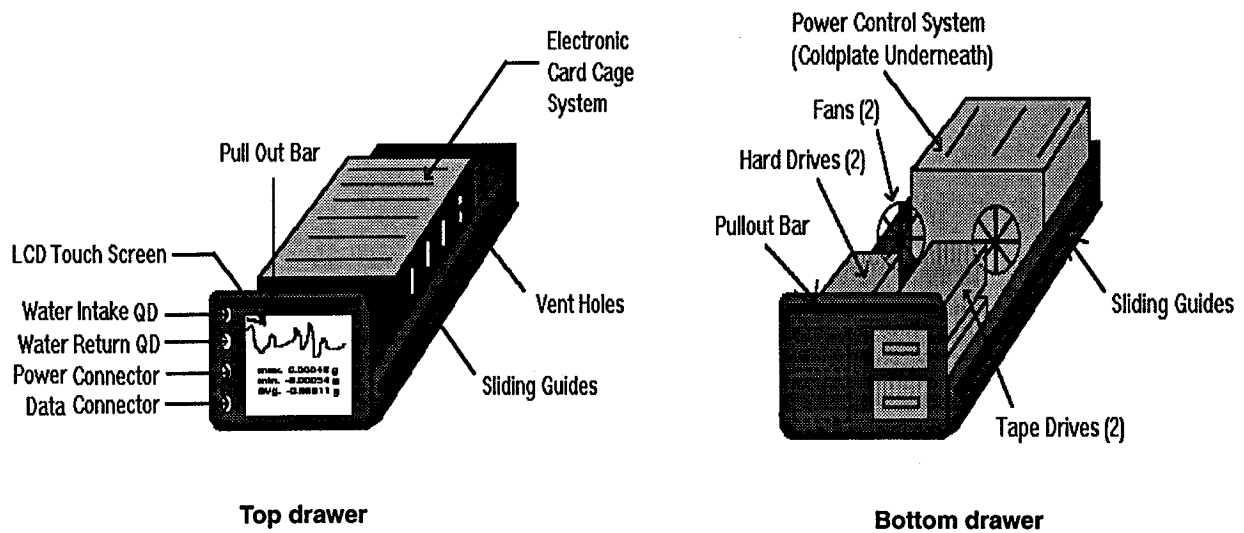


Figure 5: CU conceptual design

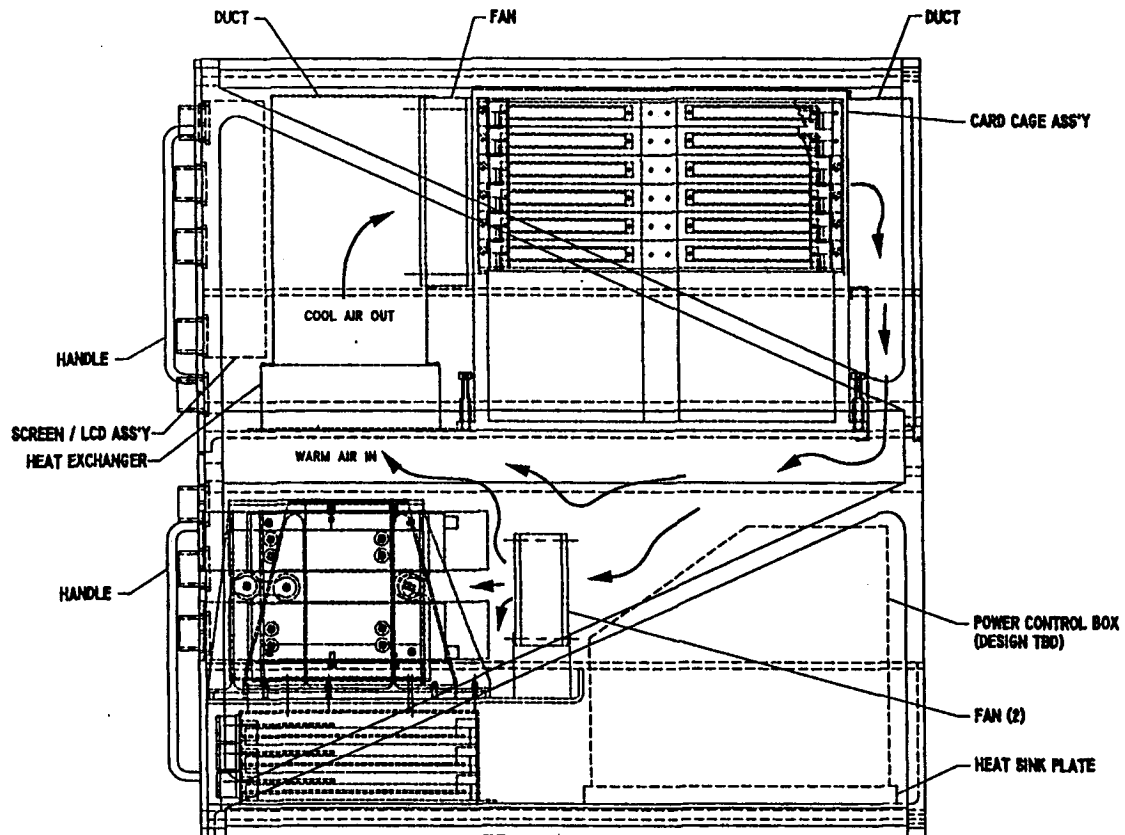


Figure 6: CU early design iteration, side view

level. To accomplish this, a thermally conductive and electrically isolating gap material was added above and below the processor board. The gap material and board is sandwiched between two aluminum heat sink plates which mount into the PC/104 stackup. This configuration dissipates heat from the processor to the heat sink plates efficiently, and also provides additional structural support and vibrational dampening during launch. In addition, the resulting stackup can be easily assembled and disassembled into the enclosure chassis (see Fig. 3).

PRELIMINARY DESIGN

The final iteration chosen as the preliminary design employs both active and passive cooling techniques. In the CU, water is used to cool all heat generating components via closed loop air circulation and a coldplate. The air loop begins at the fan/heat exchanger assembly in the top drawer and is forced through a hole under the heat exchanger to the bottom drawer. A second fan in the bottom drawer draws the cooled air through the hard drive assembly, and exhausts it through the tape drive assembly. Air is returned to the heat exchanger via a slot in the floor of the top drawer. Figure 7 is a top view sketch of the CU preliminary design.

The ECS is conductively cooled with a coldplate using water exiting the heat exchanger. Water leaving the coldplate is then returned to the MTL. Finally, the MSP conducts generated heat through its enclosure sidewalls and baseplate, to the bottom drawer. Ultimately, the bottom drawer dissipates heat to the internal circulating air.

For the RTS, all heat dissipation is primarily accomplished by conduction to the mounting structure. This passive cooling approach minimizes induced vibrations as well as the interface requirements for the RTS. The RTS-EE also has the capability to be mounted to a standard ISS supplied coldplate.

Thermal Hardware Description

Primary hardware elements of the thermal control system include the heat exchanger, fans, coldplate, tubing and fittings, and passive components. A compact finned-tube heat exchanger provides air cooling for the CU. The heat exchanger is a commercially available air-to-water unit constructed of all welded stainless steel 9.5 mm (3/8 inch) tubing and brazed copper fins. The selected model accommodates mounting of a standard 127 mm (5 inch) fan directly to the unit. The heat exchanger is mounted to floor of the top drawer at the back of the CU, and draws water from the ISS MTL.

Tubeaxial fans provide air circulation within the CU. The 127 mm (5 inch) square by 38.1 mm (1.5 inch) deep fans accept a voltage range of 20 to 28 VDC, and provide a free delivery flow of 59 l/s (125 cfm). Two identical fans are used in the CU: one mounted to the heat exchanger, and the other placed between the hard drive and tape drive assemblies.

A custom coldplate design is used to conductively cool the ECS. The design of the coldplate incorporates 9.5 mm (3/8 inch) stainless steel tubing which is vacuum brazed to an aluminum plate. Paths for multiple tube passes are machined into the plate, and headers are installed at the front of the plate to minimize

spacing between tube passes. The headers are press fit and silver soldered; a technique that has been successfully used in applications to a few thousand kPa (several hundred psi) working pressure. The footprint of the coldplate identically matches the ECS, with an overall thickness of 14.3 mm (9/16 inch).

Tubing in the coldplate and heat exchanger, and lines running between these components, are 9.5 mm (3/8 inch) diameter stainless steel. Compression style fittings are used to isolate components for assembly or disassembly. ISS supplied quick disconnects are utilized at the top drawer front panel for connection to the MTL water loop. Since these quick disconnects are 12.7 mm (1/2 inch), fittings are required to reduce to the 9.5 mm (3/8 inch) tubing within the CU. All wetted surfaces are stainless steel to comply with deionized water service.

A thermally conductive gap material is utilized for the microprocessor board within the RTS-EE. This material conducts heat from the circuit board to aluminum plates above and below the board. Other thermally conductive materials are used throughout the RTS and CU to insure adequate interface conductances for mounted components/assemblies. In addition, card and plate edge guides provide good thermal contact to the sidewalls of the various enclosures for conductive dissipation.

ANALYSIS

Initial design and sizing calculations were made by hand in the early stages of the development cycle. As the design progressed, finite-difference models were created and used for optimization. All modeling was performed assuming steady state conditions and maximum power dissipation.

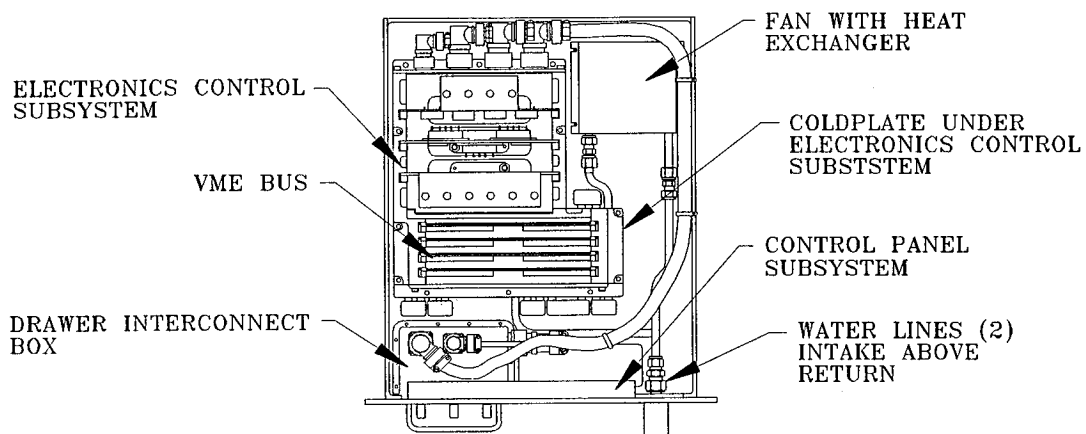
Specification of the heat loads for the CU and RTS was the first step in determining feasible cooling options. Table 2 summarizes the maximum heat dissipated within the CU during operation. Maximum power draw is assumed for the various components, with one hard drive writing to one tape drive, and the remaining drives powered down. Similar data for the RTS subsystem is given in Table 3.

Electronic Control Subsystem (ECS)

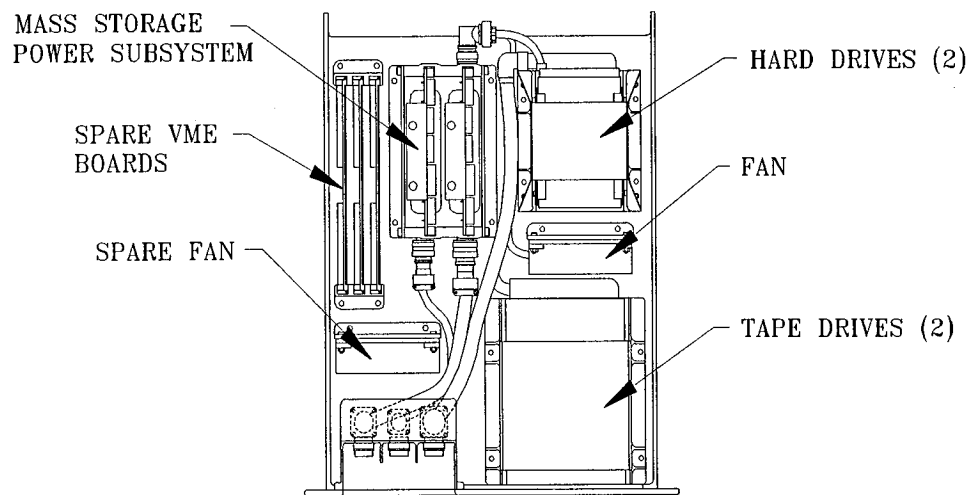
The ECS is composed of two discrete sections: a VME section containing processor, graphics, DSP, and custom circuit boards; and a power supply section containing components mounted on aluminum plates. The walls and top plate of the ECS are bolted together to allow complete disassembly of the enclosure. No bottom plate is used; the top of the coldplate serves as the bottom surface of the ECS. Two of the three aluminum plates in the power supply section of the ECS have an integral breaker panel bent 90 degrees (i.e. horizontal) to the plate. Magnetic breakers are mounted to the breaker panels, and their switches protrude through the top cover for astronaut access.

Initial thermal design and sizing of the ECS was based on hand calculations, and later refined using thermal analysis software (Naughton, 1994). A top view of the ECS model is shown in Fig. 8. Structural nodes and resistors have been omitted for clarity.

Conduction through the ECS sidewalls to the coldplate is the primary cooling mode for the ECS. Since the maximum allowable



Top drawer



Bottom drawer

Figure 7: CU Preliminary Design

VME sidewall temperature is vendor specified, and details of the VME boards are not available, all boards are modeled as simple circuit boards of arbitrary construction with a distributed heat load. This modeling approach provides accurate evaluation of the sidewall temperatures, but does not provide temperature data on the boards themselves. VME card guides are modeled with the resistance specified by the guide vendor.

Table 2: Control Unit Maximum Heat Dissipation

Heat Source	Load (W)	Heat Source	Load (W)
ECS:	197.7	MSS:	54.1
Processor board	31.2	Hard drives	19.1
Graphics board	36.8	Tape Drives	15.0
DSP board	15.2	Fans	20.0
Custom board	11.0	MSP:	43.0
Breakers	20.0	Breakers	8.0
Current sensor	2.0	5V supplies	13.8
Converters	64.9	12V supplies	18.0
EMI filters	10.6	EMI filters	3.2
Output filter	6.0	Misc.	18.4
CPS	15.1	TOTAL	328.3

Table 3: Remote Triaxial Sensor Maximum Heat Dissipation

Heat Source	Load (W)	Heat Source	Load (W)
RTS-EE:	19.97	RTS-SE:	2.94
Processor board	3.50	Accelerometers	0.96
Other boards	9.00	A/D boards	1.08
Converters	6.90	I/O board	0.81
EMI filter	0.32	Cables/connectors	0.09
Cables/connectors	0.25	TOTAL	22.91

Power supply section components (i.e. current sensor, converters, and filters) are modeled as plates with the footprint and thickness of the component's baseplate. Distributed heat loads, equivalent to the total estimated heat dissipated by each component, are then applied to the baseplates. Contact resistance at the component mounting interface is estimated based on available vendor information, and conservative extrapolation of empirical data (Steinberg, 1991). Guides used in the power supply section were modeled with the vendor quoted thermal resistance. Breakers were modeled as footprint heat sources at their respective locations on the breaker plates. Internal radiation in the power

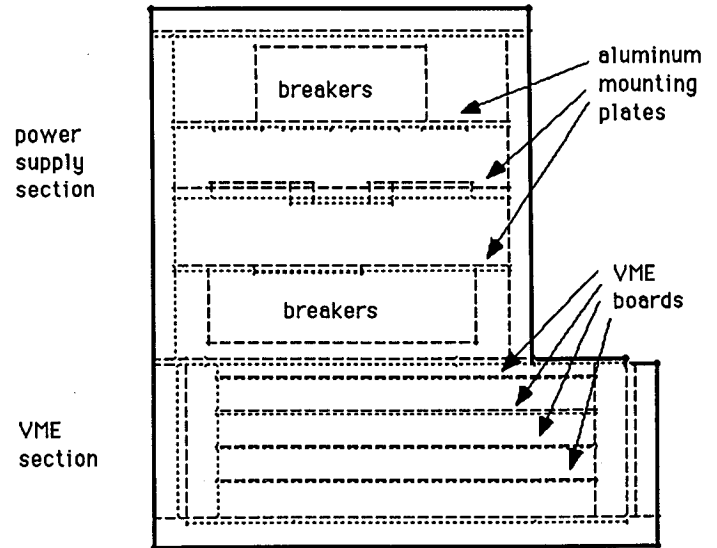


Figure 8: ECS model, top view

supply section was simulated, and found to reduce temperatures by less than 1°C for all components and plates. Therefore, radiation was conservatively omitted from the model.

Thermal analysis results of the ECS model are summarized in Fig. 9. Temperatures for the current sensor, converters, and filters represent the component baseplate. Breaker temperatures are a lumped average for the entire breaker assembly.

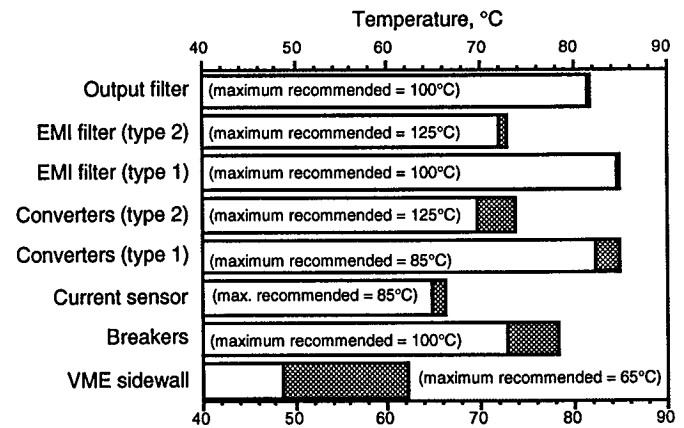


Figure 9: Calculated maximum ECS component temperature ranges

Cold Plate

Initial design and layout of the cold plate was accomplished with hand calculations to estimate the total tube length and plate thicknesses required. Subsequent refinements and analytical verification of the design were made with a finite-difference model.

Figure 10 shows a top view of the coldplate model with the resistors and structural nodes omitted for clarity. The water flow path through each tube pass is indicated. Note that water nodes exist in each tubing pass to represent the sink water temperature at that location. Resistors between the water nodes and the coldplate represent the equivalent resistance of: convection from the water to the tube wall, conduction through the tube wall, and conduction through the brazing material.

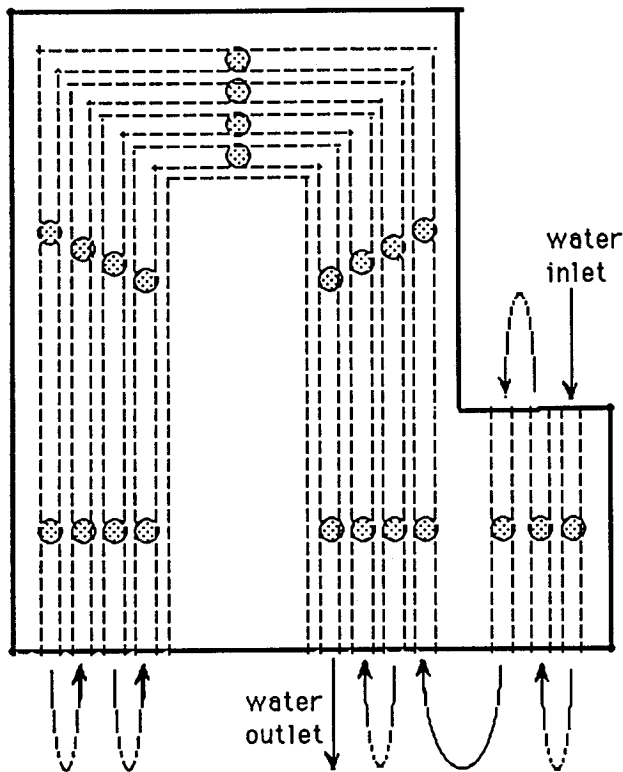


Figure 10: Coldplate model, top view

Each of the water node temperatures was estimated by using the heat dissipated to each node to calculate the water temperature rise from node to node. The results of this simulation were compared to a simulation where an average constant water temperature was used for each water node. Comparing temperatures between the two simulations indicated less than 0.6°C variance in temperature in the ECS; less than 1.2°C temperature variance in the cold plate.

The coldplate model was joined with the ECS model to obtain steady state temperatures under the maximum ECS heat loads. The combined ECS and coldplate models contain 1900 nodes and 4906 resistors. Temperature distributions at the top of the coldplate for this simulation are shown in Fig. 11. The maximum temperature at the coldplate surface was 46.3°C; minimum was 37.3°C.

Mass Storage Power (MSP) Subsystem

Heat generated within the MSP is conductively dissipated to the sidewalls, through the baseplate, and to the bottom drawer.

Circulating air is the ultimate heat sink for the bottom drawer. A simultaneous convective cooling path also exists directly from the MSP walls to the circulating air.

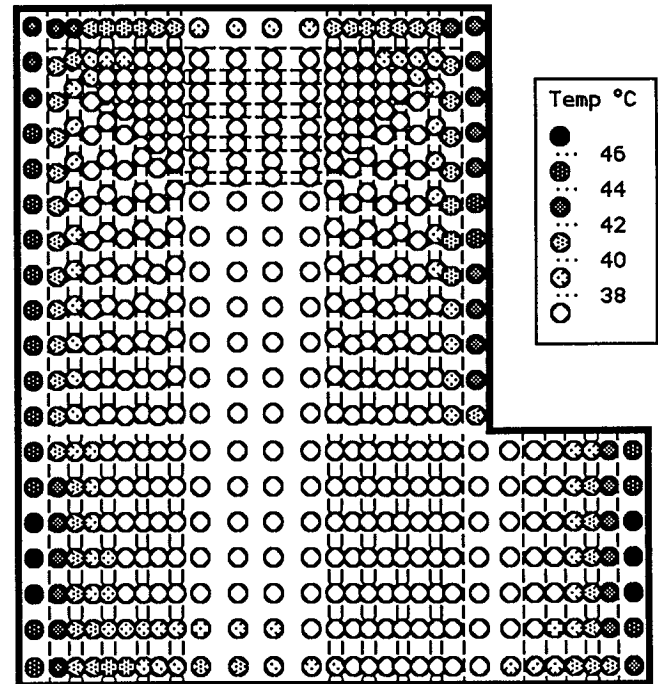


Figure 11: Coldplate temperature distribution

Hand calculations were used to size the mounting plates and enclosure wall thicknesses. A subsequent integrated computer model of the ECS mounted in the bottom drawer was created, and is shown in Fig. 12. The combined MSP and bottom drawer model contains 1093 nodes and 2881 resistors.

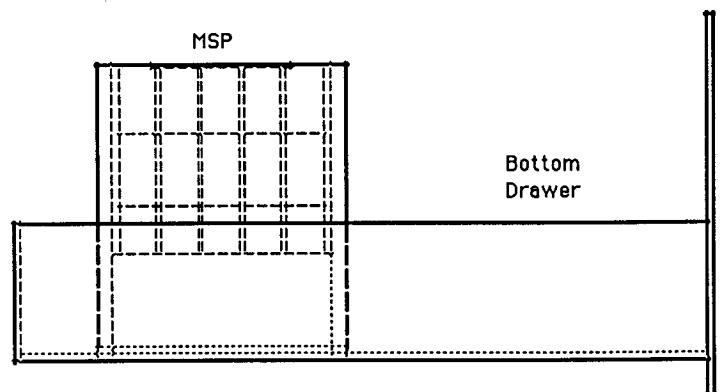


Figure 12: MSP and bottom drawer model, side view

The MSP contains converters, filters, and breakers mounted on two aluminum plates. Similar to the ECS, the converters and filters were modeled as plates with the footprint and thickness of the component's baseplate, and with a distributed heat load equal to the total heat dissipated by the component. Likewise, the breakers were modeled as footprint heat sources. Card guides identical to those in the power supply section of the ECS attach the aluminum plates to the MSP sidewalls. General construction of the MSP is similar to the ECS in terms of bolted walls, and breaker assemblies.

In addition to conduction paths, several forced convection dissipation paths were simulated to account for circulating air in the bottom drawer. Assumed air velocities around the MSP range from 0.51 m/s (100 ft/min) for the front wall, 0.25 m/s (50 ft/min) for the side walls, and no air flow at the back wall. Air velocities modeled for the bottom drawer surfaces include: 1.02 m/s (200 ft/min) along the drawer floor section directly below the hard and tape drives; and 0.25 m/s (50 ft/min) at the inside face of the front panel. All air velocities are conservative estimates based on tests performed with an airflow mockup (described later). Air temperature is estimated from hand calculations, and assumed constant at 35°C throughout the bottom drawer.

Thermal analysis results of the MSP and bottom drawer model are summarized in Fig. 13. Temperatures for the converters and filters represent the component baseplate. Breaker temperatures are a lumped average for the entire breaker assembly.

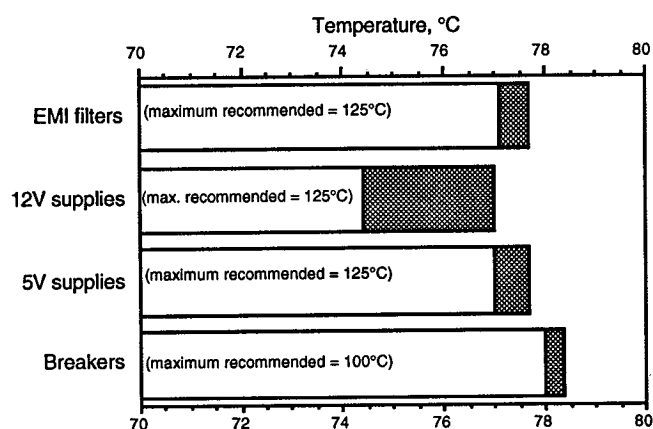


Figure 13: Calculated maximum MSP component temperature ranges

Remote Triaxial Sensor - Electronics Enclosure

The RTS-EE contains PC/104 circuit boards, DC/DC converters, and an EMI filter. Design layout of the components was carefully chosen to isolate those with high heat dissipation, and optimize conduction paths for critical components. A finite-difference model of the RTS-EE containing 280 nodes was constructed to estimate key temperatures.

Heat loads were based on conservative estimates for the various components, resulting in a total heat dissipation of 22.71 W in the RTS-EE. Heat dissipation is uniformly distributed across the

circuit boards in the model, except for the processor board where the heat load of the processor chip was locally modeled. Likewise, converter and filter loads were placed at the appropriate mounting locations. Conductivity of the circuit boards was estimated to be 6.3 W/m°C, which approximates a 1.56 mm thick epoxy board with less than 1 ounce average copper coverage over one surface.

Conduction, and internal and external radiation were simulated, with an effective environment and mounting structure temperature of 30°C. Key RTS-EE temperature results are summarized in Table 4. Note that increasing the environment and mounting temperature to a maximum temperature of 45°C resulted in the same magnitude temperature rise in all component temperatures (i.e. 15°C) since conduction is the dominant heat transfer mode.

Table 4: Calculated RTS Temperatures		
Component/ Assy	Calculated Temp (°C)	Max Allowable Temp (°C)
RTS-EE:		
processor case	50.4	100
boards	49.0	70
converters	41.0	125
filter	34.6	125
RTS-SE:		
Accelerometers	31.0	70
A/D board	37.2	70
I/O board	39.2	70

Converter/Filter Mounting Assemblies

A more refined finite-difference model was constructed of the mounting assemblies for the converters and filters within the RTS-EE to investigate effects of design options on component level temperatures. The model contains 172 nodes, and conservatively ignores radiation from the converters/filter to the surrounding structure. Mounting surface temperature was assumed to be 30°C. Temperature results for the filter and hottest converter are shown in Table 4. A load fault failure mode was also investigated with this model (123% increase in total power dissipated by converters), and indicated a maximum converter temperature of 55.2°C, and a filter maximum temperature of 41.0°C.

Remote Triaxial Sensor - Sensor Enclosure

The finite-difference model of the RTS-SE contained 51 nodes, and assumed a mounting interface temperature of 30°C. Similar to the RTS-EE model, an increase in the mounting interface temperature was found to result in a nearly identical increase in component temperatures. External radiation to the environment was conservatively omitted, but internal radiation between components was modeled. Conductivity of all circuit boards was

set at 6.3 W/m°C. The A/D board heat loads were uniformly distributed, whereas, the primary I/O heat sources were positioned at the component locations on the board.

For the wall channels where the cards slide in, an air gap of 1.6 mm (1/16 inch) is assumed over 50% of the overlapping surface area. The remaining 50% surface area is in contact, with an estimated thermal interface resistance based on empirical data (Steinberg, 1991). This scenario provides a conservative estimate of the overall contact resistance between the circuit boards and the sidewalls. Resulting temperatures from the RTS-SE finite-difference simulation are also given in Table 4.

Other Subsystems And Assemblies

Other heat generating sources include the Drawer Interconnect Box (DIB) at the CU front panels, and other cables/connectors within and between the CU and RTS. The heat load contributed by these items was accounted for in the overall heat dissipation calculations. However, DIB, cable, and connector temperatures were not estimated. Likewise, the CPS contains several heat dissipating circuit boards which were accounted for in the overall heat load, but not analyzed for local temperatures.

Air Cooling Loop

Heat from the MSS, CSP, MSP, and various cables and connectors are ultimately dissipated to the water through the heat exchanger. The maximum total heat generated by these sources is estimated to be 130.6 W. Performance of the heat exchanger is a function of water and air flow rates, total heat dissipated, and the difference between the inlet air and water temperatures. Using vendor performance data; for a water flow rate of 0.0076 kg/s (60 lbm/hr) and an air flow rate of 0.0236 m³/s (50 cfm), the air inlet and outlet temperatures are 40.1°C (104.2°F) and 35.1°C (95.2°F), respectively

Adequate air flow is required within the CU to cool all heat loads except the ECS. Specifications for the hard drives indicate that a local average air velocity of 0.61 m/s (120 fpm) maintains the case temperature of key drive components within the limits required for 500K hrs MTBF. No air flow requirements are supplied by the vendor for the tape drives. Figure 14 shows some of the heat dissipating electronics in the hard drive; Fig. 15 is a photograph of one of the tape drives with the outer case removed.

Initial tests with an air flow mockup indicated acceptable air velocity through the hard drives (i.e. greater than 0.61 m/s), and an overall air flow rate on the order of 24 l/s (50 cfm). The maximum air temperature in the vicinity of each CU assembly was calculated by accounting for all heat sources upstream of the that assembly.

TESTING

Several screening tests were performed to aid in developing the preliminary design concept for the thermal control system, and demonstrate survivability of the RTS commercial boards. These tests and the subsequent results are briefly described below.

Infrared (IR) Scans

Infrared temperature measurements were taken for several of the SAMS-II circuit boards to identify hot components. Two PC/104 commercial boards for the RTS-EE were tested: a microprocessor board, and an ethernet board. The hottest component on the microprocessor board was the 486 chip. A temperature of 50°C was recorded for the 486 chip under laboratory conditions (i.e. natural convection) during operation in a horizontal position. The second hottest component, under the same test conditions, was at 38 to 40°C. The nominal board temperature was approximately 33°C. By comparison, the hottest component on the ethernet board under the same conditions was 36°C, with the remaining components between 30 and 34°C. Based on these temperature scans, isolation and enhanced conduction paths for the microprocessor board were incorporated into the enclosure design. This data was also used to estimate the junction-to-board thermal resistance for the 486 chip; and the heat dissipation of the chip via convection, radiation, and conduction under the test conditions.

IR temperature measurements were also recorded for the hard drives' circuit boards. Under laboratory conditions with attempts to minimize extraneous air circulation, key component temperatures ranged from 41 to 57°C during operation. In all cases, the components were below the maximum values recommended by the vendor.

Airflow Mockup

Due to the complex parallel circulation paths within the CU, a plexiglas air flow mockup was constructed to verify air velocities in key locations. Rough calculations were performed to select suitable test fans, and wood boxes were used to simulate the ECS, MSP, and other miscellaneous equipment within the CU. The actual hard drives, tape drives, and heat exchanger were used in the mockup to properly simulate the air flow through these critical assemblies. Cables and water lines were modeled with rubber hoses of roughly equivalent diameter.

Results from initial testing indicated acceptable air velocity through the hard drives as measured by an anemometer inserted into the flow. Performance of the fans in the voltage range of 24 to 28 VDC was found to be constant. In addition, several potential design modifications were identified to improve the performance of the air loop. These modifications included: holes in the tape drive mounting assembly for reduced exhaust resistance; increase area of top drawer slots for the heat exchanger exit and air return; and a shroud between the bottom drawer fan and the hard drives to increase the induced air velocity between the drives.

Thermal Cycling

Operating and non-operating thermal cycle tests were performed on PC/104 boards for the RTS-EE as an initial screening. The purpose of these tests was to screen the commercial PC/104 boards at the board level for defects in design or workmanship. A total of eight cycles were performed on the boards in both operating and non-operating modes, with a one hour soak at each extreme (or no more than 2°C/hr change in component temperature, whichever was longer), and a maximum ramp rate of 10°C/min. The non-operating temperature cycle range

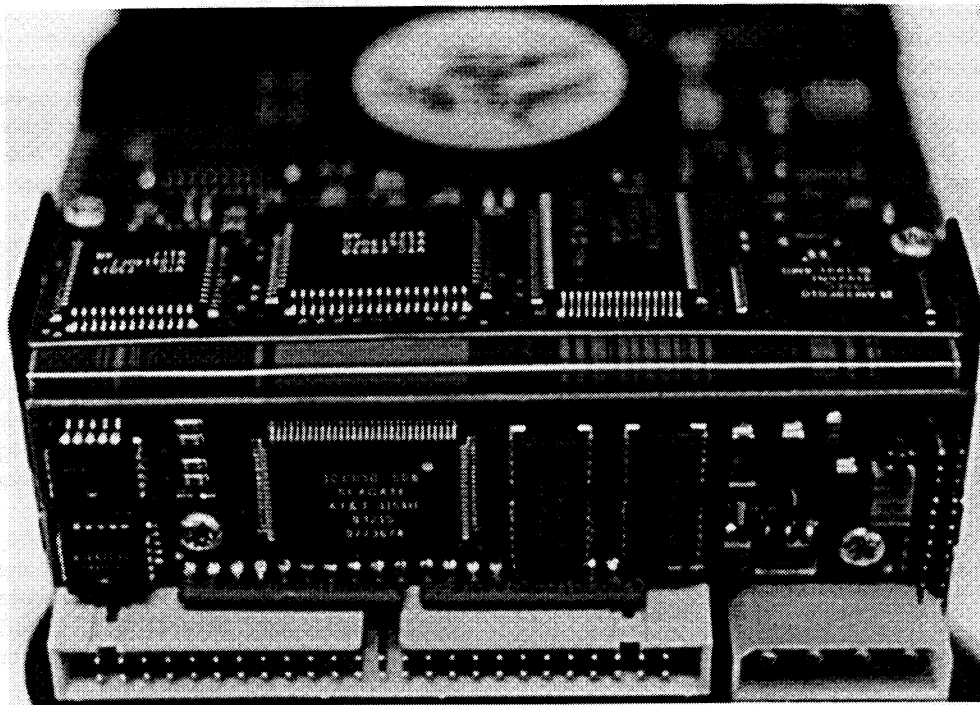


Figure 14: Hard drive electronic components

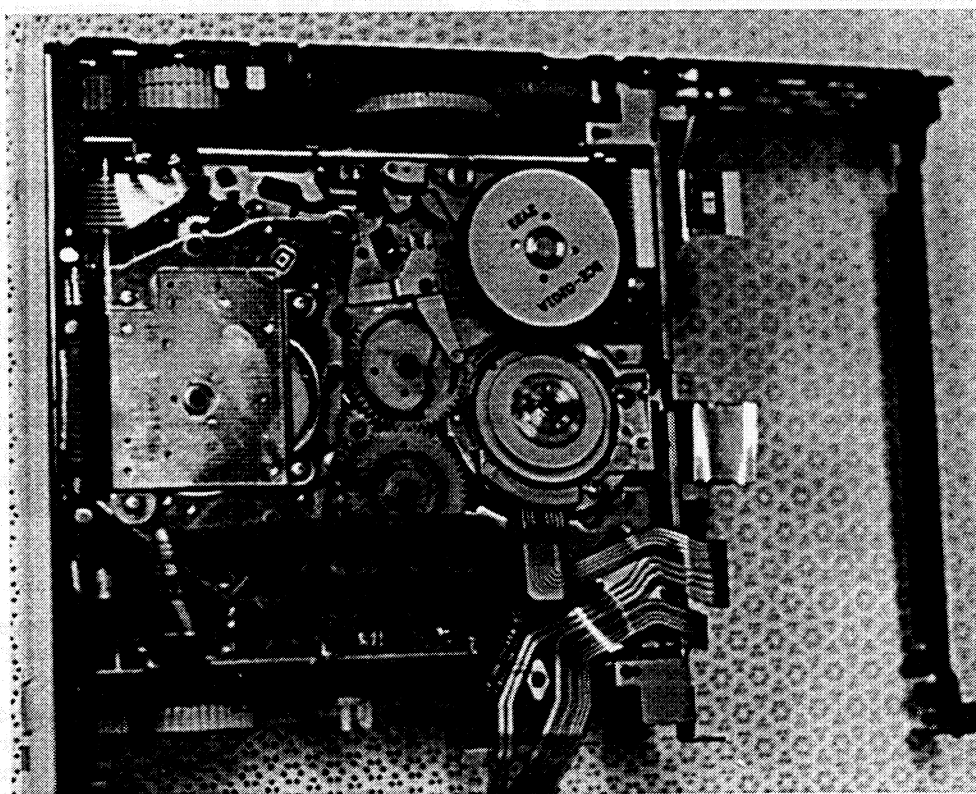


Figure 15: Tape drive internals

was -35 to 70°C; 5 to 50°C for the operating cycle. A functional test of the boards was performed near room temperature: at the start of the test; at the end of the first cycle; and at the completion of the last cycle. All boards passed the thermal cycling tests.

CONCLUDING REMARKS

Development of a thermal control subsystem for a space station manifested payload relies heavily on concurrent engineering techniques to achieve the design objectives within the imposed system level constraints. Use of these techniques early in the design cycle accelerated the successful development of the SAMS-II preliminary design while meeting all of the multidisciplinary objectives of the project. Accomplishment of these objectives within the imposed constraints was achieved through iterative designs involving all design team members.

Hand calculations were used for concept and early design guidance, while more sophisticated computer models were generated as the design progressed. This analytical approach provided valuable and quick insights early in the design cycle, as well as a check on later simulations. The more sophisticated and time consuming computer models gave better detailed results as the design itself becomes more detailed. Finally, testing provided verification of critical analysis assumptions, and uncovered areas requiring additional attention.

Elevated Component Temperatures

Analysis showed that some component temperatures in the power section of the CU were near maximum recommended values (see Fig. 9). Since the analysis was performed assuming the maximum steady state power dissipation values, the actual component temperatures would be less. Confirmation of this assumption could be accomplished with more detailed transient analysis and/or testing.

However, to insure additional margin in the design, modifications were investigated to provide better cooling for the hottest components. One promising approach is the use of thermally conductive composite materials for the mounting plates and possibly the ECS structure itself. These materials have as much as seven times the unidirectional thermal conductivity of aluminum. Tradeoff analyses using such a composite material indicated potential component temperature reductions of 4 to 10 °C depending on the implementation. Although there appears to be no "show stoppers" for this application, experimental characterization of the thermal performance is needed.

Another option considered is the addition of an internal coil spring within the tubing of the coldplate. Since the water flow is laminar, a spring would greatly enhance heat transfer by breaking up the boundary layer near the tube walls. The penalty is a corresponding increase in water pressure drop which must be evaluated within the overall system constraints.

Epilogue

Design requirements often change during the development process. Depending on the magnitude of these changes, the design may need minor tweaking, or require a complete redesign from the

ground up. Unfortunately, SAMS-II sustained a change in the CU requirements shortly after completion of the preliminary design that falls into the latter category. At a point in the development cycle where prototype fabrication was starting, a redesign directive was issued. The primary focus of the directive was to reduce the payload volume by approximately 60% while retaining functionality; and as much reliability, redundancy, and maintainability as possible.

In order to achieve this significant volume reduction, the forced air cooling portion of the CU design was abandoned. The volume required to maintain adequate air flow passages is not available within the new design envelope. As a result, the new CU design concept is entirely conduction cooled using a coldplate to which all heat dissipating components are thermally connected. This approach allows for a much more compact design. However, customization of several commercial components (e.g. drives) will be necessary to accommodate conduction cooling in the absence of both forced and natural convection.

ACKNOWLEDGEMENTS

The author wishes to thank Khanh Dang for his work on the RTS thermal analysis; and the SAMS-II design team for their efforts and assistance in the integrated development of the thermal control subsystem.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE October 1996	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Thermal Control Subsystem Design for the Avionics of a Space Station Payload			5. FUNDING NUMBERS WU-963-60-0B	
6. AUTHOR(S) Matthew E. Moran				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-10463	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, D.C. 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-107334	
11. SUPPLEMENTARY NOTES Prepared for the International Mechanical Engineering Congress and Exposition sponsored by the American Society of Mechanical Engineers, Atlanta, Georgia, November 17-22, 1996. Responsible person, Matthew E. Moran, organization code 6743, (216) 433-8324.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories 33 and 34 This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A case study of the thermal control subsystem development for a space based payload is presented from the concept stage through preliminary design. This payload, the Space Acceleration Measurement System II (SAMS-II), will measure the acceleration environment at select locations within the International Space Station. Its thermal control subsystem must maintain component temperatures within an acceptable range over a 10 year life span, while restricting accessible surfaces to touch temperature limits and insuring fail safe conditions in the event of loss of cooling. In addition to these primary design objectives, system level requirements and constraints are imposed on the payload, many of which are driven by multidisciplinary issues. Blending these issues into the overall system design required concurrent design sessions with the project team, iterative conceptual design layouts, thermal analysis and modeling, and hardware testing. Multiple tradeoff studies were also performed to investigate the many options which surfaced during the development cycle.				
14. SUBJECT TERMS Electronics cooling; Thermal control; Heat transfer; Avionics			15. NUMBER OF PAGES 17	
			16. PRICE CODE A03	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	