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Energy Smart Data Center (ESDC) Final Report

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1 Glossary

BurnI2—Program which uses a calculation loop to exercise an Itanium II processor.
BurnP6—Program which uses a calculation loop to exercise a 32-bit Xeon processor
MPB—Multiple Processor Board
Node M####—PNNL supercomputer network label for a node in the HP rx2600 test rack.
TMU—Thermal Management Unit, manages heat generated by a computer, usually composed of a pump, reservoir, heat exchanger, and logic controller.
FMU—Fluid Module Unit, component of TMU which houses the pump and logic controller.
HXU—Heat Exchanger Unit, component of the TMU, which houses the heat exchanger and reservoir.
Dense Memory—Random Access Memory (RAM) which is much denser than today's standard Dual Inline Memory Module (DIMM).

2 Executive Summary

Per the well-known Moore's Law, the number of transistors packed onto microprocessors has been doubling approximately every 18 months. This increase in transistor density has been facilitated by semiconductor manufacturing gains that have consistently driven line size down. As of the writing of this report (Q3 2005), Intel and AMD had already introduced microprocessors with 90 nm lines. As the line sizes decrease, more transistors are packed into smaller areas, which exacerbates existing hotspots and produces a higher number of die thermal non-uniformities. The inexorable push for more computing power forces microprocessor speeds up, and drives the need for ever more memory. The increasing power dissipation at the server level increases the power dissipation first at the rack level and finally at the facility level. To accommodate the increasing facility level power dissipation (and power density), facility managers are having to provide greater air flow rates, with the air at lower temperatures – to the extent possible. Facilities are also resorting to more precise air flow management using the services of HP's (and others) computational fluid dynamics and analysis. The increased power dissipations at the rack levels are scaling to higher facility operating costs.

The Pacific Northwest National Labs (PNNL) has teamed with Isothermal Systems Research (ISR) and Tessera Technologies to deliver solutions to the key challenges faced by data centers today. With DOE funding, and under the multi-phase "Energy Smart Data Center" Program, PNNL, ISR, and Tessera have set out to demonstrate how the combination of ISR's SPRAYCOOL™

Technology, and Tessera's Chip-Scale Packaging (CSP) Technology, can be used to achieve the following objectives:

1. Reduce overall data center energy consumption while simultaneously raising facility coefficient of performance (COP).
2. Significantly drive up server, rack, and facility densification.
3. Increase electronics reliability.
4. Demonstrate an attractive total cost of ownership for a SprayCool Energy Smart Data Center.

As part of the program, four major tasks were proposed as follows:

Task 1: Side-by-Side Demonstration
Task 2: Technology Development
Task 3: Impact/Study Report
Task 4: Technology Insertion and Reporting

For Task 1, a full rack of HP rx2600 servers (dual Itanium2 servers) were converted from air-cooling to evaporative cooling and installed at PNNL. The performance of this converted rack is now undergoing a full year of testing to quantify uptime, reliability, and maintainability, relative to a comparable air-cooled rack of servers. Also as part of Task 1, a sub rack of RLX blade servers (dual Intel Xeon blades) was also converted to evaporative cooling and installed at PNNL.

For Task 2, ISR and Tessera set out to demonstrate the advantages of designing electronics for evaporative cooling (as opposed to retrofitting from air-cooling to evaporative cooling). A dense dual AMD Opteron blade server (known as the multi-processor board, or MPB) with dense stacked memory [1] was designed, built, and demonstrated. The MPB also integrated a dense power supply module (-48 VDC to 12 and 5 VDC) which utilized SprayCool technology. Two of the MPBs were integrated into a Global SprayCool System for subsequent characterization.

For Task 3, ISR worked with PNNL to develop a total cost of ownership (TCO) model for the implementation of SPRAYCOOL Technology in a data center (starting with PNNL as a baseline).

For Task 4, ISR worked with PNNL to outline a plan for insertion of the dense blade and dense memory into the PNNL facility (for eventual integration with the PNNL cluster). This final report also forms part of Task 4.

[1] Dense stacked memory incorporates un-packaged memory chips three dimensionally stacked one on top of each other

Key Results/Accomplishments

Rack of HP rx2600 Servers

The air-cooled rack was delivered from the vendor (Hewlett Packard) directly to PNNL. Once fully installed at PNNL, the air-cooled servers were thermally characterized with BurnI2—CPUs were read directly from BIOS, the motherboard components were measured with attached thermocouples, the inlet and outlet air temperatures were measured with thermocouples, the air flow velocity out of the supply tile was measured with a handheld anemometer, and the server inlet/outlet air velocities were measured with a handheld anemometer. The air-cooled rack of servers was then delivered to ISR, where it was again thermally characterized. This was followed by conversion to SprayCool products and subsequent characterization.

In ambient air in ISR's Integration Lab (air temperature approximately 22°C), the air-cooled CPUs ran 8 – 19°C hotter than the SprayCool CPUs when the CPUs were steadily and fully exercised with BurnI2. Under the same testing conditions at ISR, the hottest peripheral motherboard components were the FETs, which ran 1 - 21°C hotter for the air-cooled servers (note that the FETs directly downstream of the CPUs ran 14 – 21°C hotter). Of the balance of the motherboard components, the memory controller (Northbridge), and memory DIMMs ran 7.7°C – 9.6°C, and 1°C – 5°C hotter with air-cooling, respectively.

Tests were run on the air-cooled and SprayCool servers to quantify component cycling. For the air-cooled servers, BurnI2 was used and the servers were cycled between idle and full power. For the SprayCool servers, a dynamic script was written by PNNL (also using BurnI2) to "randomly" cycle the servers. The dynamic script was designed to dynamically cycle the server components, specifically the CPUs, between idle and full power. In an ambient air environment of approximately 22°C (at ISR), the air-cooled CPUs cycled an average of 20°C, or an average of 48% more than the SprayCool servers. The balance of the server components did not cycle measurably.

Prior to shipment of the rack of SprayCool servers to PNNL, limited burn-in testing was conducted in an effort to thermally, mechanically, and electrically stress the server and cooling system components. No issues were unveiled during the burn-in testing at ISR.

The SprayCool Rack of servers was shipped to PNNL and installed in the EMSL lab. The servers were then characterized with BurnI2 (same characterization as that done for the air-cooled servers when first delivered to PNNL), and the comparison made between the air-cooled and SprayCool servers. In the 15°C ambient air of PNNL's EMSL facility, the air-cooled CPUs ran 6°C – 13°C hotter than the SprayCool CPUs. Under the same testing conditions at ISR, the hottest peripheral motherboard components were the FETs, which ran 3.3 – 7.1°C hotter for the three hottest air-cooled servers (nodes M1005, M1014, and M1022). Of

the balance of the motherboard components, and for the three hottest nodes only, the memory controller (Northbridge) and memory DIMM1A ran 3.3°C–7.1°C and 6.5°C–8.1°C hotter with air-cooling, respectively.

The SprayCool servers were also tested running a script written by PNNL. The script was designed to dynamically cycle the server components, specifically the CPUs, between idle and full power (as performed at ISR). In PNNL's ambient air environment of approximately 15°C, the CPUs cycled between 12°C and 16°C, or an average of 14°C. This data was very similar to the 13.5°C cycling measured at ISR.

The server characterization results obtained at PNNL were found to be consistent with those obtained at ISR prior to shipment to PNNL. The rack is now undergoing a full year of evaluation to quantify uptime, reliability, and maintainability.

Sub-Rack of RLX Blade Servers

The sub-rack of air-cooled blade servers was characterized at ISR using BurnP6. The CPU temperatures for all blades were read directly from BIOS. A single blade was additionally instrumented with a number of thermocouples to measure key components such as memory DIMMs, FETs, Northbridge and Southbridge, hard drives, etc. In an ambient air environment of 22°C, the CPU temperatures ranged from 54°C to 60°C, and the downstream peripheral device temps were somewhat cooler. The five blades were then converted to SprayCool and fully characterized with BurnP6. In an ambient environment of 22°C, the SprayCool CPUs ran at 40°C to 44°C, significantly cooler than the air-cooled servers. When comparing the balance of the blade components (blades 1 and 2 only), the components on the SprayCool blade all ran cooler than on the air-cooled blade:

- the memory DIMMs ran 8°C–12°C cooler
- the FETs ran 6–15°C cooler
- the Northbridge ran 6°C cooler
- the Southbridge ran 7°C–9°C cooler.

The blades were then subjected to a 96 hour continuous burn-in. No issues were experienced during the burn-in.

The sub-rack of SprayCool blades was then shipped to PNNL and installed in room #1125. The blades were then characterized at PNNL running BurnP6. In an ambient environment of 15°C, the SprayCool CPUs ran at 40 to 46°C, which is consistent with the range measured at ISR.

Global SPRAYCOOL System

The Global SPRAYCOOL System was fully characterized at ISR prior to shipment to PNNL. The MPBs, and more specifically the CPUs, were fully exercised and simultaneously benchmarked using CPU Burn and nBench. To assist in the thermal stress, the MPBs were cooled with 50°C coolant, with the

system pressure up to approximately 21 psia (note that high system pressure drives the coolant's boiling point up). Under these conditions, the CPU edge diode temperatures were in the approximate range of 70°C–73°C, the dense stacked memory temperature range was 51°C–57°C, the dense power supply module temperature range was 50°C–56°C, and the nVidia graphics chip temperature was 67°C.

For the benchmark testing, CPU Burn was used to fully exercise the CPUs while nBench benchmarked the computational performance, in iterations/sec, for up to ten different routines. Of these ten different routines, the MPB executed 1,197 iterations/sec for Number Sort, and 1,005 iterations/sec for LU Decomposition while running SuSe 9.2 Linux (32-bit). The coolant delivered to the CPUs was at 37°C (ambient air to which heat is rejected would be cooler). A comparable 1U COTS server (dual Intel Xeon 3.6 GHz CPUs) executed 566 iterations/sec for Number Sort, and 564 iterations/sec for LU Decomposition in an ambient of 20°C air (while running Redhat Linux). Under the selected conditions, the MPB significantly outperformed a much larger dual CPU server. No testing has been conducted against a Compact PCI shelf yet.

The MPBs, and more specifically the memory, were then fully exercised running the combination of CPU Burn (for the CPUs) and Memtest86 v3.2 (for the memory). To assist in the thermal stress, the MPBs were cooled with 50°C coolant, with the system pressure up to approximately 20.9 psia. Under these conditions, the CPU edge diode temperatures were in the approximate range of 70°C–72°C, the dense stacked memory temperature range was 51°C–60°C (backside of memory board to top of 10 die stack), the dense power supply module temperature range was ??°C to ??°C, and the nVidia graphics chip temperature was 68°C.

For all tests conducted, the MPBs and all their components met ISR's target specifications.

TCO Model

A total cost of ownership model was developed to investigate the cost savings potential of migrating to SprayCool technology in data centers. Cost impacts from energy savings, reliability gains, maintenance concerns, and finally densification were included in a pay-back time analysis. Cost savings per year were generated from measurements and other analysis collaboratively with PNNL. These were then compared to the initial capital investment of retro-fitting commodity servers with SprayCool systems to determine the resulting pay-back period.

The densification analysis looked at several ways of calculating the cost savings resulting from the higher computer density allowed by SprayCool technology, such as migrating from 2U to 1U servers, or going to a Global SprayCool System. In one analysis, the impact of recapturing data center floor area from air conditioning equipment and rededicating it to computing was analyzed. In a

second approach, the cost savings from deferred construction costs were included. Depending on the methodology used, the pay-back period of an investment in SprayCool technology ranged from 0.5 to 2.7 years.

Scale-Up Case Studies

To better understand the density gains that can be achieved with SprayCool technology, ISR and PNNL conducted two studies to compare the present day high performance computer that utilizes 2U servers, with a similar configuration using 1U servers and eventually a Global SprayCool system.

The move from 2U to 1U servers does not result in a 2 to 1 space savings, because substantial rack space is also dedicated to mass storage and switches. The current PNNL computer requires 84 racks, but transitioning to 1U servers would result in a 15 rack reduction to a total of 69. If these 15 ‘spare’ racks were fitted with additional 1U servers, the overall computing power of the supercomputer would be increased by 51%.

A further densification could be achieved by migrating to a Global SprayCool System that was also demonstrated in this program. The current system has 16 slots per chassis for SprayCool server blades, each with two processors. In this scenario, a total of 36 racks would be freed up for new computer elements, resulting in a computing power increase of 74%.

A final note on the density gains involves the space savings achieved by removal of air handlers. In the energy analysis performed, it was determined that a minimum of 6 of the 17 total air handlers in PNNL’s facility could be removed if the CPUs alone were SprayCool. Air handlers are quite large, so if this additional area were rededicated to computer applications, the gains would be even larger.

3 Introduction

Few industries have seen the rapid increases in performance that have characterized computing and electronics, but this performance has come with a price. It is estimated that as much as 12% of the nation’s electricity is used to power the Internet and its associated data centers and electronics. Compounding the problem is the need to cool the massive amounts of heat generated by this computing power, a process that is carried out today with a very inefficient method that relies on convective cooling from air flow.

This demonstration was undertaken to investigate an alternative cooling methodology that relies on the more efficient method of liquid evaporative cooling the electronics. Because this approach utilizes a higher density transport medium and a more efficient evaporative cooling process, it is believed that the resulting system will enable substantial savings in energy costs. In this instance, the heat

generated by the processors can be transported out of the facility through the chilled water loop, rather than through the deployment of an inefficient and noisy HVAC system.

Further advantages to the SprayCool approach include the increased densification of electronics through advanced 3-dimensional chip-scale packaging. These packages allow semiconductors to occupy a much smaller portion of the board, which also creates better performance by shortening electrical paths throughout the system. The area required by these packages can be further reduced through the use of stacked structures so that the semiconductors grow vertically rather than laterally—taking up less board space. These advances are leading to densities that are beyond the threshold of traditional air cooling, and that require the use of advanced liquid evaporative cooling.

There are currently two variations of SprayCool technology that are in use, with a development effort towards a third. Task 1 of this effort will involve a spot cooling approach where the traditional fan heat sink on the processor is removed and then replaced with a spray module. Accordingly, the spray module primarily cools only the processor. However, this does result in cooler air being delivered to downstream components and therefore a lower temperature for all components.

For task 2 we will implement a global SprayCool system in which the entire PCB and backplane are enclosed in a sealed chassis. With this approach, all the electronics on the board are sprayed with the fluid with specific spray nozzles located directly above the hottest components—particularly the processor. Since the more efficient evaporative cooling is thus employed for all the computer electronics, this method results in greater energy savings for the data center.

Finally, a future approach to evaporative cooling involves a hybrid methodology. In this instance, certain cards that plug into a backplane would be enclosed in a sealed container, or ‘clamshell”, enabling these boards to use SprayCool technology. The dielectric fluid would be delivered to each individual clamshell through appropriate plumbing specific to each slot. And should the user want to use a traditional air cooled card in the neighboring slot, the system design would allow for this. Therefore the overall system could contain a hybrid mix of spray and air cooled cards inserted into a common backplane within the system.

This program sponsored a trade study with Venture Development Corporation to determine the current state of large data centers, and identify the most critical issues they face. When asked what the primary technical challenges were that data center managers were facing, the number one response was air flow management, followed by HVAC, density, and reliability. The implementation of SprayCool technology addresses these critical issues in several ways.

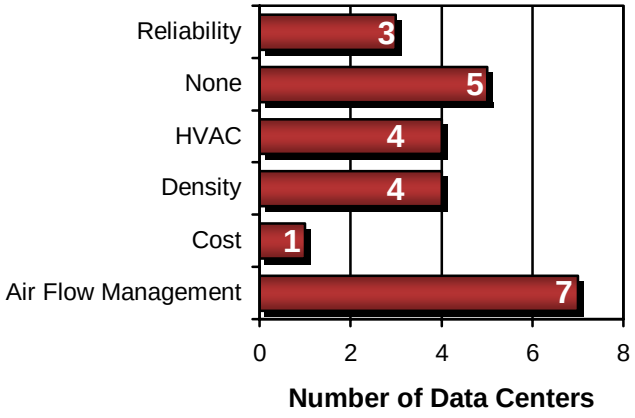


Figure 1 : Survey results on the primary technical challenges for thermal solutions in data centers

Note: “None” means respondent did not specify any specific thermal issues.

Of greatest concern are the challenges surrounding the air delivery system. SprayCool technology is a direct replacement for this system. The costs associated with large CRAC units, raised floors and ducting are substantial, but even more problematic are the design considerations. Proper location of perforated tiles, CRAC units, and return plenums are not straightforward to design and often require complex CFD models. Too often the expertise to perform this analysis is lacking, and so a design overkill method is applied resulting in even greater operational costs. Conversely, a SprayCool system is comparatively simple to design. CPU and server power requirements are well known and can be easily translated into the required number of Thermal Management Units required to cool the system. SprayCool equipped servers are then loaded into the racks and the fluid I/Os connected. Finally, once the system is turned up, the heat from the electronics is rejected to the water supply and transported out of the room efficiently, greatly reducing the amount of HVAC required within the data center. Since it is a closed system, complex modeling of the overall data center is not required.

The advantages in density were touched on earlier in terms of enabling advances in chip-scale packaging. However, much simpler and easier gains in density can be achieved by simply going from a 2U to a 1U server for increased rack space utilization. While this would be difficult to impossible with standard air cooling methods, removing all the CPU heat from the air to the water supply makes 1U server clusters feasible.

Reliability gains are also expected due to the reduced temperatures at which SprayCool CPUs will operate. The data presented in section 3 shows an average temperature reduction of over 10°C for a SprayCool vs. air cooled processor. A common industry rule of thumb is that for every 10 degrees cooler an electronic component operates, the mean time between failure should double (when accounting for temperature as the only stress factor) per the Arrhenius equation.

Also, by removing processor heat from the air flow through the server, the downstream components run at substantially lower temperatures.

Data center managers are also seeking ways to environmentally isolate the electronics and better address fire suppression. As SprayCool systems move from a spot cooling to global cooling solution, the systems will provide both functionalities. A sealed global chassis constructed of metal will provide a controlled environment for the electronics that is virtually impenetrable to both contaminants and water from fire sprinklers. Indeed, initial deployments of SprayCool technology were built using similar chassis that were ruggedized for use in military vehicles both on the ground and in the air. The data center is a very mild operating environment in comparison.

Another concern of data centers is the ineffective and congested cable routing that typically takes place under the raised floor system, an area difficult to access and manage. With SprayCool, the need for a raised floor can actually be eliminated, and the cabling can be located overhead, a common practice in the Telecom arena. By locating the cable overhead where it is visible, more easily accessed, and more easily managed, the occurrence of tangled cables under the floor tiles will be reduced.

4 Program Description

The Energy Smart Data Center (ESDC) program has been conducted in four separate tasks as follows:

Task 1: Side-by-Side Demonstration
Task 2: Technology Development
Task 3: Impact/Study Report
Task 4: Technology Insertion and Reporting

Additional detail for each task is provided in the following sections.

4.1 Side-by-Side Demonstration (Task 1)

A side-by-side demonstration for a complete rack of HP rx2600 servers was proposed. As part of the demonstration, a full rack of servers was converted from air cooling to evaporative cooling. A sub-rack of commercial blade servers from RLX Inc. was also converted from air cooling to evaporative cooling. The converted rack of HP rx2600 servers will be compared to all of PNNL's air-cooled racks for a period of one year. The comparison will focus on uptime, reliability, maintainability, and respective costs associated with running a SprayCool system in a true data center environment. The results of this testing will be integrated into a complete technical and economic assessment of the advantages and disadvantages of the application of SprayCool to high performance data centers

as compared to standard air cooling. A complete total cost of ownership model will be developed, and recommendations for implementation in servers and data centers will be provided. In total, this study will provide all the information needed for server OEMs and Data Center operators to effectively evaluate the benefits of implementing SprayCool technology.

The converted sub-rack of RLX blade servers will be monitored for CPU and component temperatures as well as for SprayCool system parameters such as fluid temperature and system pressure. The intent of this system is to show the viability of SprayCool technology in blade server form factor in addition to the 2U style servers. Similar temperature reductions are expected even in this higher density application, and energy savings should be consistent across both platforms.

Further details for this task are provided in the following sections.

4.1.1 Single HP rx2600 Server

Prior to receiving the full rack of HP rx2600 servers, ISR took delivery of a single rx2600 server from PNNL. This server was performance baselined with air cooling on the bench at ISR. The performance base lining consisted of measuring the temperature of the air coming into the chassis, the temperature of both CPUs within the chassis, and the overall system power consumption. A single CPU for this server was then converted to evaporative cooling and the server performance baselined again (see **Figure 1**), which included measuring all of the parameters noted above in addition to the temperature of the cooling fluid. Finally, the full server was converted to evaporative cooling, followed by performance base lining (see **Figure 2**). The tests demonstrated the lower CPU operating temperatures and reduced power usage expected with SprayCool.

Figure 2: Size comparison of HP fan heat sink (left) to ISR spray module (right)

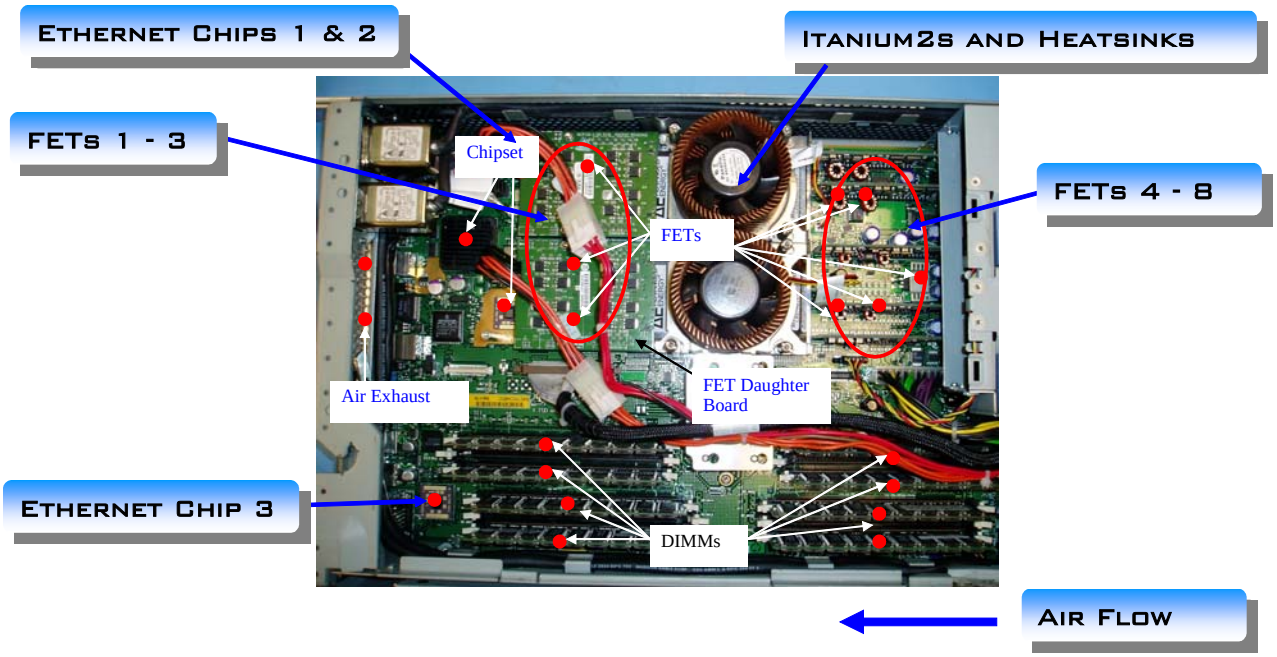


Figure 3: HP rx2600 instrumented components, air cooled state

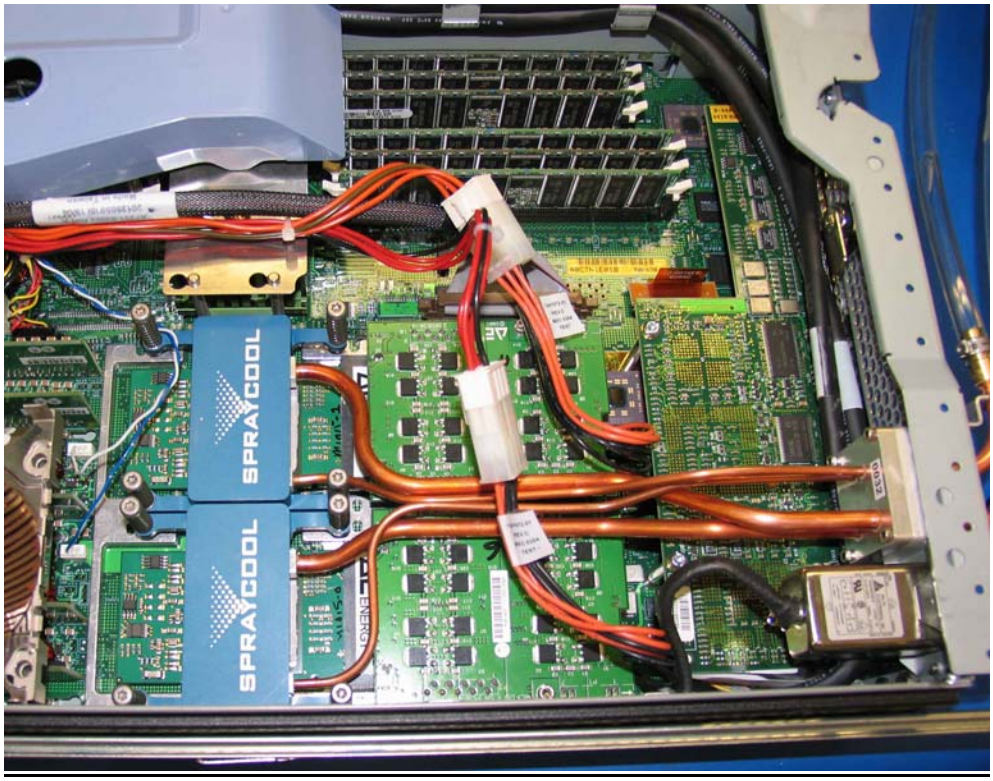


Figure 4: Closer view of HP Integrity rx2600 converted to Spray

4.1.2 Rack of HP rx2600 Servers

Air baseline and SprayCool testing of the PNNL rx2600 system consisted of the following components: Eighteen rx2600 dual Itanium II servers, housed in an HP A4902A 41RU 19” rack, are interconnected by (3) HP 6108 Procurve switches, and a single Cyclades TS2000 console switch. The (3) HP switches and single Cyclades switch are located in the center of the rack with (9) HP RX2600 servers located above, and (9) servers below the switches. Component temperatures and air flow temperatures were monitored by a single Keithley Integra 2750 digital multi-meter with (5) model 7708 switch modules, and (160) type-T thermocouples. The CPU temperatures were monitored using each server’s BMC bus, which was monitored using PNNL temperature monitoring software. Itanium CPU power was monitored using the Keithley system to measure supply voltage and voltage drop across precision resistors on a PNNL designed power measurement board. The power measurement board monitored the CPU power for nodes M1005, M1014, and nodes M1022.

In addition to the component and air temperatures, the SprayCool testing included system fluid temperature and pressure monitoring. The majority of the testing employed the TMU ECS (controller) to monitor pressure transducers and thermistors which are internal to the TMU. The pressure transducers reported TMU reservoir pressure and pump discharge pressure, and the thermistors monitored coolant reservoir inlet temperature, reservoir outlet temperature, and pump outlet temperature. Supplementing the TMU outputs, a fluid test harness outfitted with a pressure transducer, thermocouple, and flow meter was used to perform more detailed system characterization. Operation of the test harness required two digital multi-meters, two 0-24 V power supplies, and a handheld thermocouple reader.

Air cooled system benchmarking employed six instances of BurnI2, at a given ambient temperature. Component temperatures, all CPU temperatures and nodes’ M1005/M1014/M1022 CPU power, chassis power as well as total rack power were monitored and reported once the system came to steady state.

The SprayCool Rack of rx2600 servers is shown in **Figure 4**. SprayCool tests were conducted at given pump discharge pressures, fluid temperatures, and reservoir pressures. Component temperatures, fluid temperatures, reservoir pressure, pump discharge pressure, all CPU temperatures and nodes’ M1005/M1014/M1022 CPU power, chassis power as well as total rack power were monitored and reported once the system came to steady state.

Figure 4: SprayCool Rack of rx2600 servers at PNNL, with the TMU under the raised floor.

4.1.3 RLX Blade Servers

The RLX system consists of five RLX 3200ix blades installed in a 600ex sub-rack chassis, controlled by an RLX control tower server. A single Keithley Integra 2700 digital multi-meter with five 7708 switch modules, and (90) “T” type thermocouples comprise the data acquisition system.

In addition to the component and air temperatures measured by the Keithley digital multi-meter, the SprayCool testing included system fluid temperature and pressure monitoring. The majority of the testing employed the TMU ECS (controller) to monitor pressure transducers and thermistors which are internal to the TMU. The pressure transducers reported TMU reservoir pressure and pump discharge pressure, and the thermistors monitored coolant reservoir inlet temperature, reservoir outlet temperature, and pump outlet temperature. Supplementing the TMU outputs, a fluid test harness outfitted with a pressure transducer, thermocouple and flow meter were used to perform more detailed

system characterization. Operation of the test harness required two digital multi-meters, two 0-24 V power supplies, and a handheld thermocouple reader.

Figure 5a: Picture of the RLX blade in air cooled state

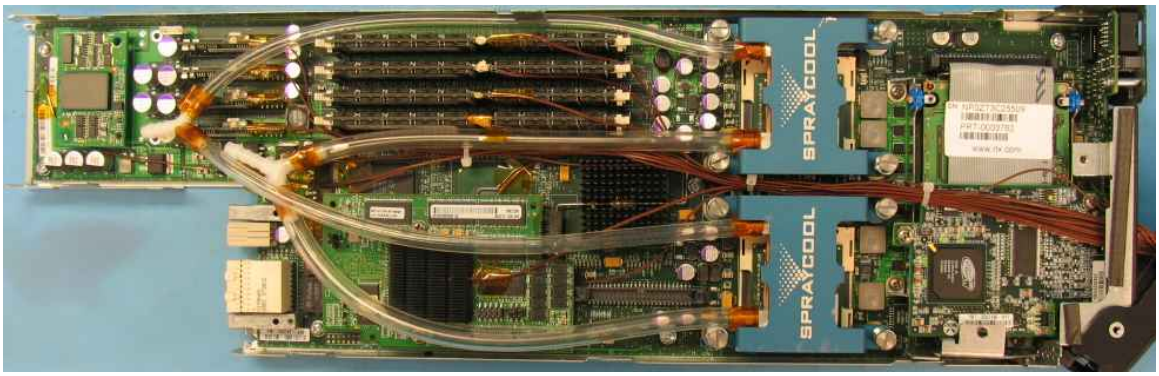


Figure 5b: Picture of an RLX blade converted to SprayCool

4.1.4 Global SprayCool System with Four Multi-Processor Boards

The Global SprayCool System (GSCS) consists of an extruded chassis which is designed to house and cool (18) cPCI form factor PCBs, (2) high speed switches, and a shelf monitor. This iteration of the shelf monitor was only capable of managing the power state of the (4) blades based upon the status of the cooling system. The chassis is paired with a Mustang/Liberator TMU which supplies coolant and rejects the dissipated heat to facility water. For this particular system (4) Multiple Processor Boards (MPBs) were integrated with the GSCS. The MPBs are SprayCool only and equipped with dual 2.4 GHz 64 bit Opteron processors, and 2 GB of high density memory.

TMU temperatures were monitored by the TMU ECS which includes pump discharge pressure, fluid supply temperature, fluid return temperature, and reservoir pressure. The CPU temperatures were characterized in a separate effort. During characterization the CPU temperatures were measured with

thermocouples mounted to the side of the bare die near the core. A Keithley 7708 switch module and Keithley 2700 DMM were used to record the data to an Excel file. The processors were exercised and benchmarked using Burn P6 and nBench, and the high density memory was benchmarked using Memtest86. The (4) boards were cooled with 456 ml/(min*board) of 20°C PF5060, delivered at 20 psid discharge pressure, in a 1 atmosphere chamber.

4.2 Technology Development (Task 2)

The technology development of densified electronics is included in a separate report appended to this one. It follows the structure below.

Overview: Technology Development (Task 2) – Server Blade Project

- 1.2.1 Densified Memory Integration with Server
- 1.2.2 Backplane Design and Power Distribution
- 1.2.3 Shelf Management Module
- 1.2.4 Next Generation Densified Server (Multi-Processor Board)
  - 1.2.4.1 Initial Plan
  - 1.2.4.2 Program Re-scope
  - 1.2.4.3 Dual Opteron Board Design
- 1.2.5 Data Center Market Study

4.3 Impact Study/Report (Task 3)

The Impact Study deliverable includes this report in addition to the Total Cost of Ownership (TCO) model. This section will focus on a description of the TCO model.

The intent of the TCO model is to analyze the cost savings gained by switching to SprayCool in terms of energy savings, reliability gains, and space savings. Full consideration was also given to cost implications in areas such as installation and turn-up time, maintenance, consumables, and other operational factors, both positive and negative. These costs savings are then weighed against the capital investment required to retro-fit equipment with SprayCool technology, and a payback period is then calculated.

Initial consideration was given to the energy savings aspect with a great deal of input from PNNL. A Coefficient of Performance (COP) analysis was performed on the existing air cooled infrastructure where heat from the CPUs is rejected initially to the chilled water, then through the chillers and eventually to the cooling towers. This analysis was then repeated with a SprayCool system based on actual data collected during development and integration. This analysis includes the current configuration of rejecting the heat to the chilled water, as well as in a future iteration where the heat is rejected directly to the cooling tower water loop.

The next category of costs analyzed focused on operational impacts, including reliability gains of the components and the subsequent effect on the service contract. Testing shows CPU temperatures average over 10°C cooler with evaporative vs. air cooled. A common rule of thumb used is that a 10°C reduction in temperature results in a doubling of reliability. Using actual failure data from PNNL and assuming a factor of 2 reduction in failures, it was assumed that a percentage decrease in the service contract could be negotiated.

The final main consideration of the model is the impact of densification to the cost of operating and expanding a data center. Several sources estimate the cost per square foot to build a data center at upwards of $1200. Commonly, data centers must expand every 3 years or so to accommodate increases in computing power. However, the use of SprayCool technology allows densification of computing hardware through the elimination of white space, a reduction in the number of CRACs needed, and potentially a move to 1U vs. 2U servers.

When creating the TCO model, it was recognized that each data center would have different criteria and different variables in terms of number of nodes, construction cost per square foot, service contracts, cost per kWh energy, etc. The model was therefore designed to have all key inputs as variables that the user could manipulate to reflect the realities of their own environment. So while the initial model is set up to reflect the current situation at the PNNL EMSL laboratory, it should be applicable to a wide range of data centers for costs analysis.

4.4 Technology Insertion and Reporting (Task 4)

This task refers to SOW deliverable X007. The Phase II plan has been submitted and approved by PNNL.

5 Results

Results for the following four tasks will be presented in this section:

Task 1: Side-by-Side Demonstration
Task 2: Technology Development
Task 3: Impact/Study Report
Task 4: Technology Insertion and Reporting

Additional detail for each task is provided in the following sections.

5.1 Side-by-Side Demonstration (Task 1)

Prior to conducting the investigation on the full rack of HP rx2600 servers, ISR conducted an initial investigation on a single HP rx2600 on the bench (server was not subject to the air flow impedance created by the rack's cable management). The results from the investigation are shown in **Table 1**. The single server was fully exercised using BurnI2. The baseline testing in air established the performance of the manufacturers Itanium II cooling solution, which includes an active fan-cooled heat sink and a thermal interface material (TIM). Upon completion of the baseline testing in air, CPU 1 was then removed and a SprayCool spray module was installed with ShinEtsu X-23-7783D TIM, a custom spray module bracket, and the original preload fasteners. The single server was tested with a PLSU and a Wildcat TMU (both liquid-to-air TMUs). Tubing was run towards the side of the server and out the top as shown in **Figure 6**. A modified chassis cover was used which had a pass through for the fluid plumbing.

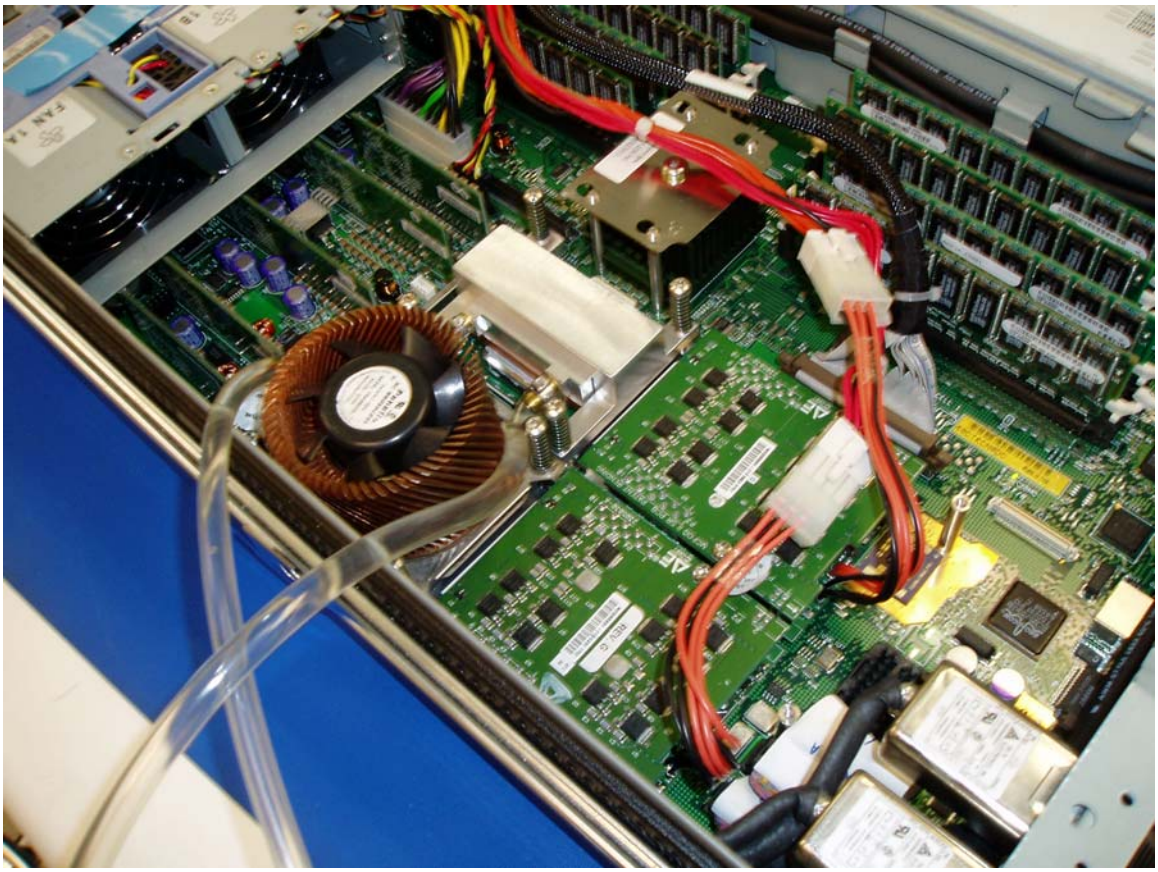


Figure 6: HP Integrity rx2600 server - CPU0 is cooled with the OEM heat sink, CPU1 is cooled using a SprayCool generation 2 spray module

	Units	Single rx2600	Single rx2600	Single rx2600	Single rx2600	Single rx2600
Node	(-)	Bench	Bench	Bench	M1005 (#3)	M1005 (#3)
Test Environment	(-)	ISR; Bench	ISR; Bench	ISR; Bench	ISR; Rack	ISR; Rack
Air or Spray	(-)	Air-Cool CPU 0 Air-Cool CPU 1	Air-Cool CPU 0 SprayCool CPU 1	Air-Cool CPU0 Spray CPU1	Air-Cool CPU 0 Air-Cool CPU 1	SprayCool CPU 0 SprayCool CPU 1
SprayCool Kit	(-)	N/A	Gen 2	Gen 2	NA	Gen 2
Coolant	(-)	N/A	PF5050	PF5050	NA	Gen 2
TIM2	(-)	HP Supplied (CPU0) HP Supplied (CPU1)	HP Supplied (CPU0) ShinEtsu 7783D (CPU1)	HP Supplied (CPU0) ShinEtsu 7783D (CPU1)	HP Supplied (CPU0) HP Supplied (CPU1)	ShinEtsu 7783D (CPU0) ShinEtsu 7783D (CPU1)
Ambient Temp	°C	20.5°C	21°C	23.6°C	24.9°C	22.2°C
Spray Temp	°C	N/A	24°C	25.8°C	NA	19.5°C
Supply Pressure	psid	N/A	10	20	NA	20
Coolant Flow Rate	ml/min	N/A	152	209	NA	NA
Reservoir Press	psia	N/A	13.1	14.1	NA	14
CPU 0 Power	W	107 Watts (est)	107 Watts (est)	107 Watts (est)	97.1 Watts (meas)	91.2 Watts (meas)
CPU 1 Power	W	107 Watts (est)	107 Watts (est)	107 Watts (est)	86.3 Watts (meas)	83.1 Watts (meas)
Node Power	W	NA	NA	NA	388 Watts	372 Watts
CPU Excerciser	(-)	6xBurnI2	6xBurnI2	6xBurnI2	6xBurnI2	6xBurnI2
CPU0 Temp	°C	65°C	65°C	65°C	80°C	61°C
CPU1 Temp	°C	68°C	51°C	54°C	74°C	59°C
HDD Temp	°C	N/A	N/A	N/A	N/A	N/A
DIMM Temp	°C	N/A	N/A	N/A	N/A	N/A
Broadcom Chip	°C	N/A	N/A	N/A	N/A	N/A

Table 1: Air- Cooling and SprayCool data for a single node on the bench and within the HP rack

The air-baseline data indicates that the server's CPUs ran between 65°C and 68°C in a 20.5°C ambient environment, with OEM fan heat sink, on the bench. No power measurements were taken for the chassis or the CPUs. Data with CPU 1 being cooled by a spray module indicates that CPU 1 temperature drops from 68°C to 51°C under the same load and ambient conditions as air, while spraying 24°C PF5050 on the processor with a reservoir pressure of 13.1 psia. The third set of data indicates that the SprayCool CPU 1 temperature is sensitive to the fluid temperature and reservoir pressure. **Table 1** indicates that CPU 1 went from 51°C to 54°C, while the air-cooled CPU 0 maintained its temperature at 65°C with an ambient of 23.6°C

The M1005 head node from the HP rack was employed for the last two tests. The goal was to quantify the effect of the air flow impedance of the rack on the CPU temperatures. The M1005 node was air-baselined in the lower most position of the rack. CPU temperatures were 80°C and 74°C for CPUs 0 and 1 respectively. After converting to SprayCool, the CPU 0 temperature was reduced from 80°C to 61°C, while the CPU 1 temperature was reduced from 74°C to 59°C.

5.1.1 Rack of HP rx2600 Servers

Upon initial delivery to PNNL, the rack was housed in EMSL 1124 at location R3C25, and cooled with facility air. The air-cooled rack of servers was then performance benchmarked using Linpack and BurnI2. Both of these tests are designed to stress the CPUs. In addition to collecting CPU temperature information, the three hottest nodes were fully instrumented (approximately 40 thermocouples), and additional thermocouples were placed throughout the rack per rx2600 air baseline test plan (see **Appendix A**). Following this characterization, the rack was then delivered to ISR and the tests were repeated

in ISR's integration lab. The servers were then converted to SprayCool, and the servers benchmarked under the following primary conditions:

1. PF5050 as the coolant.
2. System testing conducted with system pressure at approx. 1 atm.
3. Nodes exercised using BurnI2, a continuous loop program which causes the processors to dissipate their maximum heat load.
4. Nodes benchmarked using Linpack benchmark.
5. Nodes subjected to various load profiles as defined by PNNL to include turning all nodes to full power, all nodes to idle, cascading from the top down toggling each node between full power and idle, and finally stepping down through the rack maintaining 9 nodes at full power.

System testing was initially conducted with a quick-turn liquid-to-liquid TMU, referred to as the R&D TMU. These results will be presented in detail in **Section 5.1.1**. Upon completion of testing with the R&D TMU, testing was then conducted with the first generation TMU designed for delivery to PNNL, i.e., the Mustang/Liberator TMU. Detailed results are presented in **Section 5.1.1**. Finally, on-site acceptance testing for the rack was conducted upon delivery of the rack to PNNL. Detailed results are presented in **Section 5.1.1**.

To keep this document at a manageable size, the reporting will focus primarily on the three hottest nodes in the rack, i.e., M1022 (Node 1), M1014 (Node 2), and M1005 (Node3). These three servers were selected based upon initial testing conducted PNNL.

Modeling

Upon completion of the investigation of the single HP rx2600 (see **Section 5.1**), ISR started the investigation of the full rack of (18) rx2600 servers. The first step of the investigation involved mathematical modeling of the full rack, including the TMU. The analysis focused on predicting pressure drop on the supply and return sides, system pressure, system fill percentage, coolant flow rate, heat rejection from the heat exchanger, and CPU temperatures. The model involved a combination of analytical (of the single-phase flow) and empirical (of the two-phase flow) modeling, and relied heavily on Roberson and Crowe [1] and the Wolverine Engineering Data Book III [2]. Upon completion of the model, the model's predictions for straight pipes were compared to actual data for refrigerant R-134a. Results of the comparison are shown in **Figure 7** below

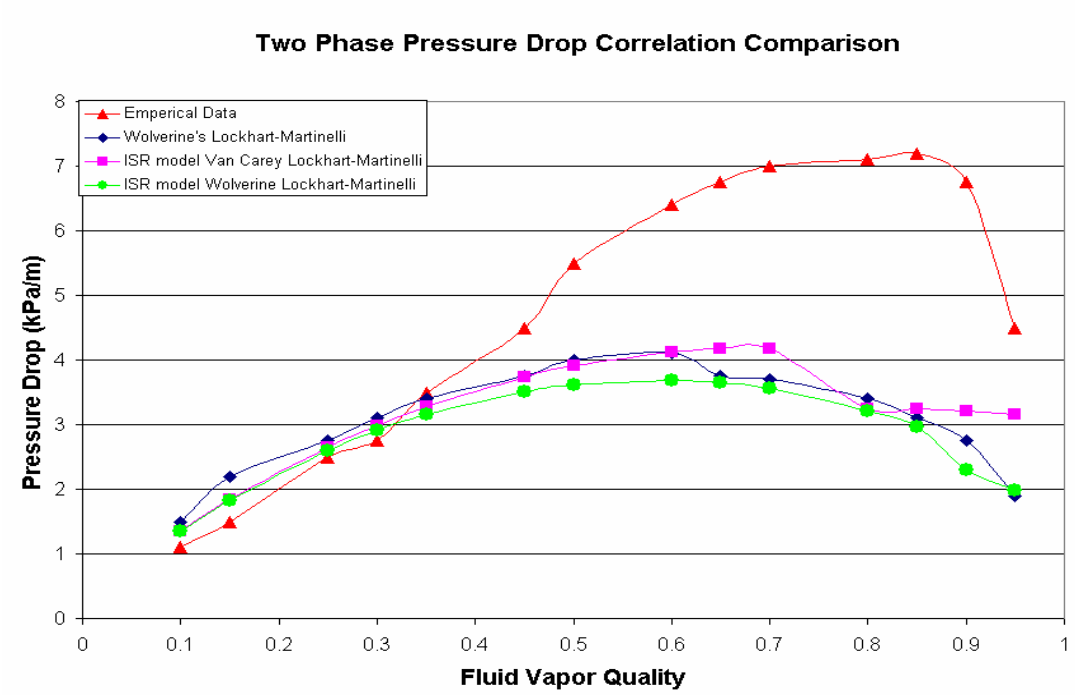


Figure 7: Comparison of predicted pressure drop (using ISR model) to experimental results.

Figure 7 shows that the Lockhart-Martinelli correlation does not closely predict pressure drop above 45% vapor quality. While the Wolverine Engineering Data Book III presented several other correlations for predicting pressure drop for two-phase flow, initial analysis indicated that the system would not experience a vapor quality greater than 40%. As a result, the Lockhart-Martinelli correlation appears to be the most suitable for prediction purposes with the perfluorocarbons employed.

Model Validation

The system level pressure drop analysis provided an initial estimation of the pressure drops that the SprayCool system would experience. Testing with the R&D TMU was the first chance to collect data of the pressure drops occurring at specific points within the system. The experimental results were then compared to the model's predictions at the points shown in **Figure 8**. **Table 2** shows the single-phase pressure drop and flow rate values for a mated metallic CPC brand ¼" flow, self shutoff and quick disconnect fluid coupling. This table also shows the results for the rack's supply manifold measured from the supply interconnect (see **A, Figure 8**), located at the bottom of the manifold, to the uppermost distribution interconnect (see **B, Figure 8**), located at the top of the manifold. As shown, the predicted CPC pressure drop value is 75% of the experimental value. This was not a directly comparable prediction, but it did allow the model to be tweaked to better match the measured value. The rack supply manifold

prediction was significantly better at 92% of the measured value. The model also predicted the total volumetric flow rate for the system to 99% of the measured value

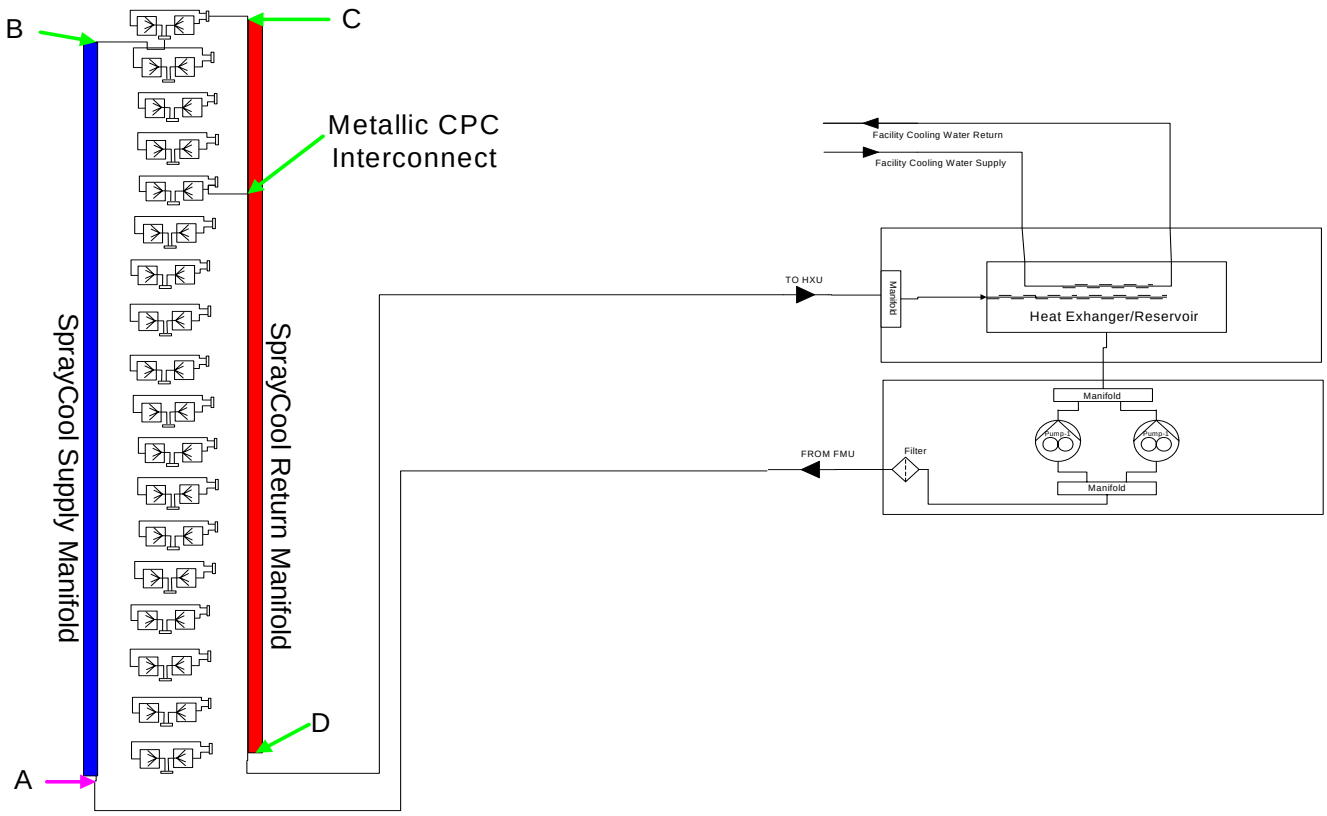


Figure 8 *Block diagram of the HP rx2600 SprayCool system*

Single Phase Fluid Flow		CPC 1/4" Quick Disconnect Fluid Connector	Rack Supply Manifold
Predicted	**Pressure Drop (Psid)**	0.15	4.33*
	Flow Rate (mL/min)	172	2620
Experimental	**Pressure Drop (Psid)**	0.2	4.7*
	Flow Rate (mL/min)	140	2630

**Note: Includes the rack head of 4.318 psi*

Table 2: Single phase Pressure drop calculations and experimental results

Two-phase flow rates and pressure drop were also calculated using the system pressure drop model. Instrumentation did not allow us to measure pressure drop of the two-phase flow because of the high flow velocities. **Table 3** shows the predicted pressure drops for a mated metallic CPC brand ¼" flow, self shutoff and quick disconnect fluid coupling. The table also shows the pressure drop predictions for the rack return manifold measured from the top distribution

interconnect (see C **Figure 8**), to the return interconnect, located at the bottom of the manifold (see D **Figure 8**).

Once the pressure drop was calculated the CPU diode temperatures were predicted, as shown in **Table 4,** using correlations generated from experimental SprayCool component data.

Two Phase Fluid Flow		CPC 1/4" Quick Disconnect Fluid Connector	Rack Return Manifold
Predicted	Pressure Drop (Psid)	1	-0.096
	Flow Rate (mL/min)	172	NA
	Quality	34%	34%
Experimental	Pressure Drop (Psid)	NA	NA
	Flow Rate (mL/min)	NA	NA
	Quality	NA	NA

Table 3: Two Phase pressure drop calculations and experimental results

M1005 (Node 3)	Predicted Diode Temp (°C)	Predicted Power (W)	Experimental Diode Temp (°C)	Experimental Power (W)
CPU 0 Diode Temperature	59.7	90	64.0	87.5
CPU 1 Diode Temperature	59.7	90	62.0	81.3

Table 4: Predicted CPU diode temperature vs. Experimental data

R&D TMU

The R&D TMU is a test thermal management unit designed with two ISR turbine pumps, a small reservoir, a liquid-to-liquid heat exchanger, and an ISR environmental control system (ECS). This TMU does not possess the full functionality of the Mustang Liberator TMU (M/L TMU), e.g., failover capability, hot swapability, etc. By reducing the requirements on this unit, ISR was able to build and deliver this unit rapidly. This enabled testing of the full rack to proceed prior to delivery of the final M/L TMU.

The R&D TMU testing and results demonstrated early on that the rx2600 SprayCool system was functioning as expected. Initial thermal performance data could be gathered and evaluated at the CPU level as well as components at the server level. Finally, an investigation, comparison, and tuning of the system pressure drop analysis was enabled by testing with the available R&D TMU. The SprayCool test matrix in **Table 5** outlines testing which was executed to verify that the SprayCool system was operating per specifications. This matrix focused on testing the system at a combination of fluid temperatures (15°C–25°C) and pump discharge pressures (15 psid–30 psid). To start the matrix included tests which would verify the stability of the system under dynamic loads, the thermal performance of the system using PF5060 and PF5050 as coolants, and the effect

on CPU temperatures when reservoir pressure was varied. Due to time constraints, the full matrix could not be executed. The tests marked with an “x” were not conducted. However, additional tests were conducted with the M/L TMU both at ISR (see **Section 3.1.1**), and on-site at PNNL (see **Section 3.1.1**). Also note that several planned tests involving high discharge pressures and low coolant temperatures were also abandoned due to the system’s inability to reach the specified parameters (e.g., 10°C coolant, 30 psid pump discharge pressure).

R&D TMU									
	Variable 2 10C Fluid	20C Fluid	30C Fluid	15psid TMU Discharge press	20psid TMU Discharge press	25psid TMU Discharge press	30psid TMU Discharge press	FULL M1005, OFF Remain	FULL M1005_ IDLE Remain
Variable 1 10C Fluid				X	X	X	X		
15C Fluid				041105c	041105b	041205a	X		
20C Fluid				040405a	033005a	040405b	041205b	X	X
25C Fluid				040605c	040605a	040605b	X		
15psid TMU Discharge press									
20psid TMU Discharge press								X	X
25psid TMU Discharge press									
30psid TMU Discharge press									
FULL M1005, OFF Remain									
FULL M1005_ IDLE Remain									
FULL M1005,M1014,M1022_ OFF Remain									
FULL M1005,M1014,M1022_ IDLE Remain									
PF5060		X							
+1psi restriction on fluid return to TMU @ 20C Fluid					X				
+2psi restriction on fluid return to TMU @ 20C Fluid					X				
+3psi restriction on fluid return to TMU @ 20C Fluid					X				
+4psi restriction on fluid return to TMU @ 20C Fluid					X				
+5psi restriction on fluid return to TMU @ 20C Fluid					X				

Table 5: Test matrix for all the tests conducted on the SprayCool rack with the R&D TMU.

ISR Test Results

Prior to conversion to SprayCool, the air-cooled rack was characterized in ISR’s Integration Lab. The full rack was then converted to SprayCool, with the nodes cooled by the R&D TMU. The TMU liquid-to-liquid heat exchanger was cooled on the water side with a stand-alone chiller. Through manipulation of the chiller, the coolant temperature was adjustable over a wide range that encompassed the typical operating conditions at PNNL (e.g., the upper part of the range was designed to demonstrate that the heat could be rejected directly to PNNL’s cooling tower water).

Results from the air and spray characterization are shown in **Tables 6, 7**, and **8**, as well as in **Figures 9**–**12**. For air cool and SprayCool testing, nodes were exercised using BurnI2 in 22°C–25°C ambient conditions. SprayCool testing was conducted with 20 psid discharge pressure, 20°C coolant, and 14.8 psia reservoir pressure. **Table 6** tabulates the key data for the air-cooled servers. **Table 7** tabulates the key data for the SprayCool servers. Finally, **Table 8** tabulates the results of the differences between the air-cooled and SprayCool servers (essentially the values shown in **Table 6** less those in **Table 7**). **Table 6** shows CPU0 of the air-cooled servers ranging in temperature between 71°C and 80°C, while CPU1 ranged from 71°C to 80°C. The power dissipation for CPU0 ranged from 92.7 to 97.4 W, while the power dissipation for CPU1 ranged from 82.8 to 86.5W. For the full rack, the maximum CPU0 temperature for all CPUs was 80°C, the minimum was 71°C, the average was 73.4°C, and the standard deviation was

2.4°C. For the full rack, the maximum CPU1 temperature for all CPUs was 80°C, the minimum was 71°C, the average was 72.9°C, and the standard deviation was 2.1°C. The data reveals processor to processor variations in temperatures. These variations can be attributed to manufacturing tolerances of each CPU core. This causes power dissipations to vary, which drives the temperature differences. **Figure 9** graphically represents the differences in temperature for the air-cooled and SprayCool CPUs. **Figure 9** shows that the majority of the CPUs are between 9°C and 13°C cooler with SprayCool technology. This is supported by the standard deviation shown in **Table 8**, which indicates that 70% of the CPUs are between 8.6°C and 14.4°C cooler when using SprayCool technology. **Figure 10** graphically represents the differences in temperature for the air-cooled and ged FETs. The figure shows that the FETs for the SprayCool server are running cooler. Additional detail for the balance of the components in all the servers for the R&D and M/L TMUs is presented in **Appendix C**.

Figure 11 presents the CPU temperatures for Nodes 1, 2, and 3, as a function of coolant temperature, while **Figure 12** presents the same as a function of pump discharge pressure (flow rate). Based upon the data presented in **Figure 11**, the edge diode temperatures rise 1°C for 2°C rise in coolant temperature. Based upon the data presented in **Figure 12**, the edge diode temperatures rise 1°C for 5 psid increase in atomizing pressure. There is a greater sensitivity to coolant temperature than atomizing pressure. This is related to the mechanism for heat rejection. When the coolant temperature is lowered, a higher percentage of heat is removed via sensible heat transfer instead of latent heat transfer (heat removed by vaporization). Sensible heat transfer occurs below the saturation temperature of the fluid, the processor temperatures can be cooled to temperatures below the saturation temperature driving a greater sensitivity. Increasing the atomizing pressure does not dramatically increase the amount of sensible heat transfer but it does have an effect on the latent heat. Latent heat transfer is only effective when cooling components are above the saturation temperature. For example, if atomizing pressure, of saturation temperature fluid, were to be increased to an infinitely high value, the processor temperature can only ever be equal to the saturation temperature.

File	012705d			
Ave ambient (°C)	23.9			
stdev amb (°C)	0.4			
Pump Disch (psid)	NA			
Res Press (psia)	NA			
PF Temp (°C)	NA			
	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)
M1005 (Node3)	77.0	72.0	97.4	86.5
M1006 (Node4)	72.0	74.0		
M1007 (Node8)	74.0	74.0		
M1008 (Node6)	80.0	73.0		
M1009 (Node15)	73.0	74.0		
M1010 (Node16)	72.0	72.0		
M1011 (Node9)	76.0	72.0		
M1012 (Node13)	72.0	73.0		
M1013 (Node5)	71.0	75.0		
M1014 (Node2)	73.0	71.0	92.7	82.8
M1015 (Node14)	75.0	72.0		
M1016 (Node12)	74.0	72.0		
M1017 (Node10)	72.0	71.0		
M1018 (Node7)	71.0	72.0		
M1019 (Node18)	71.0	73.0		
M1020 (Node11)	71.0	71.0		
M1021 (Node17)	73.0	72.0		
M1022 (Node1)	75.0	80.0	97.4	86.5
average	73.4	72.9		
max	80.0	97.4		
min	71.0	71.0		
stdev	2.4	2.1		

Table 3.6 Thermal performance results for the air-cooled rack (all nodes fully exercised by running BurnI2).

File	032905b
Spray or Air	spray
Ave ambient (°C)	22.5
stdev amb (°C)	1.0
Pump Disch (psid)	20.0
Res Press (psia)	14.8
PF Temp (°C)	20.0

CPU Temps/Power	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)
M1005 (Node3)	66.0	63.0	92.4	83.6
M1006 (Node4)	NA	NA		
M1007 (Node8)	62.0	61.0		
M1008 (Node6)	61.0	64.0		
M1009 (Node15)	63.0	61.0		
M1010 (Node16)	63.0	61.0		
M1011 (Node9)	59.0	62.0		
M1012 (Node13)	60.0	62.0		
M1013 (Node5)	62.0	59.0		
M1014 (Node2)	62.0	61.0	88.9	81.2
M1015 (Node14)	62.0	62.0		
M1016 (Node	65.0	62.0		
M1017	60.0	57.0		
M1018	62.0	62.0		
M1019	63.0	61.0		
M1020	59.0	61.0		
M1021	62.0	63.0		
M1022	62.0	64.0	81.5	87.8

average	61.9	61.5
max	66.0	64.0
min	59.0	57.0
stdev	1.9	1.7

Table 3.7 Thermal performance results for the SprayCool rack (all nodes fully exercised by running Burnl2).

NOTE: node M1006 was out of commission for this test.

File	difference
Spray or Air	
Ave ambient (°C)	1.4
stdev amb (°C)	-0.6
Pump Disch (psid)	NA
Res Press (psia)	NA
PF Temp (°C)	NA

CPU Temps/Power	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	
M1005 (Node3)	11.0	9.0	5.0	2.9	Bottom
M1006 (Node4)	NA	NA			
M1007 (Node8)	12.0	13.0			
M1008 (Node6)	19.0	9.0			
M1009 (Node15)	10.0	13.0			
M1010 (Node16)	9.0	11.0			
M1011 (Node9)	17.0	10.0			
M1012 (Node13)	12.0	11.0			
M1013 (Node5)	9.0	16.0			
M1014 (Node2)	11.0	10.0	3.8	1.6	Middle
M1015 (Node14)	13.0	10.0			
M1016 (Node	9.0	10.0			
M1017	12.0	14.0			
M1018	9.0	10.0			
M1019	8.0	12.0			
M1020	12.0	10.0			
M1021	11.0	9.0			
M1022	13.0	16.0	15.9	-1.3	Top

average	11.6	11.4
max	19.0	16.0
min	8.0	9.0
stdev	2.9	2.3

Table 3.8 Thermal performance difference between air-cooled and SprayCool racks (Air values minus SprayCool values). All nodes are fully exercised using BurnI2.

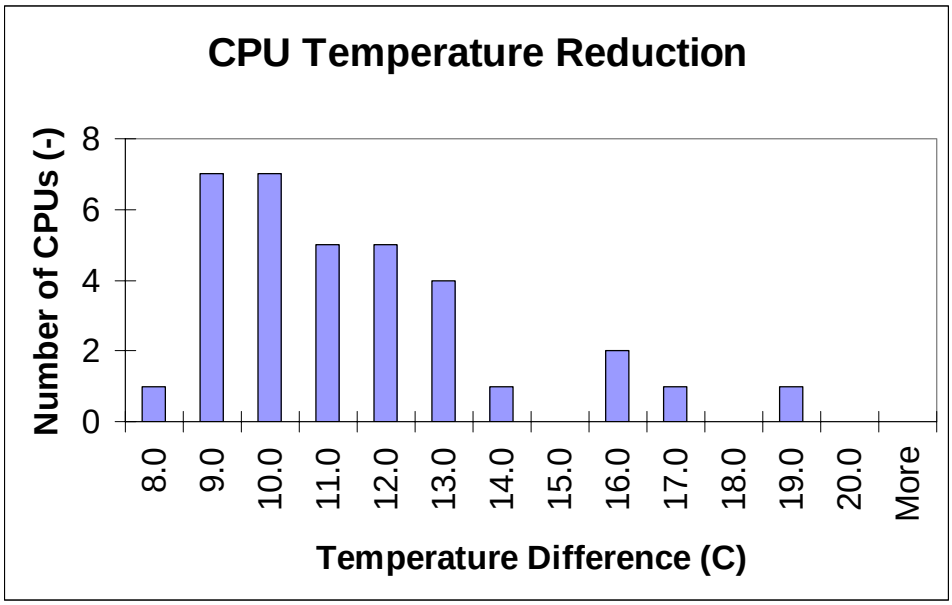


Figure 9: *Histogram of CPU edge diode temperature differences between air-cooled and SprayCool rack (positive value means the air-cooled rack CPUs are running hotter)*

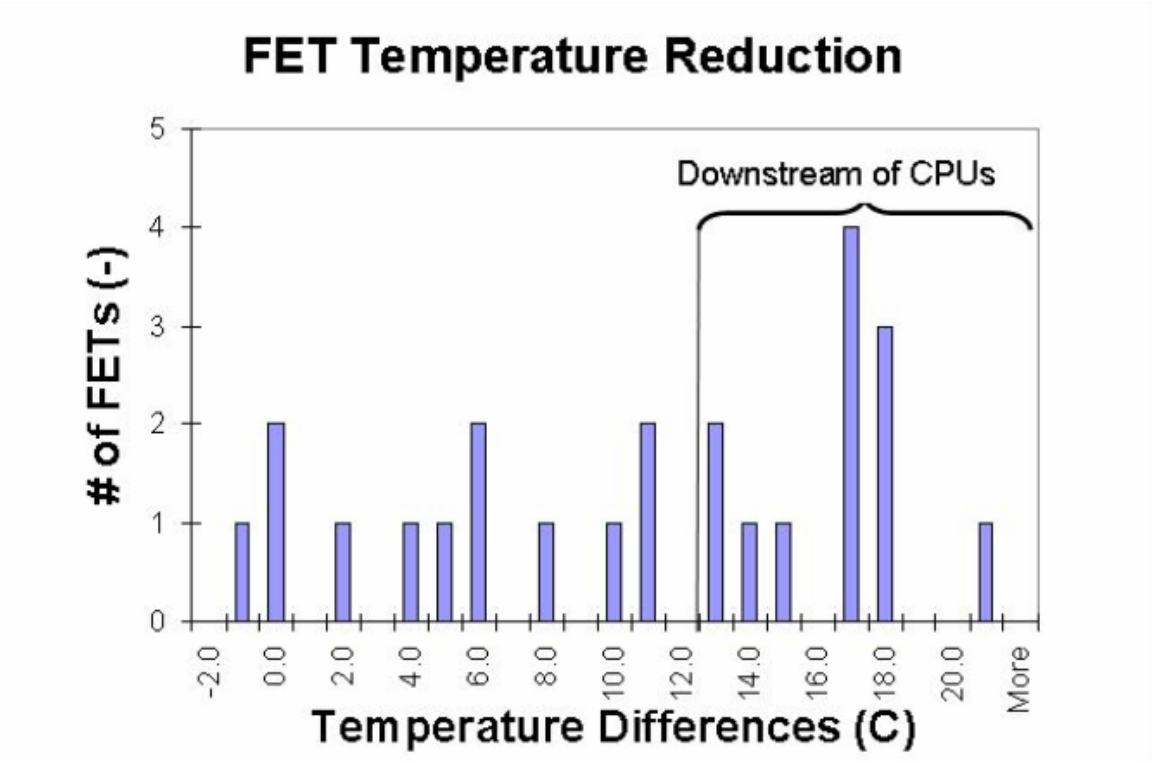


Figure 10: *Histogram of temperatures deltas for various different FETs (positive value means the air-cooled rack FETs are running hotter)*

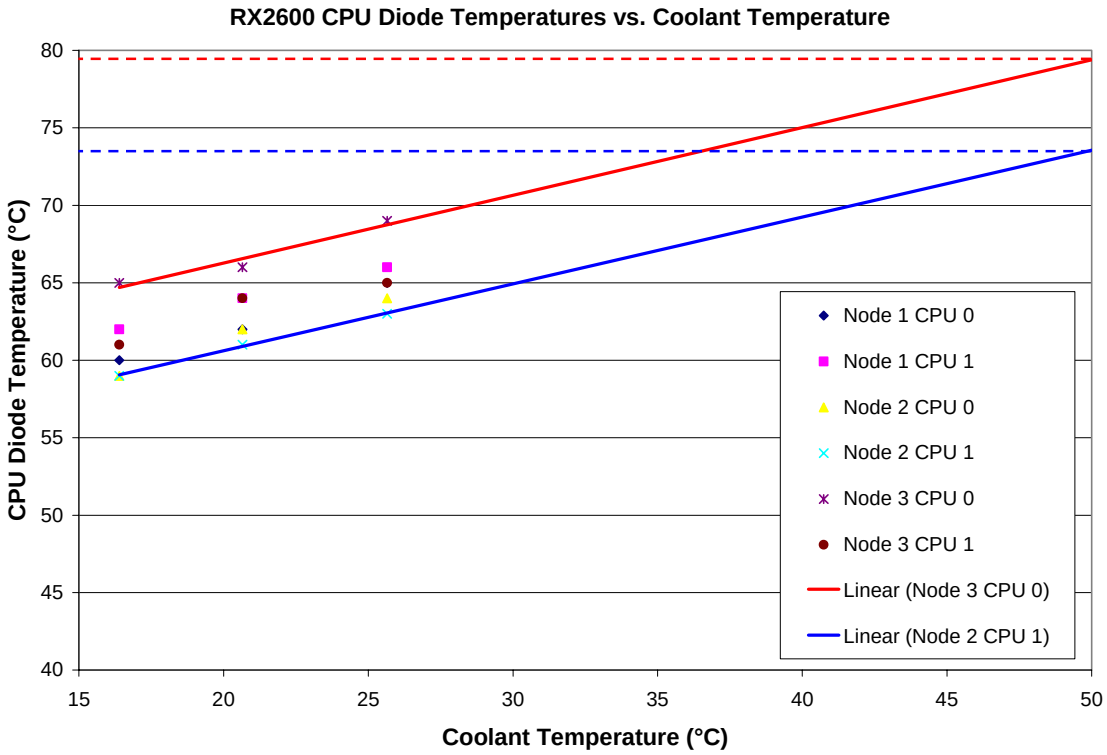


Figure 11: *CPU temperatures versus Fluorinert coolant temperature with the R&D TMU at 20psid pump discharge pressure.*

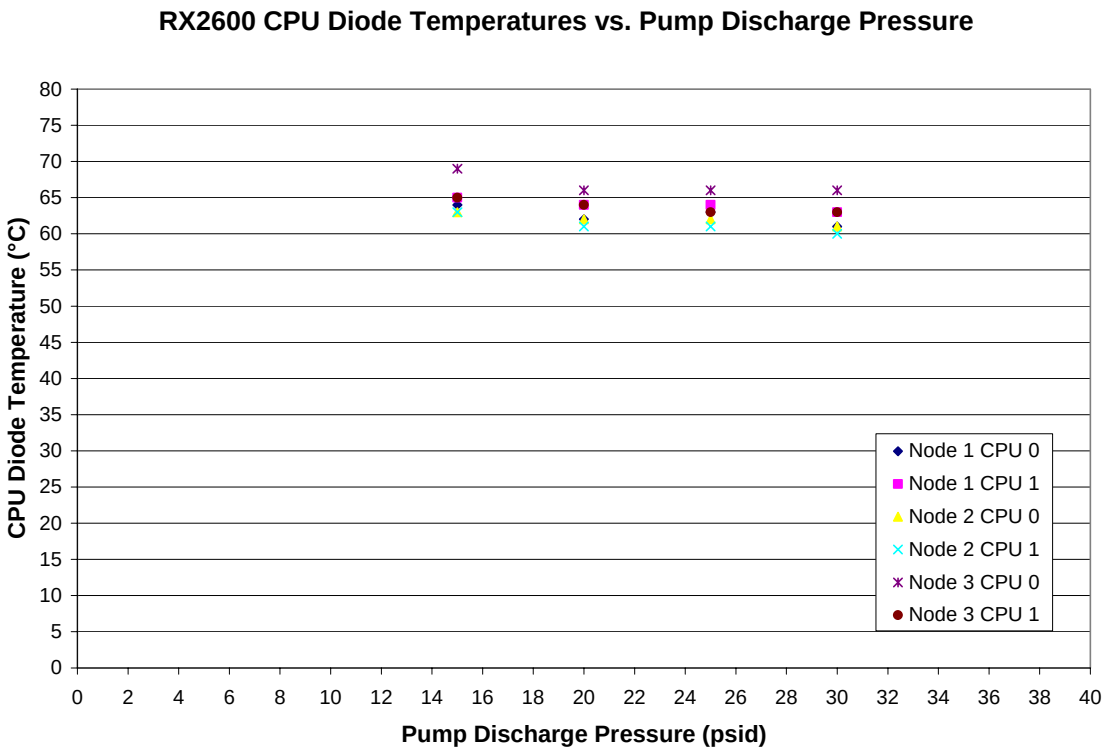


Figure 12: *CPU temperatures versus pump discharge pressure with the R&D TMU at 20°C coolant temperature.*

Mustang Liberator TMU

The Mustang Liberator TMU (M/L TMU), has a different configuration than the R&D TMU (please see **Figure 13**). The M/L is composed of two separate units: a Heat Exchanger Unit (HXU) called Mustang, and a Fluid Module Unit (FMU) called Liberator. The HXU houses the condenser and a reservoir, and is joined to the FMU with a fluid interconnect. The Liberator employs a fluid manifold to distribute the condensed and sub-cooled fluid from the Mustang to the two redundant pumps. Like the R&D TMU at any given moment, only one of the pumps is running. In the event of a pump failure, the TMU has the ability to failover to the redundant pump. The differences between the R&D and M/L are directly related to the reservoir—fluid union between the Mustang and Liberator, and the manifold for the redundant pumps in the Liberator. These differences affect pressure drop and can be quantified by the change in CPU temperatures (system pressure) and operation of the TMU (priming).

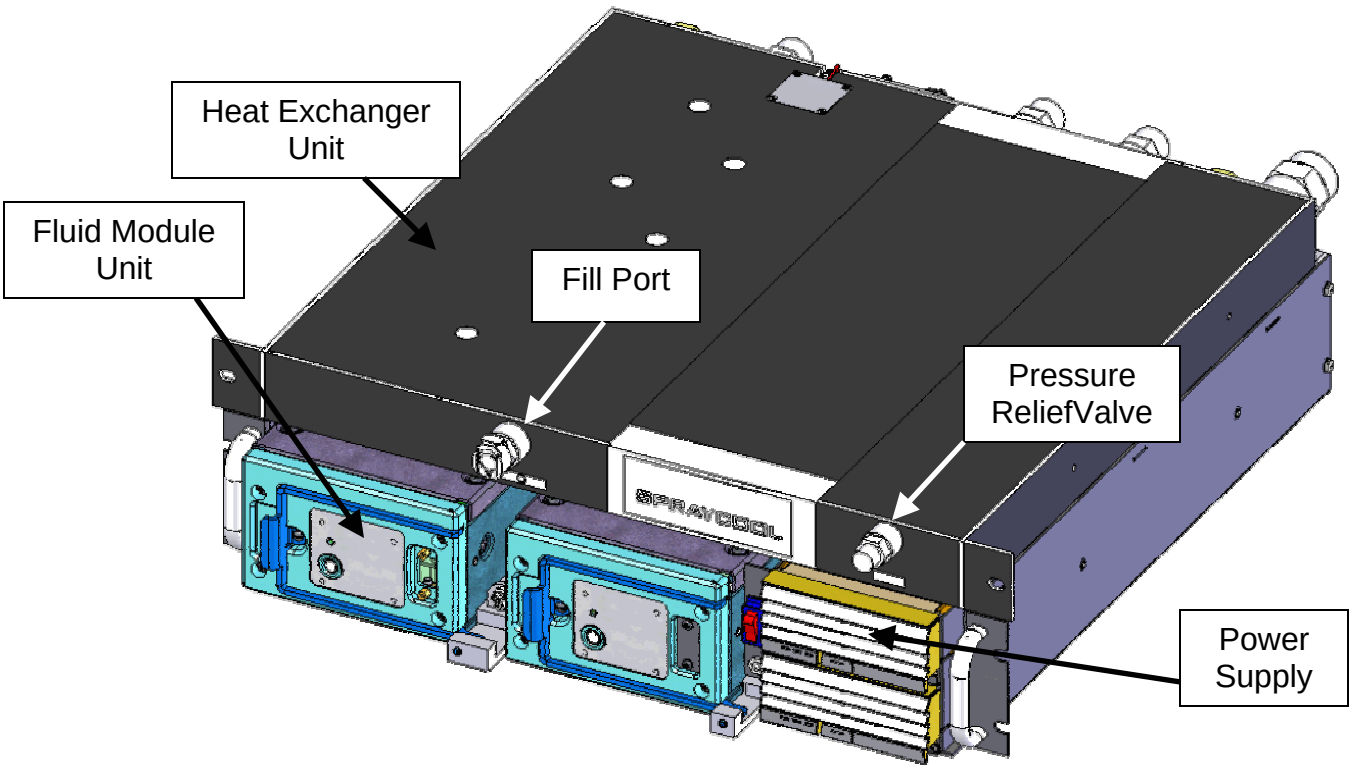


Figure 13: Solid model of the Mustang Liberator

Testing at ISR

A number of tests were run on the SprayCool Rack upon integration of the M/L TMU. The first set of tests was designed to determine the case-to-ambient thermal resistance for the SprayCool solution. This representation of the thermal resistance is the standard industry metric for comparing one thermal solution to another. The second set of tests was designed to investigate the response of the cooling system to a simulated TMU failure. In the event of a TMU failure, it is imperative that no damage be sustained by any of the servers. The third set of tests was a series of burn-in tests designed to expose weak points in the thermal solution. Further details are provided in the ***Thermal Resistance***, ***Simulated TMU Failure***, and ***Burn-In Tests*** sub-sections of this section.

Thermal Resistance

The thermal resistance measurements were conducted with two Itanium IIs provided by PNNL. According to PNNL, these CPUs were rejected by PNNL due to excessive CMC errors, but that they remained fully functional, and fully

capable of generating their maximum power dissipation. For the thermal resistance measurements, it was important that the CPUs dissipate their maximum power.

The integrated heat sinks (i.e., lids) of the CPUs had a 0.030" diameter blind hole drilled to their centers. This enabled ISR to insert a single “T” type thermocouple in order to measure the case or lid temperature. A spray module was also modified with a 0.030” diameter hole in the center of its base plate to accept a thermocouple.

Results of these tests are shown in **Table 9**. The average case-to-water thermal resistance for the SprayCool solution was 0.421°C/W, while that for the air-cooled solution averaged 0.595°C/Watt, which is 41% higher. It is important to note that the ambient for both thermal solutions is in fact the facility’s process chilled water.

On average, the diode temperatures are 13°C warmer than the case temperature. Qualitatively one would expect the diode temperature to be greater than the case measurement. Of course this is very dependent on the actual location of the diode, whether it is on the edge or is actually measuring a junction value. It is also very dependent on the accuracy and precision of the thermal diode. However, because two different CPUs are reporting with very similar traits it may be that the location is the more likely cause of the discrepancy. Efforts to research this disparity did not indicate the true location of the diode nor did it reveal any indications of the transducer's accuracy.

File	Processor	Amb (°C)	Processor Power (W)	Res Press (psia)	Pump Discharge (psid)	Facility Water (°C)	Coolant In (°C)	Cold Plate (°C)	Lid Temp (°C)	Diode (°C)	Spray Module to Coolant (°C)	Diode to Lid (°C)	Resistance Case-to-Water (°C/W)	Resistance Diode-to-Water (°C/W)
SPRAY COOLING														
051905f	CPU 0	24.5	85.6	13.5	20.0	7.0	18.2	37.8	42.2	55.0	19.6	12.8	0.41	0.56
	CPU 1	24.5	82.5	13.5	20.0	7.0	18.2	37.0	41.9	56.0	18.8	14.1	0.42	0.59
051905f	CPU 0	24.5	85.7	13.5	20.0	7.0	18.2	37.9	42.3	55.0	19.7	12.7	0.41	0.56
	CPU 1	24.5	82.5	13.5	20.0	7.0	18.2	36.6	41.5	55.0	18.4	13.5	0.42	0.58
051905G	CPU 0	24.5	85.7	14.1	20.0	7.0	19.8	39.2	43.6	57.0	19.4	13.4	0.43	0.58
	CPU 1	24.5	82.9	14.1	20.0	7.0	19.6	39.0	43.8	57.0	19.4	13.2	0.44	0.60
AIR-COOLING														
012705d	CPU 0	23.9	92.7	NA	NA	7.0	NA	NA	60*	73.0	NA	13.0	0.57	0.71
	CPU 1	23.9	82.8	NA	NA	7.0	NA	NA	58*	71.0	NA	13.0	0.62	0.77

Table 9: Thermal resistance results for air-cooling and SprayCool thermal solutions (*Note: the air cooled lid temperatures were interpolated from the SprayCool lid-to-diode data taken with modified CPUs.

Simulated TMU Failure

A TMU failure is of significant concern to PNNL. In the event of a TMU failure, it is imperative that none of the servers sustain any damage.

ISR worked with PNNL to implement a shutdown procedure for the rack in the event of a TMU failure. The head node was programmed to accept a continuous heartbeat from the TMU. In the event of a TMU failure, the heartbeat will cease, signaling that there is an issue with the TMU. At this point, the head node is

programmed to execute an orderly shutdown of all the servers in the rack. The success of this approach hinged on the ability of the head node to bring all the servers down before any of the CPUs reached their shutdown temperature (thought to be a junction temperature of between 120 and 130°C) due to a loss of coolant supply. Even though the Itanium IIs are designed to disable their power input in the event of a loss of cooling, PNNL did not want to risk any damage to any of the CPUs, and also did not want to have to deal with a server's OS being corrupted due to a hard shutdown. This was verified by simulating a TMU failure first for a single server, then for the full rack of servers.

A test was conducted in which the coolant supply to a single node (M1014 or Node 2) was suspended. It took approximately 46 seconds for the server to issue a warning that the CPUs were in an overheat condition, after which the server shut itself down. The same test was then conducted on the full rack, with the head node "in control" of all the servers in the rack. The head node took approximately 30 seconds to shut the full rack of servers down, meaning that none of servers went into a hard shutdown.

Burn-In Tests

Three series of burn-in tests were run on the rack prior to shipping to PNNL. The burn-in tests were run for a fixed set of conditions as outlined in **Tables 10** and **11**. **Table 10** outlines the steady-state conditions used for the burn-in tests, while **Table 11** outlines the dynamic conditions used for the burn-in tests. For the steady-state tests, BurnI2 was used to fully exercise all the CPUs in all the servers. For the dynamic tests, the servers executed a dynamic script developed by PNNL.

Mustang Liberator

Steady State Test matrix (conducted as near to 1 atm TMU reservoir pressure and 22°C ambient room temperature as possible)

* tests conducted with Tygon tubing installed between TMU and rack manifold

	Variable 2 10C Fluid	20C Fluid	30C Fluid	15psid TMU Discharge press	20psid TMU Discharge press	25psid TMU Discharge press	30psid TMU Discharge press	FULL M1005, OFF Remain	FULL M1005_ IDLE Remain
Variable 1 10C Fluid				X	X	X	X		
15C Fluid				X	X	X	X		
20C Fluid				052105e	052105d	052105b	052105c	X	X
25C Fluid				052005d	052005c	052105a	052005e		
15psid TMU Discharge press									
20psid TMU Discharge press								X	X
25psid TMU Discharge press									
30psid TMU Discharge press									
FULL M1005, OFF Remain									
FULL M1005_ IDLE Remain									
FULL M1005,M1014,M1022_ OFF Remain									
FULL M1005,M1014,M1022_ IDLE Remain									
PF5060		X							
+1psi restriction on fluid return to TMU @ 20C Fluid									
+2psi restriction on fluid return to TMU @ 20C Fluid									
+3psi restriction on fluid return to TMU @ 20C Fluid									
+4psi restriction on fluid return to TMU @ 20C Fluid									
+5psi restriction on fluid return to TMU @ 20C Fluid									

Table 10: Steady-state test matrix for the rx2600 system (tests that were executed are shown with a file name).

Mustang Liberator									
Dyanmic Test matrix (conducted as near to 1 atm TMU reservoir pressure and 22°C ambient room temperature as possible)									
		Variable 2 10C Fluid	20C Fluid	30C Fluid	15psid TMU Discharge press	20psid TMU Discharge press	25psid TMU Discharge press	30psid TMU Discharge press	FULL M1005_INSTANT ON remain (video of Return line)	FULL M1005,M1014,M1022_INSTANT ON remain (video of return line)
Variable 1	10C Fluid				X	X	X	X	X	X
	20C Fluid				X	070805a	X	X	X	X
	30C Fluid				X	X	X	X	X	X
	15psid TMU Discharge press								X	X
	20psid TMU Discharge press								X	X
	25psid TMU Discharge press								X	X
	30psid TMU Discharge press								X	X
	FULL M1005_INSTANT ON remain (video of Return line)									
	FULL M1005,M1014,M1022_INSTANT ON remain (video of return line)									

Table 11: Dynamic test matrix for the rx2600 system (tests that were executed are shown with a file name).

The primary objectives of the burn-in tests were to mechanically, thermally, and electrically stress key components: pumps, controller (ECS), atomizers, power supplies, switches, cabling, fluid connectors, and seals (o-ring and glue joints), at a minimum. Two steady-state and one dynamic burn-in tests were specified as follows:

BI Test #1: Run the rack fully powered and test fluid module unit (FMU) failover capability, test the ability to extract and re-insert FMU and power supplies, verify heartbeat shutdown of the rack, mechanically stress the TMU power switch and mechanically stress the failover switches. This test was designed to run over a period 10 hours, with a maximum of 30 cycles.

BI Test #2: Run the rack fully powered, with all servers running (8) instances of BurnP6. This test was designed to run 48 hours non-stop.

BI Test #3: Under normal operating procedure, PNNL's servers may cycle between idle and full power, between idle and some level below full power, or some other variation. This results in temperature cycling of the CPUs and full servers, and contributes to thermal stresses on the CPUs and peripheral devices. In order to simulate typical operating conditions, ISR worked with PNNL to create some dynamic scripts to run on the SprayCool Rack:

1. "runfseq" initiates BurnI2 on nodes starting them in a forward sequence (M1005-M1022)
2. "runrseq" initiates BurnI2 on nodes starting them in reverse sequence (M1022-M1005)
3. "runpfseq" initiates BurnI2 on nodes starting them in forward sequence with a small delay between start ups (M1005-M1022).
4. "runprseq" initiates BurnI2 on the nodes starting them in reverse sequence with a small delay between start ups (M1022-M1005).

5. “runall” initiates the entire rack simultaneously.
6. “runme” initiates a continuous loop executing commands 1-5 sequentially.

Data collection was conducted in real-time for all of the tests outlined above.

BI Test #1 Results

This test was designed to mechanically, electrically, and thermally stress the cooling solution components. A specific test procedure was designed then executed a total of thirty times. All tests began with the SprayCool Rack running normally.

The test sequence started with failing the pump module over to the fluid module unit (FMU) by engaging the appropriate button on the front of the FMU[2]. During the failover, the coolant supply pressure dropped by approximately 15 psid, before recovering to the set point of 20 psid (this drop in pressure is not considered to be serious, resulting in less than a 5°C increase in CPU temperature, as shown in **Figure 12**). The time to recover was measured at less than one second. The pump module was then disengaged and removed from the system, and then reinserted and re-engaged. Another failover was then initiated from the fluid module back to the pump module. The top power supply was then disengaged and removed. Once the capacitors on the power supply had discharged, it was then reinserted. This was repeated with the bottom power supply. A TMU soft power down was initiated using the front mounted power down button on the fluid module unit. Once power down was completed, rack shutdown was timed to verify the heartbeat communication and execution between the rack and TMU. The main power switch on the TMU was cycled and the TMU was allowed to execute its normal startup and run sequence. All of the nodes in the rack were then powered on. This completed one cycle of the test sequence.

The results from Burn-In Test #1 are tabulated below in **Table 12**. There were no observed or measured mechanical, electrical, or thermal failures during the testing[3]. There were some observations about insertion force on the bottom power supply. This is not a wear out issue, but more of a design improvement issue related to component alignment. In every situation, the failover pump recovered the system discharge pressure back to 20 psid in less than one second. For the ninth cycle, node M1020 took 8 seconds longer to shutdown than the rest of the rack. The average shutdown time was 24 seconds, with the

[2] The fluid module unit (FMU) is the “smart” module that is packaged with an ECS. The pump module is not packaged with an ECS. The default is to run the pump module and failover to the FMU in the event of a problem. The pump module can then be replaced with a fully pre-charged pump module. Failure of the FMU would require rack power down in order to replace it.
[3] Ultimately, it is desirable to achieve a greater number of cycles on a fully productized rack.

shortest time being 20 seconds and the longest taking 33. The longest time still fits within the 46 second CPU overheat window as described in the “Simulated TMU Failure” section (**Section 3.1.1**).

Cycle #	Time (hr:min)	Time to Recover Dischage Pressure (sec)	Time to Shutdown Rack (sec)	Observations
1	7:00	<1	20.0	NA
2	7:20	<1	22.0	NA
3	7:40	<1	21.8	NA
4	8:00	<1	21.5	NA
5	8:20	<1	23..5	NA
6	8:40	<1	20.5	NA
7	9:00	<1	22.1	NA
8	9:20	<1	21.8	NA
9	9:40	<1	29.0	Node M1020 took 8 sec longer than rest of rack to shutdown
10	10:00	<1	22.4	Installation o fthe bottom power supply required more effort than previously
11	10:20	<1	21.5	NA
12	10:40	<1	32.9	NA
13	11:00	<1	22.8	NA
14	11:20	<1	24.6	NA
15	11:40	<1	21.2	Installation o fthe bottom power supply required more effort than previously
16	12:00	<1	31.0	NA
17	12:20	<1	31.4	NA
18	12:40	<1	23.5	NA
19	1:00	<1	30.2	NA
20	1:20	<1	31.8	NA
21	1:40	<1	21.2	NA
22	2:00	<1	21.9	NA
23	2:20	<1	21.7	NA
24	2:40	<1	30.0	NA
25	3:00	<1	24.3	NA
26	3:20	<1	21.8	NA
27	3:40	<1	31.1	NA
28	4:00	<1	22.1	NA
29	4:20	<1	21.2	NA
30	4:40	<1	21.8	NA

Table 12: Tabular results from BI Test #1

BI Test #2 Results

This test was designed to run the rack fully powered, executing BurnP6, for a continuous 48 hour period. Selected results from Burn-In Test #2 are shown in **Figures 14** and **15**. **Figure 14** shows the reservoir pressure and temperature versus time, for the duration of the 48 hour burn-in test (Note that the spikes in Figure 14 are a result of temporary chiller malfunctions). Within the resolution of the data acquisition system (temperatures were reported to the nearest 1°C), the fluid in the reservoir held steady at approximately 21°C for the duration of the test. Similarly, the reservoir pressure held steady within the range of 13.1–13.3 psia. The fact that the reservoir pressure held constant, while all other variables held constant for the most part, is a very good indicator that the system was not leaking. **Figure 15** shows the CPU edge diode temperatures for the CPUs in Nodes M1014 and M1022 (all CPUs cannot be shown due to the extent of the data acquired). For Node M1014, CPU0 stayed in the temperature range of 59–60°C, while CPU1 stayed in the range of 60–62°C. For Node M1022, CPU0

stayed in the range of 61–63°C, while CPU1 stayed in the range of 63–65°C. The results demonstrate successful completion of Burn-In Test #2.

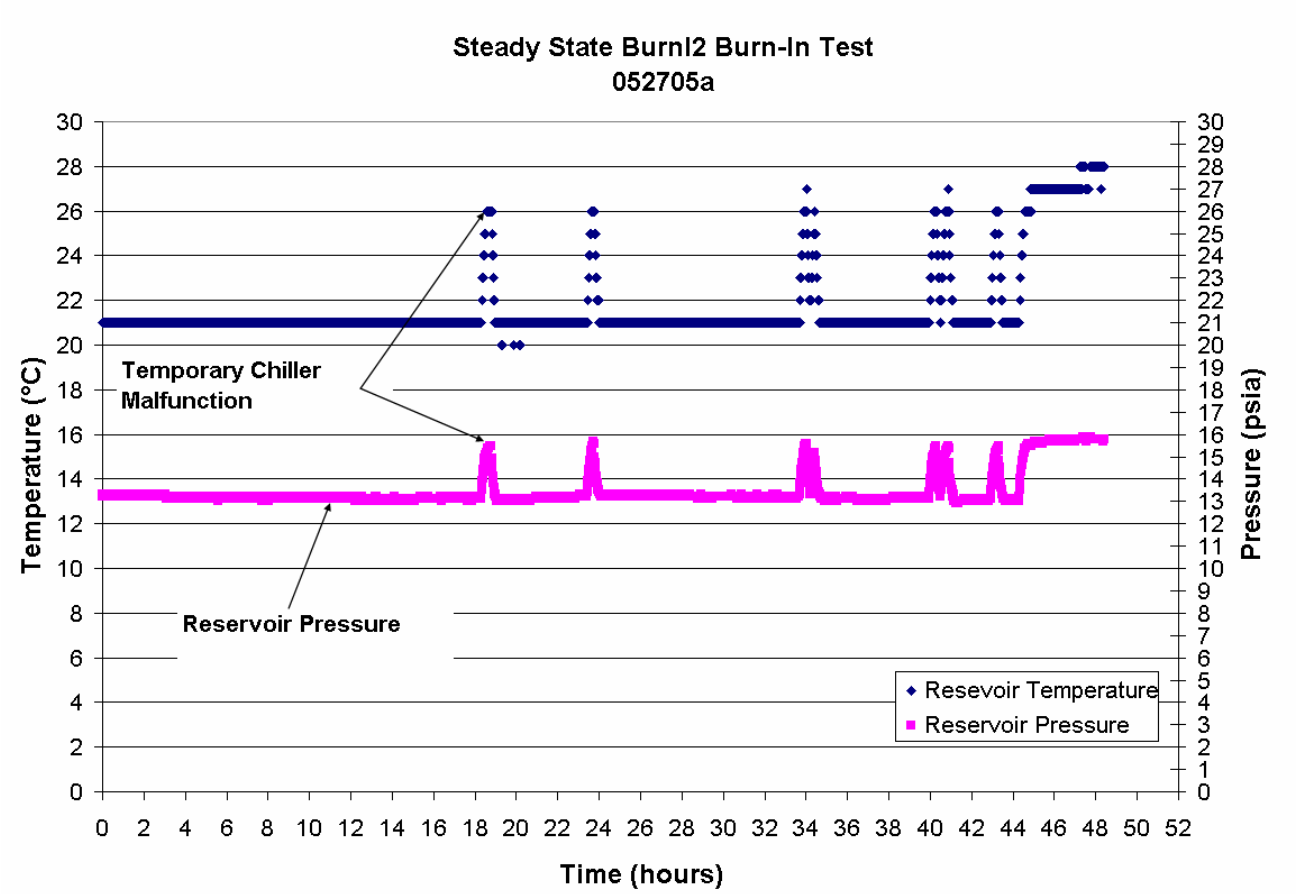


Figure 14: *Reservoir temperature and pressure during 48 hr Burn-In 052705a*

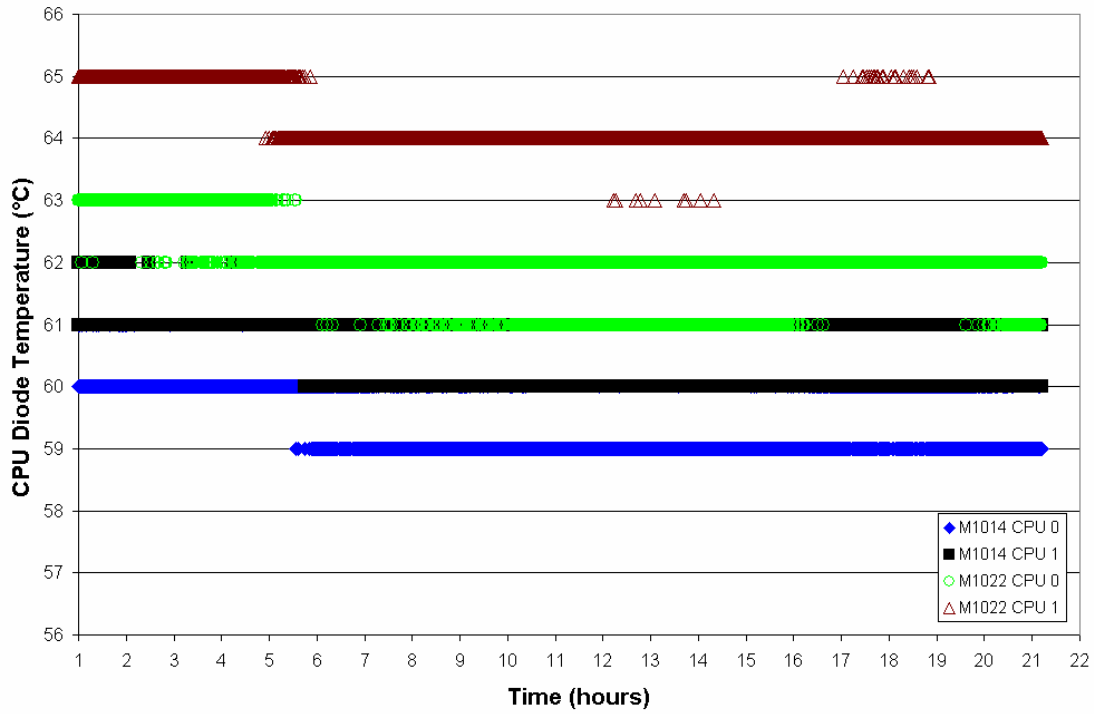


Figure 15: *Edge diode temperature readings during 48 hr Burn-In 052705a*

BI Test #3 Results

This sequence of tests was designed to run the rack under a simulated job that mimics a real job at PNNL. Only the results from the execution of Script #6 (see description for "BI Test #3) are presented in this report. Shown in **Figure 16** is a CPU edge diode temperature versus time plot for Nodes 1014 and 1022, running Script #6 for a period of 12.9 hours. Also shown on this plot is the coolant temperature over time (toggling between 20–21°C). The cooling system reservoir pressure was at approximately 13.6 psia, and the atomizing pressure was 20 psid. For clarity, the same data for Node 1022 only is shown in **Figure 17**. Accompanying **Figures 16** and **17** are **Tables 13** and **14**. **Table 13** presents results for the air-cooled rack running in two states, i.e., all nodes at idle (Test #012105B), and all nodes running BurnI2 (Test #012105A). **Table 14** presents the results for all nodes in the SprayCool rack running Script #1. As described above, the dynamic script cycles the nodes between idle and full execution. This change of state causes the processor and accompanying device temperatures to cycle, which has a direct impact on reliability. As shown in **Table 13**, the air-cooled processors cycle an average of 21.2°C, while the SprayCool processors cycle an average of 52% less at 13.9°C.

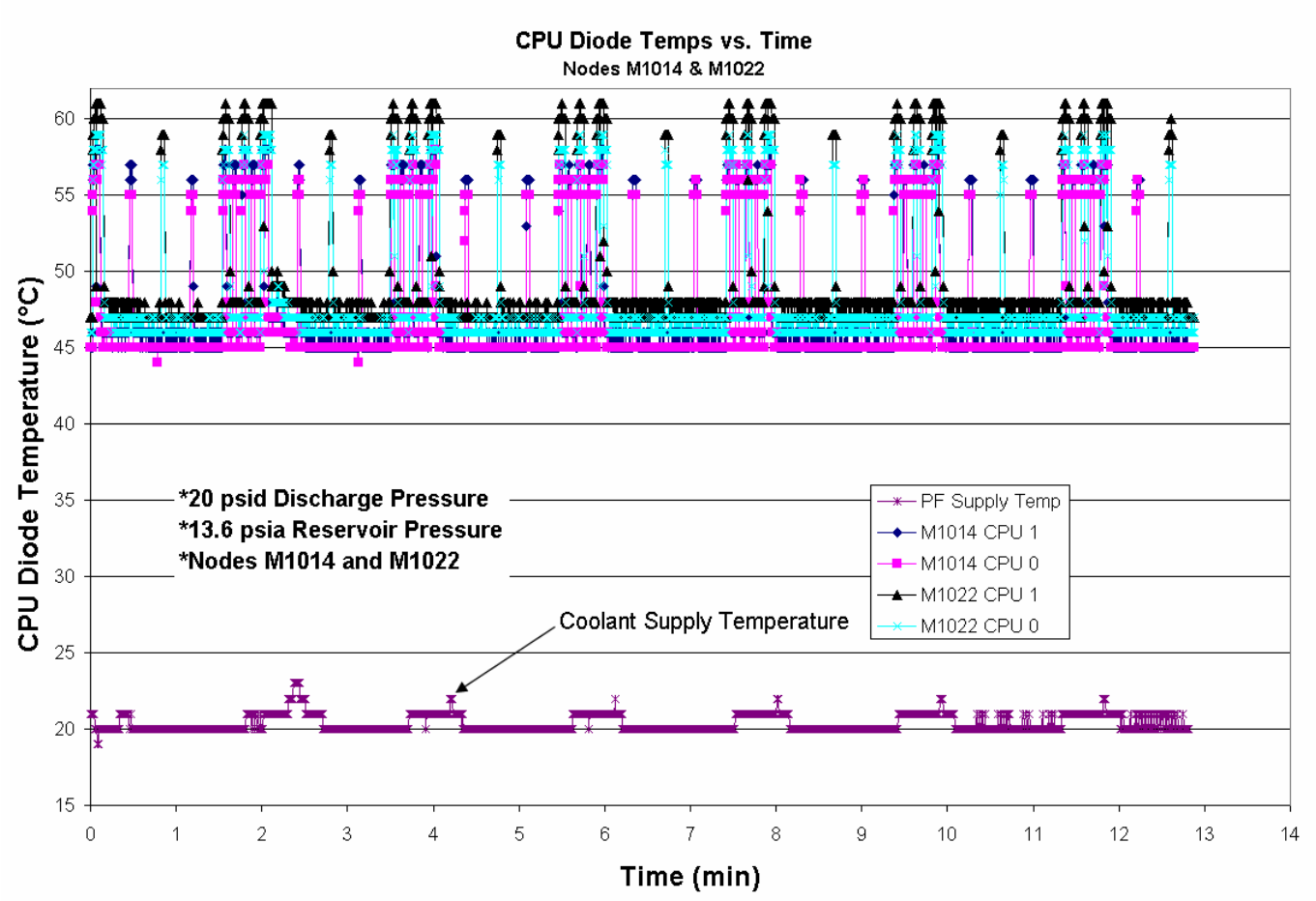


Figure 16: *rx2600 edge diode temperatures for Nodes M1014 and M1022 running dynamic scripts (051905I)*

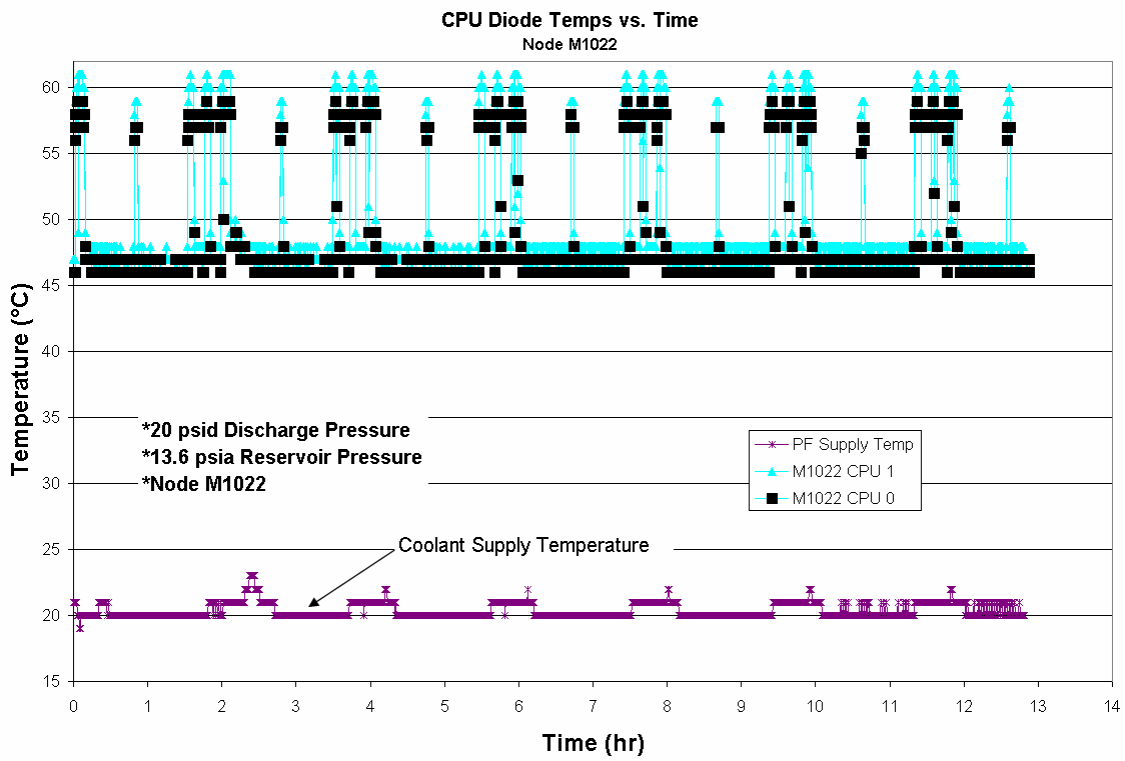


Figure 17: *rx2600 edge diode temperatures for Node M1022 running dynamic scripts (051905I)*

Node	Max CPU Temperature (°C)	Min CPU Temperature (°C)	Delta (°C)
File Name	012105b	012105a	NA
M1005 CPU 0	76	53	23
CPU 1	72	52	20
M1014 CPU 0	74	53	21
CPU 1	71	52	19
M1022 CPU 0	76	53	23
CPU 1	72	58	14
Average	73.8	52.6	21.2

Table 13: Edge diode results for air-cooled rx2600 servers running BurnI2 (012105B) and sitting idle (no jobs running - 012105A).

File	052705B				
Spray or Air	SPRAY				
LOAD	DYNAMIC				
Ave ambient (°C)	22.8				
stdev amb (°C)	1.1				
Pump Disch (psid)	20.0				
Res Press (psia)	13.3				
PF Temp (°C)	22.8				
CPU Temps/Power	MAX CPU TEMP (°C)	MIN CPU TEMP (°C)	AVERAGE CPU TEMP (°C)	STD DEV (°C)	DELTA (°C)
M1005 CPU 0	NA	NA	NA	NA	NA
CPU 1	NA	NA	NA	NA	NA
M1006 CPU 0	47.0	44.0	45.1	0.4	3.0
CPU 1	47.0	44.0	45.1	0.4	3.0
M1007 CPU 0	61.0	46.0	47.1	4.3	15.0
CPU 1	59.0	45.0	48.0	4.3	14.0
M1008 CPU 0	59.0	45.0	47.7	4.2	14.0
CPU 1	62.0	47.0	40.1	4.5	15.0
M1009 CPU 0	61.0	47.0	49.9	4.4	14.0
CPU 1	59.0	45.0	48.1	4.4	14.0
M1010 CPU 0	62.0	47.0	50.1	4.5	15.0
CPU 1	59.0	45.0	48.0	4.2	14.0
M1011 CPU 0	57.0	44.0	46.9	4.0	13.0
CPU 1	60.0	46.0	49.0	4.3	14.0
M1012 CPU 0	60.0	45.0	48.2	4.3	15.0
CPU 1	58.0	44.0	47.5	4.0	14.0
M1013 CPU 0	60.0	46.0	48.7	4.3	14.0
CPU 1	57.0	43.0	46.0	4.0	14.0
M1014 CPU 0	58.0	44.0	46.9	4.0	14.0
CPU 1	58.0	45.0	47.3	4.2	13.0
M1015 CPU 0	58.0	45.0	47.1	4.2	13.0
CPU 1	60.0	46.0	48.4	4.4	14.0
M1016 CPU 0	62.0	47.0	50.3	4.6	15.0
CPU 1	60.0	46.0	48.4	4.4	14.0
M1017 CPU 0	58.0	45.0	47.7	4.2	13.0
CPU 1	55.0	42.0	44.1	4.3	13.0
M1018 CPU 0	59.0	46.0	48.2	4.3	13.0
CPU 1	60.0	46.0	48.9	4.3	14.0
M1019 CPU 0	60.0	46.0	49.2	4.4	14.0
CPU 1	58.0	45.0	47.2	4.3	13.0
M1020 CPU 0	47.0	44.0	46.8	4.0	3.0
CPU 1	59.0	45.0	47.9	4.3	14.0
M1021 CPU 0	60.0	46.0	48.8	4.3	14.0
CPU 1	60.0	46.0	48.8	4.4	14.0
M1022 CPU 0	59.0	46.0	48.3	4.3	13.0
CPU 1	61.0	47.0	49.6	4.7	14.0
AVERAGE	58.2	45.3	47.6	4.1	12.9
MAX	62.0	47.0	50.3	4.7	15.0
MIN	47.0	42.0	40.1	0.4	3.0
STDEV	3.9	1.2	1.9	0.9	3.2

Table 14: rx2600 edge diode results for SprayCool servers running dynamic scripts

On-Site Acceptance Results

Following on-site installation at PNNL, two acceptance tests were conducted to verify system performance. The tests were very similar to the BI #2 and BI #3 tests from **Section 5.1.1.** The first test was a 24 hour steady-state BurnI2 test. **Figure 18** shows the SprayCool system data. **Figures 19, 20,** and **21** show the CPU temperatures for the three hottest nodes M1005, M1014, and M1022. The CPU temperatures for the three nodes ranged from 58°C–64°C. The temperature standard deviation, for each of the (6) CPUs, was less than 0.5°C. A low standard deviation indicates that over the 22 hour test the CPU temperatures remained stable within ±0.5°C, while the ambient air temperature within the data center fluctuated 2°C. Selected server hardware component temperatures are shown in **Figures 22—26**. Air-cooled and SprayCool server peripheral device temperatures are compared in **Table 15a,b.** The air baseline testing of the full rack was conducted at PNNL August 27, 2004, while the SprayCool baseline testing was conducted at PNNL July 18, 2005. Due to a 1.3°C difference in ambient air temperatures, a 1.3°C correction was used to compare air-cool and SprayCool temperatures for each component. Positive values in **Table 15** indicate that the SprayCool server device temperatures were running cooler. All device temperatures were cooler for the SprayCool servers, with the exception of the hard drives for nodes 2 (M1014) and 3 (M1022).

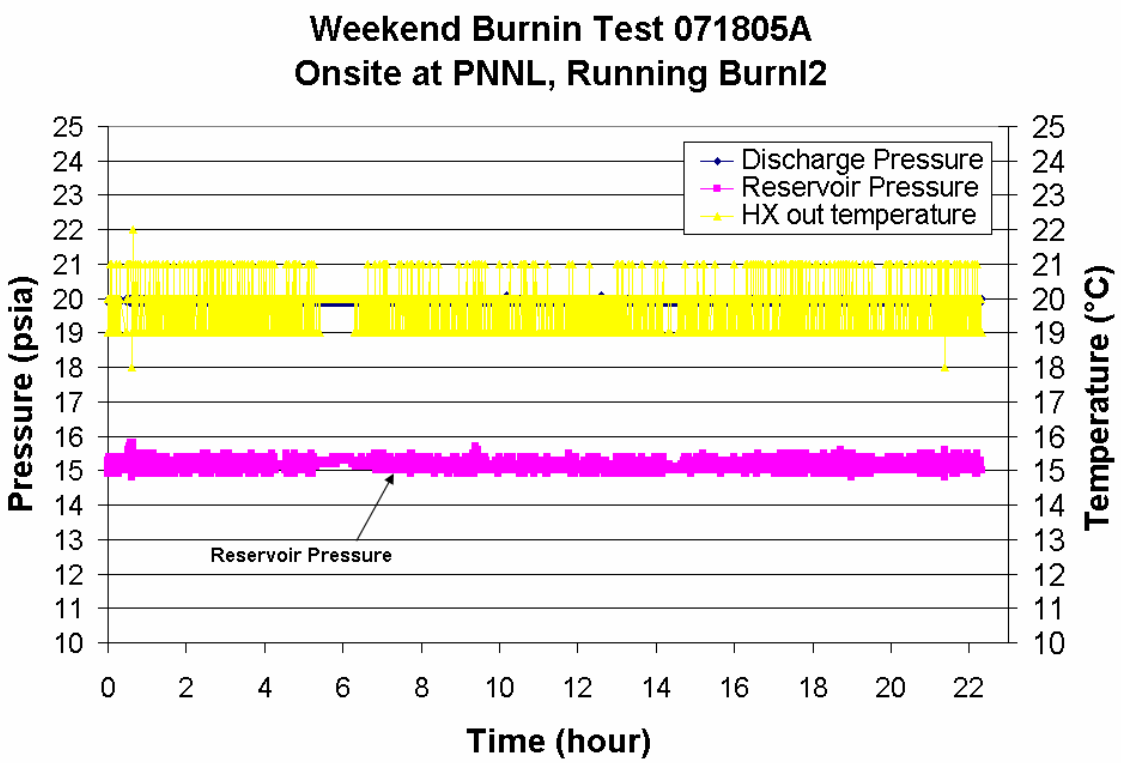


Figure 18: SprayCool rx2600 system data during steady-state acceptance test

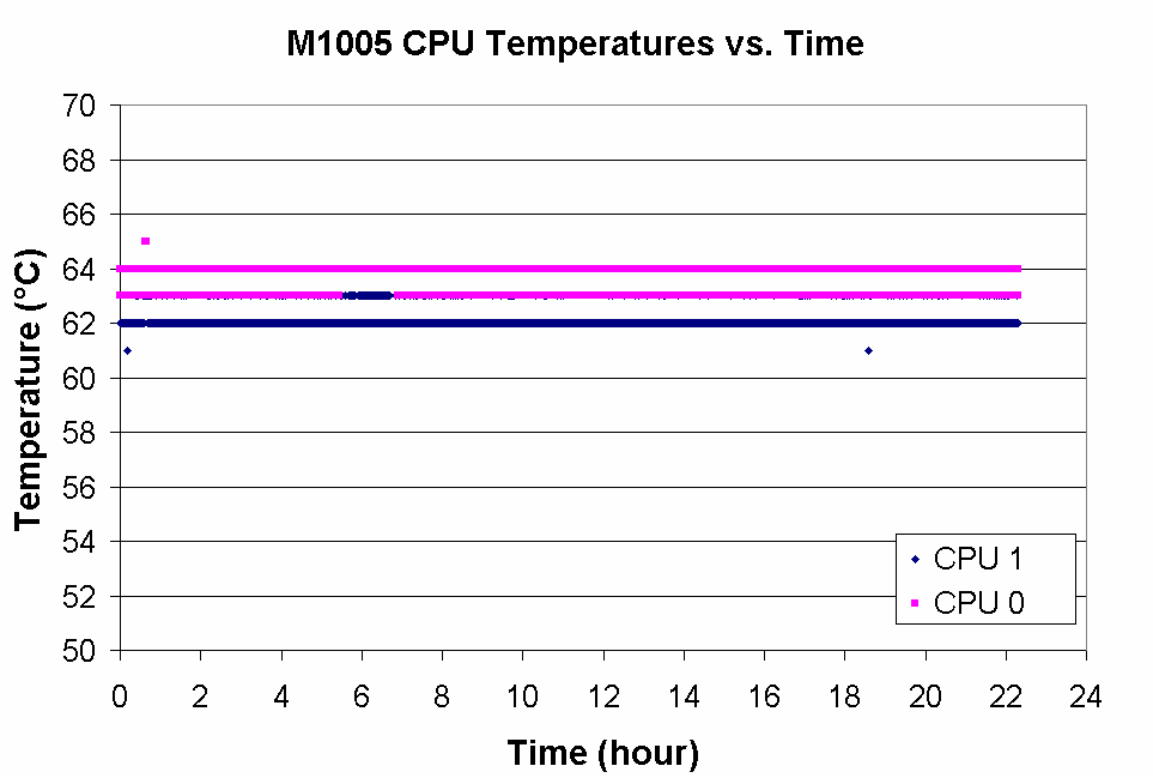


Figure 19: rx2600 node M1005 CPU diode temperature during steady state acceptance test

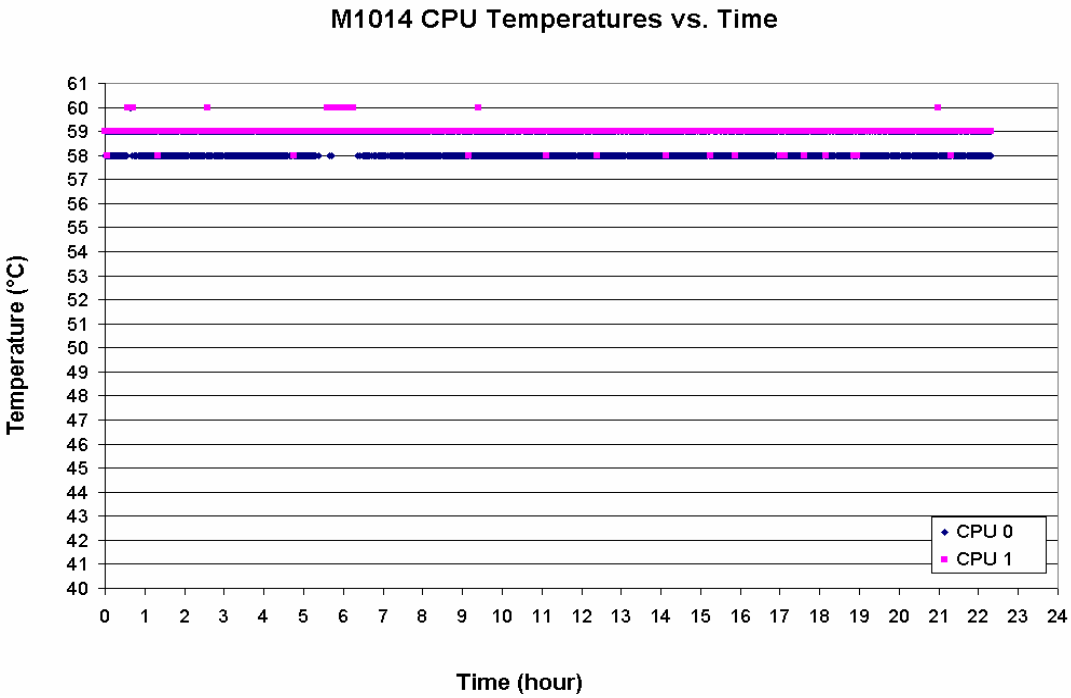


Figure 20: rx2600 node M1014 CPU diode temperature during steady state acceptance test

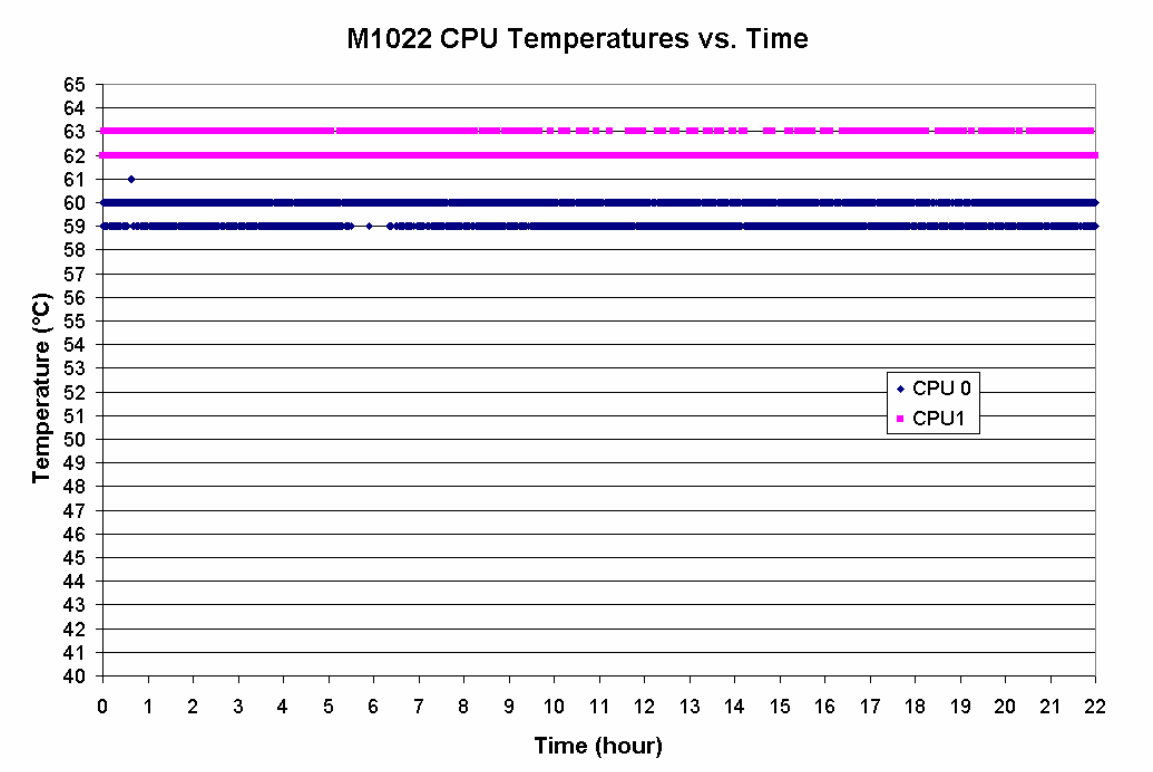


Figure 21: rx2600 node M1022 CPU diode temperature during steady state acceptance test

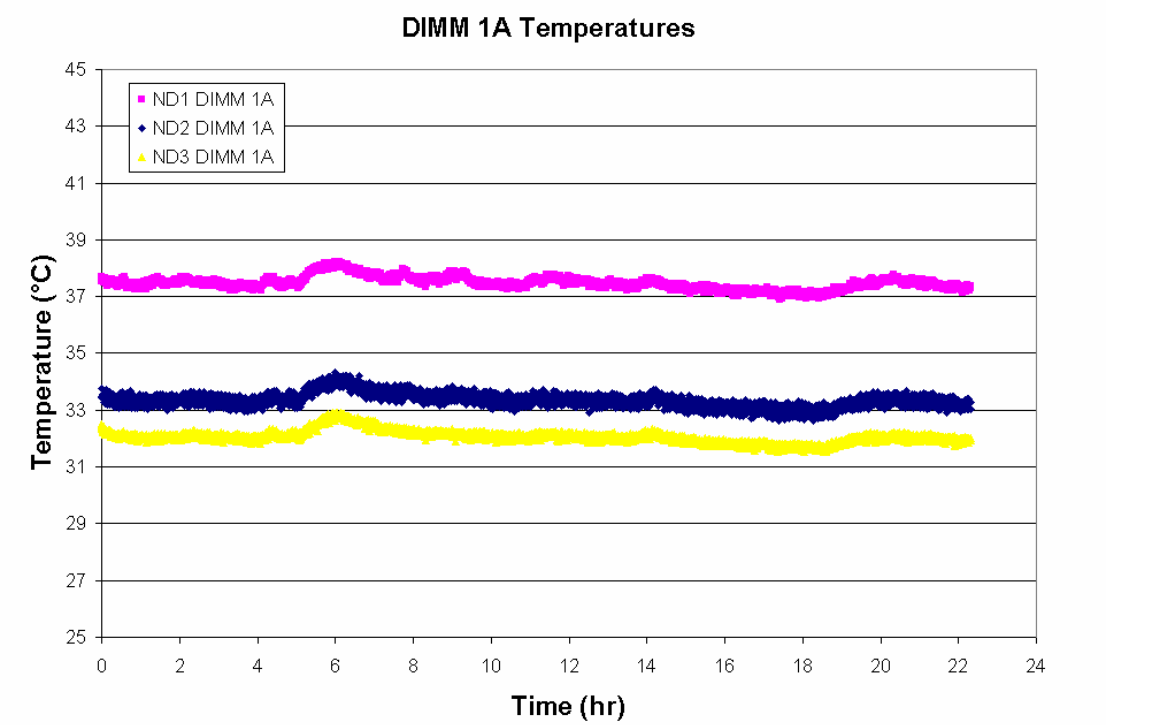


Figure 22: rx2600 DIMM 1A component temperatures during steady state acceptance test

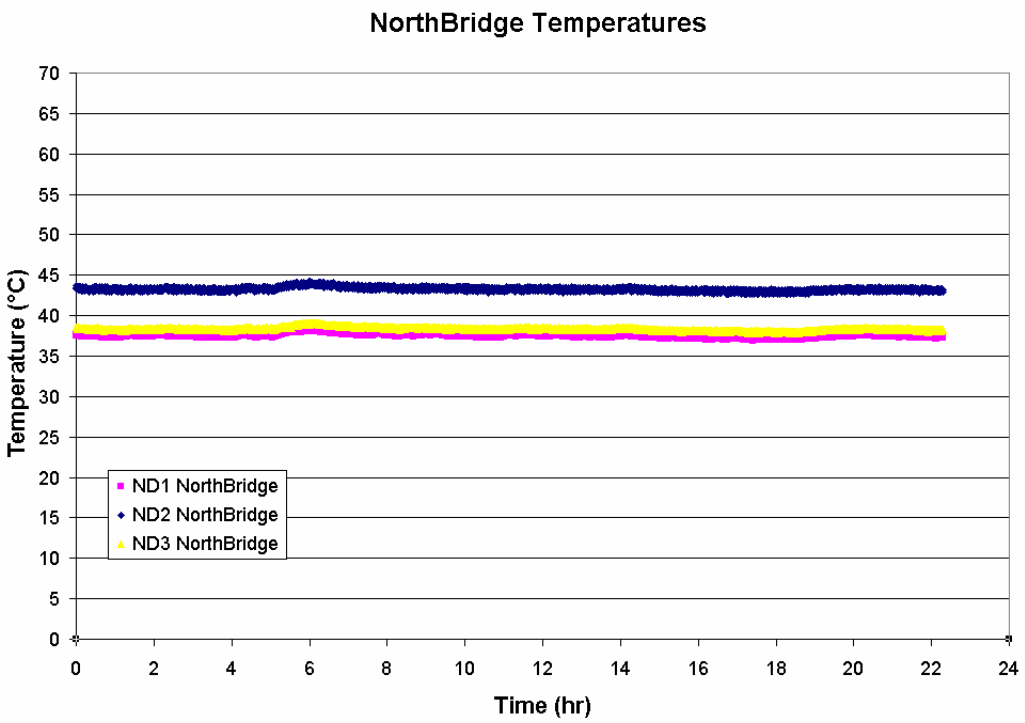


Figure 23:rx2600 north bridge component temperatures during steady state acceptance test

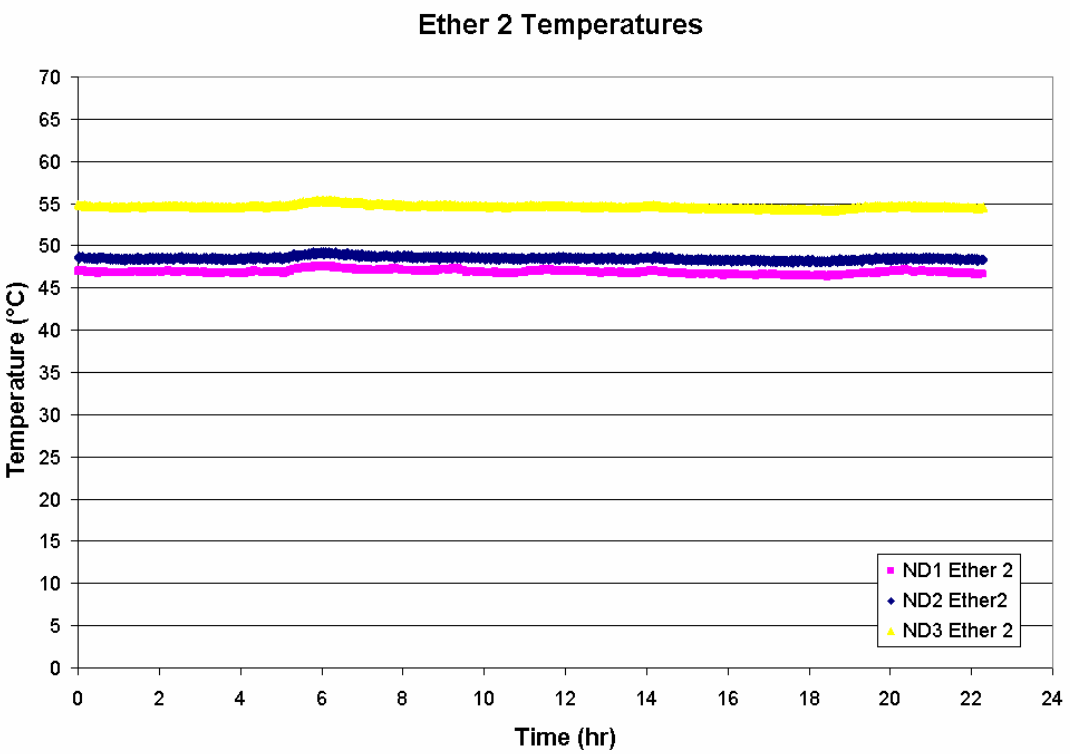


Figure 24: rx2600 Ethernet 2 component temperatures during steady state test

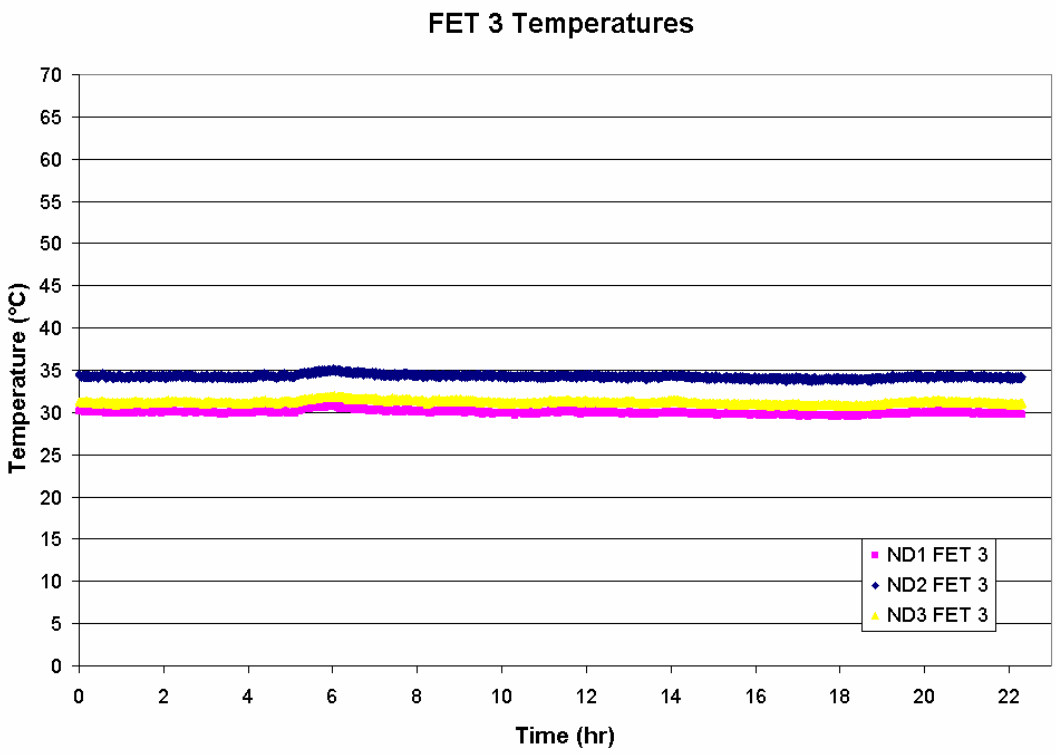


Figure 25: rx2600 FET 3 component temperatures during steady state acceptance test

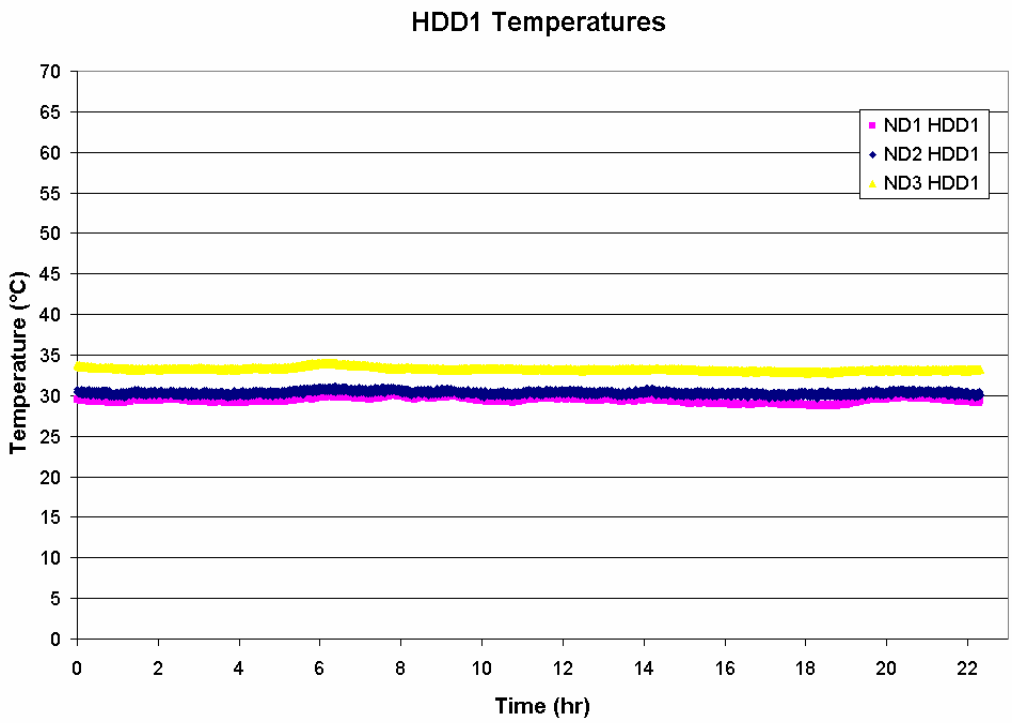


Figure 26: rx2600 Hard-Drive 1 component temperatures during steady state acceptance test

File	082705b
Spray or Air	AIR
LOAD	BURNI2
Ave ambient (°C)	14.8
stdev amb (°C)	2.1
Pump Disch (psid)	NA
Res Press (psia)	NA
PF Temp (°C)	NA

	CPU0 (°C)	CPU1 (°C)
M1005 (Node3)	73.0	68.0
M1014 (Node2)	70.0	72.0
M1022 (Node1)	67.0	71.0
average	70.0	70.3
max	73.0	72.0
min	67.0	68.0
stdev	3.0	2.1

File	071805A
Spray or Air	SPRAY
LOAD	BURNI2
Ave ambient (°C)	15.5
stdev amb (°C)	1.5
Pump Disch (psid)	20.0
Res Press (psia)	15.1
PF Temp (°C)	19.0

	CPU0 (°C)	CPU1 (°C)
M1005 (Node3)	64.0	62.0
M1014 (Node2)	58.5	59.0
M1022 (Node1)	59.5	62.1
average	60.7	61.0
max	64.0	62.1
min	58.5	59.0
stdev	2.9	1.8

Table 15a: Comparison of rx2600 server CPU temperatures (Air-cool versus SprayCool) at PNNL. A positive value indicates that Air-cool is warmer than SprayCool

File	082705b
Spray or Air	Air
LOAD	BurnI2
Ave ambient (°C)	20.4
stdev amb (°C)	3.6
Pump Disch (psid)	na
Res Press (psia)	na
PF Temp (°C)	na

Node	Component Description	Air-Cool Temperature (°C)
1	Ambient	17.0
	DIMM 1A	43.4
	NorthBridge	44.5
	ETHER 2	63.4
	FET 3	45.8
	HDD1	31.1
2	Ambient	24.1
	DIMM 1A	49.0
	NorthBridge	52.5
	ETHER 2	71.3
	FET 3	54.3
	HDD1	35.5
3	Ambient	20.0
	DIMM 1A	49.0
	NorthBridge	51.4
	ETHER 2	70.4
	FET 3	53.6
	HDD1	37.9

File	071805a
Spray or Air	SPRAY
LOAD	BurnI2
Ave ambient (°C)	16.0
stdev amb (°C)	
Pump Disch (psid)	20.0
Res Press (psia)	14.4
PF Temp (°C)	19.6

Node	Component Description	SprayCool Temperature (°C)	*Normalized Difference (°C)
1	Ambient	15.7	1.3
	DIMM 1A	34.0	8.1
	NorthBridge	37.5	5.8
	ETHER 2	53.1	9.0
	FET 3	30.0	14.6
	HDD1	29.4	0.4
2	Ambient	18.2	5.9
	DIMM 1A	35.3	7.8
	NorthBridge	43.3	3.3
	ETHER 2	57.6	7.8
	FET 3	34.3	14.1
	HDD1	30.4	-0.8
3	Ambient	14.0	6.0
	DIMM 1A	36.5	6.5
	NorthBridge	38.3	7.1
	ETHER 2	54.6	9.8
	FET 3	31.2	16.4
	HDD1	33.3	-1.4

Table 15b: Comparison of rx2600 server component temperatures (Air-Cool versus SprayCool at PNNL. A positive value indicates that Air-Cool is warmer than SprayCool. *Normalized difference takes into account the differences in ambient air temperature between Air-cool and SprayCool tests.

The second on-site acceptance test executed the PNNL dynamic script for 24 hours running script #6. SprayCool system data is shown in **Figure 27** with the first 5 minutes of test plotted in **Figure 28 (for clarity)**. The coolant supply (HX out), discharge pressure, and reservoir pressure were all held relatively constant for the duration of the testing. The reservoir pressure fluctuated between 14.0 and approximately 15.3 psia, for a corresponding 3°C fluctuation in coolant supply temperature. These fluctuations are all related to the fluctuating thermal loads from the servers, the loads of which fluctuated as the servers executed the dynamic scripts (see **Figures 29–31** for CPU temperatures). Given the thermal load fluctuations, the 1.3 psia fluctuation in reservoir pressure appears to be normal. The fact that the average reservoir pressure was constant is a very good indicator that the system did not leak.

CPU temperature data is shown in **Figures 29, 30,** and **31** for the three hottest nodes, i.e., M1005, M1014, and M1022, respectively. Server component temperatures are captured in **Figures 32—36**. For this dynamic test, the CPU temperatures did average a range of 15°C, from idle temperature to full load temperature. For the rest of the server components, temperatures were much more stable. They did not vary with CPU loading, but were more dependent on the variations in ambient air temperature.

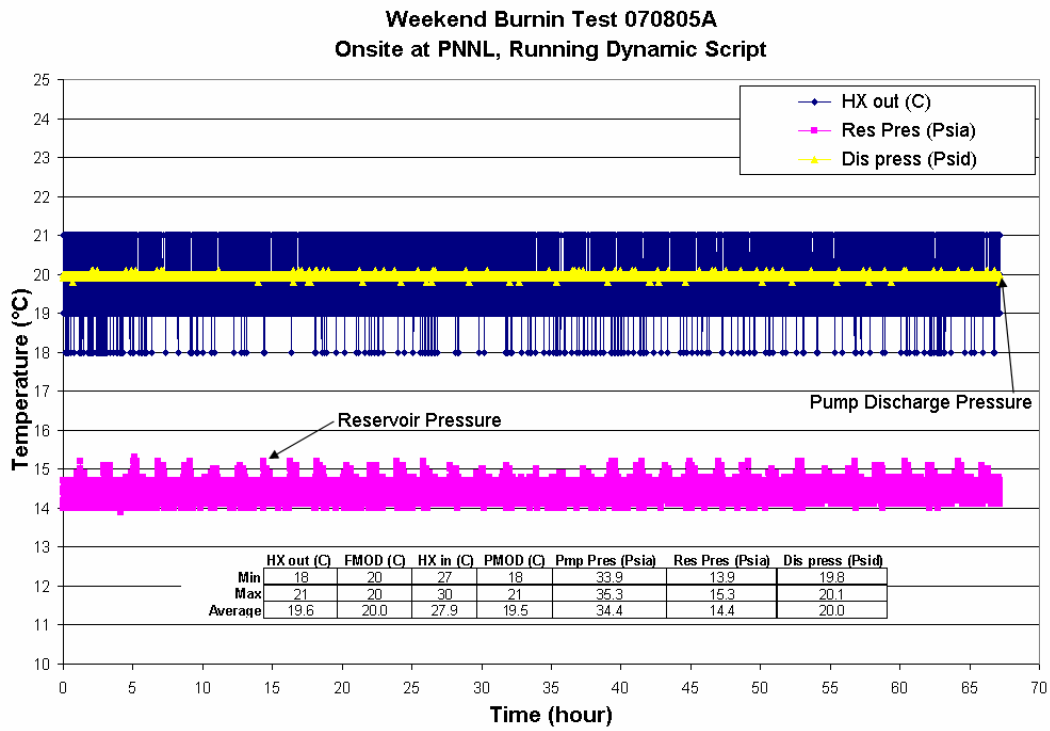


Figure 27: rx2600 SprayCool system data during dynamic on-site acceptance test.

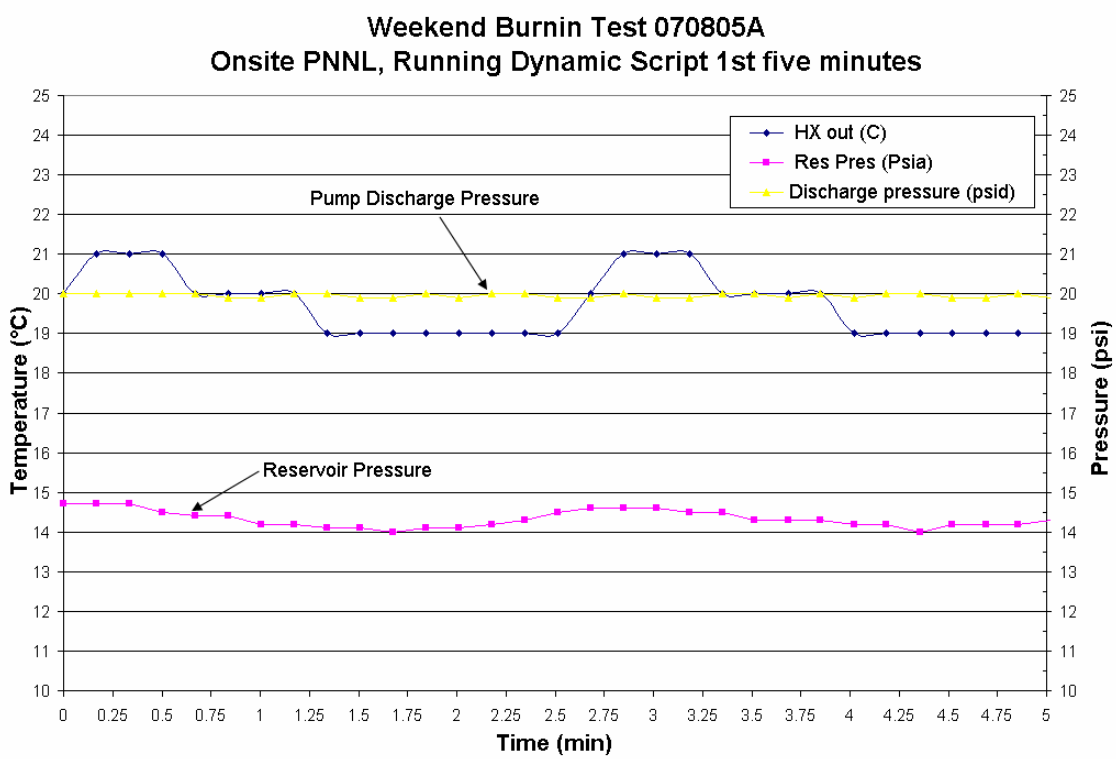


Figure 28: rx2600 node M1014 CPU0 diode temperature during 1st five minutes of dynamic acceptance test

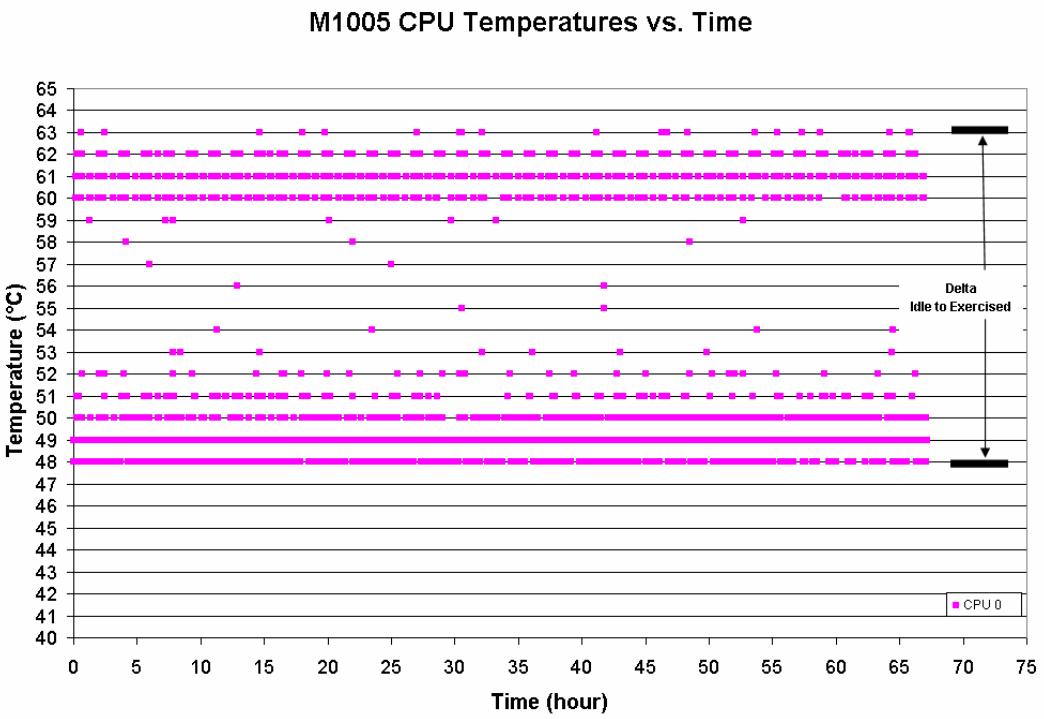


Figure 29: rx2600 node M1005 CPU0 diode temperature during dynamic acceptance test (CPU0 cycled between 48°C and 63°C)

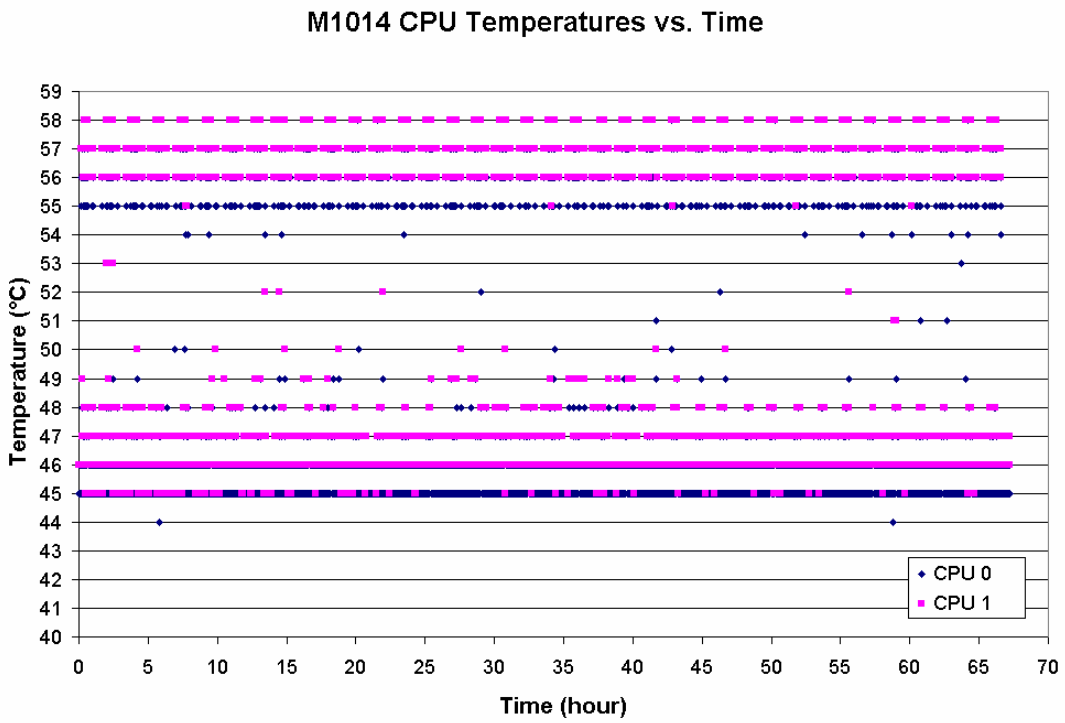


Figure 30: rx2600 node M1014 CPU diode temperature during dynamic acceptance test (CPU0 cycled between 44°C and 58°C, while CPU1 cycle between 45°C and 58°C)

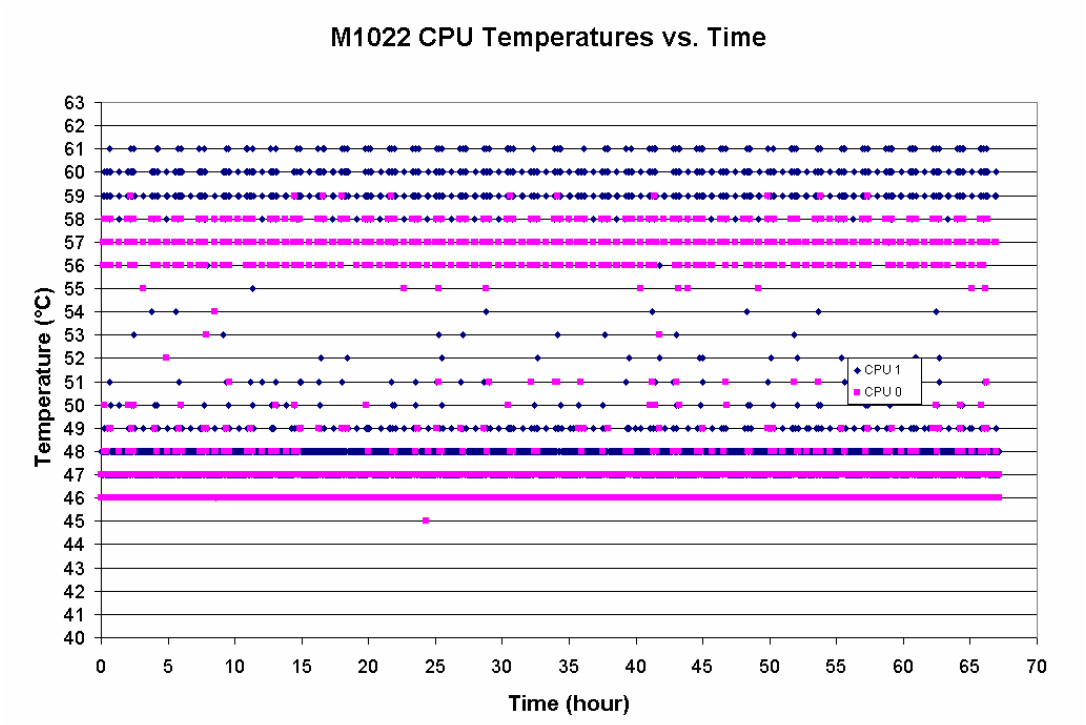


Figure 31: rx2600 node M1022 CPU diode temperature during dynamic acceptance test (CPU0 cycled between 45°C and 59°C, while CPU1 cycled between 46°C and 61°C)

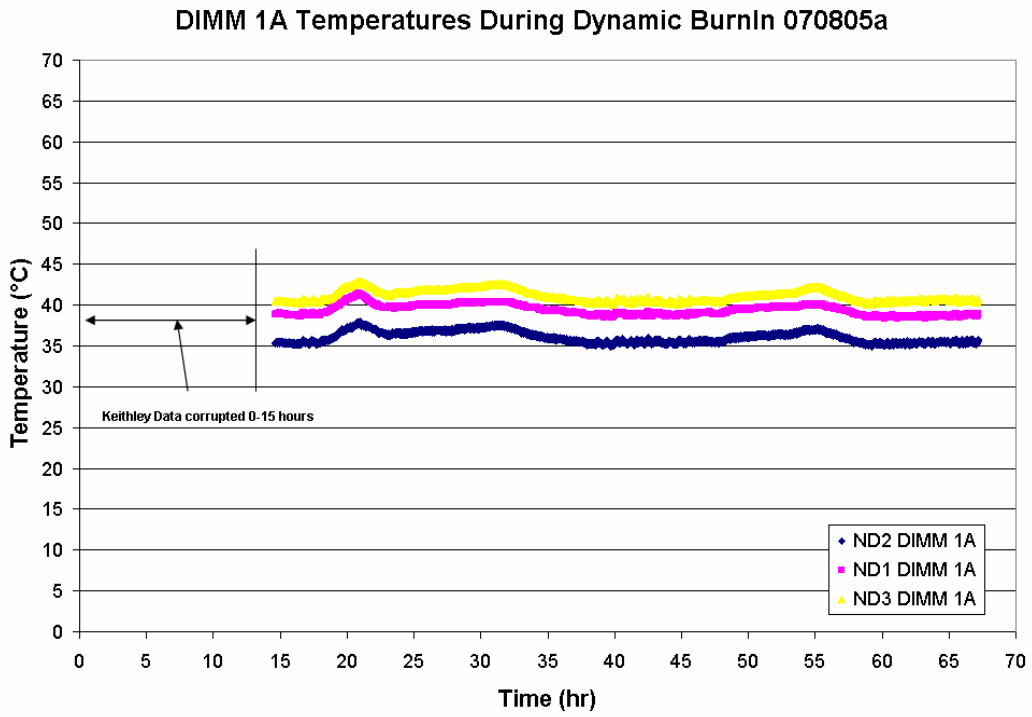


Figure 32: rx2600 DIMM 1A component temperatures during dynamic acceptance test

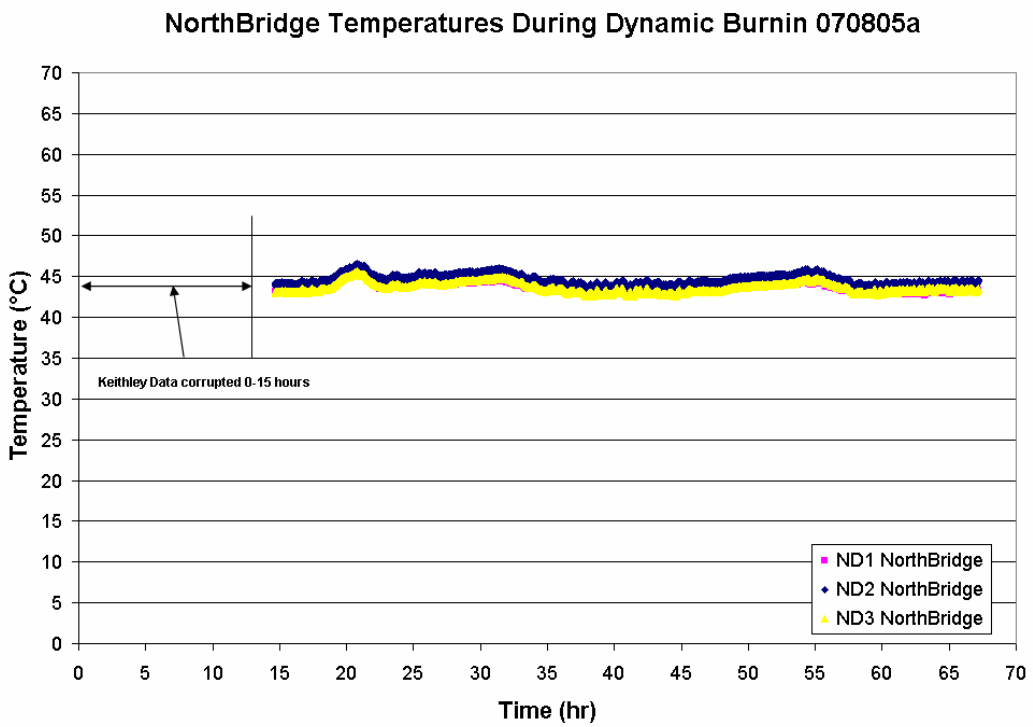


Figure 33: rx2600 north bridge component temperatures during dynamic acceptance test

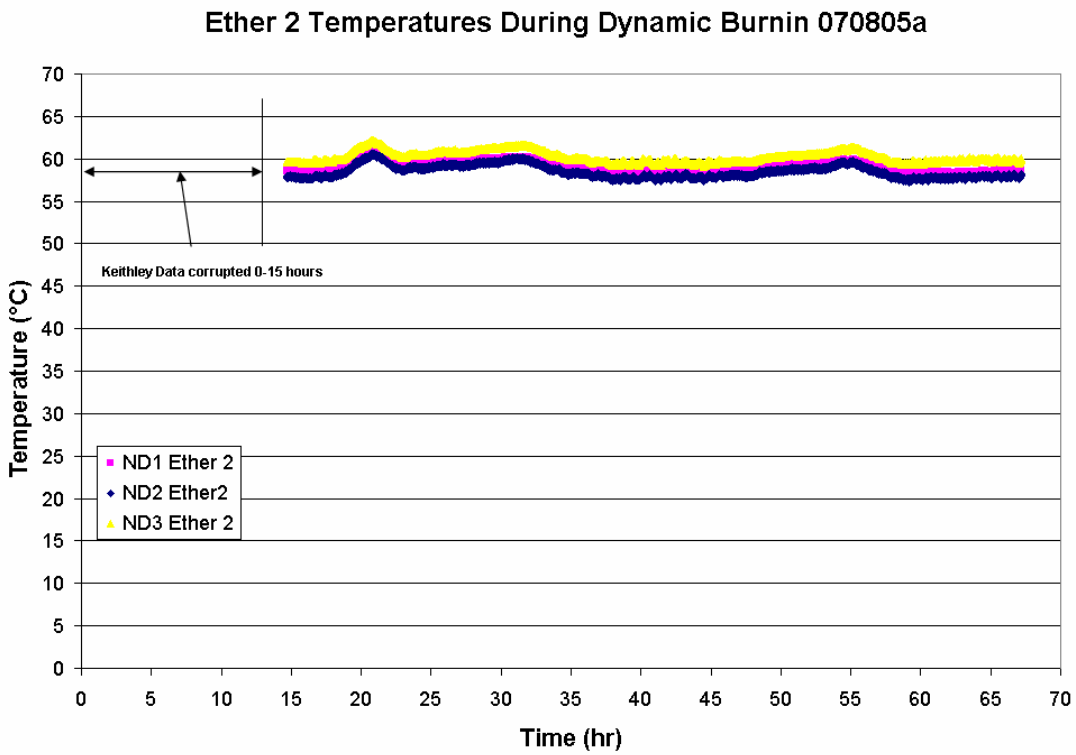


Figure 34: rx2600 Ethernet 2 component temperatures during dynamic acceptance test

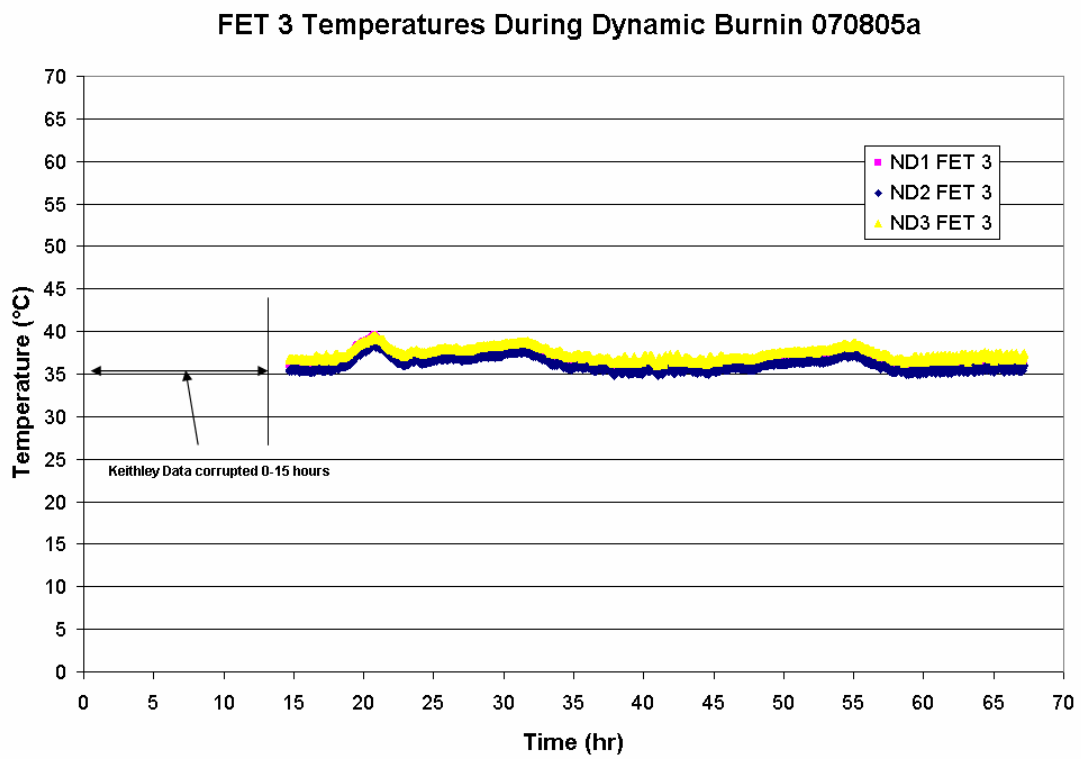


Figure 35: rx2600 FET 3 component temperatures during dynamic acceptance test

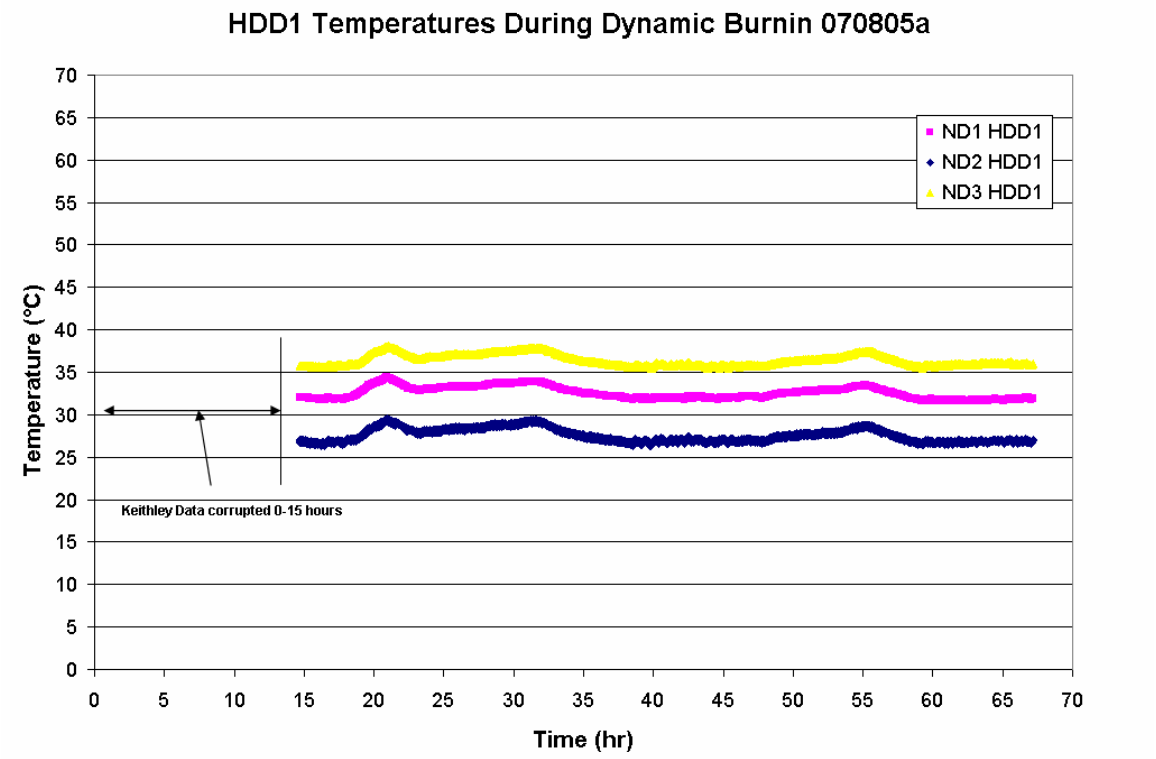


Figure 36: rx2600 Hard Drive 1 component temperatures during dynamic acceptance test

5.1.2 RLX Blade Servers

An RLX 600ex blade center and five RLX 3200ix server blades were fully instrumented with a number of thermocouples (see **Appendix B**). The servers were baselined in air in the ISR Integration Lab, then converted to SprayCool. An M/L TMU was used to cool the fluid supplied to the blades. Results from testing at ISR are provided in **Section 5.1.2**, with results from on-site acceptance testing at PNNL provided in **Section 5.1.2**. The CPUs were fully exercised using BurnP6 for all of the testing. All of the tests were steady state tests on the bench.

ISR Test Results

The comparison of the air baseline and SprayCool tests are shown in **Table 16**. The average diode temperatures for the five air-cooled blades were 56.4°C for CPU 1 and 59.8°C for CPU2. The same temperatures for the SprayCool blades were 42°C and 43°C, respectively. This resulted in an average CPU temperature reduction, after converting to SprayCool, of 14.4°C for CPU1 and 16.8°C for CPU2.

Figure 37 shows the diode temperatures plotted as a function of coolant temperature. The balance of the component data is located in **Appendix D**. There is a small amount of sensitivity of CPU temperature to coolant

temperature. RLX component temperatures are shown in **Table 17**. SprayCool equipped blades were on average 7.5°C cooler than the air cool blades.

RLX 600ex SprayCool vs. Air baseline data

FILE	030105A-H	061405B	
Cooling Solution	Air	Spray	
AMB TEMP (°C)	21.0	21.0	
EXERCISE	(8) BurnP6	(8) BurnP6	
FAN SPEED (HIGH/LOW)	HIGH	HIGH	
FLUID TEMP (°C)	NA	21.0	
DISCHARGE PRESSURE (PSID)	NA	20.0	
RESERVOIR PRESSURE (PSIA)	NA	14.1	
Blade #	CPU1 (°C)	CPU1 (°C)	DELTA (°C)
1	54.0	40	14
2	55.0	42	13
3	57.0	42	15
4	60.0	44	16
5	56.0	42	14
average	56.4	42.0	14.4
Blade #	CPU2 (°C)	CPU2 (°C)	
1	59.0	42	17
2	55.0	43	12
3	62.0	43	19
4	58.0	44	14
5	65.0	43	22
average	59.8	43.0	16.8
Blade #	BOARD (°C)	BOARD (°C)	
1	36.0	33	3
2	36.0	34	2
3	36.0	35	1
4	35.0	35	0
5	37.0	36	1
average	36	35	1
RLX Predicted CPU Temperature: Ambient + 33°C	54	54	2

Table 16: Comparison of air-cooled and SprayCool processor temperatures

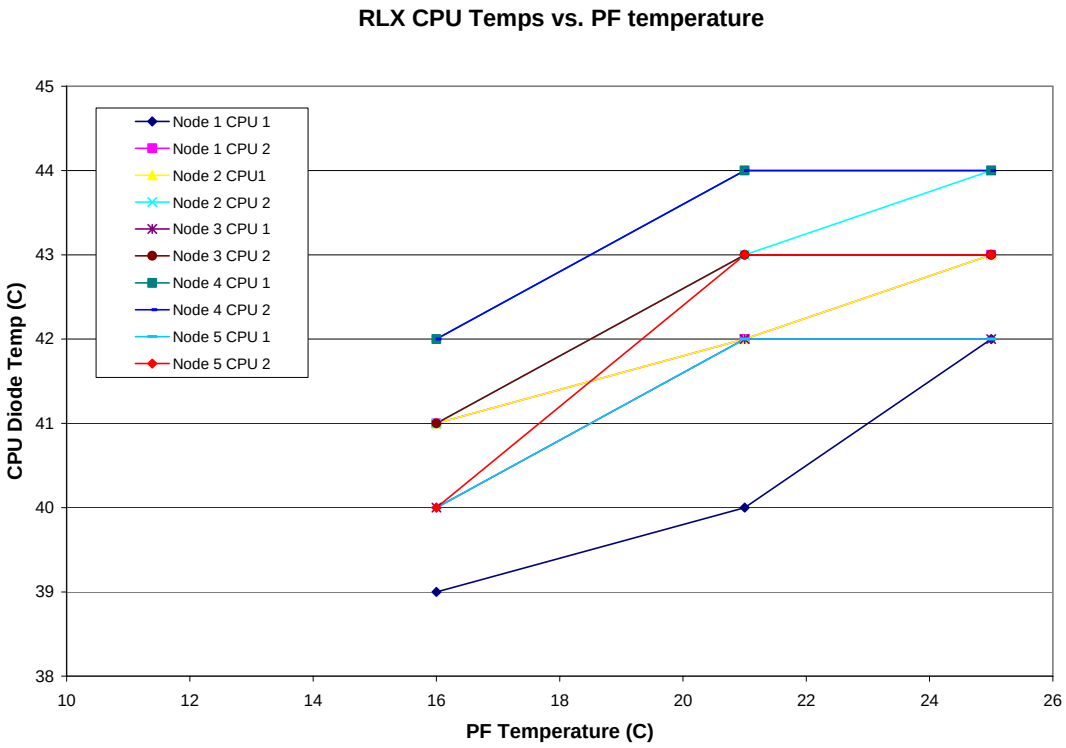


Figure 37: RLX CPU diode temperatures as a function of coolant temperature

COMPONENT DESCRIPTION	Air Cool (°C)	SprayCool (°C)	*Difference (°C)
FILE NAME	**030105A-H**	**061405B**	
ND1 AIR IN	23.2	21.2	2
ND1 AIR OUT	42.0	29.2	11
ND1 NB	45.0	36.9	6
ND1 DIMM1	44.5	35.5	7
ND1 DIMM2	46.0	35.9	8
ND1 DIMM3	47.8	37.6	8
ND1 DIMM4	50.0	36.9	11
ND1 NB2	60.4	49.0	9
ND1 PulseDC	38.0	33.3	3
ND1 LAN	48.6	38.2	8
ND1 INFINI	50.8	36.8	12
ND1 HDD	26.0	25.6	-2
ND1 FET1	44.3	35.3	7
ND1 FET2	47.0	36.1	9
ND1 FET3	48.7	35.7	11
ND1 FET4	44.5	33.5	9
ND1 FET5	39.8	31.8	6
ND1 FET6	42.0	33.7	6
ND2 AIR IN	22.3	21.3	1
ND2 AIR OUT	34.9	29.9	4
ND2 NB	43.9	37.0	6
ND2 DIMM1	46.5	37.3	8
ND2 DIMM2	48.3	37.4	10
ND2 DIMM3	50.0	38.4	11
ND2 DIMM4	51.8	39.0	12
ND2 NB2	61.9	53.7	7
ND2 PulseDC	38.2	33.6	4
ND2 LAN	45.3	37.2	7
ND2 INFINI	49.3	NA	NA
ND2 HDD	26.1	25.9	-1
ND2 FET1	44.4	35.8	8
ND2 FET2	47.2	36.3	10
ND2 FET3	48.0	35.4	12
ND2 FET4	49.4	33.9	15
ND2 FET5	45.4	33.1	11
ND2 FET6	41.0	NA	NA
Average	44.0	34.9	7.5

Table 17: RLX component temperature comparison of air cool to SprayCool for nodes 1 & 2 (Note: *the difference accounts for the slightly different ambient air temperatures).

On-Site Acceptance Test Results

Upon delivery of the RLX blade servers to PNNL, a 90-hour steady-state burn-in test was conducted to verify system performance. The processors were exercised using BurnP6 and allowed to come to steady state. Data was captured for the TMU, CPUs, and peripheral devices. TMU data is presented in **Figure 38**.

For clarity, a 2 hour section of the test is shown in **Figure 39**. The coolant temperature fluctuated between 18°C–23°C throughout the test due to variations in water flow rate. This caused the reservoir pressure to vary from 14.8 psia-16.4 psia. The correlation between coolant temperature and reservoir pressure is evident in **Figure 39** (vertical dashed lines highlight that the coolant temperature rise slightly precedes the reservoir pressure rise). Figures 39 and 40 highlight the fact that the average reservoir pressure held steady over the duration of the 90-hour test. This is a very good indication that the system was not leaking. The CPU temperatures are shown in **Table 18**. All CPU temperatures were constant over the duration of the 90-hour test.

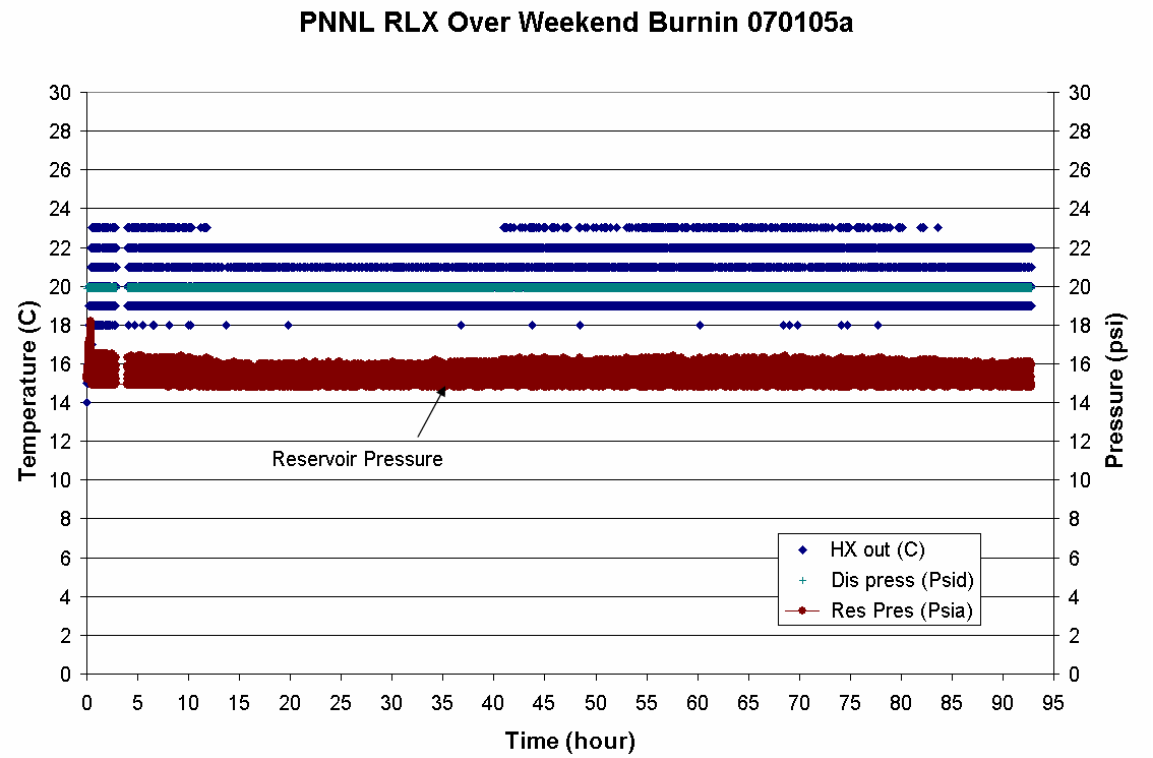


Figure 38: RLX acceptance test, SprayCool system data

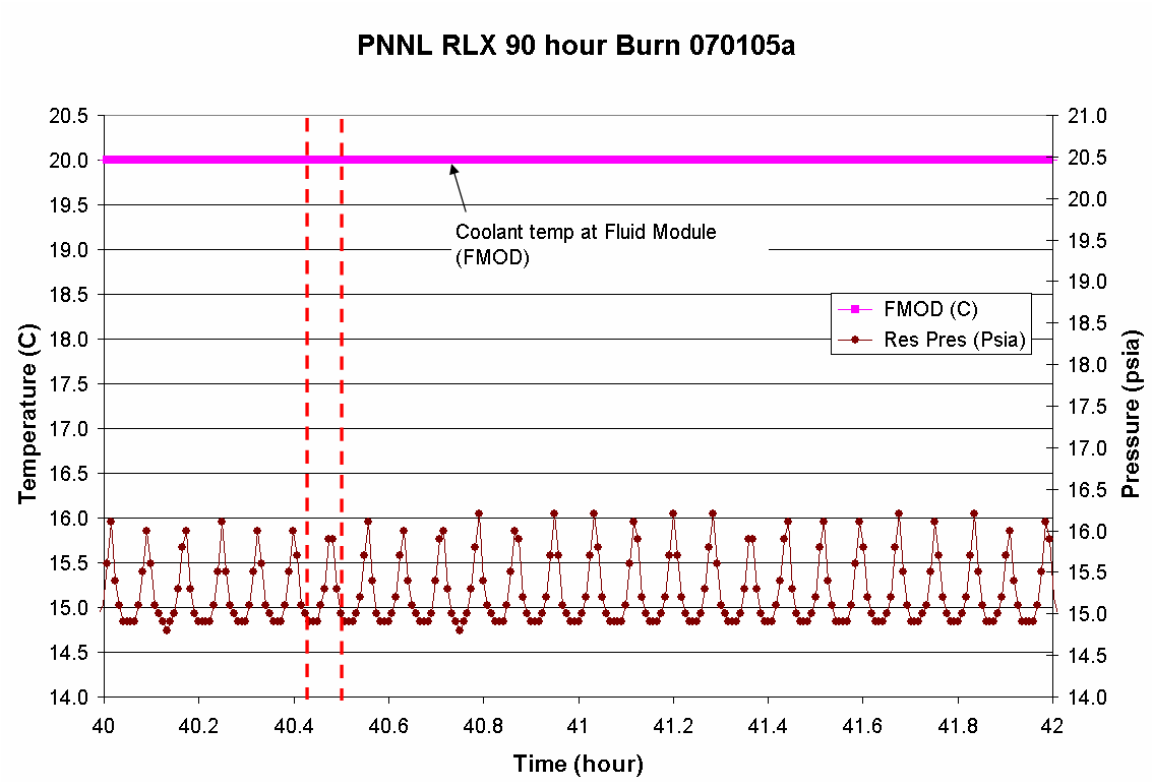


Figure 39: RLX acceptance test, SprayCool system results for 2 hour section from 40-42 hour marks

CPU Diode Temperatures for 90 hr Acceptance Test 070105a																
		Slot 1			*Slot 2*			*Slot 3*			*Slot 4*			*Slot 5*		
Date	Time	Internal	CPU1	CPU2	Internal	CPU1	CPU2	Internal	CPU1	CPU2	Internal	CPU1	CPU2	Internal	CPU1	CPU2
070105	12:00pm	28	43	45	29	45	46	31	45	46	31	44	45	32	44	45
	1:00pm	29	41	43	30	43	43	31	42	43	31	43	44	31	42	43
	2:00pm	29	40	43	30	43	43	31	42	43	31	44	44	32	42	43
	3:30pm	28	41	43	30	43	44	31	42	43	31	44	44	31	42	43
070505	8:30am	29	40	42	30	43	43	31	42	43	31	43	44	31	42	43

Table 18: RLX acceptance test SprayCool CPU data

5.1.3 Global SprayCool System

The Phase 1 program was re-scoped to include not only the demonstration of a multi-processor board optimized for SprayCool, but also the delivery of a system with four of these boards in place. Unlike the HP rx2600 servers cooled with a spray module on the CPU, these boards have all the electronics sprayed in a sealed card cage. This Global SprayCool system enables large advances in densification due to the more efficient heat removal characteristics of evaporative cooling, with the current system demonstrating 380W per slot in a 20 slot cPCI form factor chassis.

Figure 40: Global SprayCool System

ISR Test Results

The testing overview for the Global SprayCool System (GSCS) is documented in **Section 4.1.4**.

The GSCS was fully characterized by ISR under a different effort (non-DOE funding). The only difference between the system tested and the one delivered to PNNL is that 2.2 GHz CPUs were test under a separate effort, while 2.4 GHz CPUs were delivered for this effort. For all tests, bare CPU die were employed. The version of the MPB tested does not have the capability to read the CPU edge diode, so an alternate means of determining whether the CPUs were within specifications had to be devised. This was done by attaching thermocouples to the side of the CPUs on both the core side and the cache side of a specific bare die. This CPU was then tested using a different board (i.e., High Performance Thermal Emulator, HPTE) that does have the capability to read the edge diode.

An additional CPU with its integrated heat sink (i.e. lid was still attached), and a thermocouple embedded within the lid, were also used. All testing was done in an effort to provide a correlation between the core-side thermocouple, the edge diode, and the lid[4]. The results are shown in **Figures 44** and **45**. There is a very close correlation between the edge diode and core-side thermocouple for the conditions tested (note that this was for the same die). The comparison to the lidded die results (please see **Figure 45**) shows an approximate 1–2°C temperature difference with the lid. For the results reported in **Figure 46**, the results reported for the thermocouple attached to the core side of the CPU should be adjusted upwards by 2°C in order to approximate the actual lid temperature.

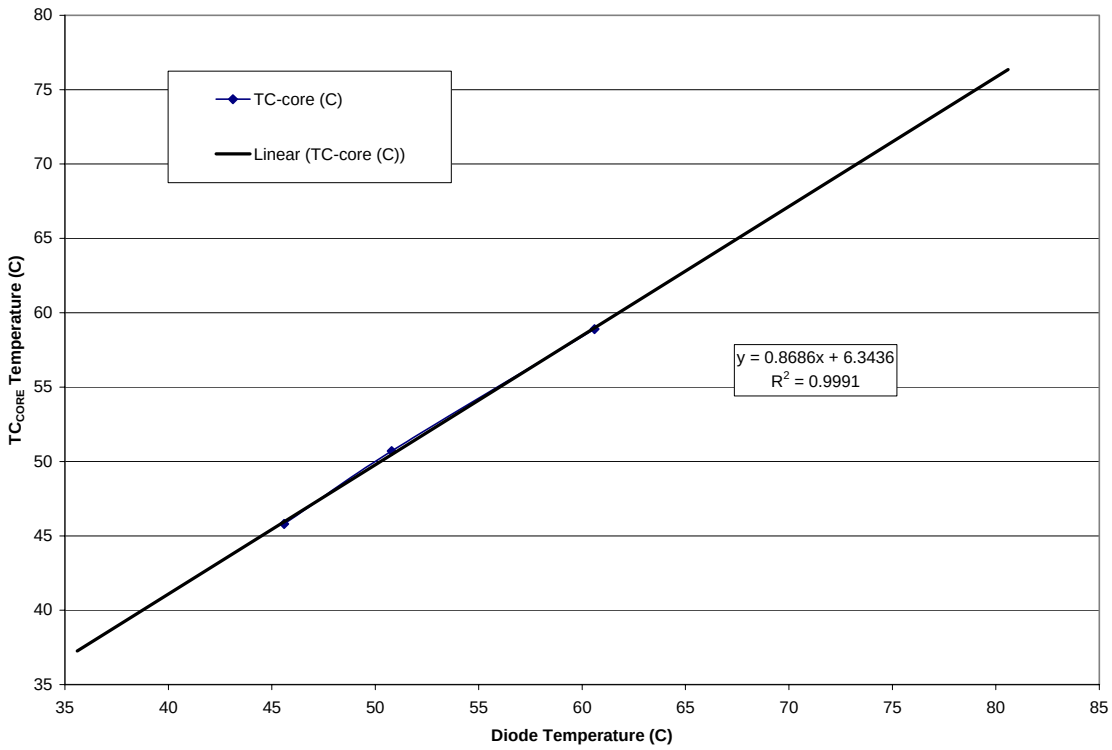


Figure 41: *MPB bare die (thermocouple attached to core) to edge diode temperature comparison.*

[4] Ultimately, it is advantageous to be able to correlate the readings from the thermocouple attached to the side of the bare die to AMD's specifications for the CPU. For the 2.4 GHz CPU, AMD specifies that the lid temperature should not exceed 70C.

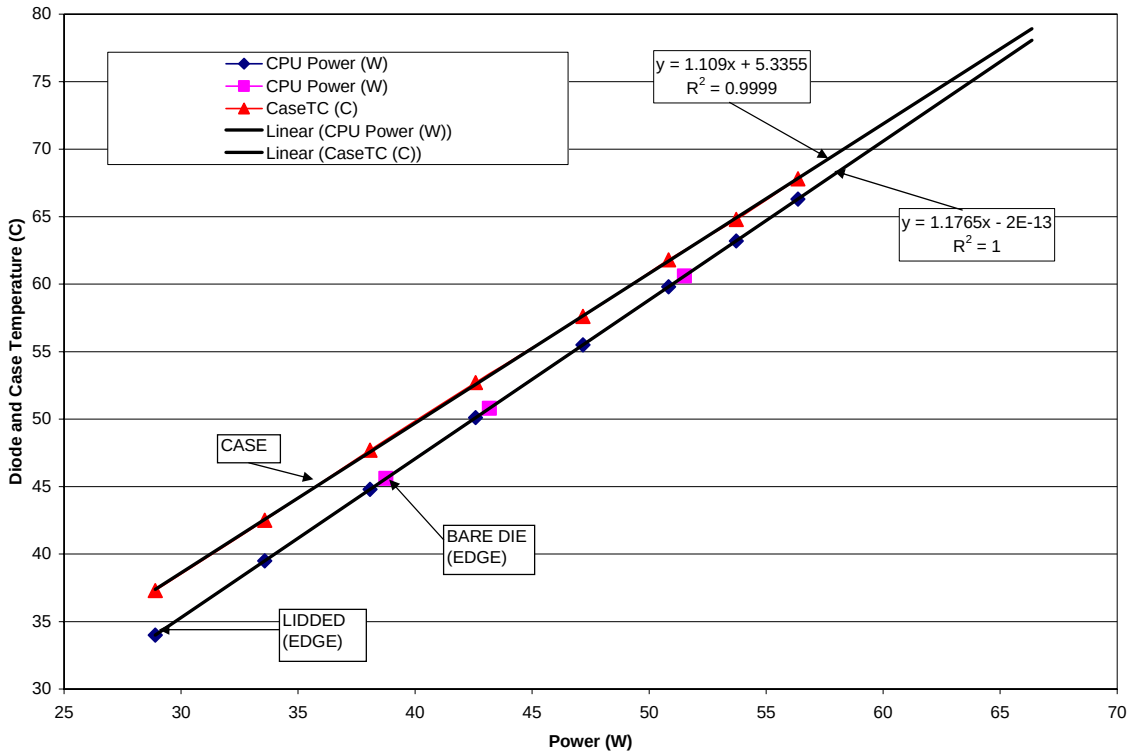


Figure 42: *MPB diode and case temperature as a function of power dissipation, "EDGE" temperatures are the thermocouples bonded to the CPU core. Note: "CASE" temperature was measured using the HPTE board in a separate test setup. This data is used to correlate the attached thermocouples to the CPU reported case temperature*

Figures 43 – 46 present the results for testing of the MPB subsystems (i.e., the dense stacked memory, dense power supply module, MPB motherboard, and the CPUs). Note that the CPU temperatures for **Figure 46** were measured with a thermocouple attached to the core-side of the CPU. The results were generated using a benchmark routine designed to stress the CPUs and memory to the highest combination level possible[5].

[5] The benchmark routine consisted of a combination of CPU Burn and nBench to fully exercise the CPUs and benchmark performance, along with Memtest86 v3.2 to fully exercise and diagnose the dense memory.

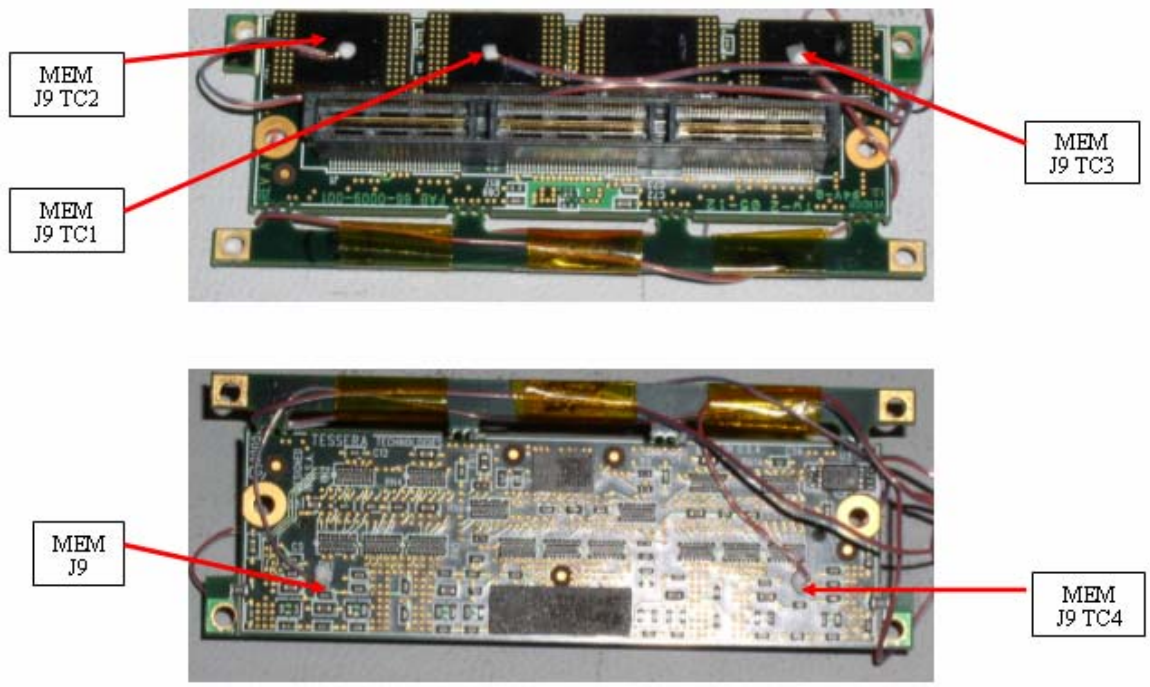


***Figure 4**3a: Thermocouple measurement points **on the MPB memory daughter boards for the** below time-averaged dense memory temperatures*

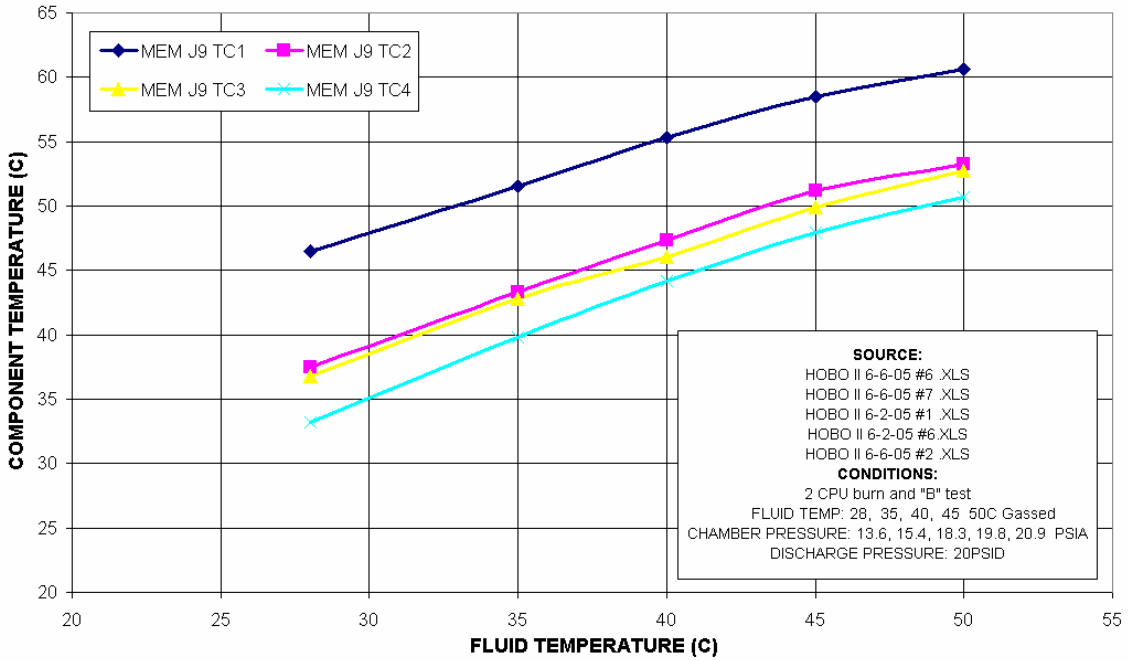


***Figure 43b:** Time-averaged dense memory temperature results*

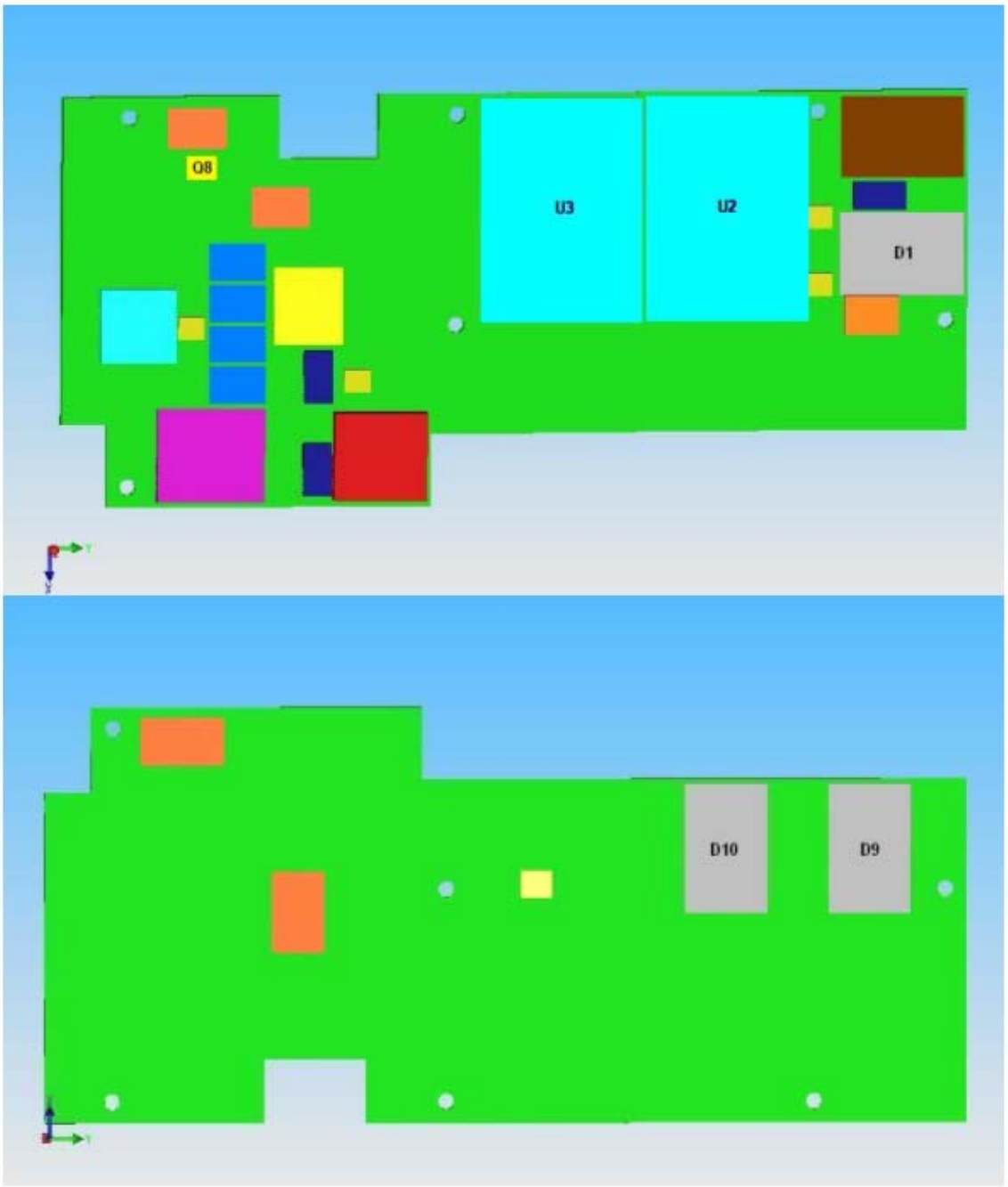


Figure 44a: Thermocouple measurement points on the MPB on board power supply, which includes the power conversion FETs.

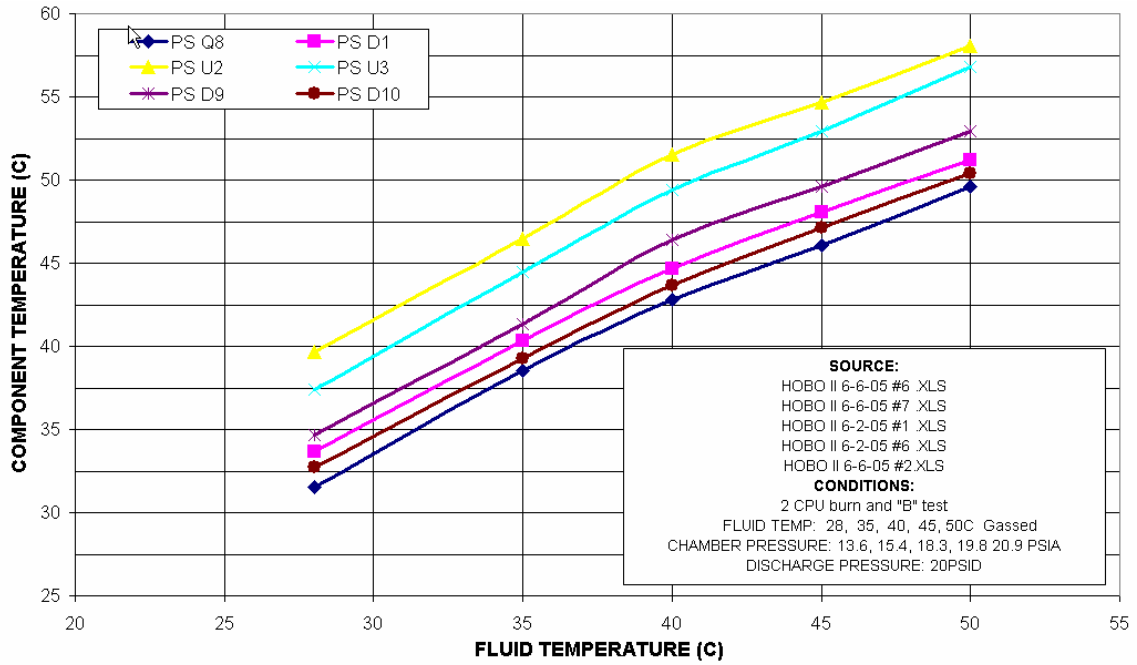


Figure 44b: *Time-averaged power supply module temperature results.*

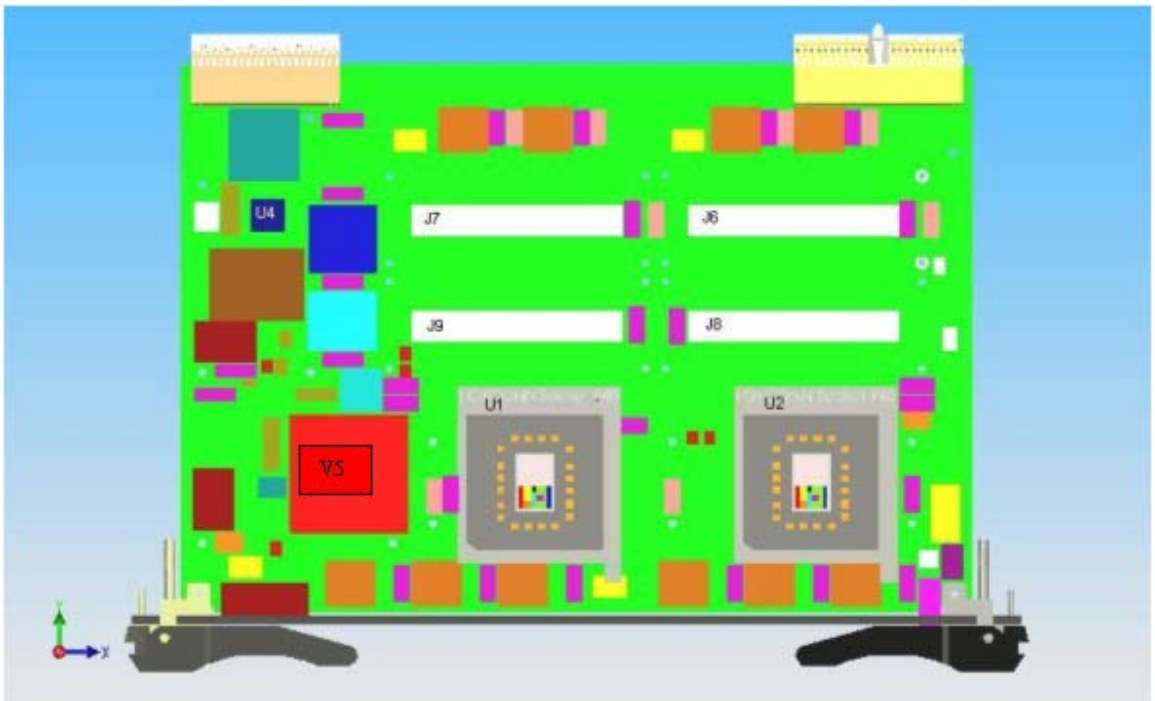


Figure 45a: Components being monitored via thermocouples on the MPB, including several point of load power converters, CPU sockets, memory board sockets and the I/O hub

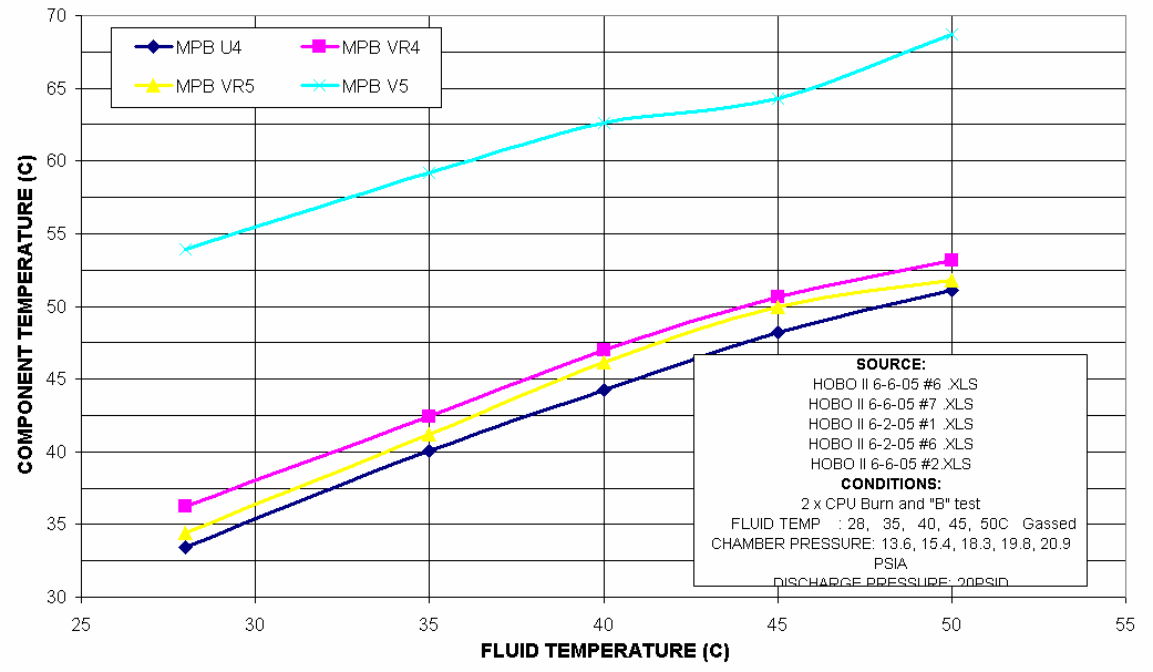


Figure 45b: *Time-averaged MPB motherboard component temperature results.*

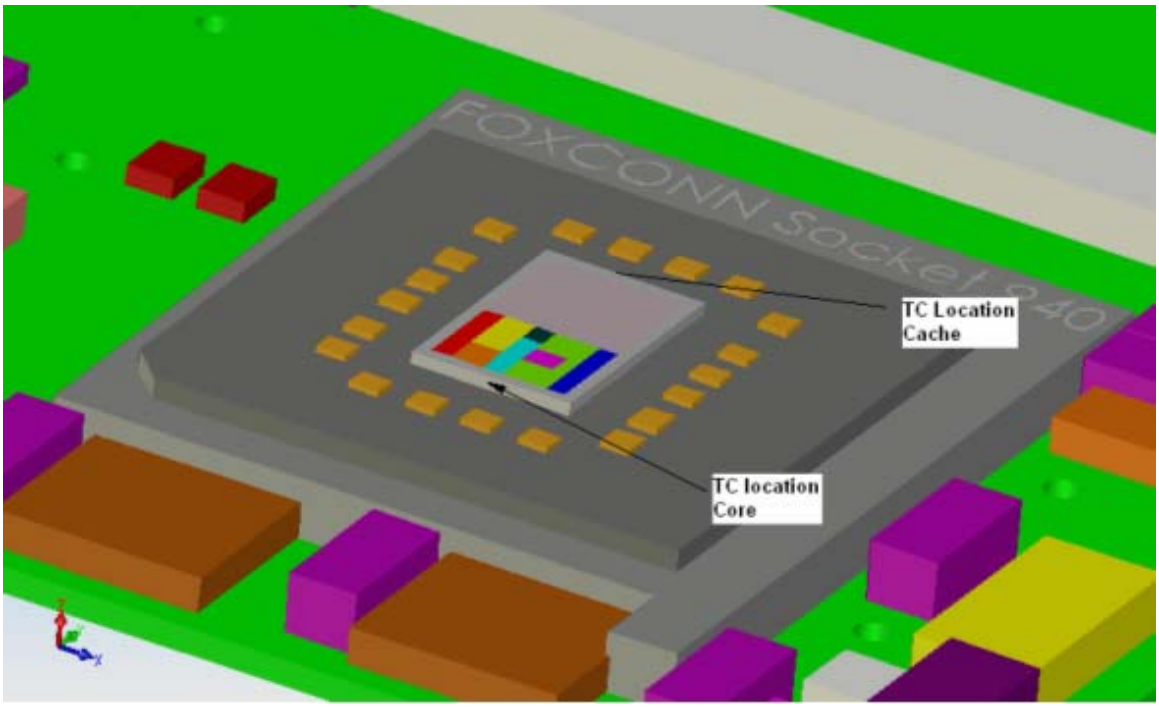


Figure 46a: Locations of the (2) thermocouples on the MPB CPU

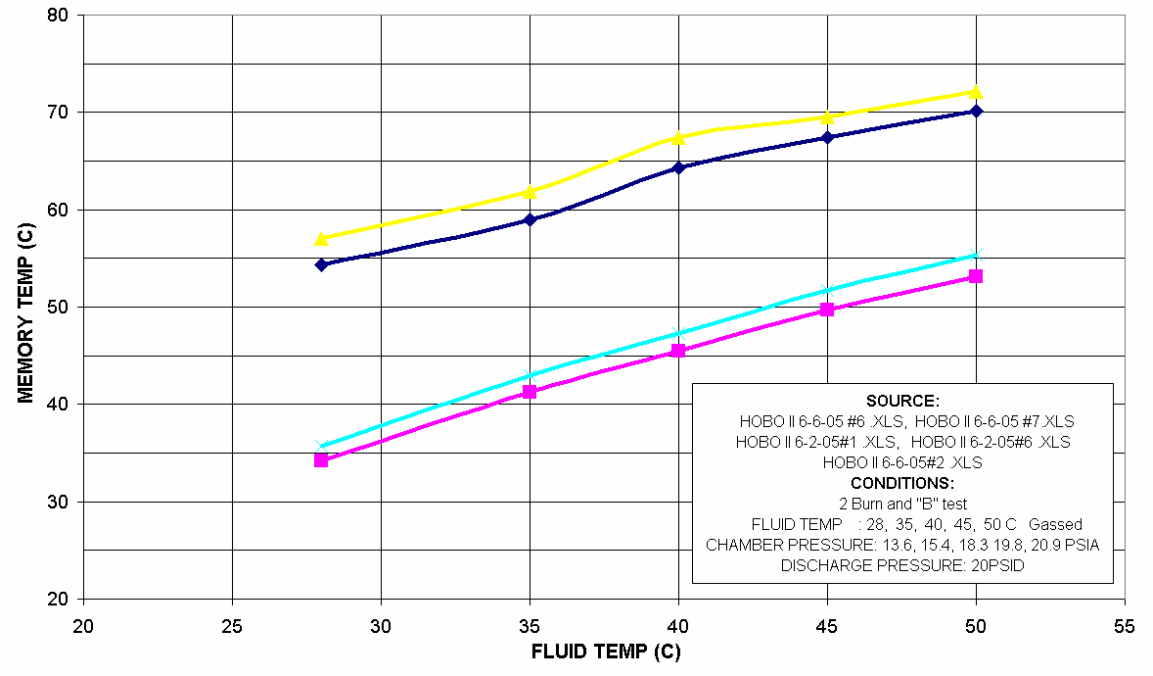


Figure 46b: *Time-averaged CPU temperature results (note that CPU temperatures are measured using a thermocouple attached to the core-side of the bare die).*

On-Site Acceptance Test Results

Upon delivery to PNNL, the system was monitored to ensure that all parameters (fluid temperature, system pressure, etc.) were in line with expectations from testing performed at ISR. Once this was established, each individual board was booted over Ethernet and Memtest9 was run through one cycle of approximately 45 minutes. Finally, an ISR version of Suse Linux 9.3 was booted via the network to demonstrate the ability of the MPB to boot over the network. Overall, the system performed as expected and the hand off to PNNL was completed.

5.2 Technology Development (Task 2)

The results of the technology development effort are included in a separate report appended to this report. This appended report follows the structure outlined below.

Results: Technology Development (Task 2) – Server Blade Project

- 5.2.1 Densified Memory Integration with Server
- 5.2.2 Backplane Design and Power Distribution
- 5.2.3 Shelf Management Module
- 5.2.4 Next Generation Densified Server (Multi-Processor Board)

5.2.4.1 Initial Plan
5.2.4.2 Program Re-scope
5.2.4.3 Dual Opteron Board Design
5.2.5 Data Center Market Study by VDC
5.2.5.1 Goals of the Data Center Market Study
5.2.5.2 Targets of the Data Center Market Study
5.2.5.3 Questionnaire for the Data Center Market Study
5.2.5.4 Findings of the Data Center Market Study
5.2.5.4.1 Applications and Solution Requirements
5.2.5.4.2 SprayCool Market Opportunity Assessment
5.2.5.4.3 SprayCool Total Cost of Ownership Model
5.2.6 Next Steps

5.3 Impact Study/Report (Task 3)

5.3.1 Implementation of SprayCool Technology

Advantages of SprayCool

Like any new technology, SprayCool has advantages and disadvantages. The primary appeal of the system is the increased efficiency of the cooling mechanism, which results in energy savings. When only the CPUs use evaporative cooling, the facility level energy savings are incremental, but when all computer electronics use evaporative cooling in a Global SprayCool system, the energy savings can be quite substantial. When considering that most national labs have energy budgets in the five to tens of millions range, there is real opportunity for significant cost savings. An added bonus is that a SprayCool data center is much quieter due to a reduction in the number of fans required in the server, and from the reduced need for air handlers.

The increased cooling efficiency also results in a cooler CPU and other electronic components, which directly correlates to increased reliability. A common industry rule-of-thumb is that for every 10°C cooler an electronic component operates, its reliability doubles. In the case of PNNL, CPU temperatures average more than 10 degrees cooler, and the components downstream of the CPUs in the server saw even greater decreases in temperature. Another important consideration is that this heat is not simply rejected into the facility to create problems elsewhere in the data center, but rather it is rejected to the building's chilled water loop and carried far away from any electronics. This greatly reduces the strain on the facility A/C system.

Perhaps the greatest advantage of SprayCool technology is the opportunity for densification of electronics. Current data centers have a great deal of "white space" to allow adequate air flow, but this is really just wasted space. Reductions in server sizes are limited by the need for massive heat sinks on the processors

and other server fans. But SprayCool technology can eliminate the need for such measures, allowing increased density of computer electronics. An initial iteration would be a simple move from 2U to 1U servers, and a concurrent reduction in white space in the racks. This step alone could result in a substantial reduction in the numbers of racks required in the data center. And the remaining racks could be centrally located in order to get performance gains in the form of reduced latency. Yet this only addresses rack level space savings. SprayCool technology enables the densification of electronics at the chip scale package level, allowing more computing power to be placed on smaller form factor PCBs. Technology currently exists to densify one rack of 2U servers into a single 8U Global SprayCool chassis, as developed under this program. More details are included in section 5.1.3.

The performance gains of densification are substantial, but the correlating cost savings are most compelling. Floor space of a typical data center is estimated to be valued at approximately $1200/sqf in construction costs alone. So every square foot of floor space that can be reclaimed from cooling and placed into operation is a substantial savings. With SprayCool applied only to the CPUs, there is a substantial decrease in the amount of heat being rejected to the air. This reduces the number of air handlers required to cool the facility, and these large pieces of equipment can be replaced with more nodes. Similarly, most data centers upgrade their systems every few years, and the increase performance of the machines consumes more power and vents more heat, often requiring costly facility expansions. Again, the introduction of SprayCool technology allows increased compute power in a smaller space, obviating the need for costly facility expansions.

Disadvantages of SprayCool

The chief disadvantage of SprayCool is the perception barrier of moving from an air cooled system that is familiar to all, to a liquid cooled system that is not as well understood. There is always some trepidation and resistance with new technology, and not many people are familiar with dielectric fluids. However, the tide does seem to be turning as such industry leaders as Cray, SGI, and IBM are adopting liquid cooling methodologies for their higher end systems.

The fluid itself, 3M's Fluorinert, is a commercially available product and is by all measures a very safe fluid. It is a Perfluorocarbon compound that is odorless and colorless. It is not flammable, and has no known physical, health, or environmental hazards. In fact, certain individuals have actually ingested the substance to prove this point.

Fluorinert is a stable compound, but there is the theoretical possibility of a hazardous decomposition. It is believed that a toxic decomposition could result in hydrogen fluoride and perfluoroisobutylene at temperatures above 200°C. However, in practice, this seems virtually impossible. The presence of oxygen acts as an inhibitor to this decomposition, and oxygen will surely be present

anywhere that Fluorinert is being used. In addition, attempts at both NASA and the University of Idaho to create this decomposition have both failed. In the case of the university, temperatures as high as 500°C still failed to precipitate the reaction.

Still, for the sake of caution, typical chemical handling guidelines should be followed. Additional guidelines should also be implemented to make sure that open flames and welding operations not take place in an area that has an appreciable concentration of Fluorinert vapor. Again, these types of conditions are not anticipated in a data center environment.

A main item of concern is the question of what the impact will be on the service and maintenance of a liquid cooled system. During installation users will see an increase in the time it takes to install a new system, as several fluid connections will need to take place. These would be very basic operations that any facilities staff would find easy to perform. And the additional time would be incremental compared to the time required to make other connections, such as power feeds and particularly interconnects. The fluid interconnects can use the same cable arms as the other system interconnects, so accessing the servers for routine tasks remains largely unchanged.

Once installed, the maintenance of the fluid interconnects should be minimal, and the existing facilities staff should be equal to any tasks that arise on account of the SprayCool system.

5.3.2 Power Savings

The power savings realized through conversion to SprayCool technology is a key component of the economic impact to the facility and a major focus of the program. In testing, power savings at the CPU level were measured an average of 5 W per CPU. Greater savings than these have been seen in other CPUs when they were run cooler, but the Itanium CPU power consumption appears to be less sensitive to temperature changes. However, other components in the system also run cooler when the CPU heat is removed from the server, and so an overall rack savings of 460 W was measured. This is offset to some degree by the power requirements of the TMU (130 W), resulting in a net savings per rack of 330 W. Scaled to the entire data center, this results in an energy savings of 17.9 kW in the computer power consumption alone.

But this addresses only a portion of the savings to be realized. With 1/3 of the system heat being removed directly to the chilled water, the overall load on the A/C system is reduced. Conservatively, it was calculated that 6 of the 17 air handlers in the PNNL facility could be removed with the implementation of SprayCool. This step results in an additional 18.7 kW of energy savings.

Further gains are envisioned in future applications that bypass the chilled water supply and go directly to the cooling tower water. Data from this program demonstrated the feasibility of this approach, with a projected COP of greater than 3 due to an additional 37 kW of energy savings from the bypassed chillers.

In summary, while the energy savings from evaporative cooling only the CPUs are substantial, the greatest gains are achieved by approaching the overall cooling system from CPU to outside ambient air. By rejecting the heat directly to the cooling tower water, data center operators can reduce both the number of CRACs and chillers that are required for cooling. Equipment costs aside, the energy savings alone from this approach could result in energy savings of 20-30% for the facility.

5.3.3 Economic Assessment – Total Cost of Ownership (TCO) Model

Note: **Appendix E** includes a hard copy of the TCO model.

The TCO model was intended to capture all the costs and cost savings associated with migrating to a SprayCool data center. The initial model is based on the PNNL EMSL laboratory and was created with a great deal of input from PNNL, but all of the key inputs were implemented as variables so that the model could quickly be tailored to reflect the system elements of most major data centers.

The TCO analysis demonstrated cost savings in several areas, most notably in energy, reliability, and facility (deferred construction). The actual model is included in the appendix, and begins with an “Assumptions” page where users can input data that most accurately reflects the realities of their given data center. Some major facility inputs include number of nodes or CPUs, number of servers per rack, price of SprayCool components, and maintenance costs. In the reliability section, inputs range from service contract pricing to average job size (number of CPUs as well as job duration), as well as cost per hour per CPU and the average failure rates for CPU and DIMM components. Energy savings are determined by the reduction in numbers of CRACs and Chillers needed to cool the system, and the price per kWh of electricity. In addition, other relevant inputs were given placeholders for future expansion of the model.

Based on these inputs, two versions of the model are calculated. The first model, “SprayCool – Retro”, reflects the cost savings associated with retrofitting an existing data center with SprayCool equipment that is connected to the chilled water supply, such as in the case of PNNL. The energy savings here are a bit more modest because cooling only the CPUs with water that is rejecting heat first through the chiller and then through the cooling towers is not very efficient. The second model, “SprayCool – Optimized”, shows the gains to be made by bypassing the chiller and rejecting heat directly to the facility water from the cooling tower.

In both models, the annual and yearly costs associated with air cooling and SprayCool products are listed side by side in a columnar profit and loss type format. The difference in cost between the two is then calculated in the final column, and totaled at the bottom. This final figure is then compared with the initial capital investment in the SprayCool system to determine break-even time in years.

Costs in the Energy Savings section were derived from actual measurements of power consumption in the air vs. SprayCool racks. In the Maintenance Costs section a few assumptions were required as detailed in the notes portion of the model, but in each case it was assumed that the SprayCool system would require additional costs to operate. In the reliability section we used actual failure data from PNNL, together with an assumption of doubling MTBF with a 10°C reduction in temperature, to estimate a cost savings in the service contract. Downtime in the form of lost jobs was also calculated based on PNNL input. The costs in these three sections should be fairly straightforward and consistent among data centers.

The final cost center, and the one most difficult to quantify, is the one related to savings from deferred construction. The idea is that by switching to a SprayCool infrastructure, a data center manager can retake precious floor space from the cooling equipment and rededicate it to computing space. There could be several manifestations of this. First, assuming that CPU heat is no longer rejected to the air but rather to the chilled water, that would amount to an approximate 1/3 reduction in the heat vented to the air. This would result in a reduced load on the CRACs, and a portion of them could be removed from the data center with more nodes put in their place.

A second approach would be to migrate from 2U servers to 1U servers. The savings here would depend on the particular configuration of a given data center in terms of compute space vs. mass storage space, number and size of racks, etc. But in the case of PNNL, it was determined that the Supercomputer could be reduced in size from 83 to 58 racks, for a cost savings of $240k.

Finally, an analogous approach is to look at the feasibility of building a more powerful Supercomputer in the same space occupied by the current one. PNNL recently added on 3000 sqf of data center to accommodate their next generation computer, and this is a fairly typical addition. If one considers that a typical data center costs $1200/sqf to build that amounts to a $3.6 M construction expense that could have been avoided with SprayCool.

But because these construction costs are highly dependent on individual circumstances, they were included on separate lines for the final TCO break-even calculation. In looking at the worst case example of a SprayCool data center utilizing chilled water, the first line shows the payback period with the construction costs included as being 0.56 years, or a little over 6 months. On the next line, construction costs are not included but the floor space savings are, for a payback period of 1.56 years. Finally, the last line includes none of the space savings accorded by the densification of SprayCool electronics, which results in a payback of 2.79 years.

In summary, these cost savings are very real and quite compelling, even in the 'worst case' scenario. Further savings could be realized by bypassing chillers, recapturing floor space from the A/C system, and by moving to a Global SprayCool system where all compute electronics are liquid cooled, not just the processors.

6 CONCLUDING REMARKS AND RECOMMENDATIONS

PNNL, ISR, and Tessera have just completed Phase I of the DOE-funded Energy Smart Data Center Program. The primary objectives of this phase were:

1 Reduce overall data center energy consumption while simultaneously raising facility coefficient of performance (COP).
2 Significantly drive up server, rack, and facility densification.
3 Increase electronics reliability.
4 Demonstrate an attractive total cost of ownership for a SprayCool Energy Smart Data Center.

As part of the program, four major tasks were proposed as follows:

Task 1: Side-by-Side Demonstration
Task 2: Technology Development
Task 3: Impact/Study Report
Task 4: Technology Insertion and Reporting

Under **Task 1**, the side-by-side demonstration was accomplished by converting a rack of 18 HP rx2600 2U servers from air-cooling to SprayCool. When tested in a 22°C ambient in ISR's Integration Lab, the CPUs ran 8-12°C cooler, while the server peripheral devices such as the memory DIMMs, FETs, Northbridge chip, etc. all ran cooler. For example, the FETs downstream of the CPUs ran 14-21°C cooler. When installed at PNNL and in a much cooler ambient of 15°C, the CPUs ran 6-17.5°C cooler, while the server peripheral devices all ran cooler.

The reliability, uptime, and serviceability of the SprayCool Rack of HP servers are now being quantified over the next year (start date of 8/1/05). The results of this part of the study will be reported in a separate document.

Under **Task 2**, the advantage of building for SprayCool technology was demonstrated by building and demonstrating a dense dual Opteron blade server. Tessera's chip-scale packaging was used to develop dense memory modules that will enable the eventual deployment of up to 16 GB of stacked memory per CPU. The dual Opteron blades were housed in a Global SprayCool chassis wherein all computer electronics employ SprayCool technology. This system has capacity for up to 700W per slot, with the current boards running at a theoretical max of 380W. In this system and with 50°C coolant, the CPU edge diode

temperatures ranged from 70°C to 73°C, while the dense stacked memory temperature range was 51°C to 57°C, and the nVidia graphics chip temperature was 67°C.

Two of the dense blade servers were housed and tested in a SprayCool chassis, then finally benchmarked against a commercially available (military) 1U server. For the benchmark testing, CPU Burn was used to fully exercise the CPUs while nBench benchmarked the computational performance, in iterations/sec, for up to ten different routines. Of these ten different routines, the MPB executed 1,197 iterations/sec for Number Sort, and 1,005 iterations/sec for LU Decomposition while running SuSe 9.2 Linux (32-bit). The coolant delivered to the CPUs was at 37°C. A comparable 1U COTS server (dual Intel Xeon 3.6 GHz CPUs) executed 566 iterations/sec for Number Sort, and 564 iterations/sec for LU Decomposition in an ambient of 20°C air (while running Redhat Linux). Under the selected conditions, the MPB significantly outperformed a much larger dual CPU server. No testing has been conducted against a Compact PCI shelf yet.

Under **Task 3**, a Total Cost of Ownership model was developed to investigate the costs savings to be realized by migrating to SprayCool technology. The methodology used was to consider the capital investment required to retrofit commercially available servers to SprayCool and then compare that with annual savings to compute the pay-back period for the investment. Major components of the cost model included energy savings, maintenance costs, reliability increases, and savings from densification. For energy savings, a Coefficient of Performance (COP) for a SprayCool system with retrofitted racks ranged from 1.56 to 1.97 when the chillers are bypassed. Future applications involving a Global SprayCool System such as that developed in the Technology Development portion of this program demonstrate a potential COP of 3.33 or greater. But even assuming the most modest energy savings and depending on assumptions in the densification category, the pay-back period ranged from 0.5 to 2.8 years.

The densification potential of adopting SprayCool was developed further in additional case studies that considered the move from 2U servers at PNNL's facility to 1U and Global SprayCool systems. It was determined that the move to 1U servers would free up enough rack space to accommodate a 51% increase in computing power. Further, the move to a Global SprayCool system would result in a 74% capacity increase.

Under **Task 4**, a plan for future development of an Energy Smart Data Center was drafted. In addition, this element includes the reporting of the systems reliability while running at PNNL for a period of one year, which will be detailed in a separate report once that timeframe has completed.

Recommendations

Based on the reported results and the desire to further explore the potential impacts of SprayCool technology, the following next steps are proposed.

Side-by-Side Demo of rx2600 air-cool vs. spray-cool

- Develop an acceptable model for quantifying the reliability
- Quantify uptime and serviceability using industry standards (if any exist)

Global SprayCool System

- Maximize runtime for system, with PNNL using system to the extent possible
- PNNL to quantify performance feedback, providing specific guidance to be used in design of next version of the MPB (global and hybrid versions)

TCO Model

- Gather hard data to make existing TCO model more robust, for rx2600 implementation
- Scale TCO model to 1U servers
- Scale TCO model to Global SprayCool System

Product Adoption

- Solidify relationship with OEM such as HP, SGI, IBM, etc. to enable nearer term adoption of the technology in the HPC market

7 APPENDIX A

1.0 GOAL

The overall goal of this section of the program is to benchmark a single rack of 18 DOE PNNL HP rx2600-2 servers on location under air cooled conditions.

Specific Goals:

- Determine operating environment at PNNL
  - Typical server environment
- Measure thermal performance of the HP rx2600-2 server in typical PNNL air cooled environment.
  - Benchmark computing performance
- Measure thermal performance of the HP rx2600-2 server in ISR integration laboratory
  - Benchmark computing performance
  - Measure rack power dissipation
  - Measure nodes 1, 2 & 3 power dissipation
  - Measure CPU power dissipated in nodes 1, 2 & 3.

2.0 SCOPE

- Standardized instrumentation and test setup
- Testing will consist of:
  - Thermal performance of air cooled hardware
  - Steady state thermal performance of air cooling
- Processing benchmarks in air cooled environment.

3.0 OVERVIEW OF AIR COOLED BASELINE TEST

3.1 Measure air flow rates and air temperatures at defined points around the ISR rack
3.2 Instrument nodes to measure power and CPU temperatures only
3.3 Bench test the power and CPU temperatures of each node, and label each node per their power ranking 1-18, highest to lowest.
3.4 Instrument each node for thermal characterization, install in rack
3.5 Perform thermal characterization, and benchmark each node in the rack
3.6 Record and archive data in notebook/notebook PC

4.0 TEST PROCEDURE-RACK LEVEL AIR FLOW RATES

Table 1 Air flow rate test equipment

QTY	Description	Owner	Data Ac
1	Air Flow Meter	ISR?	Hand
1	TC Reader	ISR	Hand
1	Calibrated T-Type Thermocouple	ISR	TC Reader

4.1 Power on node to be tested
4.2 In the background initiate “temperature” software, to monitor CPU and board temps
4.3 Verify CPU temperatures are between 45-55°C at idle
4.4 Initiate (6) instances of “burnI2” (CPU exercise program)
4.5 Verify CPU temperatures
4.6 Allow steady state to occur (1°C/20min), have seen temperatures between 60-70°C
4.7 Using a hotwire anemometer (or similar) measure the air flow rate at each indicated location (see Figure 5, Figure 6 and Figure 7) 1” from the surface. Also measure the air temperature at that location. Record values in Table 2 NOTE: assume air flow is moving in the direction from the front of the racks to the back. Orient the air flow measurement device accordingly.

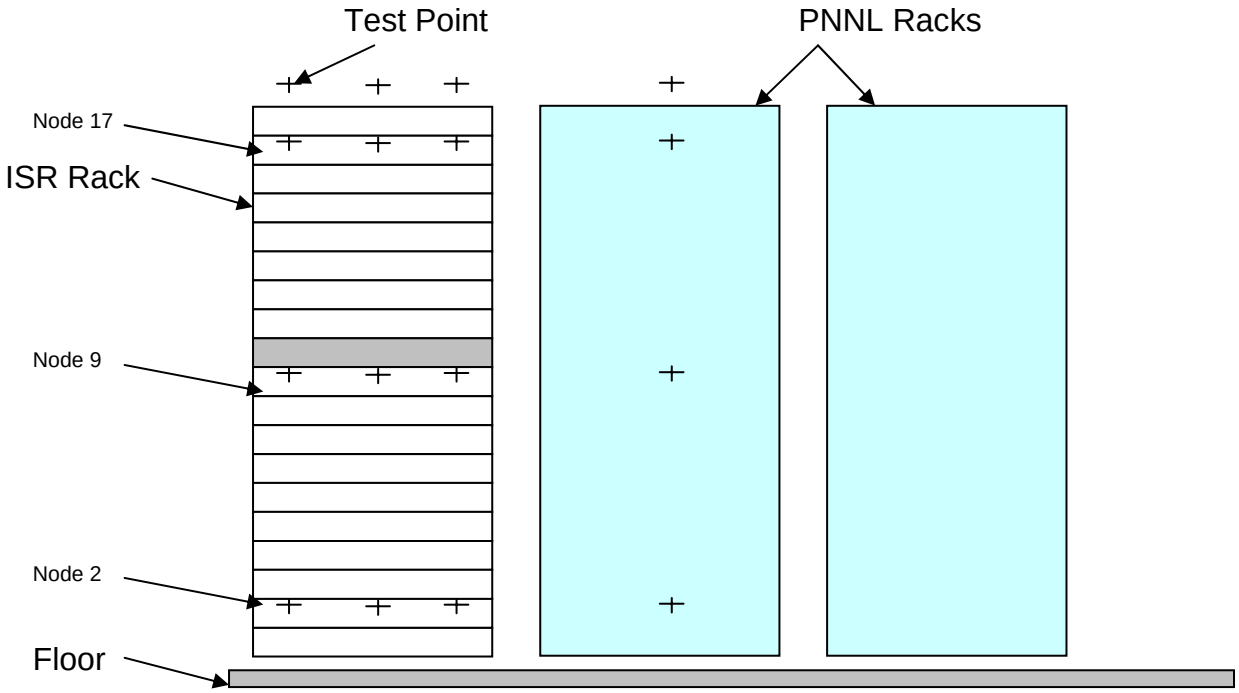


Figure 5: Rack front view, Air flow rate and temperature measurement locations

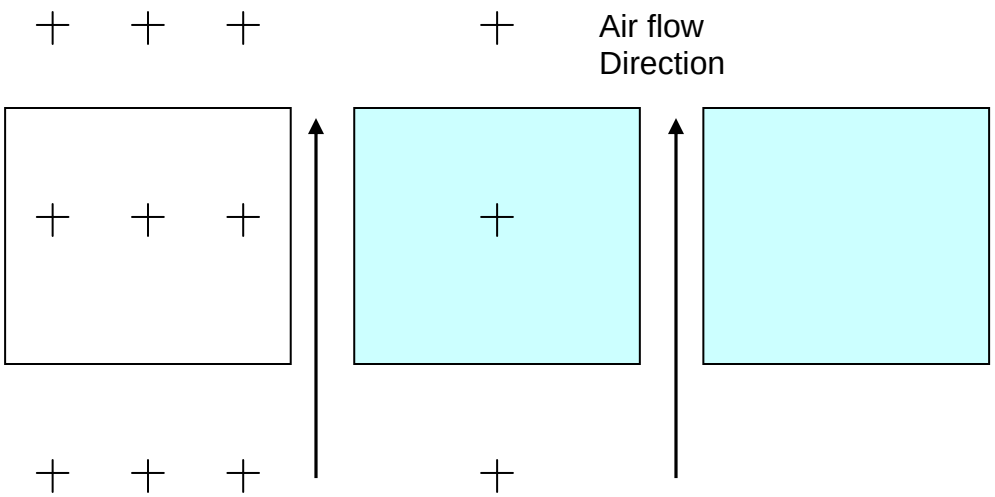


Figure 6 Rack top view, air flow rate and temperature measurement locations

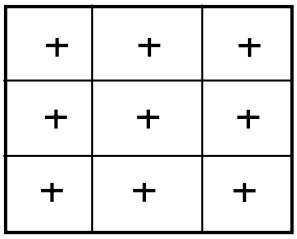


Figure 7 Perforated floor tile in front of the ISR rack

Table 2 Air flow rate data

Test Point	Location Description	Temperature [C]	Air Flow Rate [ ]
1	ISR, Front, Bottom, Left		
2	ISR, Front, Bottom, Middle		
3	ISR, Front, Bottom, Right		
4	ISR, Front, Middle, Left		
5	ISR, Front, Middle, Middle		
6	ISR, Front, Middle, Right		
7	ISR, Front, Top, Left		
8	ISR, Front, Top, Middle		
9	ISR, Fron, Top, Right		
10	ISR, Top, Left		
11	ISR, Top, Middle		
12	ISR, Top, Right		
13	ISR, Back, Top, Left		
14	ISR, Back, Top, Middle		
15	ISR, Back, Top, Right		
16	ISR, Back, Middle, Left		
17	ISR, Back, Middle, Middle		
18	ISR, Back, Middle, Right		
19	ISR, Back, Bottom, Left		
20	ISR, Back, Bottom, Middle		
21	ISR, Back, Bottom, Right		
22	PNNL, Front, Bottom		
23	PNNL, Front, Middle		
24	PNNL, Front, Top		
25	PNNL, Top		
26	PNNL, Back, Top		
27	PNNL, Back, Middle		
28	PNNL, Back, Bottom		
29	Perforated Tile, top, left		
30	Perforated Tile, top, middle		
31	Perforated Tile, top, right		
32	Perforated Tile, middle, left		
33	Perforated Tile, middle, middle		
34	Perforated Tile, middle, right		
35	Perforated Tile, bottom, left		
36	Perforated Tile, bottom, middle		
37	Perforated Tile, bottom, right		

5.0 SETUP AND INSTRUMENTATION-NODE POWER RANKING

5.1 Using label maker Label each of the (18) nodes with consecutive letters A-R, beginning with “A”
5.2 Install node “A” in bottom position of the rack
5.3 Install modified power cord (spliced to allow voltage and current measurements using DMM)
5.4 Install (2) with DMMs to modified power cord. One in parallel to measure voltage, and a second in series to measure current.
5.5 Attach a single T-type calibrated thermocouple to the node, such that it measures the air inlet temperature.

6.0 TEST PROCEDURE-NODE POWER RANKING

6.1 Power on node to be tested
6.2 Capture terminal information during the testing for each node. Save data to “*nodepowerranking_date_nodeletter”*
6.3 Initiate CPU temp monitor software “ temperature”
6.4 Verify and note CPU temperature with the system at idle
6.5 Verify and note chassis power with the system at idle, using the current and voltage measurements from the DMMs
6.6 Initiate “brunI2”
6.7 Verify temperature
6.8 Verify chassis power
6.9 Allow steady state to occur (1°C/20min)
6.10 Initiate “nbench” benchmarking program
6.11 Record CPU temps in

6.12 Table 3
6.13 Record Chassis supply voltage [ACV] and current draw [AC] in

6.14 Table 3 below
6.15 Record air inlet temperature in

6.16 Table 3 below
6.17 Archive benchmark data on the laptop.
6.18 Repeat steps 5.0-6.0 for all 18 nodes (A-R), test in the bottom position of the rack.

NODE [-]	Serial [-]	NODE SUPPLY VOLTAGE [ACV]	NODE CURRENT DRAW [A]	CALCULATED POWER [W]	CPU1 TEMP [°C]	CPU2 TEMP [°C]	AIR INLET TEMP [°C]
A	US42779135	116.3	3.0	348.90	72	73	23
B	US42779134	115.6	3.0	346.80	72	72	22.7
C	US42779133	115.8	3.1	358.98	71	71	22.6
D	US42779132	115.9	3.0	347.70	70	72	23.3
E	US42779131	116.1	3.1	359.91	70	71	23.6
F	US42779130	116.0	3.1	359.60	70	71	23.4
G	US42779129	115.6	3.1	358.36	72	73	24.1
H	US42779128	114.6	3.1	355.26	74	73	23.9
I	US42779127	116.6	3.1	361.46	68	73	24
J	US42779126	116.5	3.1	361.15	72	76	23.2
K	US42779125	115.3	3.1	357.43	73	73	24.2
L	US42779124	116.0	3.1	359.60	74	71	23.5
M	US42779123	115.9	3.2	370.88	77	73	23.7
N	US42779122	117.0	3.0	351.00	68	69	22.9
O	US42779121	116.1	3.1	359.91	77	71	22.9
P	US42779120	116.0	3.1	359.60	72	73	23.3
Q	US42779119	115.7	3.2	370.24	69	75	23.3
R	US42779118	115.9	3.2	370.88	71	71	23.4

Table 3 Power ranking data

6.19 Following the testing of all (18) nodes, rank the nodes in order of chassis power dissipation from 1-18, with “1” having the highest power dissipation.

6.20 Label each node with its ranking using the label maker. After this point, each node will be referred to based upon its ranking.

7.0 SETUP AND INSTRUMENTATION-RACK THERMAL CHARACTERIZATION

Figure 8 Test Schematic

Table 4 List of equipment/supplies

QTY	Description	Owner	Data Ac	Software
5	Keithley DAQ	TBD	N/A	
2	Data Acquisition Unit	ISR-Computing, Test	Keithley	N/A
6	Data Acquisition Unit Module	ISR-Computing, Test		
225	Thermocouple–Type T uncalibrated	ISR-Computing	TBD	TBD
1	Locktite 384,7387	ISR-TEST		
1	Polyimide tape	ISR-Integration		

2	Notebook PC	ISR-Computing		
4	Fluke DMM	ISR-Integration		
8	Test Leads	ISR-Integration		
9	Thermocouple calibrated-Type T	ISR-Computing		

Table 5 List of components to be monitored on fully instrumented nodes 1, 2 & 3

Device	QTY Thermocouples	Type of Measurement	Data Acquisition
Processor Temp(s).	NA	Diode (if available)	Software/Bios
Air Input(s) Temp.	2	TC	Keithley
Exhaust(s) Temp.	2	TC	Keithley
Memory (DIMM) Temp	8	TC	Keithley
North Bridge Temp.	1	TC	Keithley
Power Supply(s) Temp.	2	TC	Keithley
Ethernet ports	3	TC	Keithley
FET(s) Temp.	8	TC	Keithley
Hard drive (HDD) Temp.	2	TC	Keithley

Table 6 List of components to be monitored on partially instrumented nodes 4-18

Device	QTY Thermocouples	Type of Measurement	Data Acquisition
Processor Temp(s).	NA	Diode (if available)	Software/Bios
Air Input(s) Temp.	2	TC	Keithley
Exhaust(s) Temp.	2	TC	Keithley

7.1 Server Instrumentation Procedure:

7.1.1 Fully instrumented nodes (1-3) shall be instrumented according to Table 5, partially instrumented nodes (4-18) shall be instrumented according to Table 6.

7.2 Thermocouple installation instructions

7.2.1 Read device specifications to determine device specific location(s) for instrumentation.

7.2.2 Prepare 1” length piece of Polyimide acrylic tape.

7.2.3 Brush Locktite 7387 activator directly on surface to be instrumented.

7.2.4 Place dollop of Locktite 384 thermally conductive epoxy resin on top of Locktite 7387 activator

7.2.5 Press 30 gauge thermocouple wire junction tip directly into Locktite 384 thermally conductive epoxy resin until the wire junction tip is in contact with the surface to be tested.

7.2.6 Hold thermocouple junction tip stationary while applying Polyimide tape for thermocouple wire strain relief

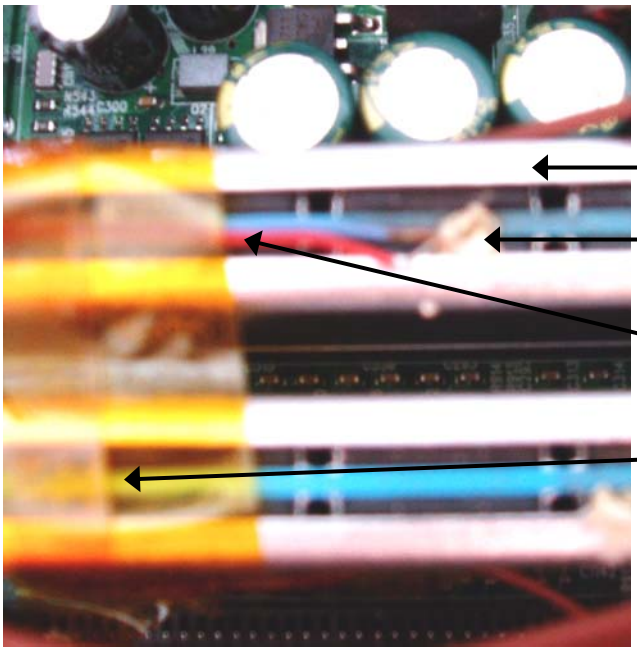
7.2.7 Brush Locktite 7387 activator directly on top of Loctite 384 thermally conductive epoxy resin dollop.

7.2.8 Repeat process for each device required according to Table 2

7.2.9 Route all thermocouple lead wires to same location for connection to DAQ in manner not to impede air flow. One channel of DAQ to remain open for ambient temperature verification with calibrated thermocouple.

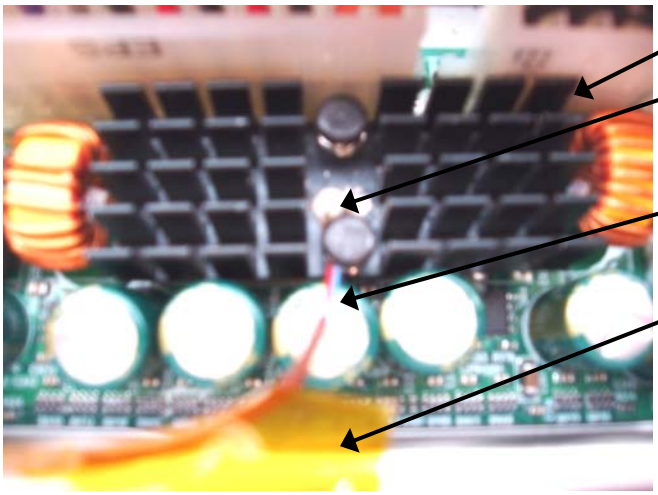
7.2.10 See Figure 2 and Figure 3 for device instrumentation examples (Appendix B)

7.2.11 Instrumentation locations shall be according to device specification



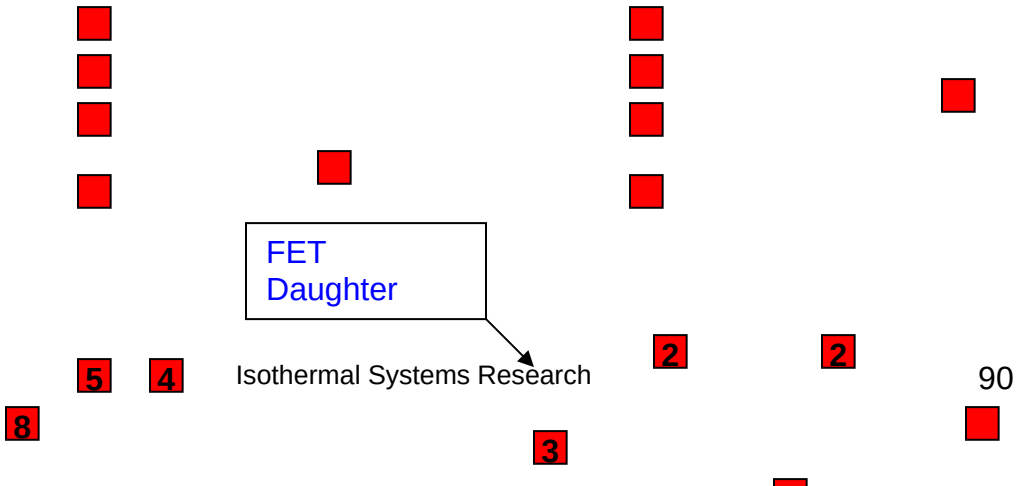
- DIMM
- Loctite 384 thermally conductive epoxy resin dollop
- Thermocouple wire
- Polymide tape for strain relief

Figure 9: DIMM Thermocouple Instrumentation



- FET
- Loctite 384 thermally conductive epoxy resin dollop
- Thermocouple wire
- Polymide tape for strain relief

Figure 10: FET Thermocouple Instrumentation



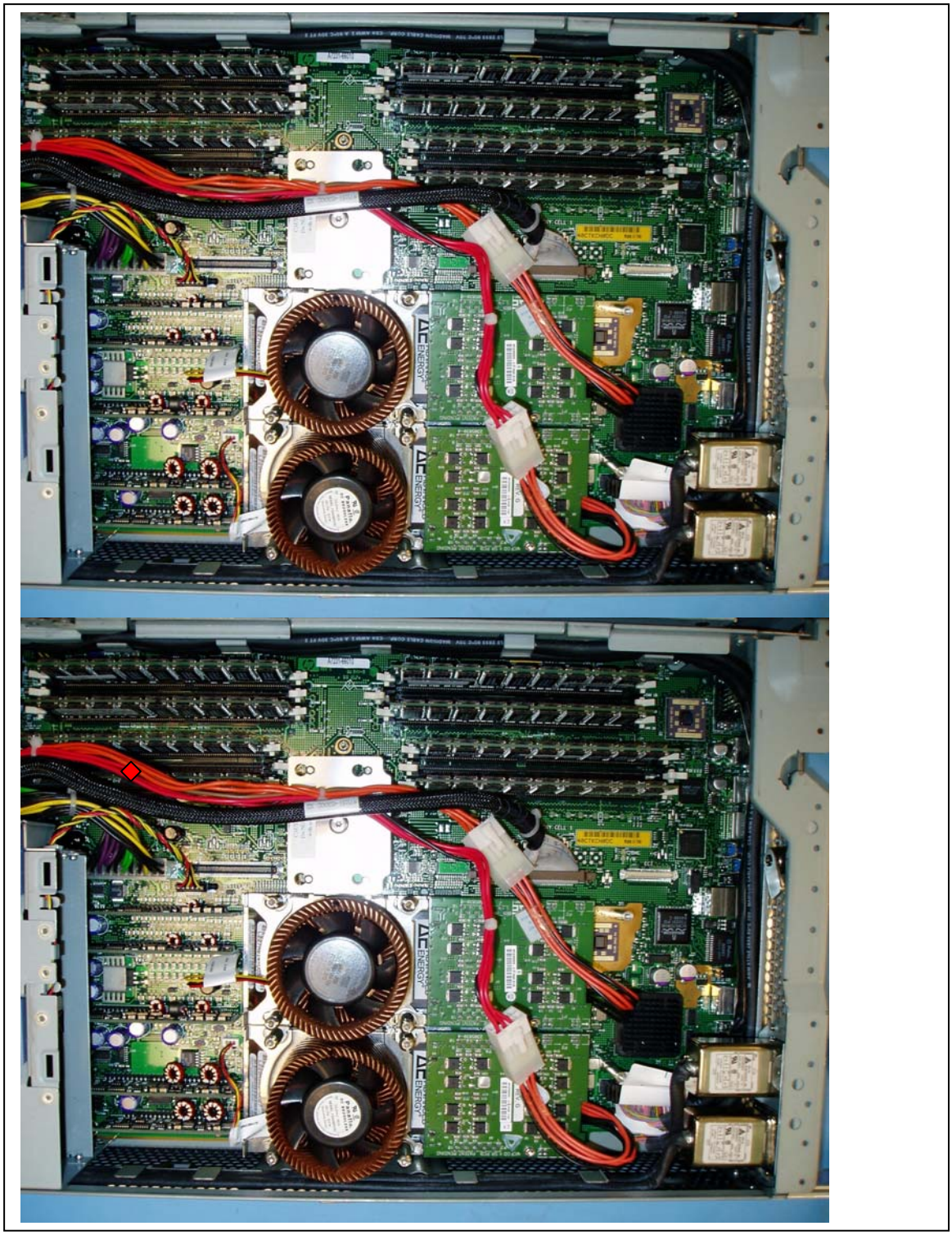


Figure 11 Top view of the HP RX2600 node with temperature monitoring locations NOTE: the FETs measured behind the processors are located underneath the shown daughter boards

7.3 Keithley DAQ setup

7.3.1 Air cooled test to be performed on the entire rack. The three highest power dissipating nodes (1-3) have been fully instrumented and will be installed in the rack in specific locations within the 18 available spaces, see Figure 12. The partially instrumented nodes (4-18) to be distributed starting with node 4 in the top most available slot and working down.

7.3.2 Install a single calibrated thermocouple into channel one of modules 1, 3, and 5, this thermocouple will be used to align all the channels within a Keithley.

7.3.3 Integrate all of the test specific thermocouples to the (6) Keithley modules. Be sure to group the TC appropriately per node working from the top to bottom. Record each thermocouple monitoring location, module number, and channel in Table 7.

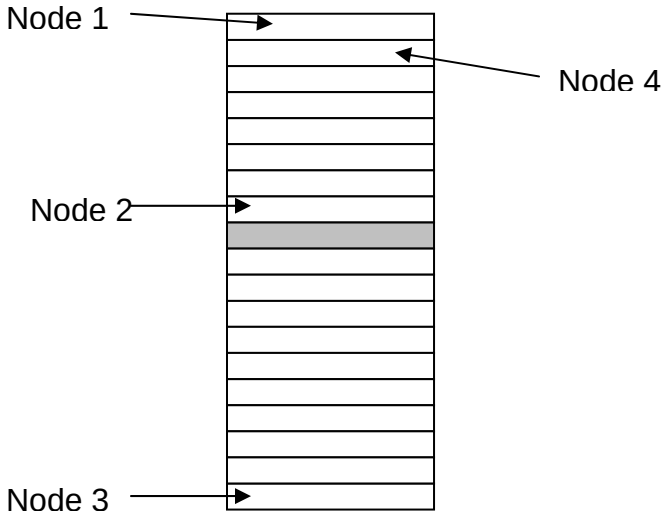


Figure 12 ISR rack with fully instrumented node locations

Table 7 Keithley DAQ connection data

MODULE #	CHANNEL #	NODE #	MONITORING LOCATION DESCRIPTION
1	1	1	HDD1
1	2	1	HDD2
1	3	1	Northbridge
1	4	1	DIMM 0A
1	5	1	DIMM 1A
1	6	1	DIMM 2A
1	7	1	DIMM 3A
1	8	1	DIMM 4A
1	9	1	DIMM 5A
1	10	1	DIMM 0B
1	11	1	DIMM 1B
1	12	1	DIMM 2B
1	13	1	DIMM 3B
1	14	1	DIMM 4B
1	15	1	DIMM 5B
1	16	1	FET 1
1	17	1	FET 2
1	18	1	FET 3
1	19	1	FET 4
1	20	1	FET 5
1	21	1	FET 6
1	22	1	FET 7
1	23	1	FET 8
1	24	1	Power Supply 1
1	25	1	Power Supply 2
1	26	1	Ethernet 1
1	27	1	Ethernet 2
1	28	1	Ethernet 3
1	29	1	Air In HDD

1	30	1	Air In Center
1	31	1	Air Out HDD
1	32	1	Air Out Center
1	33		
1	34		
1	35		
1	36		
1	37		
1	38		
1	39		
1	40		
2	1	2	HDD1
2	2	2	HDD2
2	3	2	Northbridge
2	4	2	DIMM 0A
2	5	2	DIMM 1A
2	6	2	DIMM 2A
2	7	2	DIMM 3A
2	8	2	DIMM 4A
2	9	2	DIMM 5A
2	10	2	DIMM 0B
2	11	2	DIMM 1B
2	12	2	DIMM 2B
2	13	2	DIMM 3B
2	14	2	DIMM 4B
2	15	2	DIMM 5B
2	16	2	FET 1
2	17	2	FET 2
2	18	2	FET 3
2	19	2	FET 4
2	20	2	FET 5
2	21	2	FET 6
2	22	2	FET 7
2	23	2	FET 8
2	24	2	Power Supply 1
2	25	2	Power Supply 2
2	26	2	Ethernet 1
2	27	2	Ethernet 2
2	28	2	Ethernet 3
2	29	2	Air In HDD
2	30	2	Air In Center
2	31	2	Air Out HDD
2	32	2	Air Out Center
2	33		
2	34		
2	35		
2	36		
2	37		
2	38		

2	39		
2	40		
3	1	3	HDD1
3	2	3	HDD2
3	3	3	Northbridge
3	4	3	DIMM 0A
3	5	3	DIMM 1A
3	6	3	DIMM 2A
3	7	3	DIMM 3A
3	8	3	DIMM 4A
3	9	3	DIMM 5A
3	10	3	DIMM 0B
3	11	3	DIMM 1B
3	12	3	DIMM 2B
3	13	3	DIMM 3B
3	14	3	DIMM 4B
3	15	3	DIMM 5B
3	16	3	FET 1
3	17	3	FET 2
3	18	3	FET 3
3	19	3	FET 4
3	20	3	FET 5
3	21	3	FET 6
3	22	3	FET 7
3	23	3	FET 8
3	24	3	Power Supply 1
3	25	3	Power Supply 2
3	26	3	Ethernet 1
3	27	3	Ethernet 2
3	28	3	Ethernet 3
3	29	3	Air In HDD
3	30	3	Air In Center
3	31	3	Air Out HDD
3	32	3	Air Out Center
3	33		
3	34		
3	35		
3	36		
3	37		
3	38		
3	39		
3	40		
4	1	9	Air In HDD
4	2	9	Air In Center
4	3	9	Air Out HDD
4	4	9	Air Out Center
4	5	13	Air In HDD
4	6	13	Air In Center
4	7	13	Air Out HDD

4	8	13	Ain Out Center
4	9	5	Air In HDD
4	10	5	Air In Center
4	11	5	Air Out HDD
4	12	5	Air Out Center
4	13	14	Air In HDD
4	14	14	Air In Center
4	15	14	Air Out HDD
4	16	14	Air Out Center
4	17	12	Air In HDD
4	18	12	Air In Center
4	19	12	Air Out HDD
4	20	12	Air Out Center
4	21	10	Air In HDD
4	22	10	Air In Center
4	23	10	Air Out HDD
4	24	10	Air Out Center
4	25	7	Air In HDD
4	26	7	Air In Center
4	27	7	Air Out HDD
4	28	7	Air Out Center
4	29	18	Air In HDD
4	30	18	Air In Center
4	31	18	Air Out HDD
4	32	18	Air Out Center
4	33	11	Air In HDD
4	34	11	Air In Center
4	35	11	Air Out HDD
4	36	11	Air Out Center
4	37	17	Air In HDD
4	38	17	Air In Center
4	39	17	Air Out HDD
4	40	17	Air Out Center
5	1	4	Air In HDD
5	2	4	Air In Center
5	3	4	Air Out HDD
5	4	4	Air Out Center
5	5	8	Air In HDD
5	6	8	Air In Center
5	7	8	Air Out HDD
5	8	8	Air Out Center
5	9	6	Air In HDD
5	10	6	Air In Center
5	11	6	Air Out HDD
5	12	6	Air Out Center
5	13	15	Air In HDD
5	14	15	Air In Center
5	15	15	Air Out HDD
5	16	15	Air Out Center

5	17	16	Air In HDD
5	18	16	Air In Center
5	19	16	Air Out HDD
5	20	16	Air Out Center
5	21		
5	22		
5	23		
5	24		
5	25		
5	26		
5	27		
5	28		
5	29		
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5	39		
5	40		

7.4 Once all of the instrumentation to the Keithley has been completed, run a channel verification and temperature alignment session with every module. Save the data to “PNNL_KEITHLEY_TRANSDUCER ALIGNMENT_NODES *X-Y_mmddyyx*” with “x” starting at “a” indicating test “a” then proceeds through the alphabet. The verification must include the all of the nodes.

“NODES X-Y” indicates the node numbers being sampled in this file (1-18)

7.5 Verify all of the temperatures are within ±1°C

7.6 Power Cord Setup

7.6.1 Modify remaining (17) AC power cords such that a DMM can be used in parallel to measure voltage and the “hot” wire is available for current measurement with a clamp meter.

8.0 TEST PROCEDURE-RACK THERMAL CHARACTERIZATION WITH VIRGIN RACK

NOTE: Use following file naming convention:

Keithley Data Storage location: PNNL folder located on desktop of each test notebook computer

"PNNL_KEITHLEY_mmddyyx" with "x" starting at "a" indicating test "a" then proceeds through the alphabet. A test includes the entire data set for all of the nodes independent of the module swap. Note in project notebook and data archive excel file, the details of each test.

Node name:

First tested node shall be named 1(x) starting at top node "a" then proceeds through the alphabet for all nodes in rack.

"NODES X-Y" indicates the node numbers being sampled in this file (1-18)

8.1 Power on and boot server each node individually (or startup Per PNNL instructions).

8.2 Initiate PNNL provided CPU temperature monitoring software.
8.3 Initiate CPU exercising software such as "BurnP6."
8.4 Allow all (36) processor and component temperatures to reach steady state (steady state shall be defined as no less than 1˚C/20 minutes).
8.5 For each node execute benchmarking software such as "nbench" and record results to the archival data file (TBD)
8.6 Initiate the Keithley DAQ, record file per naming convention stated previously with modules 1-4
8.7 Once Benchmarking software has completed, record the current information for the nodes instrumented with Keithley modules 1-4 which includes, Voltage [V], Current [A] CPU1 temperature [˚C], CPU2 temperature [˚C]
8.8 Swap to Keithley modules 5-6 following the completion of the first benchmark sample. Repeat sections 8.5-5.8 for the module 5-6 portion of the sample
8.9 Repeat 8.5-8.8 for a total of three complete samples (modules 1-6)

The average values from the Keithley DAQ, benchmarking software, and those hand recorded shall be archived in the archival Excel file matching Table 8.

Table 8 Example of required test data

file	060304I
SprayCool kit #	3
Coolant	PF5060
Notebook #	ECB-1148
Test personnel	LW
PLSU in chamber?	YES
Chamber Temp	20
Ambient Temp	20
Flow	220
Pump Outlet Pressure	25.4
Reservoir Pressure	7.7
Reservoir Temperature	26.2
Supply Temp	NA
Return Temp	41
CPU1	54
CPU2	54
System	29
North Bridge	48.64
SCSI	33.71
South Bridge	35.11
DIMM1	52.57
DIMM2	42.07
PS FET	61.94
PS1	42.30
PS2	48.48
PS3	50.33
HDD3	29.64
HDD2	29.81
HDD1	30.47
INLET1	19.13
INLET2	19.12
INLET3	19.23
INLET4	19.35
INLET5	19.37
INLET6	19.66
PWR INLET	33.89
PWR OUT	49.26
OUT FAN	42.48
OUT FET	40.66
OUT DIMMS	32.86
OUT MCH1	27.27
OUT MCH2	25.79
OUT SOUTH1	28.01
OUT SOUTH2	22.95
Number Sort	757.12
String	56.634
Bit Field	1.80E+08
FP Emulator	68.118

Fourier	14750
Assignment	18.164
Idea	1537.9
Huffman	913.8
Neural Net	14.956
LU Decomposition	788.76
Voltage	118.5
Current	3
Power [W]	379.5

8 APPENDIX B

Electronic location of this file:
Projects on Magneto\0085 DOE PNNL\Test\ RLX 600ex Test Plan.doc

1.0 GOAL

The overall goal of this section of the program is to benchmark five DOE PNNL RLX 600ex Blade servers under air cooled conditions.

Specific Goals:

- Measure CPU/component temperatures, computing performance and power draw of (5) air cooled RLX 600ex blades in the 600ex chassis, while varying ambient air temperature from 0-40°C.

2.0 SCOPE

- Standardized instrumentation and test setup
- Testing will consist of:
    - Thermal performance of air cooled hardware
        - Steady state thermal performance of air cooling
    - Processing benchmarks in air cooled environments.
    - Power draw during steady state operation

3.0 APPLICABLE DOCUMENTS

3.1 PNNL System level requirements document: projects on magneto\0085 DOE PNNL\System Level Specification\PNNL System Requirements Rev 11.doc

3.2 RLX instrumentation document: projects on magneto\0085 DOE PNNL\TEST\RLX Instrumentation document rev01.doc

4.0 SETUP AND INSTRUMENTATION-RACK THERMAL CHARACTERIZATION

Figure 1: Test Schematic

Table 1: List of equipment/supplies

QTY	Description	Owner	Data Ac	Software
1	Data Acquisition Unit	ISR-Computing, Test	Keithley	N/A
3	40 Channel Data Acquisition Unit Module	ISR-Computing, Test		
100	Thermocouple–Type T un-calibrated	ISR-Computing	TBD	TBD
1	Locktite 384,7387	ISR-TEST		
1	Polyimide tape	ISR-Integration		
1	Notebook PC	ISR-Computing		
2	Fluke DMM	ISR-Integration		
4	Test Leads	ISR-Integration		

3	Thermocouple calibrated-Type T	ISR-Computing		

Table 2: List of components to be monitored on fully instrumented nodes

Device	QTY Thermocouples	Type of Measurement	Data Acquisition
Processor	NA	Diode (if available)	Software/Bios
Inlet Air	1	TC	Keithley
Exhaust Air	1	TC	Keithley
Memory DIMMs	4	TC	Keithley
North Bridge	1	TC	Keithley
South Bridge	1	TC	Keithley
Gb LAN Transceiver	1	TC	Keithley
Gb Ethernet Controller	1	TC	Keithley
Infiniband Card	1	TC	Keithley
Ethernet	1	TC	Keithley
Hard Disk Drives (HDD)	1	TC	Keithley
GPU	1	TC	Keithley
FETs	6	TC	Keithley

4.1 Server Instrumentation Procedure:

4.1.1 Nodes shall be instrumented according to Table 2.

4.2 Thermocouple installation instructions

4.2.1 Read device specifications to determine device specific location(s) for individual device instrumentation.

4.2.2 Prepare 1” length piece of Polyimide acrylic tape.

4.2.3 Brush Locktite 7387 activator directly on surface to be instrumented.

4.2.4 Place dollop of Locktite 384 thermally conductive epoxy resin on top of Locktite 7387 activator

4.2.5 Press 30 gauge thermocouple wire junction tip directly into Locktite 384 thermally conductive epoxy resin until the wire junction tip is in contact with the surface to be tested.

4.2.6 Hold thermocouple junction tip stationary while applying Polyimide tape for thermocouple wire strain relief

4.2.7 Brush Locktite 7387 activator directly on top of Loctite 384 thermally conductive epoxy resin dollop.

4.2.8 Repeat process for each device required according to table 2.

4.2.9 Route all thermocouple lead wires to same location for connection to DAQ in manner not to impede air flow. One channel of DAQ to remain open for ambient temperature verification with calibrated thermocouple.

4.2.10 See Figure 2 and Figure 3 for device instrumentation examples

4.2.11 Instrumentation locations shall be according to device specification

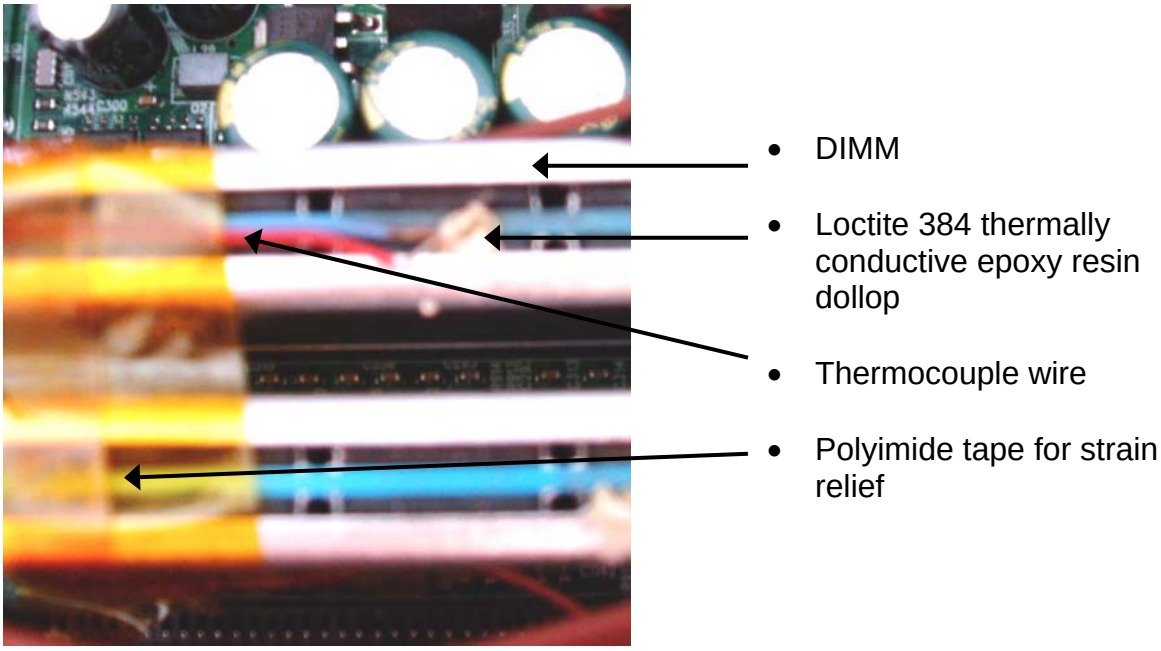
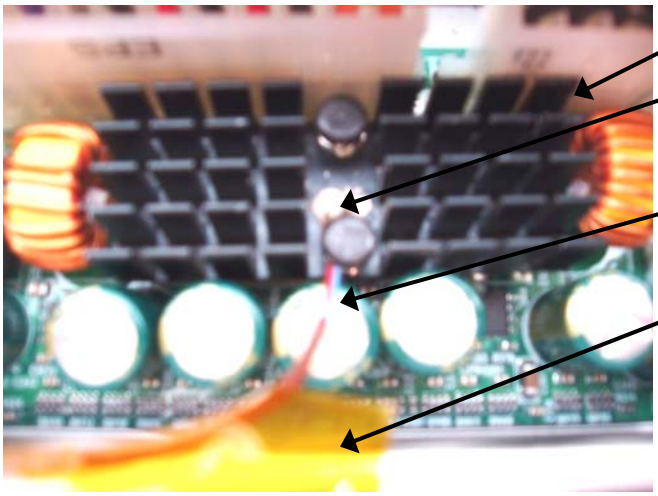


Figure 2. DIMM Thermocouple Instrumentation



- FET Heat sink
- Loctite 384 thermally conductive epoxy resin dollop
- Thermocouple wire
- Polyimide tape for strain relief

Figure 3. FET Thermocouple Instrumentation

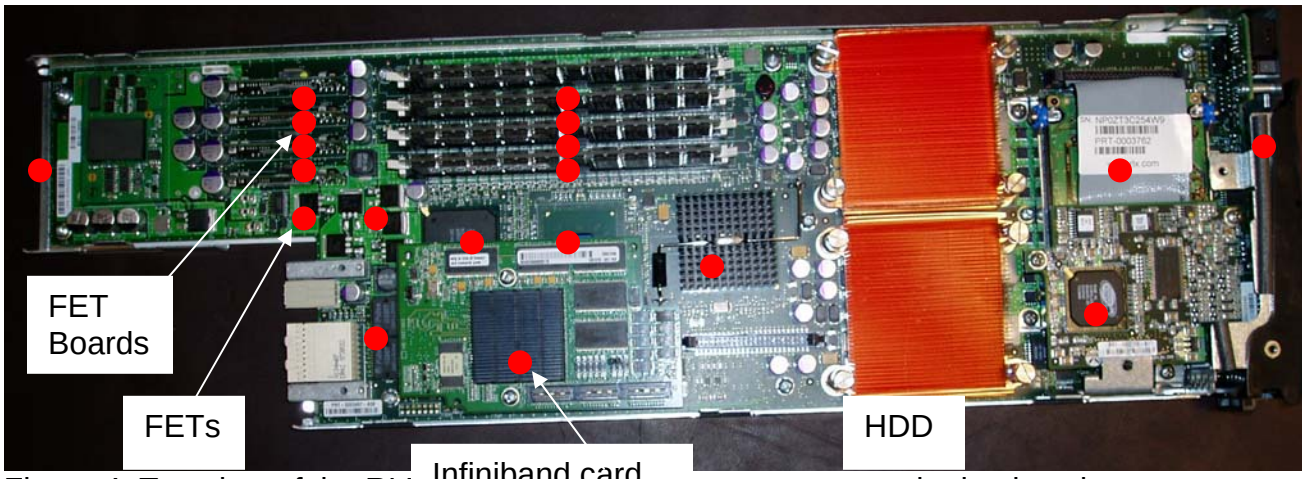


Figure 4. Top view of the RL emperature monitoring locations

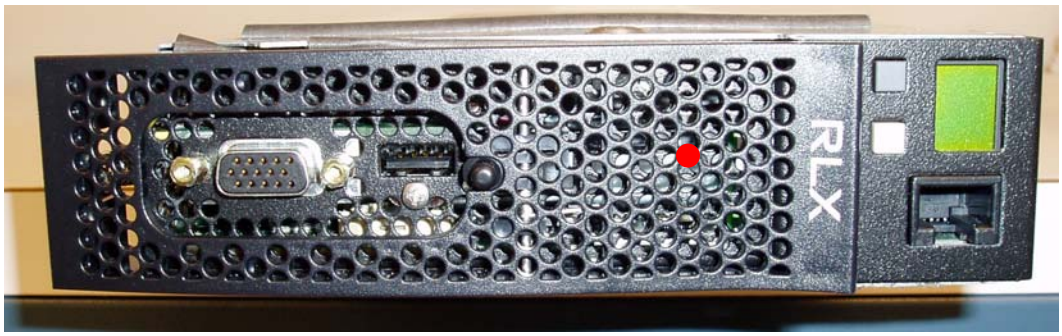


Figure 5. RLX600ex front air inlet temperature monitoring location

Keithley DAQ setup

4.2.12 Install a single calibrated thermocouple into the last channel of Keithley module 3. This thermocouple will be used to align all the channels within the Keithley system.

4.2.13 Integrate all of the test specific thermocouples to the (3) Keithley modules. Be sure to group the TC appropriately per node. Record each thermocouple monitoring location, module number, and channel according to table 3.

Table 3. Keithley DAQ connection data

MODULE #	CHANNEL #	NODE #	MONITORING LOCATION DESCRIPTION
1	1	1	Air in
1	2	1	Air out
1	3	1	Northbridge
1	4	1	DIMM 1
1	5	1	DIMM 2
1	6	1	DIMM 3
1	7	1	DIMM 4
1	8	1	North Bridge
1	9	1	Pulse DC converter
1	10	1	Gb LAN Transceiver
1	11	1	Infinaband Card
1	12	1	Hard Disk Drives (HDD)
1	13	1	FET 1
1	14	1	FET 2
1	15	1	FET 3
1	16	1	FET 4
1	17	1	FET 5
1	18	1	FET 6
1	19	2	Air in
1	20	2	Air out
1	21	2	Northbridge
1	22	2	DIMM 1
1	23	2	DIMM 2
1	24	2	DIMM 3
1	25	2	DIMM 4
1	26	2	North Bridge
1	27	2	Pulse DC converter
1	28	2	Gb LAN Transceiver
1	29	2	Infinaband Card

1	30	2	Hard Disk Drives (HDD)
1	31	2	FET 1
1	32	2	FET 2
1	33	2	FET 3
1	34	2	FET 4
1	35	2	FET 5
1	36	2	FET 6
1	37		NC
1	38		NC
1	39		NC
1	40		NC
2	1	3	Air in
2	2	3	Air out
2	3	3	Northbridge
2	4	3	DIMM 1
2	5	3	DIMM 2
2	6	3	DIMM 3
2	7	3	DIMM 4
2	8	3	North Bridge
2	9	3	Pulse DC converter
2	10	3	Gb LAN Transciever
2	11	3	Infinaband Card
2	12	3	Hard Disk Drives (HDD)
2	13	3	FET 1
2	14	3	FET 2
2	15	3	FET 3
2	16	3	FET 4
2	17	3	FET 5
2	18	3	FET 6
2	19	3	Air in
2	20	3	Air out
2	21	4	Air in
2	22	4	Air out
2	23	4	Northbridge
2	24	4	DIMM 1
2	25	4	DIMM 2
2	26	4	DIMM 3
2	27	4	DIMM 4
2	28	4	North Bridge
2	29	4	Pulse DC converter
2	30	4	Gb LAN Transciever
2	31	4	Infinaband Card
2	32	4	Hard Disk Drives (HDD)
2	33	4	FET 1
2	34	4	FET 2
2	35	4	FET 3

2	36	4	FET 4
2	37	4	FET 5
2	38	4	FET 6
2	39	4	NC
2	40	4	NC
3	1	5	Air in
3	2	5	Air out
3	3	5	Northbridge
3	4	5	DIMM 1
3	5	5	DIMM 2
3	6	5	DIMM 3
3	7	5	DIMM 4
3	8	5	North Bridge
3	9	5	Pulse DC converter
3	10	5	Gb LAN Transciever
3	11	5	Infinaband Card
3	12	5	Hard Disk Drives (HDD)
3	13	5	FET 1
3	14	5	FET 2
3	15	5	FET 3
3	16	5	FET 4
3	17	5	FET 5
3	18	5	FET 6
3	19	5	NC
3	20	5	NC
3	21	NA	Calibrated T-type thermocouple

4.3 Once all of the instrumentation to the Keithley has been completed, run a channel verification and temperature alignment session with every module. Save the data to “PNNL_KEITHLEY_TRANSDUCER ALIGNMENT_NODES *X-Y_mmddyyx*” with “x” starting at “a” indicating test “a” then proceeds through the alphabet. The verification must include all of the nodes.

“NODES X-Y” indicates the node numbers being sampled in this file (1-5)

4.4 Verify all of the temperatures are within ±1°C with all the TC measuring ambient air temperature (allow the system and components to sit in ambient air overnight to reach steady state)

5.0 TEST PROCEDURE-THERMAL CHARACTERIZATION WITH AIR COOLED SERVER

NOTE: Use following file naming convention:

Keithley Data Storage location: PNNL folder located on desktop of each test notebook computer

"PNNL_KEITHLEY_RLX_mmddyyx" with "x" starting at "a" indicating test "a" then proceeds through the alphabet. A test includes the entire data set for all of the nodes independent of the module swap. Note in project notebook and data archive excel file, the details of each test.

Node name:

First tested node shall be named (x) starting at leftmost node "1" then proceeding numerically for the all 5 nodes.

5.1 Open HTTP browser and log onto RLX control software http://172.1.1.254

5.2 Login: "rlx" Password: "rlx"

5.3 Turn on RLX control tower by clicking "Power on" button located under the Manage tab/RLX Control Tower/ActivConfig/
Login: "ADMIN" Password: "ADMIN".

5.4 Turn on the 600ex Chassis by clicking the "Chassis Power on" button under Manage tab/600ex Chassis/ Chassis ActivConfig/Chassis tab
Login: "ADMIN" Password: "ADMIN".

5.5 Monitor CPU temperatures of each blade by logging in to each Blade through separate HTTP browser window.

- Open ActiveConfig for each Blade using one HTTP browser window for each blade
- Blade slot 1-10 IP addresses to open ActivConfig are:
  http://10.0.0.101 thru http://10.0.0.110
- Login: "ADMIN" Password: "ADMIN".
- Under the Server tab, click "Server Power On."
- CPU temperatures are displayed under "Sensors" tab.
- Repeat for additional Blades

5.6 CPU burn and benchmarking are opened through a secure shell.

- From the component tree, click on the desired blade under the 600ex Chassis, and then click on "Secure Shell" button.
- Login: "root" Password: "root".
- Execute eight (8) instances of burnP6 located in the "usr/bin" directory for each blade.
- Wait for steady state steady. Steady state shall be defined as no less than 1˚C/20 minutes.

- Execute nbench from the “root/nbench-byte-2.2.1” directory for each Blade.
- Open one secure shell window for each Blade.
- Repeat for additional Blades

5.7 Initiate the Keithley DAQ, record file per naming convention stated previously with Keithley modules.

5.8 Once Benchmarking software has completed, record the current information for the nodes instrumented with Keithley modules which includes, Voltage [V], Current [A] CPU1 temperature [˚C], CPU2 temperature [˚C]

5.9 Repeat 8.5-6.8 for a total of five complete samples @ one temperature. Repeat at temperatures 0, 10, 20, 30, 40°C.

5.10 Power off each Blade server by clicking “Soft Shutdown” under the server tab in the window opened in step 5.6.

5.11 Power off Chassis by clicking “Shutdown Chassis” under the Chassis tab in the window opened in step 5.5.

5.12 Power off the Control Tower by clicking “Soft Shutdown” in the window opened in step 5.4.

The average of the five test values from the Keithley DAQ, benchmarking software, and those hand recorded shall be archived in the archival Excel file matching Table 4.

Table 4. Example of required test data

file	PNNL_RLX_mmddyyx
Server Serial number	GSOU812
SprayCool kit #	3
Coolant	PF5050
Notebook #	ECB-1148
Test personnel	EE
PLSU in chamber?	YES
Chamber Temp	20
Ambient Temp	20
Flow	220
Pump Outlet Pressure	25.4
Reservoir Pressure	7.7
Reservoir Temperature	26.2
Supply Temp	NA
Return Temp	41
CPU1	54
CPU2	54
System	29
North Bridge	48.64
SCSI	33.71
South Bridge	35.11
DIMM1	52.57
DIMM2	42.07
PS FET	61.94

PS1	42.30
PS2	48.48
PS3	50.33
HDD3	29.64
HDD2	29.81
HDD1	30.47
INLET1	19.13
INLET2	19.12
INLET3	19.23
INLET4	19.35
INLET5	19.37
INLET6	19.66
PWR INLET	33.89
PWR OUT	49.26
OUT FAN	42.48
OUT FET	40.66
OUT DIMMS	32.86
OUT MCH1	27.27
OUT MCH2	25.79
OUT SOUTH1	28.01
OUT SOUTH2	22.95
Number Sort	757.12
String	56.634
Bit Field	1.80E+08
FP Emulator	68.118
Fourier	14750
Assignment	18.164
Idea	1537.9
Huffman	913.8
Neural Net	14.956
LU Decomposition	788.76
Voltage	118.5
Current	3
Power [W]	379.5

9 APPENDIX C

Air Cool Test Results at ISR

File	**012705d**				
Ave ambient (°C)	23.9				
stdev amb (°C)	0.4				
Pump Disch (psid)	NA				
Res Press (psia)	NA				
PF Temp (°C)	NA				
CPU DATA	**CPU0 (°C)**	**CPU1 (°C)**	**CPU0 (W)**	**CPU1(W)**	**Node (W)**
M1005 (Node3)	77.0	72.0	97.4	86.5	
M1006 (Node4)	72.0	74.0			
M1007 (Node8)	74.0	74.0			
M1008 (Node6)	80.0	73.0			
M1009 (Node15)	73.0	74.0			
M1010 (Node16)	72.0	72.0			
M1011 (Node9)	76.0	72.0			
M1012 (Node13)	72.0	73.0			
M1013 (Node5)	71.0	75.0			
M1014 (Node2)	73.0	71.0	92.7	82.8	
M1015 (Node14)	75.0	72.0			
M1016 (Node12)	74.0	72.0			
M1017 (Node10)	72.0	71.0			
M1018 (Node7)	71.0	72.0			
M1019 (Node18)	71.0	73.0			
M1020 (Node11)	71.0	71.0			
M1021 (Node17)	73.0	72.0			
M1022 (Node1)	75.0	80.0	97.4	86.5	
average	73.4	72.9			
max	80.0	97.4			
min	71.0	71.0			
stdev	2.4	2.1			
Rack Power (W)	6670.0				

Table C.1 Microprocessor temperatures and power dissipations for air-cooled servers running BurnI2, in 24°C air, in ISR integration lab

File name: 012705d

Component Temps	(°C)
ND1 HDD1	36.7
ND1 HDD2	40.2
ND1 North	52.2
ND1 DIMM 0A	42.6
ND1 DIMM 1A	45.9
ND1 DIMM 2A	45.2
ND1 DIMM 3A	47.2
ND1 DIMM 4A	45.5
ND1 DIMM 5A	45.5
ND1 DIMM 0B	37.5
ND1 DIMM 1B	43.1
ND1 DIMM 2B	41.2
ND1 DIMM 3B	45.2
ND1 DIMM 4B	40.3
ND1 DIMM 5B	47.0
ND1 FET 1	60.5
ND1 FET 2	53.1
ND1 FET 3	53.0
ND1 FET 4	55.1
ND1 FET 5	58.8
ND1 FET 6	48.1
ND1 FET 7	51.5
ND1 FET 8	49.0
ND1 PS1	35.3
ND1 PS2	34.5
ND1 ETHER 1	66.1
ND1 ETHER 2	70.0
ND1 ETHER 3	64.6
ND1 IN HD	25.3
ND1 IN CENTER	25.3
ND1 OUT HD	38.5
ND1 OUT CENTER	32.5

Component Temps	(°C)
ND2 HDD1	31.3
ND2 HDD2	33.7
ND2 North	50.8
ND2 DIMM 0A	41.7
ND2 DIMM 1A	43.5
ND2 DIMM 2A	42.5
ND2 DIMM 3A	37.4
ND2 DIMM 4A	41.3
ND2 DIMM 5A	44.9
ND2 DIMM 0B	36.6
ND2 DIMM 1B	40.2
ND2 DIMM 2B	39.7
ND2 DIMM 3B	42.4
ND2 DIMM 4B	38.7
ND2 DIMM 5B	43.4
ND2 FET 1	57.6
ND2 FET 2	53.5
ND2 FET 3	52.4
ND2 FET 4	53.3
ND2 FET 5	59.0
ND2 FET 6	47.4
ND2 FET 7	50.7
ND2 FET 8	48.1
ND2 PS1	31.1
ND2 PS2	30.8
ND2 ETHER 1	63.6
ND2 ETHER 2	68.5
ND2 ETHER 3	60.9
ND2 IN HD	23.3
ND2 IN CENTER	23.3
ND2 OUT HD	35.8
ND2 OUT CENTER	41.7

Component Temps	(°C)
ND3 HDD1	36.2
ND3 HDD2	41.5
ND3 North	53.0
ND3 DIMM 0A	45.3
ND3 DIMM 1A	45.9
ND3 DIMM 2A	47.8
ND3 DIMM 3A	50.5
ND3 DIMM 4A	48.8
ND3 DIMM 5A	47.4
ND3 DIMM 0B	38.1
ND3 DIMM 1B	43.2
ND3 DIMM 2B	41.3
ND3 DIMM 3B	45.4
ND3 DIMM 4B	39.6
ND3 DIMM 5B	44.9
ND3 FET 1	61.5
ND3 FET 2	60.1
ND3 FET 3	55.5
ND3 FET 4	52.7
ND3 FET 5	60.0
ND3 FET 6	39.3
ND3 FET 7	44.4
ND3 FET 8	49.1
ND3 PS1	33.4
ND3 PS2	33.0
ND3 ETHER 1	67.7
ND3 ETHER 2	72.5
ND3 ETHER 3	67.5
ND3 IN HD	22.4
ND3 IN CENTER	24.6
ND3 OUT HD	38.8
ND3 OUT CENTER	47.2

Table C.2 Peripheral device temperatures for rx2600 air-cooled rack (data for Nodes 1 – 3 shown) running BurnI2 in 24°C air, in ISR integration lab

SprayCool Test Results- R&D TMU Test Matrix Table 3.5

File	041105C
TMU	R&D

Ave ambient (°C)	24.1
stdev amb (°C)	0.7
Pump Disch (psid)	15.0
Res Press (psia)	14.8
PF Temp (°C)	15.7

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	67.0	62.0	92.4	83.8	380.4
M1006 (Node4)	NA	NA			
M1007 (Node8)	61.0	61.0			
M1008 (Node6)	60.0	63.0			
M1009 (Node15)	62.0	61.0			
M1010 (Node16)	63.0	61.0			
M1011 (Node9)	58.0	64.0			
M1012 (Node13)	61.0	61.0			
M1013 (Node5)	62.0	59.0			
M1014 (Node2)	61.0	61.0	88.9	81.2	367.5
M1015 (Node14)	60.0	61.0			
M1016 (Node12)	64.0	62.0			
M1017 (Node10)	60.0	57.0			
M1018 (Node7)	61.0	61.0			
M1019 (Node18)	63.0	61.0			
M1020 (Node11)	60.0	61.0			
M1021 (Node17)	61.0	62.0			
M1022 (Node1)	62.0	64.0	81.7	87.8	369.7
average	61.5	61.3			
max	67.0	64.0			
min	58.0	57.0			
stdev	2.0	1.6			

Rack Power (W)	6112.4

ND1 HDD1	33.2	ND2 HDD1	30.0	ND3 HDD1	38.7
ND1 HDD2	36.7	ND2 HDD2	32.4	ND3 HDD2	35.4
ND1 North	43.6	ND2 North	43.9	ND3 North	45.2
ND1 DIMM 0A	36.5	ND2 DIMM 0A	37.0	ND3 DIMM 0A	39.6
ND1 DIMM 1A	40.1	ND2 DIMM 1A	40.0	ND3 DIMM 1A	42.4
ND1 DIMM 2A	37.2	ND2 DIMM 2A	37.4	ND3 DIMM 2A	40.1
ND1 DIMM 3A	42.5	ND2 DIMM 3A	33.5	ND3 DIMM 3A	44.0
ND1 DIMM 4A	38.2	ND2 DIMM 4A	37.1	ND3 DIMM 4A	41.4
ND1 DIMM 5A	40.5	ND2 DIMM 5A	40.6	ND3 DIMM 5A	42.7
ND1 DIMM 0B	34.4	ND2 DIMM 0B	34.3	ND3 DIMM 0B	36.4
ND1 DIMM 1B	39.4	ND2 DIMM 1B	37.8	ND3 DIMM 1B	40.1
ND1 DIMM 2B	37.5	ND2 DIMM 2B	37.1	ND3 DIMM 2B	37.8
ND1 DIMM 3B	41.1	ND2 DIMM 3B	38.9	ND3 DIMM 3B	40.8
ND1 DIMM 4B	36.7	ND2 DIMM 4B	36.5	ND3 DIMM 4B	37.2
ND1 DIMM 5B	41.8	ND2 DIMM 5B	40.3	ND3 DIMM 5B	41.0
ND1 FET 1	41.2	ND2 FET 1	41.3	ND3 FET 1	43.9
ND1 FET 2	38.0	ND2 FET 2	38.5	ND3 FET 2	43.9
ND1 FET 3	36.9	ND2 FET 3	38.6	ND3 FET 3	39.5
ND1 FET 4	53.6	ND2 FET 4	55.4	ND3 FET 4	53.2
ND1 FET 5	56.9	ND2 FET 5	58.5	ND3 FET 5	61.7
ND1 FET 6	38.6	ND2 FET 6	42.9	ND3 FET 6	28.8
ND1 FET 7	40.4	ND2 FET 7	44.0	ND3 FET 7	31.5
ND1 FET 8	38.3	ND2 FET 8	39.9	ND3 FET 8	43.5
ND1 PS1	33.0	ND2 PS1	NA	ND3 PS1	33.7
ND1 PS2	32.0	ND2 PS2	29.6	ND3 PS2	NA
ND1 ETHER 1	51.8	ND2 ETHER 1	19.5	ND3 ETHER 1	53.7
ND1 ETHER 2	59.5	ND2 ETHER 2	59.9	ND3 ETHER 2	62.2
ND1 ETHER 3	53.2	ND2 ETHER 3	51.3	ND3 ETHER 3	56.1
ND1 IN HD	23.1	ND2 IN HD	22.7	ND3 IN HD	23.8
ND1 IN CENTER	23.1	ND2 IN CENTER	22.9	ND3 IN CENTER	23.7
ND1 OUT HD	32.2	ND2 OUT HD	33.8	ND3 OUT HD	35.2
ND1 OUT CE	33.3	ND2 OUT CENTER	32.2	ND3 OUT CENTER	35.5

Table C.3 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 16°C coolant, at 15psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	041105B				
Ave ambient (°C)	24.1				
stdev amb (°C)	0.8				
Pump Disch (psid)	20.0				
Res Press (psia)	13.5				
PF Temp (°C)	16.4				
CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	65.0	61.0	92.0	83.4	379.3
M1006 (Node4)	NA	NA			
M1007 (Node8)	60.0	59.0			
M1008 (Node6)	59.0	61.0			
M1009 (Node15)	60.0	59.0			
M1010 (Node16)	61.0	59.0			
M1011 (Node9)	57.0	62.0			
M1012 (Node13)	59.0	59.0			
M1013 (Node5)	60.0	57.0			
M1014 (Node2)	59.0	59.0	88.4	80.9	366.7
M1015 (Node14)	58.0	59.0			
M1016 (Node12)	62.0	60.0			
M1017 (Node10)	58.0	55.0			
M1018 (Node7)	59.0	59.0			
M1019 (Node18)	60.0	59.0			
M1020 (Node11)	58.0	58.0			
M1021 (Node17)	59.0	60.0			
M1022 (Node1)	60.0	62.0	81.2	87.4	371.8
average	59.6	59.3			
max	65.0	62.0			
min	57.0	55.0			
stdev	1.8	1.7			
Rack Power (W)	6129.1				

File name: 041105B

Component Temps	(°C)
ND1 HDD1	32.6
ND1 HDD2	36.1
ND1 North	42.6
ND1 DIMM 0A	36.0
ND1 DIMM 1A	39.5
ND1 DIMM 2A	36.7
ND1 DIMM 3A	41.7
ND1 DIMM 4A	37.7
ND1 DIMM 5A	39.9
ND1 DIMM 0B	34.1
ND1 DIMM 1B	39.1
ND1 DIMM 2B	37.1
ND1 DIMM 3B	40.5
ND1 DIMM 4B	36.3
ND1 DIMM 5B	41.4
ND1 FET 1	40.6
ND1 FET 2	37.4
ND1 FET 3	36.3
ND1 FET 4	52.7
ND1 FET 5	55.9
ND1 FET 6	38.0
ND1 FET 7	39.5
ND1 FET 8	37.7
ND1 PS1	32.5
ND1 PS2	31.7
ND1 ETHER 1	50.4
ND1 ETHER 2	58.4
ND1 ETHER 3	52.1
ND1 IN HD	23.3
ND1 IN CENTER	23.3
ND1 OUT HD	31.8
ND1 OUT CE	32.7

Component Temps	(°C)
ND2 HDD1	29.8
ND2 HDD2	32.2
ND2 North	43.0
ND2 DIMM 0A	36.4
ND2 DIMM 1A	39.5
ND2 DIMM 2A	36.8
ND2 DIMM 3A	33.1
ND2 DIMM 4A	36.5
ND2 DIMM 5A	40.1
ND2 DIMM 0B	34.0
ND2 DIMM 1B	37.5
ND2 DIMM 2B	36.6
ND2 DIMM 3B	38.6
ND2 DIMM 4B	36.2
ND2 DIMM 5B	40.0
ND2 FET 1	40.4
ND2 FET 2	37.7
ND2 FET 3	37.9
ND2 FET 4	54.6
ND2 FET 5	57.5
ND2 FET 6	41.7
ND2 FET 7	43.2
ND2 FET 8	39.3
ND2 PS1	NA
ND2 PS2	29.2
ND2 ETHER 1	22.6
ND2 ETHER 2	59.0
ND2 ETHER 3	50.4
ND2 IN HD	22.9
ND2 IN CENTER	23.2
ND2 OUT HD	33.5
ND2 OUT CENTER	31.7

Component Temps	(°C)
ND3 HDD1	38.8
ND3 HDD2	35.4
ND3 North	45.0
ND3 DIMM 0A	39.5
ND3 DIMM 1A	42.4
ND3 DIMM 2A	39.9
ND3 DIMM 3A	43.8
ND3 DIMM 4A	41.2
ND3 DIMM 5A	42.7
ND3 DIMM 0B	36.3
ND3 DIMM 1B	40.1
ND3 DIMM 2B	37.7
ND3 DIMM 3B	40.8
ND3 DIMM 4B	37.2
ND3 DIMM 5B	41.0
ND3 FET 1	43.9
ND3 FET 2	43.9
ND3 FET 3	39.4
ND3 FET 4	52.8
ND3 FET 5	61.4
ND3 FET 6	28.8
ND3 FET 7	31.4
ND3 FET 8	43.4
ND3 PS1	33.7
ND3 PS2	NA
ND3 ETHER 1	53.4
ND3 ETHER 2	62.1
ND3 ETHER 3	55.9
ND3 IN HD	24.3
ND3 IN CENTER	25.2
ND3 OUT HD	35.1
ND3 OUT CENTER	35.5

Table C.4 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 16°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	041205A
TMU	R&D

Ave ambient (°C)	21.9
stdev amb (°C)	0.7
Pump Disch (psid)	25.0
Res Press (psia)	14.5
PF Temp (°C)	17.1

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	65.0	61.0	92.2	83.4	378.5
M1006 (Node4)	NA	NA			
M1007 (Node8)	60.0	60.0			
M1008 (Node6)	59.0	62.0			
M1009 (Node15)	61.0	60.0			
M1010 (Node16)	62.0	60.0			
M1011 (Node9)	57.0	62.0			
M1012 (Node13)	59.0	59.0			
M1013 (Node5)	61.0	58.0			
M1014 (Node2)	60.0	59.0	88.6	81.0	363.3
M1015 (Node14)	59.0	60.0			
M1016 (Node12)	63.0	60.0			
M1017 (Node10)	59.0	55.0			
M1018 (Node7)	60.0	60.0			
M1019 (Node18)	61.0	59.0			
M1020 (Node11)	58.0	59.0			
M1021 (Node17)	61.0	61.0			
M1022 (Node1)	60.0	62.0	81.4	87.5	365.8
average	60.3	59.8			
max	65.0	62.0			
min	57.0	55.0			
stdev	1.9	1.7			

Rack Power (W)	6112.4

ND1 HDD1	32.7	**ND2 HDD1**	29.2	**ND3 HDD1**	37.7
ND1 HDD2	36.5	**ND2 HDD2**	31.8	**ND3 HDD2**	34.3
ND1 North	42.5	**ND2 North**	42.6	**ND3 North**	43.3
ND1 DIMM 0A	35.3	**ND2 DIMM 0A**	35.4	**ND3 DIMM 0A**	37.9
ND1 DIMM 1A	39.5	**ND2 DIMM 1A**	39.1	**ND3 DIMM 1A**	41.4
ND1 DIMM 2A	36.0	**ND2 DIMM 2A**	35.9	**ND3 DIMM 2A**	38.5
ND1 DIMM 3A	41.8	**ND2 DIMM 3A**	32.2	**ND3 DIMM 3A**	42.7
ND1 DIMM 4A	36.9	**ND2 DIMM 4A**	35.4	**ND3 DIMM 4A**	39.9
ND1 DIMM 5A	39.9	**ND2 DIMM 5A**	39.7	**ND3 DIMM 5A**	41.7
ND1 DIMM 0B	33.2	**ND2 DIMM 0B**	32.8	**ND3 DIMM 0B**	34.8
ND1 DIMM 1B	38.8	**ND2 DIMM 1B**	36.8	**ND3 DIMM 1B**	39.1
ND1 DIMM 2B	36.2	**ND2 DIMM 2B**	35.3	**ND3 DIMM 2B**	36.1
ND1 DIMM 3B	40.3	**ND2 DIMM 3B**	37.6	**ND3 DIMM 3B**	39.5
ND1 DIMM 4B	35.4	**ND2 DIMM 4B**	34.5	**ND3 DIMM 4B**	35.3
ND1 DIMM 5B	41.3	**ND2 DIMM 5B**	39.4	**ND3 DIMM 5B**	39.8
ND1 FET 1	39.8	**ND2 FET 1**	39.2	**ND3 FET 1**	41.3
ND1 FET 2	36.6	**ND2 FET 2**	36.5	**ND3 FET 2**	41.5
ND1 FET 3	35.4	**ND2 FET 3**	36.7	**ND3 FET 3**	37.1
ND1 FET 4	51.8	**ND2 FET 4**	53.0	**ND3 FET 4**	50.6
ND1 FET 5	55.3	**ND2 FET 5**	56.2	**ND3 FET 5**	59.7
ND1 FET 6	36.9	**ND2 FET 6**	40.1	**ND3 FET 6**	26.3
ND1 FET 7	38.8	**ND2 FET 7**	41.9	**ND3 FET 7**	29.0
ND1 FET 8	36.9	**ND2 FET 8**	38.2	**ND3 FET 8**	41.3
ND1 PS1	31.6	**ND2 PS1**	NA	**ND3 PS1**	31.8
ND1 PS2	30.6	**ND2 PS2**	27.9	**ND3 PS2**	NA
ND1 ETHER 1	50.7	**ND2 ETHER 1**	15.5	**ND3 ETHER 1**	51.8
ND1 ETHER 2	58.5	**ND2 ETHER 2**	58.5	**ND3 ETHER 2**	60.6
ND1 ETHER 3	52.3	**ND2 ETHER 3**	50.2	**ND3 ETHER 3**	54.4
ND1 IN HD	21.2	**ND2 IN HD**	21.1	**ND3 IN HD**	21.3
ND1 IN CENTER	21.1	**ND2 IN CENTER**	21.8	**ND3 IN CENTER**	21.2
ND1 OUT HD	31.6	**ND2 OUT HD**	32.7	**ND3 OUT HD**	33.8
ND1 OUT CE	31.6	**ND2 OUT CENTER**	30.6	**ND3 OUT CENTER**	33.4

Table C.5 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 22°C air, 17°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	040405A
TMU	R&D

Ave ambient (°C)	24.2
stdev amb (°C)	0.6
Pump Disch (psid)	15.0
Res Press (psia)	15.0
PF Temp (°C)	20.9

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	69.0	65.0	93.2	84.0	377.3
M1006 (Node4)	NA	NA			
M1007 (Node8)	64.0	63.0			
M1008 (Node6)	63.0	65.0			
M1009 (Node15)	65.0	63.0			
M1010 (Node16)	65.0	62.0			
M1011 (Node9)	61.0	64.0			
M1012 (Node13)	62.0	64.0			
M1013 (Node5)	64.0	61.0			
M1014 (Node2)	63.0	63.0	89.5	81.6	362.9
M1015 (Node14)	63.0	64.0			
M1016 (Node12)	67.0	64.0			
M1017 (Node10)	62.0	59.0			
M1018 (Node7)	64.0	64.0			
M1019 (Node18)	64.0	62.0			
M1020 (Node11)	61.0	63.0			
M1021 (Node17)	63.0	64.0			
M1022 (Node1)	64.0	65.0	81.9	88.1	367.3
average	63.8	63.2			
max	69.0	65.0			
min	61.0	59.0			
stdev	2.0	1.6			

Rack Power (W)	6150.5

ND1 HDD1	33.6	**ND2 HDD1**	30.7	**ND3 HDD1**	39.7
ND1 HDD2	37.1	**ND2 HDD2**	33.1	**ND3 HDD2**	36.3
ND1 North	44.4	**ND2 North**	44.7	**ND3 North**	46.2
ND1 DIMM 0A	37.2	**ND2 DIMM 0A**	37.6	**ND3 DIMM 0A**	40.6
ND1 DIMM 1A	40.8	**ND2 DIMM 1A**	40.7	**ND3 DIMM 1A**	43.5
ND1 DIMM 2A	37.8	**ND2 DIMM 2A**	38.1	**ND3 DIMM 2A**	41.1
ND1 DIMM 3A	43.2	**ND2 DIMM 3A**	34.1	**ND3 DIMM 3A**	45.2
ND1 DIMM 4A	38.6	**ND2 DIMM 4A**	37.7	**ND3 DIMM 4A**	42.6
ND1 DIMM 5A	41.1	**ND2 DIMM 5A**	41.4	**ND3 DIMM 5A**	44.0
ND1 DIMM 0B	34.9	**ND2 DIMM 0B**	34.9	**ND3 DIMM 0B**	37.5
ND1 DIMM 1B	39.9	**ND2 DIMM 1B**	38.4	**ND3 DIMM 1B**	41.4
ND1 DIMM 2B	37.9	**ND2 DIMM 2B**	37.5	**ND3 DIMM 2B**	38.8
ND1 DIMM 3B	41.4	**ND2 DIMM 3B**	39.3	**ND3 DIMM 3B**	41.8
ND1 DIMM 4B	36.8	**ND2 DIMM 4B**	36.5	**ND3 DIMM 4B**	38.1
ND1 DIMM 5B	42.6	**ND2 DIMM 5B**	41.2	**ND3 DIMM 5B**	41.9
ND1 FET 1	42.1	**ND2 FET 1**	42.4	**ND3 FET 1**	45.0
ND1 FET 2	38.9	**ND2 FET 2**	39.4	**ND3 FET 2**	44.9
ND1 FET 3	37.7	**ND2 FET 3**	39.7	**ND3 FET 3**	40.6
ND1 FET 4	54.1	**ND2 FET 4**	56.4	**ND3 FET 4**	54.4
ND1 FET 5	57.4	**ND2 FET 5**	59.5	**ND3 FET 5**	62.8
ND1 FET 6	38.2	**ND2 FET 6**	43.4	**ND3 FET 6**	29.8
ND1 FET 7	41.2	**ND2 FET 7**	44.7	**ND3 FET 7**	32.4
ND1 FET 8	39.8	**ND2 FET 8**	40.8	**ND3 FET 8**	44.1
ND1 PS1	33.3	**ND2 PS1**	NA	**ND3 PS1**	34.3
ND1 PS2	32.5	**ND2 PS2**	30.2	**ND3 PS2**	NA
ND1 ETHER 1	52.5	**ND2 ETHER 1**	12.1	**ND3 ETHER 1**	54.7
ND1 ETHER 2	60.1	**ND2 ETHER 2**	60.9	**ND3 ETHER 2**	63.2
ND1 ETHER 3	53.9	**ND2 ETHER 3**	52.7	**ND3 ETHER 3**	56.9
ND1 IN HD	23.4	**ND2 IN HD**	23.5	**ND3 IN HD**	24.4
ND1 IN CENTER	23.3	**ND2 IN CENTER**	23.7	**ND3 IN CENTER**	24.1
ND1 OUT HD	33.0	**ND2 OUT HD**	34.3	**ND3 OUT HD**	36.1
ND1 OUT CE	33.7	**ND2 OUT CENTER**	32.8	**ND3 OUT CENTER**	36.5

Table C.6 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack BurnI2, in 24°C air, 21°C coolant, at 15 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	033005a				
Ave ambient (°C)	24.2				
stdev amb (°C)	0.4				
Pump Disch (psid)	20.0				
Res Press (psia)	14.7				
PF Temp (°C)	20.7				
CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	66.0	64.0	92.4	83.7	380.7
M1006 (Node4)	NA	NA			
M1007 (Node8)	62.0	61.0			
M1008 (Node6)	61.0	66.0			
M1009 (Node15)	63.0	62.0			
M1010 (Node16)	63.0	61.0			
M1011 (Node9)	60.0	63.0			
M1012 (Node13)	61.0	61.0			
M1013 (Node5)	63.0	60.0			
M1014 (Node2)	62.0	61.0	88.9	81.2	369.4
M1015 (Node14)	62.0	62.0			
M1016 (Node12)	65.0	62.0			
M1017 (Node10)	61.0	67.0			
M1018 (Node7)	62.0	62.0			
M1019 (Node18)	63.0	61.0			
M1020 (Node11)	60.0	61.0			
M1021 (Node17)	62.0	64.0			
M1022 (Node1)	62.0	64.0	81.6	87.8	372.9
average	62.2	62.5			
max	66.0	67.0			
min	60.0	60.0			
stdev	1.6	1.9			
Rack Power (W)	6159.3				

File name: 033005a

Component Temps	(°C)
ND1 HDD1	33.5
ND1 HDD2	36.8
ND1 North	44.5
ND1 DIMM 0A	37.2
ND1 DIMM 1A	40.8
ND1 DIMM 2A	37.9
ND1 DIMM 3A	43.1
ND1 DIMM 4A	38.7
ND1 DIMM 5A	41.1
ND1 DIMM 0B	35.1
ND1 DIMM 1B	39.8
ND1 DIMM 2B	38.0
ND1 DIMM 3B	41.4
ND1 DIMM 4B	37.1
ND1 DIMM 5B	42.5
ND1 FET 1	42.6
ND1 FET 2	39.1
ND1 FET 3	38.1
ND1 FET 4	54.4
ND1 FET 5	57.1
ND1 FET 6	39.5
ND1 FET 7	41.2
ND1 FET 8	39.4
ND1 PS1	33.8
ND1 PS2	32.7
ND1 ETHER 1	52.6
ND1 ETHER 2	60.1
ND1 ETHER 3	53.9
ND1 IN HD	24.1
ND1 IN CENTER	24.1
ND1 OUT HD	32.4
ND1 OUT CE	34.3

Component Temps	(°C)
ND2 HDD1	30.3
ND2 HDD2	32.7
ND2 North	44.0
ND2 DIMM 0A	37.0
ND2 DIMM 1A	40.4
ND2 DIMM 2A	37.4
ND2 DIMM 3A	33.7
ND2 DIMM 4A	37.1
ND2 DIMM 5A	40.9
ND2 DIMM 0B	34.5
ND2 DIMM 1B	37.9
ND2 DIMM 2B	37.0
ND2 DIMM 3B	38.8
ND2 DIMM 4B	36.1
ND2 DIMM 5B	40.6
ND2 FET 1	41.4
ND2 FET 2	38.6
ND2 FET 3	38.8
ND2 FET 4	55.1
ND2 FET 5	58.1
ND2 FET 6	42.5
ND2 FET 7	44.0
ND2 FET 8	40.1
ND2 PS1	NA
ND2 PS2	30.1
ND2 ETHER 1	4.2
ND2 ETHER 2	60.0
ND2 ETHER 3	51.5
ND2 IN HD	23.6
ND2 IN CENTER	23.6
ND2 OUT HD	33.6
ND2 OUT CENTER	32.2

Component Temps	(°C)
ND3 HDD1	37.5
ND3 HDD2	34.5
ND3 North	44.7
ND3 DIMM 0A	39.6
ND3 DIMM 1A	42.5
ND3 DIMM 2A	40.3
ND3 DIMM 3A	44.1
ND3 DIMM 4A	41.8
ND3 DIMM 5A	43.1
ND3 DIMM 0B	36.8
ND3 DIMM 1B	40.2
ND3 DIMM 2B	38.0
ND3 DIMM 3B	40.9
ND3 DIMM 4B	37.3
ND3 DIMM 5B	40.6
ND3 FET 1	43.4
ND3 FET 2	43.6
ND3 FET 3	39.3
ND3 FET 4	53.5
ND3 FET 5	62.0
ND3 FET 6	28.9
ND3 FET 7	30.5
ND3 FET 8	42.7
ND3 PS1	33.8
ND3 PS2	NA
ND3 ETHER 1	53.3
ND3 ETHER 2	61.8
ND3 ETHER 3	55.6
ND3 IN HD	24.4
ND3 IN CENTER	24.3
ND3 OUT HD	35.0
ND3 OUT CENTER	35.3

Table C.7 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 21°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	040405B
TMU	R&D

Ave ambient (°C)	23.6
stdev amb (°C)	0.6
Pump Disch (psid)	25.0
Res Press (psia)	15.0
PF Temp (°C)	20.8

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	66.0	63.0	92.4	83.5	379.5
M1006 (Node4)	NA	NA			
M1007 (Node8)	62.0	61.0			
M1008 (Node6)	61.0	63.0			
M1009 (Node15)	63.0	62.0			
M1010 (Node16)	64.0	62.0			
M1011 (Node9)	59.0	62.0			
M1012 (Node13)	61.0	63.0			
M1013 (Node5)	63.0	59.0			
M1014 (Node2)	62.0	61.0	88.8	81.2	363.1
M1015 (Node14)	61.0	62.0			
M1016 (Node12)	65.0	62.0			
M1017 (Node10)	61.0	57.0			
M1018 (Node7)	62.0	63.0			
M1019 (Node18)	63.0	61.0			
M1020 (Node11)	60.0	61.0			
M1021 (Node17)	63.0	63.0			
M1022 (Node1)	63.0	64.0	81.6	87.7	366.9
average	62.3	61.7			
max	66.0	64.0			
min	59.0	57.0			
stdev	1.8	1.7			

Rack Power (W)	6189.5

ND1 HDD1	32.4	**ND2 HDD1**	29.1	**ND3 HDD1**	38.5
ND1 HDD2	35.8	**ND2 HDD2**	31.4	**ND3 HDD2**	35.0
ND1 North	43.0	**ND2 North**	43.4	**ND3 North**	44.6
ND1 DIMM 0A	35.8	**ND2 DIMM 0A**	36.2	**ND3 DIMM 0A**	38.9
ND1 DIMM 1A	39.5	**ND2 DIMM 1A**	39.5	**ND3 DIMM 1A**	41.9
ND1 DIMM 2A	36.5	**ND2 DIMM 2A**	36.8	**ND3 DIMM 2A**	39.3
ND1 DIMM 3A	41.9	**ND2 DIMM 3A**	32.8	**ND3 DIMM 3A**	43.3
ND1 DIMM 4A	37.4	**ND2 DIMM 4A**	36.4	**ND3 DIMM 4A**	40.7
ND1 DIMM 5A	39.9	**ND2 DIMM 5A**	40.2	**ND3 DIMM 5A**	42.2
ND1 DIMM 0B	33.7	**ND2 DIMM 0B**	33.7	**ND3 DIMM 0B**	35.6
ND1 DIMM 1B	38.6	**ND2 DIMM 1B**	37.3	**ND3 DIMM 1B**	39.6
ND1 DIMM 2B	36.7	**ND2 DIMM 2B**	36.4	**ND3 DIMM 2B**	37.0
ND1 DIMM 3B	40.4	**ND2 DIMM 3B**	38.4	**ND3 DIMM 3B**	40.3
ND1 DIMM 4B	35.9	**ND2 DIMM 4B**	35.6	**ND3 DIMM 4B**	36.4
ND1 DIMM 5B	41.2	**ND2 DIMM 5B**	39.9	**ND3 DIMM 5B**	40.6
ND1 FET 1	41.0	**ND2 FET 1**	41.2	**ND3 FET 1**	43.5
ND1 FET 2	37.6	**ND2 FET 2**	38.0	**ND3 FET 2**	43.3
ND1 FET 3	36.5	**ND2 FET 3**	38.2	**ND3 FET 3**	38.9
ND1 FET 4	52.8	**ND2 FET 4**	54.9	**ND3 FET 4**	51.8
ND1 FET 5	56.0	**ND2 FET 5**	57.8	**ND3 FET 5**	60.7
ND1 FET 6	37.2	**ND2 FET 6**	42.3	**ND3 FET 6**	28.3
ND1 FET 7	39.8	**ND2 FET 7**	43.3	**ND3 FET 7**	31.1
ND1 FET 8	37.9	**ND2 FET 8**	39.3	**ND3 FET 8**	42.8
ND1 PS1	32.4	**ND2 PS1**	NA	**ND3 PS1**	33.0
ND1 PS2	31.2	**ND2 PS2**	28.9	**ND3 PS2**	NA
ND1 ETHER 1	51.3	**ND2 ETHER 1**	NA	**ND3 ETHER 1**	53.0
ND1 ETHER 2	58.9	**ND2 ETHER 2**	59.6	**ND3 ETHER 2**	61.7
ND1 ETHER 3	52.7	**ND2 ETHER 3**	51.2	**ND3 ETHER 3**	55.5
ND1 IN HD	22.7	**ND2 IN HD**	22.2	**ND3 IN HD**	23.8
ND1 IN CENTER	22.7	**ND2 IN CENTER**	22.3	**ND3 IN CENTER**	24.1
ND1 OUT HD	31.9	**ND2 OUT HD**	33.0	**ND3 OUT HD**	34.7
ND1 OUT CE	32.8	**ND2 OUT CENTER**	31.6	**ND3 OUT CENTER**	34.9

Table C.8 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 21°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	041205B
TMU	R&D

Ave ambient (°C)	27.0
stdev amb (°C)	0.6
Pump Disch (psid)	30.0
Res Press (psia)	15.4
PF Temp (°C)	18.9

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	66.0	63.0	92.1	83.6	380.9
M1006 (Node4)	NA	NA			
M1007 (Node8)	62.0	61.0			
M1008 (Node6)	60.0	63.0			
M1009 (Node15)	62.0	61.0			
M1010 (Node16)	63.0	61.0			
M1011 (Node9)	59.0	63.0			
M1012 (Node13)	60.0	61.0			
M1013 (Node5)	62.0	59.0			
M1014 (Node2)	61.0	60.0	88.7	81.2	363.8
M1015 (Node14)	60.0	62.0			
M1016 (Node12)	64.0	62.0			
M1017 (Node10)	60.0	57.0			
M1018 (Node7)	61.0	62.0			
M1019 (Node18)	62.0	60.0			
M1020 (Node11)	59.0	60.0			
M1021 (Node17)	61.0	62.0			
M1022 (Node1)	61.0	63.0	81.5	87.8	367.5
average	61.4	61.2			
max	66.0	63.0			
min	59.0	57.0			
stdev	1.8	1.6			

Rack Power (W)	6174.6

ND1 HDD1	36.4	**ND2 HDD1**	33.3	**ND3 HDD1**	39.3
ND1 HDD2	39.7	**ND2 HDD2**	36.0	**ND3 HDD2**	36.3
ND1 North	47.2	**ND2 North**	47.1	**ND3 North**	46.5
ND1 DIMM 0A	39.9	**ND2 DIMM 0A**	40.0	**ND3 DIMM 0A**	41.4
ND1 DIMM 1A	43.1	**ND2 DIMM 1A**	43.1	**ND3 DIMM 1A**	43.9
ND1 DIMM 2A	40.6	**ND2 DIMM 2A**	40.7	**ND3 DIMM 2A**	41.8
ND1 DIMM 3A	45.5	**ND2 DIMM 3A**	36.9	**ND3 DIMM 3A**	45.4
ND1 DIMM 4A	41.4	**ND2 DIMM 4A**	40.3	**ND3 DIMM 4A**	43.1
ND1 DIMM 5A	43.5	**ND2 DIMM 5A**	43.8	**ND3 DIMM 5A**	44.2
ND1 DIMM 0B	37.7	**ND2 DIMM 0B**	37.6	**ND3 DIMM 0B**	38.2
ND1 DIMM 1B	42.4	**ND2 DIMM 1B**	41.0	**ND3 DIMM 1B**	41.4
ND1 DIMM 2B	40.6	**ND2 DIMM 2B**	39.9	**ND3 DIMM 2B**	39.5
ND1 DIMM 3B	43.9	**ND2 DIMM 3B**	41.7	**ND3 DIMM 3B**	42.1
ND1 DIMM 4B	39.7	**ND2 DIMM 4B**	39.0	**ND3 DIMM 4B**	38.9
ND1 DIMM 5B	44.9	**ND2 DIMM 5B**	43.4	**ND3 DIMM 5B**	42.4
ND1 FET 1	46.5	**ND2 FET 1**	45.4	**ND3 FET 1**	45.1
ND1 FET 2	42.5	**ND2 FET 2**	42.2	**ND3 FET 2**	45.4
ND1 FET 3	41.4	**ND2 FET 3**	42.4	**ND3 FET 3**	41.0
ND1 FET 4	58.4	**ND2 FET 4**	58.7	**ND3 FET 4**	55.0
ND1 FET 5	61.0	**ND2 FET 5**	61.8	**ND3 FET 5**	63.5
ND1 FET 6	42.6	**ND2 FET 6**	45.7	**ND3 FET 6**	30.4
ND1 FET 7	44.7	**ND2 FET 7**	47.3	**ND3 FET 7**	32.9
ND1 FET 8	42.5	**ND2 FET 8**	43.2	**ND3 FET 8**	44.9
ND1 PS1	36.4	**ND2 PS1**	NA	**ND3 PS1**	36.1
ND1 PS2	35.4	**ND2 PS2**	32.7	**ND3 PS2**	NA
ND1 ETHER 1	56.0	**ND2 ETHER 1**	NA	**ND3 ETHER 1**	54.7
ND1 ETHER 2	63.1	**ND2 ETHER 2**	63.4	**ND3 ETHER 2**	63.4
ND1 ETHER 3	57.0	**ND2 ETHER 3**	54.9	**ND3 ETHER 3**	57.2
ND1 IN HD	27.0	**ND2 IN HD**	26.1	**ND3 IN HD**	26.9
ND1 IN CENTER	27.3	**ND2 IN CENTER**	26.1	**ND3 IN CENTER**	26.8
ND1 OUT HD	35.1	**ND2 OUT HD**	36.4	**ND3 OUT HD**	36.6
ND1 OUT CE	37.1	**ND2 OUT CENTER**	35.5	**ND3 OUT CENTER**	37.0

Table C.9 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 27°C air, 19°C coolant, at 30 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	040605C
TMU	R&D

Ave ambient (°C)	24.4
stdev amb (°C)	0.9
Pump Disch (psid)	15.0
Res Press (psia)	15.5
PF Temp (°C)	24.8

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	69.0	65.0	92.8	83.9	380.3
M1006 (Node4)	NA	NA			
M1007 (Node8)	64.0	63.0			
M1008 (Node6)	63.0	65.0			
M1009 (Node15)	65.0	63.0			
M1010 (Node16)	65.0	62.0			
M1011 (Node9)	61.0	64.0			
M1012 (Node13)	63.0	63.0			
M1013 (Node5)	64.0	62.0			
M1014 (Node2)	64.0	64.0	89.5	81.5	370.6
M1015 (Node14)	63.0	64.0			
M1016 (Node12)	67.0	64.0			
M1017 (Node10)	63.0	60.0			
M1018 (Node7)	64.0	64.0			
M1019 (Node18)	65.0	63.0			
M1020 (Node11)	62.0	63.0			
M1021 (Node17)	64.0	65.0			
M1022 (Node1)	64.0	66.0	81.9	88.3	374.9
average	64.1	63.5			
max	69.0	66.0			
min	61.0	60.0			
stdev	1.8	1.4			

Rack Power (W)	6219.2

ND1 HDD1	36.1	**ND2 HDD1**	31.5	**ND3 HDD1**	35.9
ND1 HDD2	39.6	**ND2 HDD2**	34.5	**ND3 HDD2**	33.0
ND1 North	46.4	**ND2 North**	45.6	**ND3 North**	43.7
ND1 DIMM 0A	38.6	**ND2 DIMM 0A**	37.7	**ND3 DIMM 0A**	38.8
ND1 DIMM 1A	42.3	**ND2 DIMM 1A**	41.3	**ND3 DIMM 1A**	41.1
ND1 DIMM 2A	39.3	**ND2 DIMM 2A**	38.4	**ND3 DIMM 2A**	39.1
ND1 DIMM 3A	44.9	**ND2 DIMM 3A**	34.9	**ND3 DIMM 3A**	42.6
ND1 DIMM 4A	40.1	**ND2 DIMM 4A**	38.0	**ND3 DIMM 4A**	40.5
ND1 DIMM 5A	42.8	**ND2 DIMM 5A**	42.2	**ND3 DIMM 5A**	41.4
ND1 DIMM 0B	36.5	**ND2 DIMM 0B**	35.4	**ND3 DIMM 0B**	35.3
ND1 DIMM 1B	42.0	**ND2 DIMM 1B**	39.3	**ND3 DIMM 1B**	38.5
ND1 DIMM 2B	39.4	**ND2 DIMM 2B**	37.7	**ND3 DIMM 2B**	36.9
ND1 DIMM 3B	43.4	**ND2 DIMM 3B**	40.0	**ND3 DIMM 3B**	39.5
ND1 DIMM 4B	38.7	**ND2 DIMM 4B**	37.0	**ND3 DIMM 4B**	36.3
ND1 DIMM 5B	44.3	**ND2 DIMM 5B**	41.9	**ND3 DIMM 5B**	39.6
ND1 FET 1	45.0	**ND2 FET 1**	43.9	**ND3 FET 1**	42.0
ND1 FET 2	40.9	**ND2 FET 2**	39.9	**ND3 FET 2**	42.3
ND1 FET 3	39.9	**ND2 FET 3**	40.3	**ND3 FET 3**	38.0
ND1 FET 4	56.8	**ND2 FET 4**	55.4	**ND3 FET 4**	51.8
ND1 FET 5	59.3	**ND2 FET 5**	59.0	**ND3 FET 5**	60.7
ND1 FET 6	42.0	**ND2 FET 6**	42.2	**ND3 FET 6**	28.0
ND1 FET 7	43.5	**ND2 FET 7**	44.7	**ND3 FET 7**	29.8
ND1 FET 8	41.0	**ND2 FET 8**	41.4	**ND3 FET 8**	41.8
ND1 PS1	34.9	**ND2 PS1**	NA	**ND3 PS1**	33.2
ND1 PS2	34.1	**ND2 PS2**	30.6	**ND3 PS2**	NA
ND1 ETHER 1	55.1	**ND2 ETHER 1**	NA	**ND3 ETHER 1**	51.8
ND1 ETHER 2	62.2	**ND2 ETHER 2**	61.6	**ND3 ETHER 2**	60.5
ND1 ETHER 3	56.1	**ND2 ETHER 3**	53.2	**ND3 ETHER 3**	54.4
ND1 IN HD	24.7	**ND2 IN HD**	23.5	**ND3 IN HD**	23.4
ND1 IN CENTER	25.5	**ND2 IN CENTER**	23.4	**ND3 IN CENTER**	23.4
ND1 OUT HD	35.1	**ND2 OUT HD**	35.0	**ND3 OUT HD**	33.6
ND1 OUT CE	36.0	**ND2 OUT CENTER**	33.5	**ND3 OUT CENTER**	34.2

Table C.10 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 25°C coolant, at 15 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	040605a				
Ave ambient (°C)	23.6				
stdev amb (°C)	0.6				
Pump Disch (psid)	25.0				
Res Press (psia)	15.0				
PF Temp (°C)	20.8				
CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	69.0	65.0	93.1	83.9	380.8
M1006 (Node4)	NA	NA			
M1007 (Node8)	64.0	63.0			
M1008 (Node6)	63.0	66.0			
M1009 (Node15)	65.0	64.0			
M1010 (Node16)	65.0	63.0			
M1011 (Node9)	61.0	65.0			
M1012 (Node13)	63.0	63.0			
M1013 (Node5)	65.0	62.0			
M1014 (Node2)	64.0	63.0	89.5	81.5	368.9
M1015 (Node14)	64.0	64.0			
M1016 (Node12)	67.0	64.0			
M1017 (Node10)	62.0	59.0			
M1018 (Node7)	64.0	64.0			
M1019 (Node18)	65.0	63.0			
M1020 (Node11)	62.0	63.0			
M1021 (Node17)	65.0	66.0			
M1022 (Node1)	65.0	66.0	81.8	88.2	372.3
average	64.3	63.7			
max	69.0	66.0			
min	61.0	59.0			
stdev	1.9	1.7			
Rack Power (W)	6207.1				

File name: 040605a

Component Temps	(°C)	Component Temps	(°C)	Component Temps	(°C)
ND1 HDD1	35.7	ND2 HDD1	31.7	ND3 HDD1	36.8
ND1 HDD2	39.3	ND2 HDD2	34.6	ND3 HDD2	33.7
ND1 North	45.8	ND2 North	45.5	ND3 North	44.2
ND1 DIMM 0A	38.0	ND2 DIMM 0A	37.7	ND3 DIMM 0A	38.9
ND1 DIMM 1A	41.7	ND2 DIMM 1A	41.3	ND3 DIMM 1A	41.8
ND1 DIMM 2A	38.6	ND2 DIMM 2A	38.2	ND3 DIMM 2A	39.4
ND1 DIMM 3A	44.3	ND2 DIMM 3A	34.7	ND3 DIMM 3A	43.2
ND1 DIMM 4A	39.4	ND2 DIMM 4A	37.7	ND3 DIMM 4A	40.7
ND1 DIMM 5A	42.1	ND2 DIMM 5A	41.9	ND3 DIMM 5A	42.1
ND1 DIMM 0B	35.7	ND2 DIMM 0B	35.1	ND3 DIMM 0B	35.6
ND1 DIMM 1B	41.3	ND2 DIMM 1B	39.1	ND3 DIMM 1B	39.2
ND1 DIMM 2B	38.7	ND2 DIMM 2B	37.5	ND3 DIMM 2B	37.0
ND1 DIMM 3B	42.7	ND2 DIMM 3B	39.9	ND3 DIMM 3B	40.0
ND1 DIMM 4B	37.9	ND2 DIMM 4B	36.8	ND3 DIMM 4B	36.4
ND1 DIMM 5B	43.7	ND2 DIMM 5B	41.8	ND3 DIMM 5B	40.3
ND1 FET 1	44.2	ND2 FET 1	43.3	ND3 FET 1	42.7
ND1 FET 2	40.2	ND2 FET 2	39.5	ND3 FET 2	42.9
ND1 FET 3	39.2	ND2 FET 3	39.8	ND3 FET 3	38.5
ND1 FET 4	56.2	ND2 FET 4	55.4	ND3 FET 4	52.4
ND1 FET 5	58.6	ND2 FET 5	58.6	ND3 FET 5	61.2
ND1 FET 6	41.4	ND2 FET 6	41.6	ND3 FET 6	28.3
ND1 FET 7	42.6	ND2 FET 7	44.2	ND3 FET 7	30.2
ND1 FET 8	40.0	ND2 FET 8	41.0	ND3 FET 8	42.2
ND1 PS1	34.4	ND2 PS1	NA	ND3 PS1	33.3
ND1 PS2	33.4	ND2 PS2	30.4	ND3 PS2	NA
ND1 ETHER 1	54.4	ND2 ETHER 1	20.1	ND3 ETHER 1	52.6
ND1 ETHER 2	61.7	ND2 ETHER 2	61.3	ND3 ETHER 2	61.2
ND1 ETHER 3	55.5	ND2 ETHER 3	52.9	ND3 ETHER 3	55.1
ND1 IN HD	24.2	ND2 IN HD	23.3	ND3 IN HD	23.6
ND1 IN CENTER	24.8	ND2 IN CENTER	23.3	ND3 IN CENTER	23.5
ND1 OUT HD	34.6	ND2 OUT HD	35.0	ND3 OUT HD	34.2
ND1 OUT CE	35.3	ND2 OUT CENTER	33.3	ND3 OUT CENTER	34.4

Table C.11 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 21°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

File	040605B
TMU	R&D

Ave ambient (°C)	24.3
stdev amb (°C)	0.8
Pump Disch (psid)	25.0
Res Press (psia)	15.4
PF Temp (°C)	26.4

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	68.0	65.0	92.8	83.8	380.3
M1006 (Node4)	NA	NA			
M1007 (Node8)	64.0	63.0			
M1008 (Node6)	63.0	65.0			
M1009 (Node15)	64.0	63.0			
M1010 (Node16)	65.0	63.0			
M1011 (Node9)	61.0	64.0			
M1012 (Node13)	62.0	62.0			
M1013 (Node5)	64.0	61.0			
M1014 (Node2)	63.0	63.0	89.2	81.4	369.1
M1015 (Node14)	62.0	64.0			
M1016 (Node12)	67.0	64.0			
M1017 (Node10)	62.0	59.0			
M1018 (Node7)	63.0	63.0			
M1019 (Node18)	65.0	64.0			
M1020 (Node11)	61.0	63.0			
M1021 (Node17)	64.0	64.0			
M1022 (Node1)	64.0	65.0	81.8	88.1	373.2
average	63.6	63.2			
max	68.0	65.0			
min	61.0	59.0			
stdev	1.9	1.5			

Rack Power (W)	6147.8

ND1 HDD1	35.7	**ND2 HDD1**	31.3	**ND3 HDD1**	35.8
ND1 HDD2	39.2	**ND2 HDD2**	34.2	**ND3 HDD2**	33.0
ND1 North	45.9	**ND2 North**	45.1	**ND3 North**	43.5
ND1 DIMM 0A	38.0	**ND2 DIMM 0A**	37.4	**ND3 DIMM 0A**	38.5
ND1 DIMM 1A	41.8	**ND2 DIMM 1A**	41.0	**ND3 DIMM 1A**	40.9
ND1 DIMM 2A	38.7	**ND2 DIMM 2A**	37.9	**ND3 DIMM 2A**	38.8
ND1 DIMM 3A	44.4	**ND2 DIMM 3A**	34.4	**ND3 DIMM 3A**	42.3
ND1 DIMM 4A	39.5	**ND2 DIMM 4A**	37.5	**ND3 DIMM 4A**	40.2
ND1 DIMM 5A	42.3	**ND2 DIMM 5A**	41.7	**ND3 DIMM 5A**	41.2
ND1 DIMM 0B	35.9	**ND2 DIMM 0B**	34.8	**ND3 DIMM 0B**	35.0
ND1 DIMM 1B	41.5	**ND2 DIMM 1B**	38.9	**ND3 DIMM 1B**	38.2
ND1 DIMM 2B	38.8	**ND2 DIMM 2B**	37.4	**ND3 DIMM 2B**	36.6
ND1 DIMM 3B	42.7	**ND2 DIMM 3B**	39.8	**ND3 DIMM 3B**	39.2
ND1 DIMM 4B	37.9	**ND2 DIMM 4B**	36.8	**ND3 DIMM 4B**	35.9
ND1 DIMM 5B	43.8	**ND2 DIMM 5B**	41.6	**ND3 DIMM 5B**	39.4
ND1 FET 1	44.5	**ND2 FET 1**	42.9	**ND3 FET 1**	41.8
ND1 FET 2	40.4	**ND2 FET 2**	39.3	**ND3 FET 2**	42.2
ND1 FET 3	39.4	**ND2 FET 3**	39.6	**ND3 FET 3**	37.9
ND1 FET 4	56.2	**ND2 FET 4**	54.9	**ND3 FET 4**	51.7
ND1 FET 5	59.0	**ND2 FET 5**	58.4	**ND3 FET 5**	60.6
ND1 FET 6	41.7	**ND2 FET 6**	42.3	**ND3 FET 6**	27.9
ND1 FET 7	42.8	**ND2 FET 7**	44.4	**ND3 FET 7**	29.6
ND1 FET 8	40.3	**ND2 FET 8**	40.7	**ND3 FET 8**	41.6
ND1 PS1	34.4	**ND2 PS1**	NA	**ND3 PS1**	32.9
ND1 PS2	33.4	**ND2 PS2**	30.1	**ND3 PS2**	NA
ND1 ETHER 1	54.5	**ND2 ETHER 1**	NA	**ND3 ETHER 1**	51.7
ND1 ETHER 2	61.8	**ND2 ETHER 2**	61.2	**ND3 ETHER 2**	60.4
ND1 ETHER 3	55.6	**ND2 ETHER 3**	52.8	**ND3 ETHER 3**	54.3
ND1 IN HD	24.6	**ND2 IN HD**	23.1	**ND3 IN HD**	23.6
ND1 IN CENTER	25.1	**ND2 IN CENTER**	23.1	**ND3 IN CENTER**	23.6
ND1 OUT HD	34.7	**ND2 OUT HD**	34.7	**ND3 OUT HD**	33.5
ND1 OUT CE	35.4	**ND2 OUT CENTER**	33.1	**ND3 OUT CENTER**	33.9

Table C.12 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 26°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, R&D TMU, in the ISR integration lab

SprayCool Test Results- Mustang Liberator TMU Test Matrix Table 3.10

File	052105e
TMU	lust/Lib w/Tygon

Ave ambient (°C)	23.0
stdev amb (°C)	0.7
Pump Disch (psid)	15.0
Res Press (psia)	14.1
PF Temp (°C)	21.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	64.0	62.0	87.6	81.3	376.9
M1006 (Node4)	59.0	59.0			
M1007 (Node8)	60.0	60.0			
M1008 (Node6)	59.0	62.0			
M1009 (Node15)	62.0	60.0			
M1010 (Node16)	62.0	59.0			
M1011 (Node9)	57.0	61.0			
M1012 (Node13)	60.0	58.0			
M1013 (Node5)	61.0	56.0			
M1014 (Node2)	59.0	59.0	88.5	80.8	362.9
M1015 (Node14)	59.0	61.0			
M1016 (Node12)	64.0	61.0			
M1017 (Node10)	59.0	57.0			
M1018 (Node7)	60.0	61.0			
M1019 (Node18)	61.0	59.0			
M1020 (Node11)	59.0	60.0			
M1021 (Node17)	61.0	61.0			
M1022 (Node1)	60.0	63.0	83.4	91.7	369.2
average	60.3	59.9			
max	64.0	63.0			
min	57.0	56.0			
stdev	1.8	1.8			

Rack Power (W)	6680.0

ND1 HDD1	38.2	**ND2 HDD1**	29.6	**ND3 HDD1**	33.6
ND1 HDD2	34.8	**ND2 HDD2**	32.0	**ND3 HDD2**	37.3
ND1 North	44.2	**ND2 North**	45.2	**ND3 North**	43.2
ND1 DIMM 0A	38.3	**ND2 DIMM 0A**	36.8	**ND3 DIMM 0A**	36.1
ND1 DIMM 1A	42.5	**ND2 DIMM 1A**	37.5	**ND3 DIMM 1A**	40.2
ND1 DIMM 2A	38.7	**ND2 DIMM 2A**	36.4	**ND3 DIMM 2A**	37.0
ND1 DIMM 3A	43.7	**ND2 DIMM 3A**	40.2	**ND3 DIMM 3A**	42.6
ND1 DIMM 4A	40.4	**ND2 DIMM 4A**	36.7	**ND3 DIMM 4A**	38.1
ND1 DIMM 5A	42.9	**ND2 DIMM 5A**	37.8	**ND3 DIMM 5A**	40.7
ND1 DIMM 0B	35.5	**ND2 DIMM 0B**	34.0	**ND3 DIMM 0B**	34.4
ND1 DIMM 1B	39.5	**ND2 DIMM 1B**	36.4	**ND3 DIMM 1B**	39.7
ND1 DIMM 2B	36.7	**ND2 DIMM 2B**	37.1	**ND3 DIMM 2B**	37.2
ND1 DIMM 3B	40.3	**ND2 DIMM 3B**	37.0	**ND3 DIMM 3B**	41.0
ND1 DIMM 4B	36.1	**ND2 DIMM 4B**	35.9	**ND3 DIMM 4B**	36.3
ND1 DIMM 5B	40.3	**ND2 DIMM 5B**	38.6	**ND3 DIMM 5B**	42.0
ND1 FET 1	42.9	**ND2 FET 1**	NA	**ND3 FET 1**	41.3
ND1 FET 2	42.8	**ND2 FET 2**	39.3	**ND3 FET 2**	37.9
ND1 FET 3	38.1	**ND2 FET 3**	37.7	**ND3 FET 3**	36.7
ND1 FET 4	51.2	**ND2 FET 4**	54.5	**ND3 FET 4**	53.0
ND1 FET 5	60.4	**ND2 FET 5**	58.3	**ND3 FET 5**	56.7
ND1 FET 6	26.7	**ND2 FET 6**	43.0	**ND3 FET 6**	37.7
ND1 FET 7	28.1	**ND2 FET 7**	43.2	**ND3 FET 7**	39.9
ND1 FET 8	42.3	**ND2 FET 8**	38.7	**ND3 FET 8**	38.0
ND1 PS1	32.6	**ND2 PS1**	NA	**ND3 PS1**	32.9
ND1 PS2	NA	**ND2 PS2**	28.9	**ND3 PS2**	31.9
ND1 ETHER 1	52.0	**ND2 ETHER 1**	50.3	**ND3 ETHER 1**	51.8
ND1 ETHER 2	61.2	**ND2 ETHER 2**	60.0	**ND3 ETHER 2**	59.4
ND1 ETHER 3	55.5	**ND2 ETHER 3**	50.9	**ND3 ETHER 3**	53.3
ND1 IN HD	22.0	**ND2 IN HD**	21.8	**ND3 IN HD**	22.7
ND1 IN CENTER	21.7	**ND2 IN CENTER**	21.8	**ND3 IN CENTER**	22.7
ND1 OUT HD	34.8	**ND2 OUT HD**	32.4	**ND3 OUT HD**	32.3
ND1 OUT CE	33.2	**ND2 OUT CENTER**	25.1	**ND3 OUT CENTER**	32.9

Table C.13 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 23°C air, 21°C coolant, at 15 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052105d
TMU	Must/Lib w/Tygon

Ave ambient (°C)	23.5
stdev amb (°C)	0.7
Pump Disch (psid)	20.0
Res Press (psia)	14.0
PF Temp (°C)	21.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	63.0	62.0	87.3	81.2	376.9
M1006 (Node4)	59.0	58.0			
M1007 (Node8)	59.0	59.0			
M1008 (Node6)	59.0	61.0			
M1009 (Node15)	61.0	59.0			
M1010 (Node16)	62.0	59.0			
M1011 (Node9)	57.0	60.0			
M1012 (Node13)	59.0	58.0			
M1013 (Node5)	60.0	56.0			
M1014 (Node2)	58.0	58.0	88.4	80.7	363.0
M1015 (Node14)	58.0	60.0			
M1016 (Node12)	63.0	60.0			
M1017 (Node10)	58.0	55.0			
M1018 (Node7)	60.0	60.0			
M1019 (Node18)	61.0	59.0			
M1020 (Node11)	58.0	59.0			
M1021 (Node17)	60.0	60.0			
M1022 (Node1)	60.0	62.0	83.3	91.5	368.4
average	59.7	59.2			
max	63.0	62.0			
min	57.0	55.0			
stdev	1.7	1.8			

Rack Power (W)	6676.8

ND1 HDD1	38.0	**ND2 HDD1**	29.8	**ND3 HDD1**	33.6
ND1 HDD2	34.8	**ND2 HDD2**	32.2	**ND3 HDD2**	37.2
ND1 North	44.2	**ND2 North**	45.3	**ND3 North**	43.1
ND1 DIMM 0A	38.3	**ND2 DIMM 0A**	37.0	**ND3 DIMM 0A**	36.1
ND1 DIMM 1A	42.4	**ND2 DIMM 1A**	37.7	**ND3 DIMM 1A**	40.0
ND1 DIMM 2A	38.6	**ND2 DIMM 2A**	36.6	**ND3 DIMM 2A**	36.8
ND1 DIMM 3A	43.6	**ND2 DIMM 3A**	40.4	**ND3 DIMM 3A**	42.4
ND1 DIMM 4A	40.3	**ND2 DIMM 4A**	37.1	**ND3 DIMM 4A**	37.8
ND1 DIMM 5A	42.7	**ND2 DIMM 5A**	38.0	**ND3 DIMM 5A**	40.4
ND1 DIMM 0B	35.4	**ND2 DIMM 0B**	34.4	**ND3 DIMM 0B**	34.2
ND1 DIMM 1B	39.4	**ND2 DIMM 1B**	36.5	**ND3 DIMM 1B**	39.5
ND1 DIMM 2B	36.7	**ND2 DIMM 2B**	37.1	**ND3 DIMM 2B**	37.2
ND1 DIMM 3B	40.3	**ND2 DIMM 3B**	36.8	**ND3 DIMM 3B**	41.0
ND1 DIMM 4B	36.1	**ND2 DIMM 4B**	35.6	**ND3 DIMM 4B**	36.6
ND1 DIMM 5B	40.3	**ND2 DIMM 5B**	38.5	**ND3 DIMM 5B**	42.0
ND1 FET 1	43.2	**ND2 FET 1**	NA	**ND3 FET 1**	41.4
ND1 FET 2	43.1	**ND2 FET 2**	39.2	**ND3 FET 2**	38.1
ND1 FET 3	38.4	**ND2 FET 3**	37.6	**ND3 FET 3**	36.9
ND1 FET 4	51.1	**ND2 FET 4**	54.2	**ND3 FET 4**	53.0
ND1 FET 5	60.2	**ND2 FET 5**	57.9	**ND3 FET 5**	56.7
ND1 FET 6	26.8	**ND2 FET 6**	43.0	**ND3 FET 6**	37.8
ND1 FET 7	28.2	**ND2 FET 7**	43.0	**ND3 FET 7**	39.8
ND1 FET 8	42.1	**ND2 FET 8**	38.6	**ND3 FET 8**	37.9
ND1 PS1	32.8	**ND2 PS1**	NA	**ND3 PS1**	33.0
ND1 PS2	NA	**ND2 PS2**	29.0	**ND3 PS2**	31.8
ND1 ETHER 1	51.9	**ND2 ETHER 1**	50.2	**ND3 ETHER 1**	51.6
ND1 ETHER 2	61.1	**ND2 ETHER 2**	59.9	**ND3 ETHER 2**	59.2
ND1 ETHER 3	55.3	**ND2 ETHER 3**	50.8	**ND3 ETHER 3**	53.1
ND1 IN HD	22.9	**ND2 IN HD**	22.6	**ND3 IN HD**	23.5
ND1 IN CENTER	22.7	**ND2 IN CENTER**	22.7	**ND3 IN CENTER**	23.4
ND1 OUT HD	34.6	**ND2 OUT HD**	32.4	**ND3 OUT HD**	32.2
ND1 OUT CE	33.2	**ND2 OUT CENTER**	25.5	**ND3 OUT CENTER**	33.0

Table C.14 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 24°C air, 21°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052105b
TMU	Must/Lib w/Tygon

Ave ambient (°C)	23.0
stdev amb (°C)	0.7
Pump Disch (psid)	25.0
Res Press (psia)	13.5
PF Temp (°C)	20.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	62.0	61.0	87.0	81.0	376.3
M1006 (Node4)	58.0	57.0			
M1007 (Node8)	58.0	58.0			
M1008 (Node6)	58.0	61.0			
M1009 (Node15)	61.0	58.0			
M1010 (Node16)	61.0	58.0			
M1011 (Node9)	56.0	60.0			
M1012 (Node13)	58.0	57.0			
M1013 (Node5)	59.0	55.0			
M1014 (Node2)	56.0	57.0	88.0	80.6	362.5
M1015 (Node14)	58.0	59.0			
M1016 (Node12)	62.0	59.0			
M1017 (Node10)	58.0	54.0			
M1018 (Node7)	59.0	59.0			
M1019 (Node18)	60.0	57.0			
M1020 (Node11)	56.0	58.0			
M1021 (Node17)	59.0	59.0			
M1022 (Node1)	59.0	61.0	83.2	91.1	369.6
average	58.8	58.2			
max	62.0	61.0			
min	56.0	54.0			
stdev	1.9	1.9			

Rack Power (W)	6716.9

ND1 HDD1	37.3	**ND2 HDD1**	29.5	**ND3 HDD1**	33.9
ND1 HDD2	34.1	**ND2 HDD2**	32.1	**ND3 HDD2**	37.5
ND1 North	43.6	**ND2 North**	44.9	**ND3 North**	43.4
ND1 DIMM 0A	37.9	**ND2 DIMM 0A**	36.6	**ND3 DIMM 0A**	36.4
ND1 DIMM 1A	42.1	**ND2 DIMM 1A**	37.5	**ND3 DIMM 1A**	40.4
ND1 DIMM 2A	38.4	**ND2 DIMM 2A**	36.4	**ND3 DIMM 2A**	37.2
ND1 DIMM 3A	43.3	**ND2 DIMM 3A**	40.2	**ND3 DIMM 3A**	42.8
ND1 DIMM 4A	40.1	**ND2 DIMM 4A**	36.7	**ND3 DIMM 4A**	38.2
ND1 DIMM 5A	42.5	**ND2 DIMM 5A**	37.8	**ND3 DIMM 5A**	40.9
ND1 DIMM 0B	35.1	**ND2 DIMM 0B**	33.9	**ND3 DIMM 0B**	34.5
ND1 DIMM 1B	39.1	**ND2 DIMM 1B**	36.4	**ND3 DIMM 1B**	39.9
ND1 DIMM 2B	36.4	**ND2 DIMM 2B**	36.9	**ND3 DIMM 2B**	37.4
ND1 DIMM 3B	39.9	**ND2 DIMM 3B**	37.0	**ND3 DIMM 3B**	41.1
ND1 DIMM 4B	35.6	**ND2 DIMM 4B**	35.7	**ND3 DIMM 4B**	36.6
ND1 DIMM 5B	39.8	**ND2 DIMM 5B**	38.6	**ND3 DIMM 5B**	42.2
ND1 FET 1	42.1	**ND2 FET 1**	NA	**ND3 FET 1**	41.7
ND1 FET 2	42.2	**ND2 FET 2**	39.4	**ND3 FET 2**	38.3
ND1 FET 3	37.7	**ND2 FET 3**	37.8	**ND3 FET 3**	37.1
ND1 FET 4	50.9	**ND2 FET 4**	54.1	**ND3 FET 4**	53.6
ND1 FET 5	60.0	**ND2 FET 5**	58.1	**ND3 FET 5**	57.2
ND1 FET 6	26.4	**ND2 FET 6**	43.0	**ND3 FET 6**	37.7
ND1 FET 7	27.5	**ND2 FET 7**	43.1	**ND3 FET 7**	40.3
ND1 FET 8	41.5	**ND2 FET 8**	38.6	**ND3 FET 8**	38.3
ND1 PS1	32.3	**ND2 PS1**	NA	**ND3 PS1**	33.2
ND1 PS2	NA	**ND2 PS2**	28.9	**ND3 PS2**	32.2
ND1 ETHER 1	51.4	**ND2 ETHER 1**	50.5	**ND3 ETHER 1**	52.1
ND1 ETHER 2	60.6	**ND2 ETHER 2**	60.1	**ND3 ETHER 2**	59.6
ND1 ETHER 3	54.8	**ND2 ETHER 3**	50.9	**ND3 ETHER 3**	53.3
ND1 IN HD	21.7	**ND2 IN HD**	21.9	**ND3 IN HD**	22.7
ND1 IN CENTER	21.7	**ND2 IN CENTER**	21.9	**ND3 IN CENTER**	22.9
ND1 OUT HD	34.2	**ND2 OUT HD**	32.2	**ND3 OUT HD**	32.3
ND1 OUT CE	32.5	**ND2 OUT CENTER**	25.4	**ND3 OUT CENTER**	33.1

Table C.15 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 23°C air, 20°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052105c
TMU	Must/Lib w/Tygon

Ave ambient (°C)	23.0
stdev amb (°C)	0.7
Pump Disch (psid)	29.5
Res Press (psia)	13.7
PF Temp (°C)	20.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	63.0	61.0	87.0	81.1	376.3
M1006 (Node4)	57.0	56.0			
M1007 (Node8)	58.0	58.0			
M1008 (Node6)	57.0	59.0			
M1009 (Node15)	59.0	58.0			
M1010 (Node16)	59.0	57.0			
M1011 (Node9)	55.0	58.0			
M1012 (Node13)	57.0	56.0			
M1013 (Node5)	59.0	55.0			
M1014 (Node2)	55.0	56.0	88.2	80.6	362.3
M1015 (Node14)	56.0	58.0			
M1016 (Node12)	61.0	58.0			
M1017 (Node10)	57.0	53.0			
M1018 (Node7)	58.0	58.0			
M1019 (Node18)	59.0	57.0			
M1020 (Node11)	56.0	57.0			
M1021 (Node17)	58.0	59.0			
M1022 (Node1)	58.0	60.0	83.3	91.3	368.4
average	57.9	57.4			
max	63.0	61.0			
min	55.0	53.0			
stdev	2.0	1.9			

Rack Power (W)	6635.2

ND1 HDD1	37.8	**ND2 HDD1**	29.4	**ND3 HDD1**	33.7
ND1 HDD2	34.5	**ND2 HDD2**	31.8	**ND3 HDD2**	37.2
ND1 North	43.8	**ND2 North**	44.8	**ND3 North**	43.0
ND1 DIMM 0A	38.0	**ND2 DIMM 0A**	36.5	**ND3 DIMM 0A**	35.9
ND1 DIMM 1A	42.2	**ND2 DIMM 1A**	37.3	**ND3 DIMM 1A**	40.0
ND1 DIMM 2A	38.4	**ND2 DIMM 2A**	36.2	**ND3 DIMM 2A**	36.7
ND1 DIMM 3A	43.4	**ND2 DIMM 3A**	39.9	**ND3 DIMM 3A**	42.4
ND1 DIMM 4A	40.0	**ND2 DIMM 4A**	36.5	**ND3 DIMM 4A**	37.8
ND1 DIMM 5A	42.5	**ND2 DIMM 5A**	37.6	**ND3 DIMM 5A**	40.4
ND1 DIMM 0B	35.1	**ND2 DIMM 0B**	33.8	**ND3 DIMM 0B**	34.0
ND1 DIMM 1B	39.2	**ND2 DIMM 1B**	36.3	**ND3 DIMM 1B**	39.5
ND1 DIMM 2B	36.3	**ND2 DIMM 2B**	37.0	**ND3 DIMM 2B**	37.0
ND1 DIMM 3B	40.0	**ND2 DIMM 3B**	36.9	**ND3 DIMM 3B**	40.8
ND1 DIMM 4B	35.6	**ND2 DIMM 4B**	35.7	**ND3 DIMM 4B**	36.2
ND1 DIMM 5B	40.2	**ND2 DIMM 5B**	38.3	**ND3 DIMM 5B**	41.9
ND1 FET 1	42.5	**ND2 FET 1**	NA	**ND3 FET 1**	40.9
ND1 FET 2	42.4	**ND2 FET 2**	38.9	**ND3 FET 2**	37.7
ND1 FET 3	37.8	**ND2 FET 3**	37.3	**ND3 FET 3**	36.4
ND1 FET 4	50.6	**ND2 FET 4**	53.8	**ND3 FET 4**	52.7
ND1 FET 5	59.7	**ND2 FET 5**	57.7	**ND3 FET 5**	56.4
ND1 FET 6	26.3	**ND2 FET 6**	42.7	**ND3 FET 6**	37.1
ND1 FET 7	27.7	**ND2 FET 7**	42.8	**ND3 FET 7**	39.5
ND1 FET 8	41.9	**ND2 FET 8**	38.4	**ND3 FET 8**	37.6
ND1 PS1	32.4	**ND2 PS1**	NA	**ND3 PS1**	32.6
ND1 PS2	NA	**ND2 PS2**	28.7	**ND3 PS2**	31.7
ND1 ETHER 1	51.7	**ND2 ETHER 1**	50.0	**ND3 ETHER 1**	51.5
ND1 ETHER 2	60.8	**ND2 ETHER 2**	59.8	**ND3 ETHER 2**	59.2
ND1 ETHER 3	55.1	**ND2 ETHER 3**	50.6	**ND3 ETHER 3**	53.0
ND1 IN HD	21.7	**ND2 IN HD**	21.7	**ND3 IN HD**	22.8
ND1 IN CENTER	21.8	**ND2 IN CENTER**	21.7	**ND3 IN CENTER**	22.7
ND1 OUT HD	34.6	**ND2 OUT HD**	32.1	**ND3 OUT HD**	32.1
ND1 OUT CE	33.0	**ND2 OUT CENTER**	25.0	**ND3 OUT CENTER**	32.6

Table C.16 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 23°C air, 20°C coolant, at 30 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052005d
TMU	Must/Lib w/Tygon

Ave ambient (°C)	23.0
stdev amb (°C)	0.7
Pump Disch (psid)	15.0
Res Press (psia)	14.5
PF Temp (°C)	25.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	64.0	62.0	91.7	83.4	376.9
M1006 (Node4)	59.0	58.0			
M1007 (Node8)	60.0	60.0			
M1008 (Node6)	59.0	63.0			
M1009 (Node15)	63.0	60.0			
M1010 (Node16)	62.0	60.0			
M1011 (Node9)	57.0	61.0			
M1012 (Node13)	61.0	58.0			
M1013 (Node5)	61.0	57.0			
M1014 (Node2)	59.0	59.0	88.6	80.9	362.9
M1015 (Node14)	60.0	61.0			
M1016 (Node12)	64.0	61.0			
M1017 (Node10)	59.0	57.0			
M1018 (Node7)	60.0	61.0			
M1019 (Node18)	62.0	60.0			
M1020 (Node11)	59.0	60.0			
M1021 (Node17)	60.0	61.0			
M1022 (Node1)	60.0	63.0	81.2	87.5	370.5
average	60.5	60.1			
max	64.0	63.0			
min	57.0	57.0			
stdev	1.9	1.8			

Rack Power (W)	6683.1

ND1 HDD1	32.9	**ND2 HDD1**	29.5	**ND3 HDD1**	38.5
ND1 HDD2	36.4	**ND2 HDD2**	32.1	**ND3 HDD2**	34.8
ND1 North	42.8	**ND2 North**	45.3	**ND3 North**	44.5
ND1 DIMM 0A	35.5	**ND2 DIMM 0A**	36.7	**ND3 DIMM 0A**	38.1
ND1 DIMM 1A	39.5	**ND2 DIMM 1A**	37.5	**ND3 DIMM 1A**	42.4
ND1 DIMM 2A	36.2	**ND2 DIMM 2A**	36.4	**ND3 DIMM 2A**	38.6
ND1 DIMM 3A	41.9	**ND2 DIMM 3A**	40.4	**ND3 DIMM 3A**	43.7
ND1 DIMM 4A	37.4	**ND2 DIMM 4A**	36.6	**ND3 DIMM 4A**	40.2
ND1 DIMM 5A	39.9	**ND2 DIMM 5A**	37.8	**ND3 DIMM 5A**	42.8
ND1 DIMM 0B	33.5	**ND2 DIMM 0B**	33.8	**ND3 DIMM 0B**	35.2
ND1 DIMM 1B	38.9	**ND2 DIMM 1B**	36.4	**ND3 DIMM 1B**	39.6
ND1 DIMM 2B	36.7	**ND2 DIMM 2B**	37.0	**ND3 DIMM 2B**	36.7
ND1 DIMM 3B	40.6	**ND2 DIMM 3B**	37.1	**ND3 DIMM 3B**	40.6
ND1 DIMM 4B	36.1	**ND2 DIMM 4B**	35.9	**ND3 DIMM 4B**	36.4
ND1 DIMM 5B	41.2	**ND2 DIMM 5B**	38.9	**ND3 DIMM 5B**	40.3
ND1 FET 1	40.4	**ND2 FET 1**	NA	**ND3 FET 1**	43.5
ND1 FET 2	37.1	**ND2 FET 2**	39.7	**ND3 FET 2**	43.1
ND1 FET 3	36.0	**ND2 FET 3**	38.0	**ND3 FET 3**	38.3
ND1 FET 4	52.4	**ND2 FET 4**	54.9	**ND3 FET 4**	50.3
ND1 FET 5	56.0	**ND2 FET 5**	58.7	**ND3 FET 5**	59.8
ND1 FET 6	37.0	**ND2 FET 6**	43.7	**ND3 FET 6**	26.8
ND1 FET 7	39.3	**ND2 FET 7**	43.3	**ND3 FET 7**	28.6
ND1 FET 8	37.4	**ND2 FET 8**	38.6	**ND3 FET 8**	42.3
ND1 PS1	32.3	**ND2 PS1**	NA	**ND3 PS1**	32.4
ND1 PS2	31.2	**ND2 PS2**	28.7	**ND3 PS2**	NA
ND1 ETHER 1	51.2	**ND2 ETHER 1**	51.0	**ND3 ETHER 1**	52.4
ND1 ETHER 2	58.8	**ND2 ETHER 2**	60.6	**ND3 ETHER 2**	61.5
ND1 ETHER 3	52.6	**ND2 ETHER 3**	51.5	**ND3 ETHER 3**	55.8
ND1 IN HD	22.3	**ND2 IN HD**	21.6	**ND3 IN HD**	21.8
ND1 IN CENTER	22.3	**ND2 IN CENTER**	21.7	**ND3 IN CENTER**	21.7
ND1 OUT HD	31.7	**ND2 OUT HD**	32.6	**ND3 OUT HD**	34.8
ND1 OUT CE	32.4	**ND2 OUT CENTER**	28.0	**ND3 OUT CENTER**	33.8

Table C.17 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 23°C air, 25°C coolant, at 15 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052005c
TMU	Must/Lib w/Tygon

Ave ambient (°C)	22.3
stdev amb (°C)	0.7
Pump Disch (psid)	20.0
Res Press (psia)	14.0
PF Temp (°C)	25.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	64.0	63.0	91.8	83.7	377.7
M1006 (Node4)	59.0	58.0			
M1007 (Node8)	60.0	60.0			
M1008 (Node6)	60.0	63.0			
M1009 (Node15)	62.0	60.0			
M1010 (Node16)	63.0	60.0			
M1011 (Node9)	58.0	61.0			
M1012 (Node13)	60.0	59.0			
M1013 (Node5)	61.0	58.0			
M1014 (Node2)	58.0	59.0	88.5	80.8	363.5
M1015 (Node14)	59.0	61.0			
M1016 (Node12)	64.0	61.0			
M1017 (Node10)	60.0	56.0			
M1018 (Node7)	60.0	61.0			
M1019 (Node18)	62.0	59.0			
M1020 (Node11)	58.0	60.0			
M1021 (Node17)	61.0	61.0			
M1022 (Node1)	60.0	63.0	81.4	87.3	371.0
average	60.5	60.2			
max	64.0	63.0			
min	58.0	56.0			
stdev	1.9	1.9			

Rack Power (W)	6648.0

ND1 HDD1	33.1	**ND2 HDD1**	30.9	**ND3 HDD1**	37.6
ND1 HDD2	36.8	**ND2 HDD2**	34.0	**ND3 HDD2**	34.0
ND1 North	42.3	**ND2 North**	45.7	**ND3 North**	44.1
ND1 DIMM 0A	35.3	**ND2 DIMM 0A**	36.7	**ND3 DIMM 0A**	37.8
ND1 DIMM 1A	39.4	**ND2 DIMM 1A**	38.1	**ND3 DIMM 1A**	42.1
ND1 DIMM 2A	36.1	**ND2 DIMM 2A**	36.5	**ND3 DIMM 2A**	38.3
ND1 DIMM 3A	41.7	**ND2 DIMM 3A**	40.9	**ND3 DIMM 3A**	43.4
ND1 DIMM 4A	37.2	**ND2 DIMM 4A**	37.0	**ND3 DIMM 4A**	40.0
ND1 DIMM 5A	39.8	**ND2 DIMM 5A**	38.5	**ND3 DIMM 5A**	42.6
ND1 DIMM 0B	33.5	**ND2 DIMM 0B**	34.3	**ND3 DIMM 0B**	35.0
ND1 DIMM 1B	38.8	**ND2 DIMM 1B**	37.5	**ND3 DIMM 1B**	39.2
ND1 DIMM 2B	36.4	**ND2 DIMM 2B**	37.2	**ND3 DIMM 2B**	36.3
ND1 DIMM 3B	40.1	**ND2 DIMM 3B**	37.7	**ND3 DIMM 3B**	40.1
ND1 DIMM 4B	35.6	**ND2 DIMM 4B**	36.1	**ND3 DIMM 4B**	35.8
ND1 DIMM 5B	41.0	**ND2 DIMM 5B**	39.9	**ND3 DIMM 5B**	39.9
ND1 FET 1	39.7	**ND2 FET 1**	NA	**ND3 FET 1**	43.1
ND1 FET 2	36.6	**ND2 FET 2**	40.0	**ND3 FET 2**	42.7
ND1 FET 3	35.5	**ND2 FET 3**	38.5	**ND3 FET 3**	37.9
ND1 FET 4	51.8	**ND2 FET 4**	54.3	**ND3 FET 4**	49.5
ND1 FET 5	55.2	**ND2 FET 5**	57.9	**ND3 FET 5**	59.1
ND1 FET 6	36.7	**ND2 FET 6**	40.9	**ND3 FET 6**	26.3
ND1 FET 7	38.5	**ND2 FET 7**	43.1	**ND3 FET 7**	28.2
ND1 FET 8	36.6	**ND2 FET 8**	39.3	**ND3 FET 8**	41.9
ND1 PS1	32.2	**ND2 PS1**	NA	**ND3 PS1**	32.3
ND1 PS2	31.0	**ND2 PS2**	29.0	**ND3 PS2**	NA
ND1 ETHER 1	50.5	**ND2 ETHER 1**	51.0	**ND3 ETHER 1**	52.0
ND1 ETHER 2	58.3	**ND2 ETHER 2**	60.8	**ND3 ETHER 2**	61.1
ND1 ETHER 3	52.3	**ND2 ETHER 3**	51.7	**ND3 ETHER 3**	55.5
ND1 IN HD	22.4	**ND2 IN HD**	21.7	**ND3 IN HD**	21.4
ND1 IN CENTER	22.4	**ND2 IN CENTER**	21.6	**ND3 IN CENTER**	21.3
ND1 OUT HD	31.7	**ND2 OUT HD**	33.2	**ND3 OUT HD**	34.5
ND1 OUT CE	32.0	**ND2 OUT CENTER**	32.8	**ND3 OUT CENTER**	33.1

Table C.18 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 22°C air, 25°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052105a
TMU	Must/Lib w/Tygon

Ave ambient (°C)	23.0
stdev amb (°C)	0.4
Pump Disch (psid)	25.0
Res Press (psia)	14.0
PF Temp (°C)	25.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	64.0	63.0	87.5	81.2	377.5
M1006 (Node4)	60.0	59.0			
M1007 (Node8)	61.0	60.0			
M1008 (Node6)	60.0	63.0			
M1009 (Node15)	63.0	61.0			
M1010 (Node16)	63.0	61.0			
M1011 (Node9)	59.0	62.0			
M1012 (Node13)	61.0	59.0			
M1013 (Node5)	62.0	58.0			
M1014 (Node2)	59.0	60.0	88.6	80.9	362.3
M1015 (Node14)	60.0	61.0			
M1016 (Node12)	64.0	62.0			
M1017 (Node10)	60.0	57.0			
M1018 (Node7)	61.0	61.0			
M1019 (Node18)	62.0	59.0			
M1020 (Node11)	59.0	60.0			
M1021 (Node17)	61.0	62.0			
M1022 (Node1)	61.0	63.0	83.5	91.7	369.8
average	61.1	60.6			
max	64.0	63.0			
min	59.0	57.0			
stdev	1.6	1.8			

Rack Power (W)	6344.5

ND1 HDD1	37.6	**ND2 HDD1**	29.6	**ND3 HDD1**	34.1
ND1 HDD2	34.4	**ND2 HDD2**	32.2	**ND3 HDD2**	37.5
ND1 North	44.1	**ND2 North**	45.4	**ND3 North**	44.0
ND1 DIMM 0A	38.3	**ND2 DIMM 0A**	36.9	**ND3 DIMM 0A**	36.8
ND1 DIMM 1A	42.4	**ND2 DIMM 1A**	37.7	**ND3 DIMM 1A**	40.8
ND1 DIMM 2A	38.8	**ND2 DIMM 2A**	36.7	**ND3 DIMM 2A**	37.5
ND1 DIMM 3A	43.7	**ND2 DIMM 3A**	40.4	**ND3 DIMM 3A**	43.1
ND1 DIMM 4A	40.3	**ND2 DIMM 4A**	36.8	**ND3 DIMM 4A**	38.5
ND1 DIMM 5A	42.7	**ND2 DIMM 5A**	38.0	**ND3 DIMM 5A**	41.0
ND1 DIMM 0B	35.3	**ND2 DIMM 0B**	34.0	**ND3 DIMM 0B**	34.7
ND1 DIMM 1B	39.4	**ND2 DIMM 1B**	36.4	**ND3 DIMM 1B**	40.0
ND1 DIMM 2B	36.8	**ND2 DIMM 2B**	36.9	**ND3 DIMM 2B**	37.8
ND1 DIMM 3B	40.2	**ND2 DIMM 3B**	36.8	**ND3 DIMM 3B**	41.5
ND1 DIMM 4B	36.1	**ND2 DIMM 4B**	35.5	**ND3 DIMM 4B**	37.1
ND1 DIMM 5B	40.3	**ND2 DIMM 5B**	39.1	**ND3 DIMM 5B**	42.4
ND1 FET 1	42.7	**ND2 FET 1**	NA	**ND3 FET 1**	42.1
ND1 FET 2	42.9	**ND2 FET 2**	40.2	**ND3 FET 2**	38.7
ND1 FET 3	38.4	**ND2 FET 3**	38.6	**ND3 FET 3**	37.6
ND1 FET 4	51.6	**ND2 FET 4**	55.0	**ND3 FET 4**	54.2
ND1 FET 5	60.4	**ND2 FET 5**	58.8	**ND3 FET 5**	57.6
ND1 FET 6	26.9	**ND2 FET 6**	43.0	**ND3 FET 6**	38.3
ND1 FET 7	28.0	**ND2 FET 7**	43.2	**ND3 FET 7**	40.8
ND1 FET 8	42.0	**ND2 FET 8**	38.7	**ND3 FET 8**	38.8
ND1 PS1	32.7	**ND2 PS1**	NA	**ND3 PS1**	33.6
ND1 PS2	NA	**ND2 PS2**	28.9	**ND3 PS2**	32.6
ND1 ETHER 1	52.1	**ND2 ETHER 1**	50.6	**ND3 ETHER 1**	52.7
ND1 ETHER 2	61.2	**ND2 ETHER 2**	60.2	**ND3 ETHER 2**	60.1
ND1 ETHER 3	55.4	**ND2 ETHER 3**	51.1	**ND3 ETHER 3**	53.9
ND1 IN HD	22.3	**ND2 IN HD**	21.9	**ND3 IN HD**	23.4
ND1 IN CENTER	22.1	**ND2 IN CENTER**	21.9	**ND3 IN CENTER**	23.5
ND1 OUT HD	34.7	**ND2 OUT HD**	32.3	**ND3 OUT HD**	32.9
ND1 OUT CE	33.1	**ND2 OUT CENTER**	25.5	**ND3 OUT CENTER**	33.7

Table C.19 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 25°C air, 25°C coolant, at 25 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

File	052005e
TMU	Must/Lib w/Tygon

Ave ambient (°C)	22.0
stdev amb (°C)	0.8
Pump Disch (psid)	29.5
Res Press (psia)	14.5
PF Temp (°C)	25.0

CPU DATA	CPU0 (°C)	CPU1 (°C)	CPU0 (W)	CPU1(W)	NODE (W)
M1005 (Node3)	64.0	62.0	91.7	83.4	375.8
M1006 (Node4)	59.0	58.0			
M1007 (Node8)	60.0	60.0			
M1008 (Node6)	59.0	62.0			
M1009 (Node15)	62.0	60.0			
M1010 (Node16)	60.0	61.0			
M1011 (Node9)	58.0	61.0			
M1012 (Node13)	60.0	59.0			
M1013 (Node5)	61.0	57.0			
M1014 (Node2)	58.0	59.0	88.3	80.7	362.9
M1015 (Node14)	59.0	61.0			
M1016 (Node12)	63.0	60.0			
M1017 (Node10)	59.0	56.0			
M1018 (Node7)	60.0	60.0			
M1019 (Node18)	61.0	59.0			
M1020 (Node11)	58.0	59.0			
M1021 (Node17)	60.0	60.0			
M1022 (Node1)	60.0	62.0	81.2	87.3	356.4
average	60.1	59.8			
max	64.0	62.0			
min	58.0	56.0			
stdev	1.7	1.7			

Rack Power (W)	6686.2

ND1 HDD1	31.3	**ND2 HDD1**	27.9	**ND3 HDD1**	36.9
ND1 HDD2	34.7	**ND2 HDD2**	30.4	**ND3 HDD2**	33.4
ND1 North	41.6	**ND2 North**	44.0	**ND3 North**	43.2
ND1 DIMM 0A	34.4	**ND2 DIMM 0A**	35.4	**ND3 DIMM 0A**	36.9
ND1 DIMM 1A	38.5	**ND2 DIMM 1A**	36.4	**ND3 DIMM 1A**	41.2
ND1 DIMM 2A	35.2	**ND2 DIMM 2A**	35.2	**ND3 DIMM 2A**	37.4
ND1 DIMM 3A	40.9	**ND2 DIMM 3A**	39.1	**ND3 DIMM 3A**	42.4
ND1 DIMM 4A	36.4	**ND2 DIMM 4A**	35.6	**ND3 DIMM 4A**	39.1
ND1 DIMM 5A	38.9	**ND2 DIMM 5A**	36.8	**ND3 DIMM 5A**	41.6
ND1 DIMM 0B	32.6	**ND2 DIMM 0B**	32.9	**ND3 DIMM 0B**	34.1
ND1 DIMM 1B	37.8	**ND2 DIMM 1B**	35.2	**ND3 DIMM 1B**	38.4
ND1 DIMM 2B	35.6	**ND2 DIMM 2B**	35.6	**ND3 DIMM 2B**	35.5
ND1 DIMM 3B	39.4	**ND2 DIMM 3B**	35.4	**ND3 DIMM 3B**	39.4
ND1 DIMM 4B	35.0	**ND2 DIMM 4B**	34.0	**ND3 DIMM 4B**	35.1
ND1 DIMM 5B	40.2	**ND2 DIMM 5B**	37.5	**ND3 DIMM 5B**	39.4
ND1 FET 1	39.1	**ND2 FET 1**	NA	**ND3 FET 1**	42.4
ND1 FET 2	36.0	**ND2 FET 2**	38.1	**ND3 FET 2**	41.9
ND1 FET 3	34.8	**ND2 FET 3**	36.6	**ND3 FET 3**	37.2
ND1 FET 4	50.9	**ND2 FET 4**	53.2	**ND3 FET 4**	48.9
ND1 FET 5	54.6	**ND2 FET 5**	57.2	**ND3 FET 5**	58.4
ND1 FET 6	35.8	**ND2 FET 6**	42.1	**ND3 FET 6**	25.6
ND1 FET 7	37.9	**ND2 FET 7**	41.8	**ND3 FET 7**	27.4
ND1 FET 8	36.0	**ND2 FET 8**	37.1	**ND3 FET 8**	41.1
ND1 PS1	31.2	**ND2 PS1**	NA	**ND3 PS1**	31.4
ND1 PS2	30.1	**ND2 PS2**	27.2	**ND3 PS2**	NA
ND1 ETHER 1	49.8	**ND2 ETHER 1**	49.2	**ND3 ETHER 1**	51.1
ND1 ETHER 2	57.5	**ND2 ETHER 2**	58.9	**ND3 ETHER 2**	60.1
ND1 ETHER 3	51.4	**ND2 ETHER 3**	49.8	**ND3 ETHER 3**	54.5
ND1 IN HD	21.3	**ND2 IN HD**	20.3	**ND3 IN HD**	20.6
ND1 IN CENTER	21.3	**ND2 IN CENTER**	20.4	**ND3 IN CENTER**	20.4
ND1 OUT HD	30.5	**ND2 OUT HD**	31.0	**ND3 OUT HD**	33.6
ND1 OUT CE	30.9	**ND2 OUT CENTER**	25.8	**ND3 OUT CENTER**	32.4

Table C.20 Microprocessor temperatures, power dissipations and component temperatures for rx2600 SprayCool rack running BurnI2, in 22°C air, 25°C coolant, at 30 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

SprayCool Acceptance Test Results- Mustang Liberator TMU

Description	rx2600 Dynamic Acceptance Test		
File	051905I		
TMU	Mustang/Liberator		
Location	ISR		
Test Duration	12 hours		
	average	***min***	***max***
Ave ambient (°C)	26.7	25.2	27.3
Pump Disch (psid)	20.0	19.9	20.0
Res Press (psia)	13.7	11.9	14.8
PF Temp (°C)	24.9	23.0	25.0

CPU DATA	**CPU0 (°C)**			**CPU1 (°C)**			**CPU0 (W)**			**CPU1(W)**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
M1005 (Node3)	na	na	na	na	na	na	62.4	59.2	76.8	67.2	63.7	83.1
M1006 (Node4)	45.8	45.0	48.0	45.1	44.0	47.0						
M1007 (Node8)	48.1	46.0	61.0	48.0	45.0	59.0						
M1008 (Node6)	47.7	45.0	59.0	50.1	47.0	62.0						
M1009 (Node15)	49.9	47.0	61.0	48.1	45.0	59.0						
M1010 (Node16)	50.1	47.0	62.0	48.0	45.0	59.0						
M1011 (Node9)	46.9	44.0	57.0	49.0	46.0	60.0						
M1012 (Node13)	48.2	45.0	60.0	47.5	44.0	58.0						
M1013 (Node5)	48.7	46.0	60.0	46.0	43.0	57.0						
M1014 (Node2)	46.9	44.0	58.0	47.3	45.0	58.0	68.2	64.8	84.0	61.8	58.8	79.5
M1015 (Node14)	47.1	45.0	58.0	48.4	46.0	60.0						
M1016 (Node12)	50.3	47.0	62.0	49.0	46.0	60.0						
M1017 (Node10)	47.7	45.0	58.0	44.1	42.0	55.0						
M1018 (Node7)	48.2	46.0	59.0	48.9	46.0	60.0						
M1019 (Node18)	49.2	46.0	60.0	47.2	45.0	58.0						
M1020 (Node11)	46.8	44.0	57.0	47.9	45.0	59.0						
M1021 (Node17)	48.8	46.0	60.0	48.8	46.0	60.0						
M1022 (Node1)	48.3	46.0	59.0	49.6	47.0	61.0	70.7	67.0	90.0	63.9	60.4	79.9
average	48.2	45.5	58.8	47.8	45.1	58.4						
min	45.8	44.0	48.0	44.1	42.0	47.0						
max	50.3	47.0	62.0	50.1	47.0	62.0						
stdev	1.3	1.0	3.2	1.6	1.3	3.3						

	Node 1			**Node2**			**Node3**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
HDD1	40.9	40.1	41.2	34.3	33.7	35.2	36.1	35.7	36.7
HDD2	37.4	36.7	37.6	37.0	36.5	37.9	39.7	39.3	40.2
North	47.2	46.5	48.1	48.2	47.6	49.0	44.8	44.1	45.7
DIMM 0A	41.5	40.9	42.3	40.2	39.5	41.0	38.4	37.7	39.4
DIMM 1A	45.2	44.7	46.1	41.1	40.5	41.9	42.0	41.4	42.8
DIMM 2A	42.0	41.4	43.4	40.0	39.2	41.3	39.3	38.5	40.8
DIMM 3A	46.8	46.1	48.6	44.0	43.3	45.4	44.3	43.5	46.0
DIMM 4A	43.5	42.8	45.0	40.3	39.6	41.6	40.4	39.6	41.8
DIMM 5A	45.8	45.0	47.5	41.5	40.8	42.7	42.5	41.8	43.9
DIMM 0B	38.6	38.0	39.2	37.6	37.0	38.4	36.6	36.1	37.3
DIMM 1B	42.3	41.8	43.0	40.4	39.9	41.2	41.7	41.1	42.3
DIMM 2B	40.1	39.4	41.2	40.8	40.1	42.1	39.7	39.0	41.1
DIMM 3B	43.3	42.6	44.7	40.5	39.9	41.7	43.2	42.4	44.7
DIMM 4B	39.5	38.7	40.6	39.3	38.4	40.4	38.9	38.2	40.0
DIMM 5B	43.4	42.7	44.7	42.6	41.8	43.9	44.2	43.4	45.7
FET 1	44.3	42.9	47.3	na	na	na	40.2	39.0	43.1
FET 2	44.2	42.8	47.0	41.0	39.9	43.3	38.2	37.2	40.3
FET 3	40.3	38.9	42.6	39.6	38.6	41.7	37.0	36.1	39.0
FET 4	56.3	54.6	57.2	58.0	57.2	58.9	55.7	54.7	57.1
FET 5	64.5	63.3	65.4	61.8	60.9	62.5	58.7	57.8	59.9
FET 6	31.0	29.7	31.6	44.9	43.3	46.8	40.0	38.6	41.0
FET 7	32.0	31.3	32.6	46.8	45.9	48.2	41.7	40.9	42.6
FET 8	45.8	45.1	46.6	42.6	41.9	43.4	39.9	39.2	41.0
PS1	35.4	34.9	36.0	na	na	na	35.3	34.5	36.1
PS2	na	na	na	32.4	31.7	33.1	34.1	33.5	34.8
ETHER 1	54.8	54.0	56.0	53.3	52.6	54.4	52.5	51.8	53.8
ETHER 2	63.9	63.3	65.1	63.6	62.9	64.5	60.6	59.9	61.6
ETHER 3	57.9	57.2	59.4	53.9	53.3	55.0	54.1	53.4	55.3
IN HD	26.0	24.9	26.5	26.0	24.8	27.7	26.4	25.3	27.2
IN CENTER	26.9	24.6	27.7	26.1	24.7	26.8	26.3	25.1	27.1
OUT HD	37.9	37.4	38.6	36.3	35.7	37.1	34.2	33.7	34.6
OUT CE	36.7	35.9	37.7	36.5	35.5	37.2	34.6	33.9	35.7

Table C.21 Microprocessor temps, power dissipations and component temps for rx2600 SprayCool rack running Dynamic Script over 12hours, in 27°C air, 25°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

Description	rx2600 Steady State Accept Test		
File	052705b		
TMU	Mustang/Liberator		
Location	ISR		
Test Duration	48 hour		
	average	***min***	***max***
Ave ambient (°C)	22.9	20.2	24.9
Pump Disch (psid)	20.0	19.8	20.1
Res Press (psia)	13.3	12.4	15.9
PF Temp (°C)	22.8	21.0	29.0

CPU DATA	**CPU0 (°C)**			**CPU1 (°C)**			**CPU0 (W)**			**CPU1(W)**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
M1005 (Node3)	na	na	na	na	na	na	92.0	91.0	93.3	83.7	82.2	84.5
M1006 (Node4)	60.6	48.0	62.0	59.2	47.0	61.0						
M1007 (Node8)	61.2	48.0	62.0	60.8	48.0	62.0						
M1008 (Node6)	60.3	48.0	62.0	63.0	50.0	64.0						
M1009 (Node15)	64.1	50.0	65.0	61.2	48.0	63.0						
M1010 (Node16)	63.9	50.0	65.0	61.0	49.0	63.0						
M1011 (Node9)	58.9	47.0	60.0	62.3	49.0	64.0						
M1012 (Node13)	60.5	48.0	62.0	59.9	47.0	61.0						
M1013 (Node5)	63.3	50.0	65.0	58.1	46.0	60.0						
M1014 (Node2)	59.4	48.0	61.0	60.5	48.0	62.0	88.8	88.4	89.8	80.9	80.3	81.5
M1015 (Node14)	60.5	48.0	62.0	62.2	50.0	64.0						
M1016 (Node12)	64.9	51.0	66.0	63.0	50.0	64.0						
M1017 (Node10)	60.3	48.0	62.0	58.0	45.0	59.0						
M1018 (Node7)	62.2	49.0	64.0	61.3	49.0	63.0						
M1019 (Node18)	63.0	50.0	64.0	60.5	48.0	62.0						
M1020 (Node11)	59.8	48.0	61.0	61.2	49.0	63.0						
M1021 (Node17)	62.0	49.0	63.0	63.8	50.0	65.0						
M1022 (Node1)	62.0	50.0	64.0	64.2	51.0	66.0	81.5	80.6	82.2	87.7	85.4	88.7
average	61.6	48.8	62.9	61.2	48.5	62.7						
min	58.9	47.0	60.0	58.0	45.0	59.0						
max	64.9	51.0	66.0	64.2	51.0	66.0						
stdev	1.8	1.1	1.7	1.8	1.6	1.8						

	Node 1			**Node2**			**Node3**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
HDD1	35.5	32.9	37.7	29.9	27.9	32.0	36.6	32.7	37.9
HDD2	38.8	35.6	40.8	32.9	31.1	35.1	33.4	30.3	34.7
North	45.4	43.4	47.9	46.0	44.3	47.4	43.6	42.1	44.8
DIMM 0A	37.8	35.6	40.6	36.9	35.2	38.3	37.7	36.1	38.9
DIMM 1A	41.6	39.9	44.0	38.2	36.7	39.4	41.8	40.2	42.9
DIMM 2A	38.4	36.3	41.2	36.8	35.2	38.3	38.1	36.6	39.3
DIMM 3A	44.2	42.4	46.4	41.1	39.6	42.4	43.3	41.6	44.5
DIMM 4A	39.3	37.2	42.1	37.2	35.6	38.5	39.7	38.2	40.9
DIMM 5A	42.1	40.3	44.4	38.6	37.1	39.8	42.4	40.8	43.6
DIMM 0B	35.7	33.6	38.5	34.4	32.6	35.8	34.8	33.1	36.0
DIMM 1B	41.2	39.5	43.4	37.1	35.6	38.7	38.8	37.1	39.9
DIMM 2B	38.7	36.5	41.4	37.1	35.4	38.6	36.2	34.4	37.3
DIMM 3B	42.5	40.7	44.9	37.4	35.8	38.8	39.8	38.2	40.9
DIMM 4B	37.9	35.7	40.6	35.8	34.0	37.4	35.7	33.9	37.0
DIMM 5B	43.5	41.7	45.8	39.4	37.8	40.8	39.7	38.2	40.9
FET 1	44.2	41.9	47.2	na	na	na	41.9	39.8	43.4
FET 2	40.0	37.6	43.0	40.1	38.0	42.0	42.4	40.4	43.9
FET 3	39.0	36.7	41.9	38.6	36.7	40.5	37.8	36.1	39.2
FET 4	56.1	53.0	59.6	54.3	52.6	56.4	51.3	49.6	53.1
FET 5	58.8	56.1	61.9	58.1	56.2	60.3	60.1	58.5	61.6
FET 6	40.8	38.1	43.8	41.5	39.2	43.8	26.4	24.8	28.3
FET 7	42.2	40.0	45.1	43.4	41.6	45.3	27.1	25.6	28.4
FET 8	39.9	37.5	42.9	39.4	37.5	41.0	41.4	39.7	42.7
PS1	34.3	32.0	37.3	na	na	na	32.2	30.1	33.6
PS2	33.4	31.1	36.4	29.0	27.1	30.5	na	na	na
ETHER 1	54.1	52.0	56.7	51.4	49.3	53.0	51.4	49.0	52.7
ETHER 2	61.3	59.4	63.8	61.0	59.3	62.4	60.4	58.2	61.7
ETHER 3	55.2	53.2	57.7	51.9	50.0	53.4	54.8	52.5	56.1
IN HD	24.3	21.3	28.3	21.7	19.4	23.7	21.7	19.4	23.3
IN CENTER	24.4	21.4	28.2	21.7	19.4	24.0	21.6	19.4	23.1
OUT HD	33.8	32.2	35.7	33.1	31.4	34.7	34.0	32.4	35.1
OUT CE	35.0	32.6	37.9	26.9	24.2	29.0	32.8	31.1	34.1

Table C.22 Microprocessor temps, power dissipations and component temps for rx2600 SprayCool rack running BurnI2 over 48 hours, in 23°C air, 23°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, in the ISR integration lab

Description	rx2600 Dynamic Accept Test		
File	070705a		
TMU	Mustang/Liberator		
Location	PNNL		
Test Duration	21 hour		
	average	***min***	***max***
Ave ambient (°C)	15.3	15.7	15.0
Pump Disch (psid)	20.0	19.8	20.1
Res Press (psia)	14.4	13.9	15.4
PF Temp (°C)	19.6	18.0	22.0

CPU DATA	**CPU0 (°C)**			**CPU1 (°C)**			**CPU0 (W)**			**CPU1(W)**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
M1005 (Node3)	50.9	48.0	62.0	50.1	47.0	61.0	69.3	91.4	67.0	62.5	83.2	60.3
M1006 (Node4)	45.4	44.0	47.0	44.7	43.0	46.0						
M1007 (Node8)	48.0	45.0	59.0	47.5	45.0	58.0						
M1008 (Node6)	50.9	48.0	62.0	50.1	47.0	61.0						
M1009 (Node15)	48.7	45.0	59.0	48.2	45.0	59.0						
M1010 (Node16)	49.2	46.0	60.0	47.9	45.0	58.0						
M1011 (Node9)	46.5	44.0	57.0	48.9	46.0	60.0						
M1012 (Node13)	47.1	44.0	58.0	47.7	45.0	58.0						
M1013 (Node5)	48.9	45.0	61.0	45.5	42.0	55.0						
M1014 (Node2)	47.2	45.0	57.0	47.8	45.0	58.0	67.3	88.0	64.7	61.0	80.5	58.6
M1015 (Node14)	46.6	44.0	57.0	48.4	46.0	59.0						
M1016 (Node12)	50.0	47.0	61.0	49.2	46.0	60.0						
M1017 (Node10)	47.6	45.0	58.0	44.1	42.0	55.0						
M1018 (Node7)	47.9	45.0	59.0	48.8	46.0	59.0						
M1019 (Node18)	48.9	46.0	60.0	46.9	44.0	57.0						
M1020 (Node11)	46.8	44.0	57.0	48.0	45.0	59.0						
M1021 (Node17)	47.9	45.0	58.0	48.1	45.0	59.0						
M1022 (Node1)	48.1	45.0	58.0	49.6	46.0	61.0	61.5	81.0	59.1	66.2	87.1	63.7
average	48.1	45.3	58.3	47.9	45.0	57.9						
min	45.4	44.0	47.0	44.1	42.0	46.0						
max	50.9	48.0	62.0	50.1	47.0	61.0						
stdev	1.5	1.3	3.3	1.7	1.5	3.5						

	Node 1			**Node2**			**Node3**		
	average	***min***	***max***	***average***	***min***	***max***	***average***	***min***	***max***
HDD1	29.6	29.9	29.3	30.5	30.8	30.1	33.5	33.8	33.2
HDD2	33.5	33.7	33.2	34.4	34.6	33.9	29.4	29.7	29.2
North	36.7	37.3	36.3	42.2	43.0	41.7	38.1	38.9	37.8
DIMM 0A	29.2	29.8	28.7	32.7	33.3	32.1	32.0	32.6	31.7
DIMM 1A	34.0	34.6	33.6	34.7	35.2	34.2	36.4	37.0	36.1
DIMM 2A	30.1	31.2	29.6	32.5	33.6	31.9	32.5	33.7	32.1
DIMM 3A	36.4	37.9	35.9	37.4	38.7	36.8	37.9	39.6	37.4
DIMM 4A	31.1	32.1	30.6	33.2	34.4	32.5	34.1	35.5	33.7
DIMM 5A	34.5	35.8	33.9	35.1	36.1	34.5	37.0	38.6	36.6
DIMM 0B	27.6	28.1	27.1	30.5	31.0	30.0	29.4	29.9	29.2
DIMM 1B	34.0	34.5	33.6	34.7	35.2	34.3	33.5	33.9	33.2
DIMM 2B	30.5	31.6	30.0	33.1	34.1	32.5	30.6	31.5	30.3
DIMM 3B	35.1	36.5	34.5	34.1	35.0	33.5	34.5	35.8	34.2
DIMM 4B	29.8	30.8	29.3	31.8	32.6	31.1	30.2	31.1	29.9
DIMM 5B	36.1	37.6	35.4	36.4	37.5	35.9	34.5	35.7	34.2
FET 1	31.4	34.5	30.7	na	na	na	32.9	36.4	32.3
FET 2	28.6	30.6	28.0	32.5	35.3	31.6	33.3	36.8	32.7
FET 3	27.9	29.7	27.4	31.4	34.0	30.6	29.4	31.9	28.9
FET 4	45.3	46.1	44.9	49.1	49.7	48.5	43.2	43.7	42.9
FET 5	48.8	49.5	48.4	52.3	52.9	51.5	52.8	53.3	52.5
FET 6	31.7	32.3	31.1	35.8	36.6	35.2	20.2	20.6	20.0
FET 7	32.9	33.3	32.5	38.1	39.0	37.5	21.7	22.2	21.5
FET 8	30.8	31.2	30.4	35.4	36.0	34.9	35.7	36.3	35.4
PS1	na	na	na	na	na	na	26.8	27.6	26.6
PS2	24.4	24.8	23.9	24.5	25.1	24.0	na	na	na
ETHER 1	44.1	45.2	43.7	46.0	47.5	45.4	44.6	46.3	44.3
ETHER 2	52.3	53.0	51.8	56.5	57.5	55.9	54.0	55.3	53.7
ETHER 3	45.8	46.9	45.3	46.9	48.3	46.4	48.2	49.7	47.9
IN HD	17.1	18.4	16.0	21.0	21.9	19.8	15.5	15.7	15.2
IN CENTER	15.9	16.6	15.5	16.7	17.7	15.2	14.5	14.9	14.1
OUT HD	28.5	29.1	28.2	30.4	30.7	29.9	28.6	29.1	28.3
OUT CE	25.5	26.2	25.1	23.4	23.5	23.2	26.5	27.5	26.1

Table C.23 Microprocessor temps, power dissipations and component temps for rx2600 SprayCool rack running Dynamic script over 21 hours, in 15°C air, 20°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, at PNNL EMSL

Description	rx2600 Steady State Accep Test
File	071805a
TMU	Mustang/Liberator
Location	PNNL
Test Duration	

	average	*min*	*max*
Ave ambient (°C)	15.5	14.7	16.4
Pump Disch (psid)	20.0	19.9	20.1
Res Press (psia)	15.1	14.8	15.8
PF Temp (°C)	19.7	18.0	22.0

CPU DATA	**CPU0 (°C)**			**CPU1 (°C)**			**CPU0 (W)**			**CPU1(W)**		
	average	*min*	*max*	*average*	*min*	*max*	*average*	*min*	*max*	*average*	*min*	*max*
M1005 (Node3)	63.9	63.0	65.0	62.1	61.0	63.0	91.5	88.8	91.8	83.3	82.3	83.6
M1006 (Node4)	58.3	58.0	60.0	57.6	57.0	59.0						
M1007 (Node8)	59.9	59.0	61.0	59.3	58.0	60.0						
M1008 (Node6)	59.0	59.0	60.0	61.0	61.0	62.0						
M1009 (Node15)	60.3	60.0	61.0	60.1	59.0	61.0						
M1010 (Node16)	61.0	60.0	62.0	59.2	59.0	61.0						
M1011 (Node9)	57.3	57.0	59.0	60.8	60.0	62.0						
M1012 (Node13)	58.4	58.0	60.0	59.0	58.0	60.0						
M1013 (Node5)	61.9	61.0	63.0	56.0	55.0	57.0						
M1014 (Node2)	58.5	58.0	60.0	59.0	58.0	60.0	88.3	87.4	88.6	80.7	79.8	80.9
M1015 (Node14)	58.0	57.0	59.0	60.0	59.0	61.0						
M1016 (Node12)	62.9	62.0	64.0	61.2	61.0	62.0						
M1017 (Node10)	59.0	58.0	60.0	56.0	55.0	57.0						
M1018 (Node7)	59.3	59.0	60.0	60.5	60.0	62.0						
M1019 (Node18)	60.4	60.0	62.0	58.2	58.0	59.0						
M1020 (Node11)	58.0	57.0	59.0	60.0	59.0	61.0						
M1021 (Node17)	59.2	59.0	60.0	59.9	59.0	61.0						
M1022 (Node1)	59.6	59.0	61.0	62.1	62.0	63.0	91.5	88.8	91.8	83.3	82.3	83.6
average	59.7	59.1	60.9	59.5	58.8	60.6						
min	57.3	57.0	59.0	56.0	55.0	57.0						
max	63.9	63.0	65.0	62.1	62.0	63.0						
stdev	1.8	1.7	1.7	1.8	1.9	1.8						

	Node 1			**Node2**			**Node3**		
	average	*min*	*max*	*average*	*min*	*max*	*average*	*min*	*max*
HDD1	29.4	28.7	30.2	30.4	29.6	31.2	33.3	32.7	34.1
HDD2	33.5	32.7	34.2	34.5	33.8	35.3	29.4	28.9	30.3
North	37.5	36.9	38.2	43.3	42.6	44.2	38.3	37.7	39.1
DIMM 0A	29.5	28.9	30.3	33.4	32.6	34.3	32.1	31.5	32.9
DIMM 1A	34.0	33.3	34.8	35.3	34.6	36.3	36.5	36.0	37.4
DIMM 2A	30.1	29.4	30.8	33.0	32.3	34.0	32.4	31.8	33.2
DIMM 3A	36.5	35.8	37.2	38.1	37.3	39.0	37.9	37.3	38.7
DIMM 4A	31.1	30.4	31.9	33.7	33.0	34.7	34.1	33.6	35.0
DIMM 5A	34.4	33.6	35.2	35.6	34.8	36.6	37.0	36.5	37.9
DIMM 0B	27.7	26.9	28.4	31.0	30.2	32.1	29.5	29.0	30.4
DIMM 1B	33.9	33.1	34.6	35.0	34.3	35.9	33.6	33.1	34.5
DIMM 2B	30.5	29.8	31.3	33.5	32.6	34.5	30.6	30.0	31.5
DIMM 3B	34.9	34.2	35.7	34.5	33.6	35.5	34.6	34.0	35.5
DIMM 4B	29.8	29.0	30.6	32.3	31.4	33.4	30.3	29.6	31.2
DIMM 5B	36.0	35.2	36.7	36.8	36.0	37.8	34.6	33.9	35.5
FET 1	34.7	34.1	35.7	na	na	na	35.6	34.9	36.5
FET 2	30.8	30.2	31.8	35.5	34.8	36.5	36.0	35.3	36.9
FET 3	30.0	29.4	30.9	34.3	33.5	35.2	31.2	30.6	32.0
FET 4	46.0	45.3	47.1	50.1	49.3	51.1	43.0	42.4	43.9
FET 5	49.5	48.9	50.4	53.2	52.6	54.2	52.7	52.1	53.5
FET 6	32.4	31.6	33.4	36.6	35.8	37.5	19.9	19.1	20.8
FET 7	33.4	32.8	34.2	38.9	38.2	39.8	21.5	20.8	22.3
FET 8	31.1	30.5	31.9	36.3	35.5	37.2	35.6	35.0	36.5
PS1	na	na	na	na	na	na	27.5	27.0	28.5
PS2	24.7	24.0	25.5	25.2	24.3	26.1	na	na	na
ETHER 1	45.3	44.7	46.1	47.7	47.0	48.6	45.5	44.9	46.4
ETHER 2	53.1	52.5	53.9	57.6	56.9	58.5	54.6	54.1	55.5
ETHER 3	46.9	46.3	47.7	48.5	47.9	49.4	49.1	48.5	49.9
IN HD	17.0	15.6	19.2	20.6	18.8	22.5	15.8	14.8	17.2
IN CENTER	15.7	15.1	16.9	18.2	15.8	19.5	14.0	13.2	15.0
OUT HD	29.3	28.7	29.9	30.7	30.1	31.6	28.7	28.2	29.6
OUT CE	26.4	25.8	27.3	23.4	22.7	24.4	26.9	26.3	27.8

Table C.24 Microprocessor temps, power dissipations and component temps for rx2600 SprayCool rack running BurnI2 over 24 hours, in 15°C air, 20°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, at PNNL EMSL

10 APPENDIX D

RLX Component Test Results Data

Description	RLX Steady State Accep Test		
File	070105a		
TMU	Mustang Liberator		
Location	PNNL		
Test Duration	92 Hour		
Ave ambient (°C)	approx 15		
Pump Disch (psid)	19.9	20.0	20.0
Res Press (psia)	14.8	18.2	15.3
PF Temp (°C)	14.0	23.0	19.9

CPU DATA	**CPU1 (°C)**			**CPU2 (°C)**		
	average	***min***	***max***	***average***	***min***	***max***
Slot 1	41.0	40.0	43.0	43.2	42.0	45.0
Slot 2	43.4	43.0	45.0	43.8	43.0	46.0
Slot 3	42.6	42.0	45.0	43.6	43.0	46.0
Slot 4	43.6	43.0	44.0	44.2	44.0	45.0
Slot 5	42.4	42.0	44.0	43.4	43.0	45.0
average	42.6	42.0	44.2	43.6	43.0	45.4
min	41.0	40.0	43.0	43.2	42.0	45.0
max	43.6	43.0	45.0	44.2	44.0	46.0
stdev	1.0	1.2	0.8	0.4	0.7	0.5

Table D.1 Microprocessor temps, RLX SprayCool sub-rack running BurnP6 over 92 hours, in 15°C air, 20°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, at PNNL EMSL

Description	Air Baseline Test
File	030105a
TMU	NA
Location	ISR
Test Duration	NA
Ave ambient (°C)	
Pump Disch (psid)	NA
Res Press (psia)	NA
PF Temp (°C)	NA

CPU DATA			
	CPU1 (°C)	**CPU2 (°C)**	**Board**
Slot 1	54.0	59.0	36.0
Slot 2	55.0	55.0	36.0
Slot 3	57.0	62.0	36.0
Slot 4	60.0	58.0	35.0
Slot 5	56.0	65.0	37.0
average	56.4	59.8	36.0
min	54.0	55.0	35.0
max	60.0	65.0	37.0
stdev	2.3	3.8	0.7

ND1 AIR IN	23.2	**ND3 AIR IN**	21.6	**ND5 AIR IN**	20.9
ND1 AIR OUT	42.0	**ND3 AIR OUT**	50.5	**ND5 AIR OUT**	47.4
ND1 NB	45.0	**ND3 NB**	46.8	**ND5 NB**	46.8
ND1 DIMM1	44.5	**ND3 DIMM1**	47.8	**ND5 DIMM1**	45.7
ND1 DIMM2	46.0	**ND3 DIMM2**	51.0	**ND5 DIMM2**	52.5
ND1 DIMM3	47.8	**ND3 DIMM3**	54.2	**ND5 DIMM3**	53.8
ND1 DIMM4	50.0	**ND3 DIMM4**	53.6	**ND5 DIMM4**	54.4
ND1 NB2	60.4	**ND3 NB2**	65.4	**ND5 NB2**	65.1
ND1 PulseDC	38.0	**ND3 PulseDC**	38.0	**ND5 PulseDC**	38.0
ND1 LAN	48.6	**ND3 LAN**	51.6	**ND5 LAN**	48.2
ND1 INFINI	50.8	**ND3 INFINI**	53.2	**ND5 INFINI**	53.7
ND1 HDD	26.0	**ND3 HDD**	26.8	**ND5 HDD**	28.1
ND1 FET1	44.3	**ND3 FET1**	46.9	**ND5 FET1**	46.3
ND1 FET2	47.0	**ND3 FET2**	50.7	**ND5 FET2**	48.9
ND1 FET3	48.7	**ND3 FET3**	52.0	**ND5 FET3**	51.8
ND1 FET4	44.5	**ND3 FET4**	47.7	**ND5 FET4**	47.8
ND1 FET5	39.8	**ND3 FET5**	41.8	**ND5 FET5**	0.3
ND1 FET6	42.0	**ND3 FET6**	44.6	**ND5 FET6**	43.7
ND2 AIR IN	22.3	**ND4 AIR IN**	21.7		
ND2 AIR OUT	34.9	**ND4 AIR OUT**	49.6		
ND2 NB	43.9	**ND4 NB**	46.5		
ND2 DIMM1	46.5	**ND4 DIMM1**	47.2		
ND2 DIMM2	48.3	**ND4 DIMM2**	50.8		
ND2 DIMM3	50.0	**ND4 DIMM3**	54.6		
ND2 DIMM4	51.8	**ND4 DIMM4**	55.6		
ND2 NB2	61.9	**ND4 NB2**	66.5		
ND2 PulseDC	38.2	**ND4 PulseDC**	36.8		
ND2 LAN	45.3	**ND4 LAN**	49.8		
ND2 INFINI	49.3	**ND4 INFINI**	53.7		
ND2 HDD	26.1	**ND4 HDD**	26.0		
ND2 FET1	44.4	**ND4 FET1**	46.5		
ND2 FET2	47.2	**ND4 FET2**	49.2		
ND2 FET3	48.0	**ND4 FET3**	52.1		
ND2 FET4	49.4	**ND4 FET4**	47.5		
ND2 FET5	45.4	**ND4 FET5**	42.0		
ND2 FET6	41.0	**ND4 FET6**	44.8		

Table D.2 Microprocessor temps and component temps for RLX air-cooled sub-rack running BurnP6, in 22°C air, on the bench in ISR's integration lab

Description	SprayCool Steady State Test
File	061405B
TMU	Mustang Liberator
Location	ISR
Test Duration	NA

Ave ambient (°C)	21.0
Pump Disch (psid)	14.1
Res Press (psia)	20.0
PF Temp (°C)	21.0

CPU DATA			
	CPU1 (°C)	**CPU2 (°C)**	**Board**
Slot 1	40	42	33
Slot 2	42	43	34
Slot 3	42	43	35
Slot 4	44	44	35
Slot 5	42	43	36
average	42.0	43.0	34.6
min	40.0	42.0	33.0
max	44.0	44.0	36.0
stdev	1.4	0.7	1.1

ND1 AIR IN	NA	**ND3 AIR IN**	22.4	**ND5 AIR IN**	22.4
ND1 AIR OUT	29.2	**ND3 AIR OUT**	40.0	**ND5 AIR OUT**	37.3
ND1 NB	36.9	**ND3 NB**	39.4	**ND5 NB**	40.3
ND1 DIMM1	35.5	**ND3 DIMM1**	37.1	**ND5 DIMM1**	32.9
ND1 DIMM2	35.9	**ND3 DIMM2**	38.8	**ND5 DIMM2**	36.0
ND1 DIMM3	37.6	**ND3 DIMM3**	41.0	**ND5 DIMM3**	38.5
ND1 DIMM4	36.9	**ND3 DIMM4**	39.2	**ND5 DIMM4**	35.5
ND1 NB2	49.0	**ND3 NB2**	51.8	**ND5 NB2**	54.8
ND1 PulseDC	33.3	**ND3 PulseDC**	33.8	**ND5 PulseDC**	34.9
ND1 LAN	38.2	**ND3 LAN**	40.9	**ND5 LAN**	39.0
ND1 INFINI	36.8	**ND3 INFINI**	37.9	**ND5 INFINI**	38.7
ND1 HDD	25.6	**ND3 HDD**	27.0	**ND5 HDD**	28.4
ND1 FET1	35.3	**ND3 FET1**	36.6	**ND5 FET1**	36.0
ND1 FET2	36.1	**ND3 FET2**	37.7	**ND5 FET2**	36.3
ND1 FET3	35.7	**ND3 FET3**	37.3	**ND5 FET3**	36.5
ND1 FET4	33.5	**ND3 FET4**	35.6	**ND5 FET4**	34.5
ND1 FET5	31.8	**ND3 FET5**	32.7	**ND5 FET5**	17.0
ND1 FET6	33.7	**ND3 FET6**	36.0	**ND5 FET6**	34.5
ND2 AIR IN	21.3	**ND4 AIR IN**	22.6		
ND2 AIR OUT	29.9	**ND4 AIR OUT**	38.8		
ND2 NB	37.0	**ND4 NB**	40.0		
ND2 DIMM1	37.3	**ND4 DIMM1**	36.2		
ND2 DIMM2	37.4	**ND4 DIMM2**	39.3		
ND2 DIMM3	38.4	**ND4 DIMM3**	40.5		
ND2 DIMM4	39.0	**ND4 DIMM4**	38.8		
ND2 NB2	53.7	**ND4 NB2**	54.9		
ND2 PulseDC	33.6	**ND4 PulseDC**	33.6		
ND2 LAN	37.2	**ND4 LAN**	40.2		
ND2 INFINI	NA	**ND4 INFINI**	38.7		
ND2 HDD	25.9	**ND4 HDD**	NA		
ND2 FET1	35.8	**ND4 FET1**	36.5		
ND2 FET2	36.3	**ND4 FET2**	34.8		
ND2 FET3	35.4	**ND4 FET3**	36.1		
ND2 FET4	33.9	**ND4 FET4**	36.9		
ND2 FET5	33.1	**ND4 FET5**	33.9		
ND2 FET6	NA	**ND4 FET6**	35.9		

Table D.3 Microprocessor temps, and component temps for RLX SprayCool sub-rack running BurnP6, in 21°C air, 21°C coolant, at 20 psid discharge pressure, reservoir pressure 1ATM, M/L TMU, at PNNL EMSL

APPENDIX E

Assumptions Page

Enter estimates below that best reflect the true parameters of the datacenter.
Input cells are colored =

Data Center Construction Costs

Ron Hughes of CDCDG estimates $10 per sqf multiple on watts delivered. I.e. 40WSF = $400/sqf			
PNNL is adding 3000sqf at a cost of about $5M, which comes to $1,666 sqf			
PNNL has roughly 120WSF, so use $1,200 for construction cost in model as conservative			
40 WSF	$	400.00	Per square foot
80 WSF	$	800.00	Per square foot
120 WSF	$	1,200.00	Per square foot
PNNL Construction Costs	$	1,200.00	Per square foot
(From CDCDG Presentation)			
Usable Space 50 WSF		70%	This is not currently built into the model
Usable Space 300 WSF		45%	We've gone from 17 to 12 CRACs,
Usable Space 500 WSF		25%	could replace with computers

Size of Facility - Computer

Square feet of facility		10,000	
Number of CPUs		1,954	
Watts per CPU		85	rx2600 Itaniums are 80-90W
Watts per square foot		120	
Additional expansion per year (sqf)		1000	Based on a 3000sqf upgrade every third year
Number of racks - air		83	23 fat nodes and 40 thin nodes
Number of racks - spray		58	By using 1U servers
Difference		25	Rack space savings from Spraycool
Square feet per rack		8	Each rack effectively takes 2 floor tiles
Number of CRACs			
Number of Chillers			
Number of Cooling Towers			
Number of servers per rack		18	
Number of CPUs per rack		36	

TCO

SprayCool Hardware

TMU capacity		5000	Watts
Number of TMUs		1	
TMU price per W	$	1.60	$1/W is the long term goal
TMU Price	$	8,000.00	$5000 target price
SMK Price	$	200.00	$139 target price
Cost of coolant	$	250.00	Per Gallon
Cost of rack manifold	$	2,000.00	Target price $500

Approximate Equipment Costs

Air Handler Price	$	15,000.00
Air Handler Operation	Incl in COP	
Chiller Price		
Chiller Operation	Incl in COP	
Cooling Tower Price		
Cooling Tower Operation	Incl in COP	

Model

System Integration @ ISR	Time per rack		Based on 18 servers per rack and rx2600
Receiving		1	Hourly Rate $50
Air benchmark test		2	
Retro-fit SMKs into servers		6	About 20 minutes per SMK
TMU/Manifold integration to rack		1	
Spray benchmark test		2	
Test report		1	
Package and ship		1.5	
Total Hours		14.5	
Hourly Rate	$	50.00	

On-site System Maintenance

Labor hours to bring the system up		0.5	Hours to connect and turn up TMU
TMU Monthly Maintenance		12	Refill fluid, repair fittings, hoses, etc.
Tech labor per hour	$	100.00	

Reiliability Costs

Data Center Cost Model

Spot Cooling - retrofit

SprayCool Capital Investment

Component	Qty	Price	Total	
Thermal Management Unit	54	$ 8,000.00	$ 434,222	1 TMU per rack
Rack Manifold	54	$ 2,000.00	$ 108,556	1 Manifold per 18 SMK
Tubing for H20 & PF	54	$ 600.00	$ 32,567	
Cooling fluid	109	$ 250.00	$ 27,139	2 Gallons per Manifold
SprayCool Kit	977	$ 200.00	$ 195,400	1 SMK per 2 CPU
Water Tap Installation	54	$ 150.00	$ 8,142	
Equipment Conversion			$ 39,351	
Total Investment			$ 845,376	

	Air Cooling		Spot Spray Cooling		Difference	
Cost Type	Monthly	Yearly	Monthly	Yearly	Yearly	**Notes**
Energy Savings (kW)						
Air Handlers	64	768	41	492	276	Go from 17 to 12 air handlers
Chillers	168	2016	168	2016	0	Same load on chiller
Towers	56	672	56	672	0	Same load on Tower
Server Fans	25	300	19	228	72	Two fans removed from each server
TMU	0	0	4.5	54	-54	Assumes a 5kW TMU using 140W
Total	313	3,756	289	3,462	294	
kWh	225,360	2,704,320	207,720	2,492,640	211,680	
Dollarized	$ 11,493.36	$ 137,920.32	$ 10,593.72	$ 127,124.64	$ 10,795.68	
Install/Maint. Costs						
System turn-up	$ -	$ -	$ 2,713.89	$ 2,713.89	$ (2,713.89)	Connect and bring up TMU
TMU Maintenance	$ -	$ -	$ 1,200.00	$ 14,400.00	$ (14,400.00)	Fluid fill, fittings and hose repair, etc.
Materials	$ -	$ -	$ 150.00	$ 1,800.00	$ (1,800.00)	Extra $150 per month for consumables (PF, clamps, tubing, etc.)
Total	$ -	$ -	$ 4,063.89	$ 48,766.67	$ (48,766.67)	
Reliability Costs						
#CPU Failures	6.25	75	3.125	37.5	$ 37.50	Since spray keeps CPU 10 deg. cooler, assume 1/2 the failures
Downtime	$ 6,781.25	$ 81,375.00	$ 3,390.63	$ 40,687.50	$ 40,687.50	
#DIMM Failures	4.5	54	2.25	27	$ 27.00	Assume half the failures with SprayCool
Downtime	$ 4,882.50	$ 58,590.00	$ 2,441.25	$ 29,295.00	$ 29,295.00	These are only DIMM failures that crash jobs
TMU Failures				$ 2,355.66	$ (2,355.66)	4% Annual failure rate, same cost as CPU failure
ISR Service Contract			$ 10,567.20	$ 126,806.46	$ (126,806.46)	15% of Capital cost
OEM Service Contract	$ 166,666.67	$ 2,000,000.00	$ 133,333.33	$ 1,600,000.00	$ 400,000.00	Assume half the failures = 20% lower contract cost
Total	$ 178,330.42	$ 2,139,965.00	$ 149,732.41	$ 1,799,144.61	$ 340,820.39	
Construction Costs						
Facility Expansion		$ 1,200,000.00			$ 1,200,000.00	
Higher Density Racks				$ (240,000.00)	$ (240,000.00)	
CRAC space savings				TBD	$ -	
Total	$ -	$ 1,200,000.00	$ -	$ (240,000.00)	$ 1,440,000.00	
Cumulative Total	$ 189,823.78	$ 3,477,885.32	$ 164,390.02	$ 1,735,035.92	$ 1,742,849.40	

Payback	**Capital Investment**	**Total Savings**	**Break-even (years)**
With Facility Expansion	$ 845,376.39	$ 1,502,849.40	0.5625
With Higher Density	$ 845,376.39	$ 542,849.40	1.5573
Without Construction	$ 845,376.39	$ 302,849.40	2.7914

NOTES:
"Facility Expansion" assumes 3000sqf ugrade every 3 years, and that construction would not be needed with SprayCool
"Higher Density Racks" calculates the saving in moving to 1U servers with Spraycool

Data Center Cost Model

Spot Cooling - optimized build

SprayCool Capital Investment

Component	Qty	Price	Total	
Thermal Management Unit	54	$ 8,000.00	$ 434,222	1 TMU per rack
Rack Manifold	54	$ 2,000.00	$ 108,556	1 Manifold per 18 SMK
Tubing for H20 & PF	54	$ 600.00	$ 32,567	
Cooling fluid	109	$ 250.00	$ 27,139	2 Gallons per Manifold
SprayCool Kit	977	$ 200.00	$ 195,400	1 SMK per 2 CPU
Water Tap Installation	54	$ 150.00	$ 8,142	
Equipment Conversion			$ 39,351	
Total Investment			$ 845,376	

	Air Cooling		Spot Spray Cooling		Difference	
Cost Type	Monthly	Yearly	Monthly	Yearly	Yearly	**Notes**
Energy Savings (kW)						
Air Handlers	64	768	41	492	276	Go from 17 to 12 air handlers
Chillers	168	2016	108	1296	720	Bypass Chiller
Tower	56	672	56	672	0	Same load on Tower
Server Fans	25	300	19	228	72	Two fans removed from each server
TMU	0	0	4.5	54	-54	Assumes a 5kW TMU using 140W
Total	313	3,756	229	2,742	1,014	
kWh	225,360	2,704,320	164,520	1,974,240	730,080	
Dollarized	$ 11,493.36	$ 137,920.32	$ 8,390.52	$ 100,686.24	$ 37,234.08	
Maintenance Costs						
System turn-up	$ -	$ -	$ 2,713.89	$ 2,713.89	$ (2,713.89)	
TMU Maintenance	$ -	$ -	$ 1,200.00	$ 14,400.00	$ (14,400.00)	Assume SprayCool requires 20% more technician labor
Materials	$ -	$ -	$ 150.00	$ 1,800.00	$ (1,800.00)	Extra $100 per month for consumables (PF, clamps, tubing, etc.)
Total	$ -	$ -	$ 4,063.89	$ 48,766.67	$ (48,766.67)	
Reliability Costs						
#CPU Failures	6.25	75	3.125	37.5	$ 37.50	Since spray keeps CPU 10 deg. cooler, assume 1/2 the failures
Downtime	$ 6,781.25	$ 81,375.00	$ 3,390.63	$ 40,687.50	$ 40,687.50	
#DIMM Failures	4.5	54	2.25	27	$ 27.00	Assume half the failures with SprayCool
Downtime	$ 4,882.50	$ 58,590.00	$ 2,441.25	$ 29,295.00	$ 29,295.00	These are only DIMM failures that crash jobs
TMU Failures				$ 2,355.66	$ (2,355.66)	4% Annual failure rate, same cost as CPU failure
ISR Service Contract			$ 10,567.20	$ 126,806.46	$ (126,806.46)	15% of Capital cost
OEM Service Contract	$ 166,666.67	$ 2,000,000.00	$ 133,333.33	$ 1,600,000.00	$ 400,000.00	Assume half the failures = 20% lower contract cost
Total	$ 178,330.42	$ 2,139,965.00	$ 149,732.41	$ 1,799,144.61	$ 340,820.39	
Construction Costs						
Facility Expansion		$ 1,200,000.00			$ 1,200,000.00	
Higher Density Racks				$ (240,000.00)	$ 240,000.00	
CRAC space savings					$ -	
Total	$ -	$ 1,200,000.00	$ -	$ (240,000.00)	$ 1,440,000.00	
Cumulative Total	$ 189,823.78	$ 3,477,885.32	$ 162,186.82	$ 1,708,597.52	$ 1,769,287.80	

Payback	**Capital Investment**	**Total Savings**	**Break-even (years)**
With Facility Expansion	$ 845,376.39	$ 1,529,287.80	0.5528
With Higher Density	$ 845,376.39	$ 569,287.80	1.4850
Without Construction	$ 845,376.39	$ 329,287.80	2.5673

NOTES:
"Facility Expansion" assumes 3000sqf ugrade every 3 years, and that construction would not be needed with SprayCool
"Higher Density Racks" calculates the saving in moving to 1U servers with Spraycool

Notes on considerations while developing the model

What are the model inputs and outputs
How to define ROI?
Energy Savings
Maintenance Costs
Capital Investment
Impact on personnel - plumber, technicians, etc.
Quantify cost of downtime, reliability
$/hour
Troubleshooting
How do you calculate revenue for a data center
What is the data center output? $/unit
How to quantify throughput of air vs. spray cooled
What are the units
Dollars per MIP, FLOP, etc.

ROI = cost savings of spray vs. air cool/capital investment
PNNL costs - replace memory/processor weekly, what are the costs
from this determine labor, downtime, etc.
MTBF

What are the reliability improvements with spray cooling
Reliability - easy to determine if there is throttling, but how to attach price to higher reliability
Hard with the short life span of electronics - obsolete quickly
What is the technology refresh rate for air vs. spray cooling
How difficult to upgrad the electronics (EFV example)

Maybe separate models for hybrid and global spray cooling
Assign a cost to densification - MIPS or FLOPS/sqf
Facility costs

For VDC, ask question regarding service - how often, union based, is 3rd party ok, costs

Questions for data center manager:
What does a typical job consist of? PNNL - longest is typically three days
What are the costs associated with it? Who pays?
What is computing time worth?
What is the life expectancy of the CPU? MTBF?
What is it worth if this lifetime is increased? Material + Labor

References

[1] Roberson & Crowe, Engineering Fluid Mechanics, 6th edition, John Wiley & Sons, Inc. 1997 New York

[2] Website Wolverine Tube "Engineering Data Book III" (http://www.wlv.com/products/databook/db3/DataBo