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# Cooling Performance Testing of Attaway's Negative Pressure CDU

**David M. Smith**
*Sandia National Laboratories*
**David J. Martinez**
*Sandia National Laboratories*
**Trevor Irwin**
*Childdyne*

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## ABSTRACT

Attaway is a recently installed High-Performance Computing (HPC) machine at Sandia National Labs that is 70% water-cooled and 30% air-cooled. This machine, supplied by Penguin Computing, uses a novel new cooling system from Chilldyne that operates in a vacuum, preventing water leaks. If water-cooling is to fail, fans inside of each node will ramp up to do 100% of the cooling on Attaway. Various tests were completed on Attaway to determine the robustness of its cooling system as well as its ability to respond to sudden changes in states. These changes include an immediate change from an idle compute load to full load (Linpack) as well as running Linpack without any water cooling from Attaway's CDUs. It was discovered that Attaway could respond to sudden compute load changes very well, never throttling any nodes. When Linpack was run without water cooling, the system was able to operate for a short time before throttling happened.

## ACKNOWLEDGEMENTS

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A negative-pressure liquid cooling solution was designed to allow for leak-free, highly efficient cooling of High-Performance Computing (HPC) systems. Sandia National Labs deployed a 650kW HPC system named Attaway equipped with Chilldyne's negative-pressure liquid cooling. Attaway also contains air-cooling fans in each node to act as primary cooling for low-power components and secondary cooling for CPU's in the case of a liquid-cooling failure. Multiple tests were performed in order to prove the robustness and effectiveness of the Chilldyne solution.

Tests performed on the HPC system included running at both idle and Linpack with and without the liquid cooling in operation. The results of the testing showed that the Chilldyne system is able to keep the CPU's at temperatures under 50°C while also having a very low power draw and a highly redundant system. Each CDU draws 3.4kW under full load, giving the entire HPC system a PUE of 1.016, meaning the CDU's draw only 1.6% of the systems total power. A comparable positive-pressure CDU would draw about 4.0kW under full load, meaning the Chilldyne system is more efficient as well as being leak-proof.

## ACRONYMS AND DEFINITIONS

| Abbreviation | Definition |
|---|---|
| SNL | Sandia National Laboratories |
| DCIM | Data Center Infrastructure Management |
| CDU | Cooling Distribution Unit |
| CPU | Central Processing Unit |
| TDS | Total Dissolved Solids |
| PUE | Power Usage Effectiveness |
| HPC | High Performance Computing |
| kW | Kilowatt (1000 Watts) |
| MW | Megawatt (1000 kW) |

- PUE – Power Usage Effectiveness is a ratio that compares the total energy used by a data center to the total energy used by the computing equipment within the data center. The lower the number is, the more efficient the data center runs. The formula for PUE is:
  - PUE = $\frac{Total\ Data\ Center\ Energy\ Usage}{Compute\ Equipment\ Energy\ Usage}$
- Linpack – Linpack is a software collection designed to stress test and benchmark high-performance computers, especially supercomputers. Linpack tests a system's floating point computing power, the most common performance measure used to compare the world's fastest computers.
- DCIM – Data Center Infrastructure Management is a software combines monitoring, management, and planning into a single program that collects and analyzes data from a veriety of systems across the data center.

# 1. INTRODUCTION

Sandia National Labs, a United States Department of Energy (DOE) national laboratory, completed construction on a new data center in October of 2018. Since the finalization of this data center, SNL has been searching for new and innovative cooling ideas to reduce the energy use of the computer systems being installed. SNL installed Attaway in September of 2019. Attaway was installed with a new liquid-cooling system which operates efficiently, redundantly, and operates in a vacuum to prevent leaks.

Sandia National Labs has a rich history in the field of high performance computing. From deploying some of the early liquid cooled systems during the Cray era, to helping develop and engineer the first HPC system to reach 1 Teraflop (a measure of computer speed equal to one trillion floating-point operations per second). SNL installed some of the first plug-fan cooling units, moving away from traditional centrifugal fans to create better air distribution under a raised floor. SNL also co-designed and installed the first instance of pumped liquid refrigerant cooling doors arranged in a laminar flow configuration. SNL approached the deployment HPC systems as a partnership with the vendor where in many instances new, first of its kind technology is installed.

### 1.1. Chilldyne CDU Development History

Chilldyne's vacuum liquid cooling pump was originally developed as a higher reliability replacement for a rocket turbopump for a proposed manned NASA lunar mission. The multiple-chambered pistonless pump design aimed to couple the performance of a turbopump with the reliability of a pressure-fed fuel system. The pump was to be used to pump liquid oxygen and liquid methane for attitude control thrusters and to provide a "limp home" mode in case the main rocket engine failed. With support from NASA and DARPA, the same engineering team that developed the Chilldyne CDU iterated and improved the pump design and tested it with rocket engines in 2017.

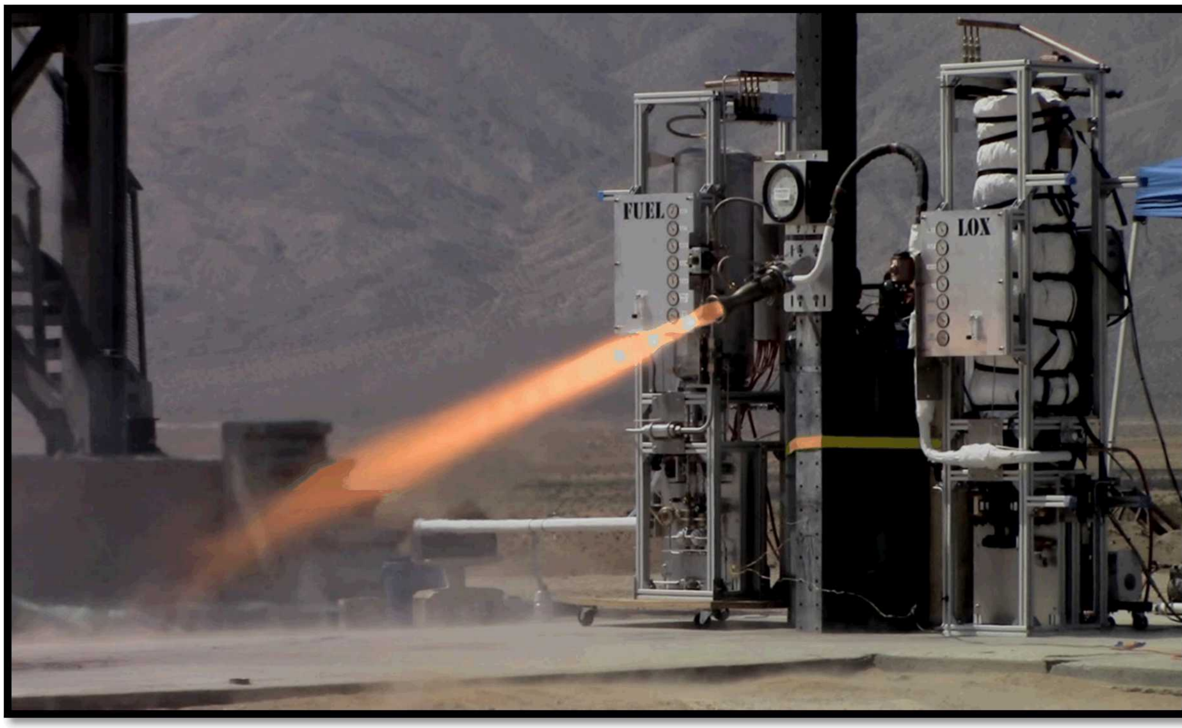


**Figure 1: The pistonless rocket fuel pump during a "hot fire" test**

The same pump technology was brought into data centers, where the pistonless pump was completely redesigned for the new vacuum application. A high reliability liquid ring pump provides the vacuum to move the coolant. The pressure chambers were made square to fit into a standard rack. Heat exchangers, automated coolant additive and temperature controls, and a management interface were added. The CDU has been improved over the years, becoming more reliable and more robust with every iteration.

## 1.2. Chilldyne's Negative Pressure CDU

Chilldyne's negative pressure CDU operates under a vacuum which allows for leak-free operation. The chamber system of the CDU, which Chilldyne calls the "ARM" chamber, (Auxiliary, Reservoir, Main) pumps the coolant and stores it. The ARM chamber is divided into three smaller chambers: Auxiliary, Reservoir, and Main. The pumping action of the CDU is cyclical. In the first stage, the CDU applies vacuum to the Main chamber. Fluid is drawn out of the reservoir and through the servers into the main chamber. When the Main chamber is nearly full, the CDU draws vacuum on the Auxiliary chamber, and the Main chamber is allowed to drain into the Reservoir. When the Auxiliary chamber is nearly full, the cycle repeats. By alternately applying vacuum to the Main and Auxiliary chambers, the CDU creates a steady flow of water out of the Reservoir chamber, through the servers, and back into the CDU.

After the warm fluid returns to the CDU, it passes through two heat exchangers that reject the heat to a source of facility cooling, such as the Thermosyphon developed by Johnson Controls (more detail provided in Section 1.3). A coolant additive management system regulates the level of anti-corrosion and biocide additives in the water.

Because the CDU keeps the entire system under vacuum, water cannot leak out. If a line is damaged or a seal fails, air leaks into the system instead. The air is evacuated from the system via the liquid ring vacuum pump and a fluid separator, so the system can continue to operate even with minor leaks present. The vacuum also allows servers to be disconnected from a live system without shutting off flow to the rack or the CDU. When a server is disconnected, the water inside is automatically evacuated, leaving the server dry for maintenance.

### 1.2.1. *CDU Hardware and Layout*

The following layout depicts the major components of Chilldyne's CDU.

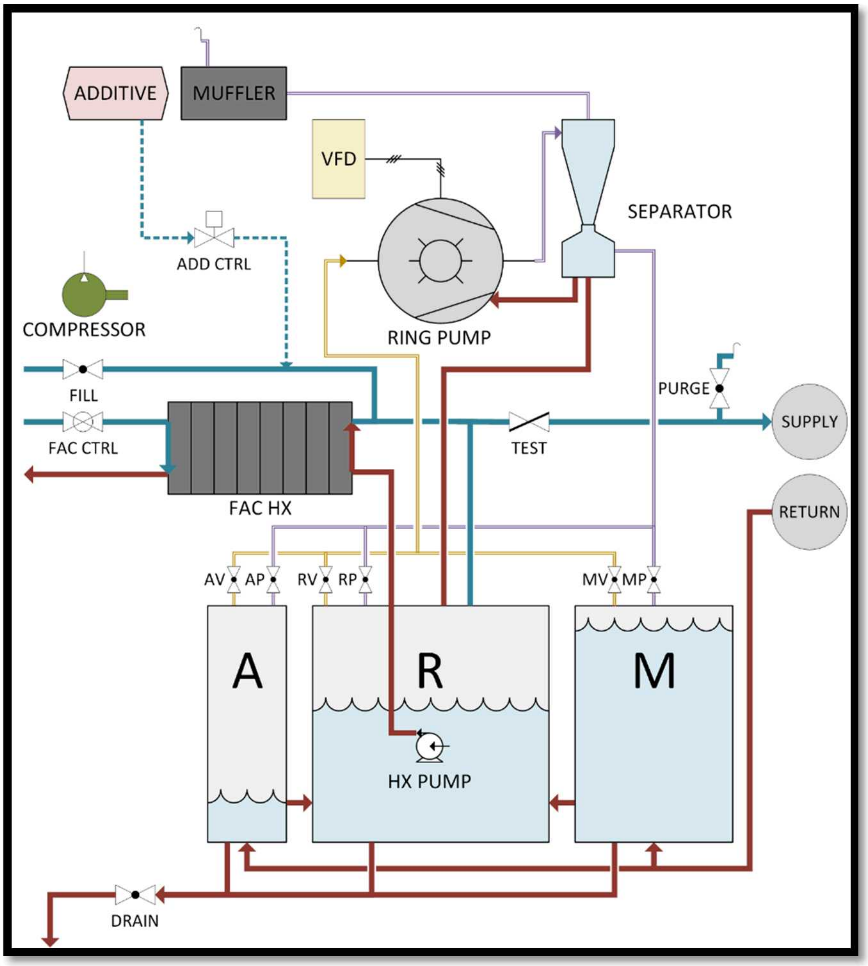


**Figure 2: CDU Hardware Layout**

| Tag | Name | Description |
|---|---|---|
| MUFFLER | Muffler | Prevents droplets from escaping and reduces audible volume of system. |
| ADDITIVE TANK | Additive Tank | Stores coolant additive solution for periodic distribution. |
| VFD | Variable Frequency Drive | Provides AC power and speed control for LRP. |
| RING PUMP | Liquid Ring Pump (LRP) | Pulls vacuum on chambers to induce flow. |
| SEPARATOR | Separator | Separates excess fluid pulled into LRP. |
| COMPRESSOR | Air Compressor | Provides pneumatic power to valves. |
| FAC HX | Facility Heat Exchanger | Moves heat from the process loop to the facility loop. |
| SUPPLY | Supply Manifold | Multiple connection point for supply coolant. |
| RETURN | Return Manifold | Multiple connection point for returning coolant. |
| R | Reservoir Chamber | Holds low vacuum to allow fluid flow out to the process loop. |
| M | Main Chamber | Alternates holding high vacuum to pull fluid through process loop. |
| A | Aux Chamber | Alternates holding high vacuum to pull fluid through process loop. |
| HX PUMP | Heat Exchanger Pump | Forces warm coolant up to the facility heat exchanger. |

The CDU pumps water to the nodes within compute racks. These nodes have two CPU's, each of which has a water and air-cooled heat sink. These heat sinks have water passages to allow heat to be rejected to water and sent back to the CDU. The heat sinks also have fins on top which create extra surface area for heat to rejected through. If there is no water cooling available, the fans within the nodes will ramp up to a higher RPM and reject heat through air-cooling.

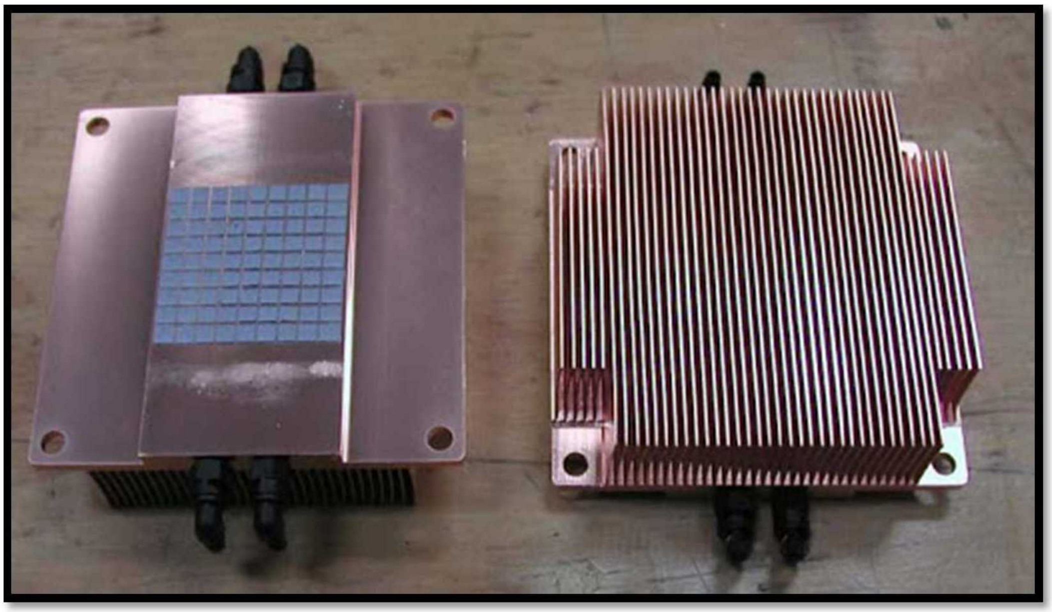

**Figure 3: Water and Air-Cooled Heat Sink**

### *1.2.2. CDU Detailed Operation*

The main pumping chamber (M) is connected to the vacuum pump by opening valve MV. It then sucks water through a check valve, filling the main chamber. Once the level reaches an upper level switch, the auxiliary chamber (A) is connected to the vacuum pump by opening valve AV. Water then flows into both pumping chambers A and M briefly. Then the MV valve is shut and the MP valve is open to atmosphere. Now the water from the servers is flowing into the auxiliary chamber and the water from the main chamber is flowing into the reservoir (R), which is maintained at a constant low vacuum level. The reservoir vacuum is controlled via the RV and RP valves which open if the vacuum level is too high or too low respectively. Once the level in the main chamber reaches a low-level switch position, the MP valve is shut and the system then opens the MV valve and the water briefly flows into both chambers again. Then the AV valve is shut and the AP valve is opened and the water in the auxiliary chamber flows into the reservoir. At this point, the cycle repeats.

The vacuum pump is a liquid ring pump, which is sealed by a continuous flow of water that gets flung to the outside of the pump due to centrifugal force. The vacuum pump has only 3 parts subject to wear, two ball bearings and a face seal. The vacuum pump should last a long time because it runs at 80% of normal speed, pumping clean water at a low temperature. The vacuum pump has a capacity of 5 times the liquid flow capacity, so it can ingest a great deal of air with very little impact on the heat transfer of the cold plates.

The liquid ring pump outflow goes into a separator which separates the water from the air and returns the water back to the pump to seal the pump. The air goes into a muffler to reduce noise and capture any water droplets and return them to the system. An air flow sensor measures the amount of air leaving the CDU and warns the operator if the air flow is too high, indicating a leak of air into the system.

The system also contains an HX (heat exchanger) pump which moves water from the reservoir to the heat exchanger and back in order to cool the water. The pump will turn off if the coolant temperature drops below the dewpoint, as measured by a humidity sensor. This way the servers will never get cold enough to collect condensation.

A facility water valve controls the flow of cooling water to the CDU heat exchanger to maintain the supply water temperature from the CDU to the servers. This valve also allows the temperature of the facility return water to be controlled. Note that the cold plate will always be a few degrees warmer than the coolant return temperature.

The CDU also includes a purge and a test valve. The test valve may be shut, and the MV valve may be opened in order to conduct a vacuum test. The CDU pulls a vacuum on the servers and then shuts the MV valve. The pressure in the main chamber is monitored to see how well vacuum is maintained. The system may also be purged of coolant by running the pump and shutting the test valve and opening the purge valve. This way most of the coolant can be removed from the servers and the cooling lines leading to and from the racks. This makes it easier to service the system.

The CDU includes automatic fill and drain. The CDU adds water or drains water as required. This allows the user to add or remove racks without adjusting the coolant volume. Chilldyne recommends RO water, but tap water can be used. The CDU also includes a coolant additive system. A TDS (Total Dissolved Solids) meter measures the amount of coolant additive in the system. If the TDS is too low, more coolant additive is added from an onboard tank. If it is too high, some treated water is drained and some fresh water is added to reduce the TDS.

If the CDU is powered off suddenly, the test valve closes and the purge valve opens so that any remaining vacuum in the pump chamber sucks coolant into the CDU. The amount of coolant in the servers and the racks is then reduced so that if there is a CDU failure and a leak, there will not be as much coolant in the racks to potentially cause problems. These problems are further prevented by running the CDU’s in an N+1 rendundancy.

### *1.2.3. Chilldyne's Server-Side Design*

The CDU pumps water to the nodes within compute racks. These nodes have two CPU's, each of which has a hybrid water and air-cooled heat sink. These heat sinks have water passages to allow heat to be rejected to water and sent back to the CDU.

The heat sinks have fins on top which allow the cold plates to draw heat from the air if they are colder than the air inside the server, or reject the heat from the CPU if the liquid cooling is off. This allows the system to capture heat produced by the DIMMs and other electronic components and reject it to the water following through the heat sink. If there is no water cooling, the fans within the nodes will ramp up to a higher RPM and reject heat through air-cooling. When water cooling is available, the motherboard fan controller keeps the fans running at a very low RPM, conserving power. The heat sinks are connected in parallel to keep the two CPU temperatures the same.

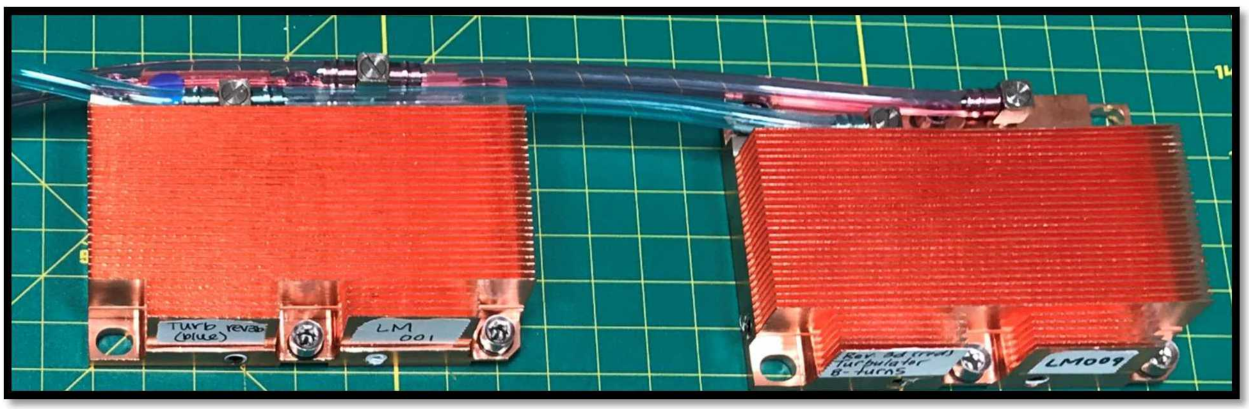


**Figure 4: Water and Air-Cooled Heat Sinks**

Each server has a check valve and sonic nozzle venturi to limit the effect of any air leaks. The check valve has a small opening that allows coolant to be sucked out of the server while limiting bubbles on the supply side. The nozzle limits air flow on the return side. The rest of the system is still adequately cooled in the event of an air leak, even if a tube within a server is completely open.

## 1.3. Sandia's HPC Data Center Cooling

Sandia National Labs built a new data center (Building 725E) specifically for High Performance Computing (HPC) applications. Building 725E attained LEED Gold status and had a year-round average PUE of 1.10. This building was the first at Sandia National Labs to achieve a LEED Gold rating. When scoring a building for its LEED rating, points are awarded based on a buildings overall performance in energy-savings, water-savings, and other environmental preservation methods.

Building 725E was completed in October of 2018 and is designed to cool high-density computers with 85% of the heat being captured directly to water and the remaining 15% being captured to air. 725E was designed to use Thermosyphons along with a plate-frame heat exchanger to reject heat from the liquid cooling loop. When the outside temperature is too high to use the Thermosyphons, the heat is transferred to a chilled water loop passing through the plate-frame heat exchanger. For more information and test results on the Thermosyphon see the White Paper: Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center [1]

**Figure 5: Sandia's Thermosyphon**

[1] See https://www.nrel.gov/docs/fy18osti/72196.pdf

**Figure 6: 725E Plate-Frame Heat Exchanger**

The Process water loop inside of 725E is under the 3-foot raised floor and makes a loop around the entire building. This water loop is designed to have a supply temperature of 78-85°F but is currently operating with a supply temperature of 72°F. The supply temperature of the water needed to be reduced to 72°F to accommodate other HPC systems within the building which would overheat at the higher design temperature. With a supply temperature of 72°F, a trailing 12-month PUE of 1.10 was achieved, making building 725E an extremely efficient data center.

The process water loop is uninsulated because of the design temperature, always being above dew point to prevent condensation from forming on the pipes. This water loop has 12" supply and return lines that are controlled through pressure differential in order to maintain flow. Throughout the data center, under the floor are 4" supply and return lines that are capped and valved. These 4" lines are placed every 16' and allow for easy build outs for future HPC systems.

Building 725E has 4 large air economizers on the roof that work as a three-stage system to provide the air-cooling needed within the data center. The air economizers are able to utilize free cooling (outside air) for 75% of the year due to the locations climate. Return air ducts have dampers to allow for a mixtures of outside and and recirculated air from within the data center. A cell deck is used to cool the air during the periods of the year where outside air is too warm. A chilled water coil is also available in extreme weather conditions where the other two cooling options cannot sufficiently reduce the air temperature.

## 1.4. Installation of the Chilldyne System at Sandia

Installation of the Chilldyne system began with running hoses under the floor to connect compute racks to the CDU's in a redundant way. Hoses can be used because of the negative pressure operation of the Chilldyne CDU's and are easier to run than rigid pipes required for positive pressure cooling systems. Attaway has a total of 24 compute racks and 3 CDU's. Under normal operating conditions, each CDU feeds 8 compute racks, but if one CDU were to fail or be brought down for service, the two remaining CDU's would provide cooling to all 24 compute racks. This redundancy is accomplished by using a total of 6 fail-over valves, each feeding 4 compute racks. Each fail-over valve is fed from two different CDU's, allowing the system to automatically switch to a different CDU if flow is lost.

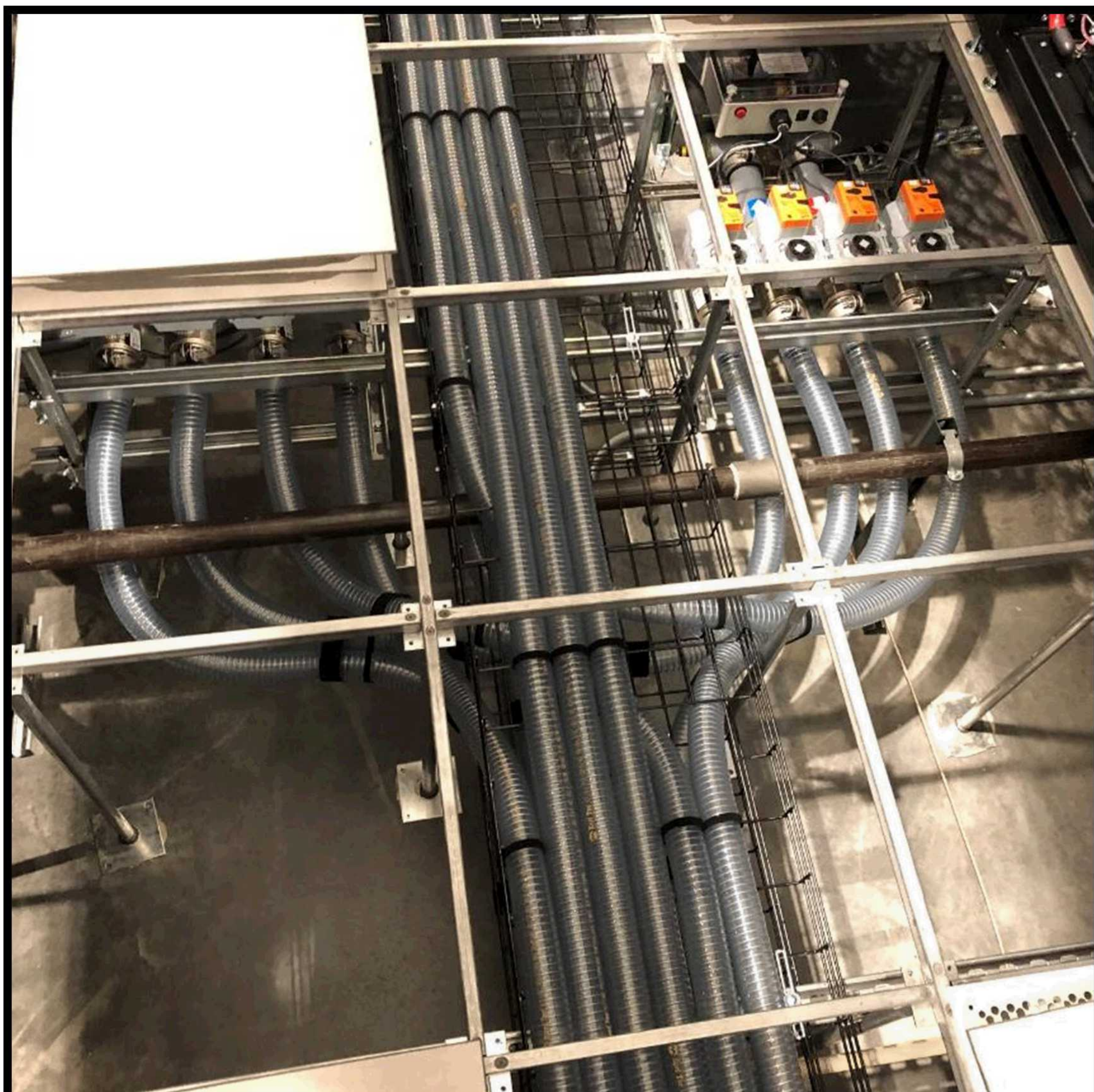

**Figure 7: Installing Tubing for CDU's**

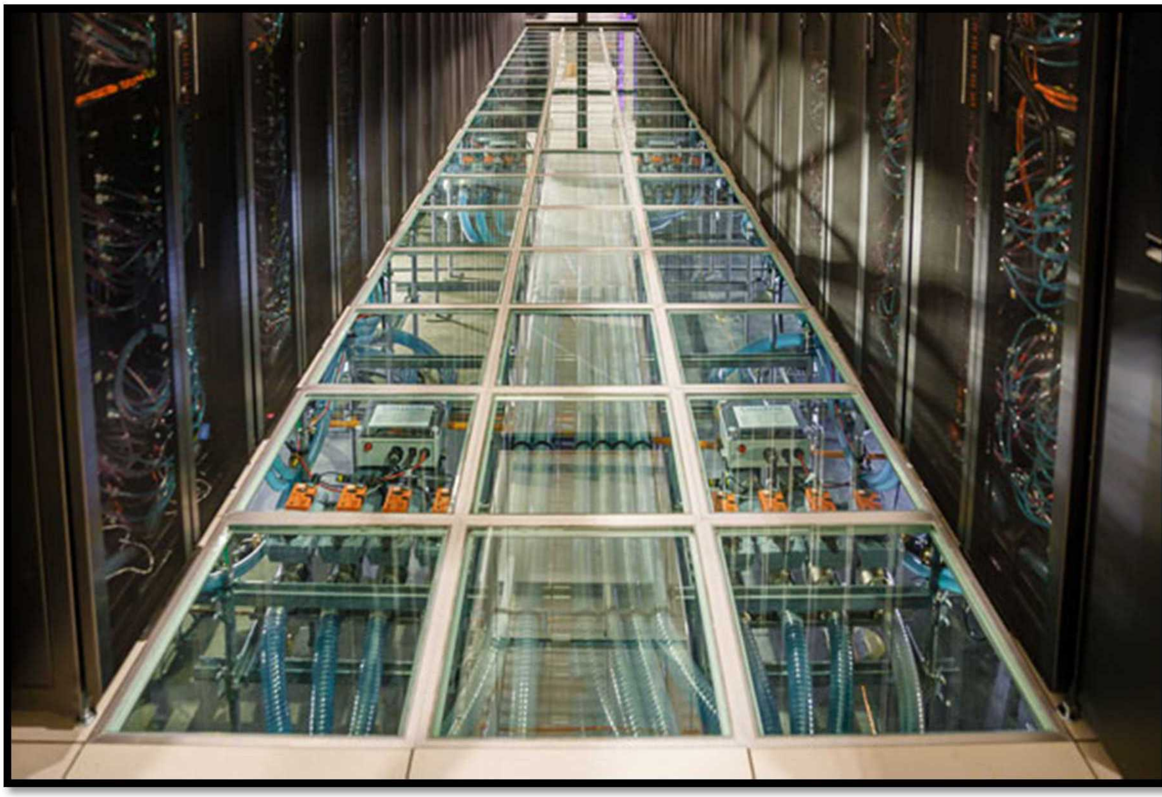

**Figure 8: Attaway With the Tubing Completed and Filled With Water**

Glass floor tiles were installed in the hot aisle of Attaway. These floor tiles allow for data center facilities team members to easily verify the operational status of the system. The fail-over valves can be visually inspected as well as the water hoses to ensure proper flow. Another benefit of glass floor tiles, is the visual improvement to the HPC system. Visitors appreciate being able to see the infrastructure installed under the floor, especially for an innovative system such as this.

## 2. TESTING ATTAWAY

The tests run on Attaway were designed to simulate real world, operational conditions which would stress the reliability and capabilities of its cooling system. Multiple test states were created in order to acquire applicable data relating to Attaway's cooling performance not only during each state but while changing states.

**The test states of Attaway along with the times beginning each state are:**

| State | Time |
|---|---|
| Idle | 11:10AM |
| Linpack Started | 11:51AM |
| Linpack Stopped | 1:58PM |
| CDU's Shut Down | 2:32PM |
| Linpack Started (No CDU's) | 3:06PM |
| CDU's Turned On (Linpack Ongoing) | 3:14PM |
| Linpack Stopped | 3:20PM |

Airflow was measured at different test states using an Alnor Balometer Capture Hood. Low flow and high flow tiles are installed in alternating positions in front of the racks of Attaway. Alternating low flow and high flow tiles allowed for the correct average airflow per rack to be achieved. Airflow readings were taken for every vented tile on Attaway and averaged to create the data points seen in the results.


**Figure 9: Measuring Airflow on Attaway**

Power readings were captured during different test states for one of the CDU's on Attaway. A Fluke FLK-430-II Power Analyzer was utilized to capture waveforms, amp draw, voltage, as well as frequency for all three phases of power feeding the CDU.

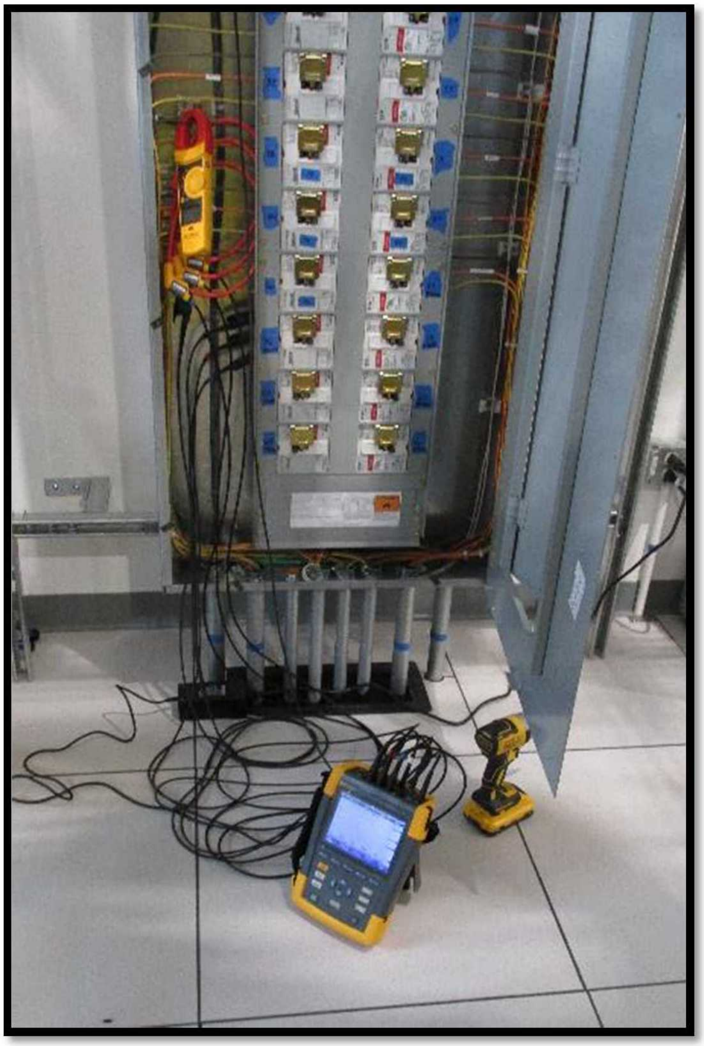

**Figure 10: Measuring Power Draw of CDU**

Readings for supply and return water temperatures as well as pressures were taken from analog gauges installed on the piping connected to the CDU's. These readings were recorded after steady state temperatures and pressures were reached. The reading for the chilled water valve position was read directly off the screen of the CDU. Digital air flow gauges are installed on the wall of building 725E and provided individual readings for each of the buildings air handlers.

Process water supply and return temperatures were attained from digital temperature gauges installed on piping adjacent to the plate-frame heat exchanger. The flow of water to the plate-frame heat exchanger was monitored to encompass the entire buildings cooling system. When the flow rate to the plate-frame heat exchanger is at 0, the entirety of the heat within the chilled water loop is being rejected by the Thermosyphon.

## 3. TEST RESULTS

The test results for Attaway show that the redundant CDU's create a reliable and effective cooling method. Below is a DCIM chart showing the power readings in Amps for the 480V compute racks of Attaway's North and South compute rows. The chart has markings which are labeled to show the different testing states. The results seen in the chart are a good representation of the low and high ranges between an idle state and a full load, Linpack state.

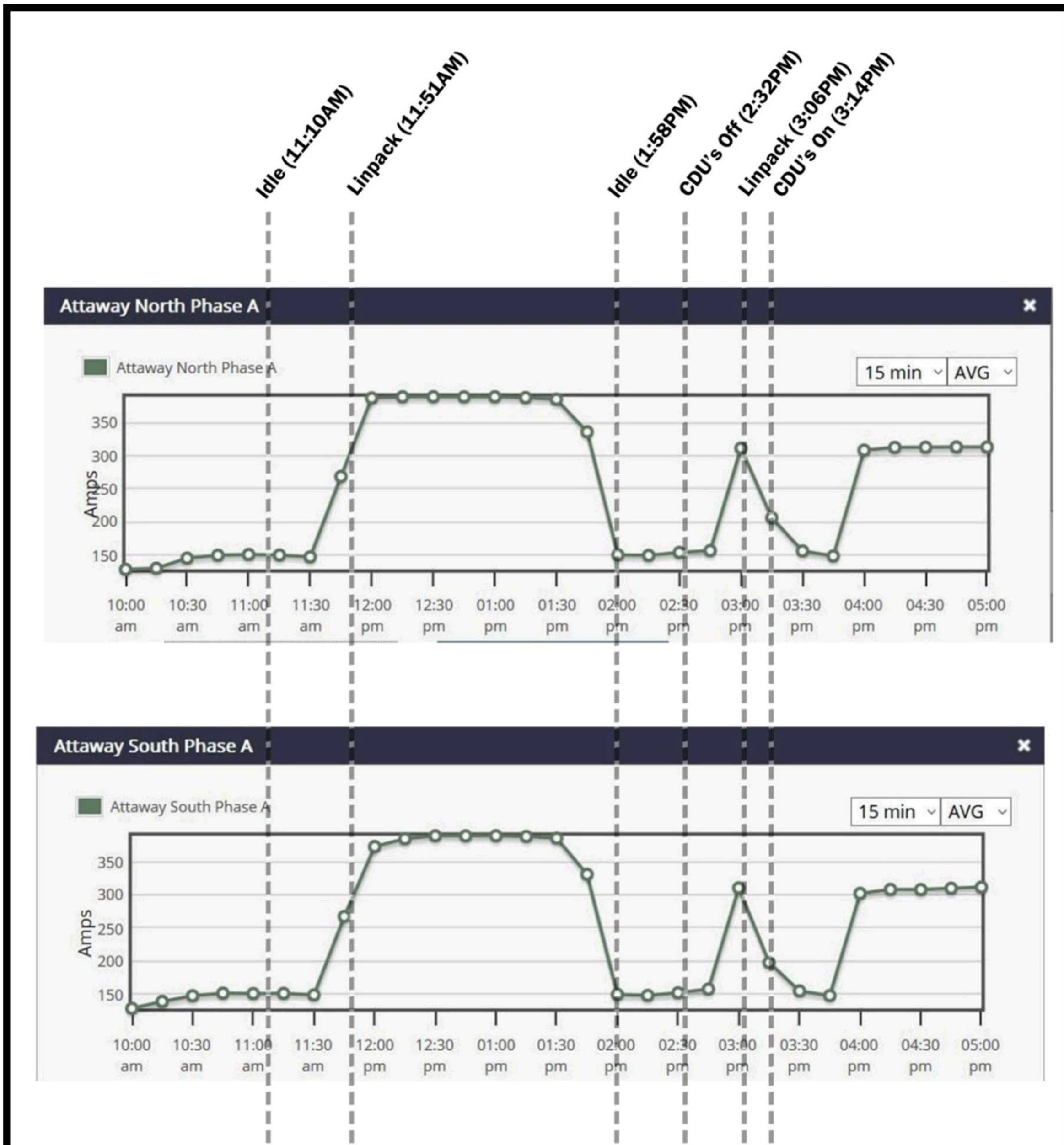


**Figure 11: Attaway North and South Test States and Current (Amps)**

The next data analyzed is the current readings from the Chilldyne CDU. Below can be seen three figures showing Amperage readings for each of the three phases of power feeding the CDU.

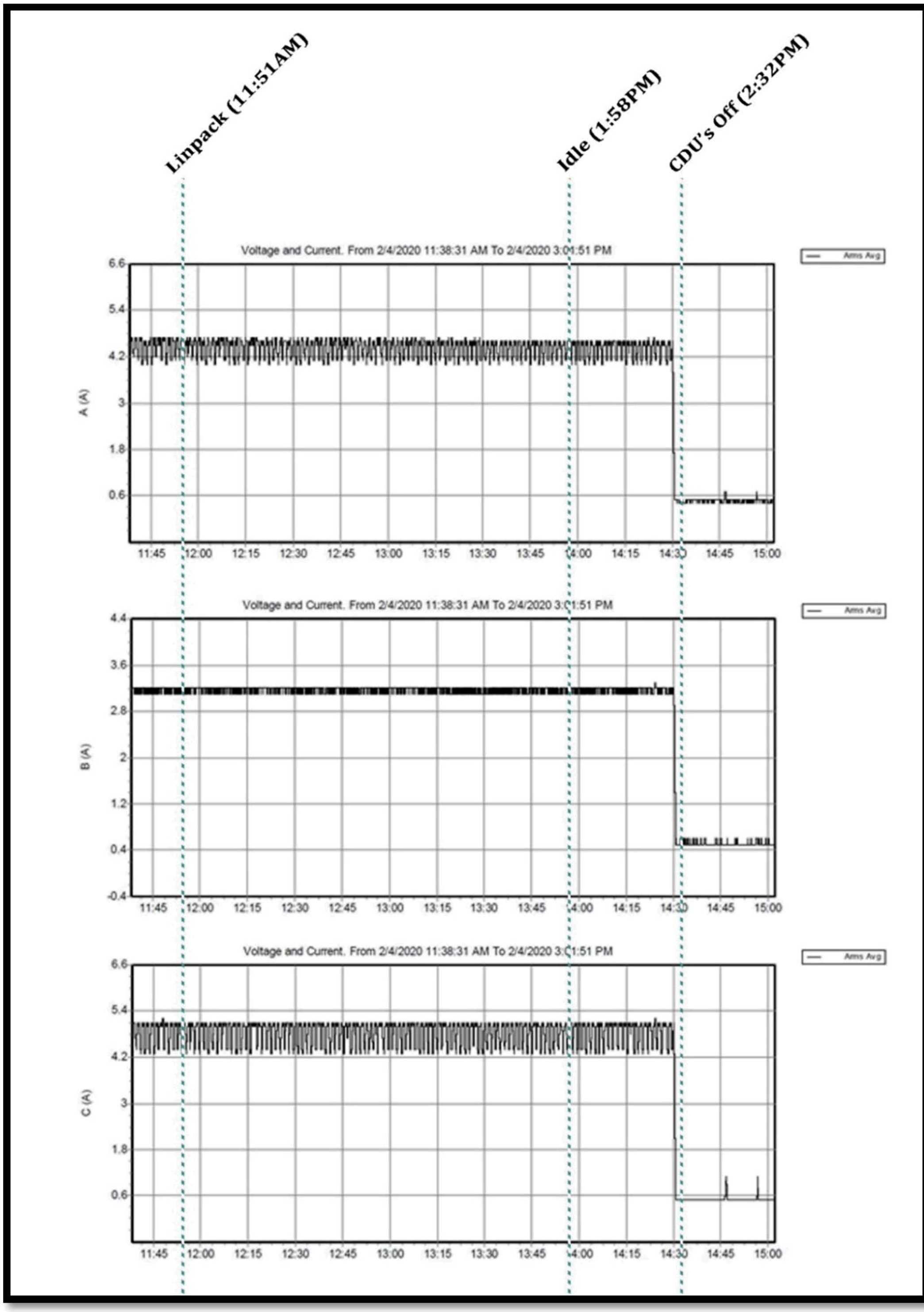


**Figure 12: CDU Current (Amps) on All Phases**

From Figure 11, the difference in current draw between the phases varies greatly, especially for phase B. Phases A and C have large variations in their Amp draw, indicating a motor load such as the vacuum pump or the air-compressor on these phases. It is important to the note that the CDU power draw doesn't change between Idle and Linpack states. The sudden drop in power at 14:30 is when the CDU's were manually stopped to simulate a Linpack run during a CDU failure.

In Figure 10 the power readings are only taken every 15 minutes. Since the Linpack run starting at 3:06PM was only sustained until 3:14PM, the current draw appears to be lower than it was during the first Linpack run at 11:51AM. This difference in reading is caused by the time duration between power readings on the DCIM tool. Since the DCIM creates an average power reading every 15 minutes and the Linpack run lasted a total of 8 minutes, the average power is in fact lower than the initial Linpack run.

Realtime data was manually read from the Attaway North and South bus ducts. In Tables 1 & 2, the current draw can be seen during each test phase. Linpack with CDU's running drew a total of 776 Amps on both bus ducts. Linpack without CDU's running drew a total of 845 Amps on both bus ducts. Turning the CDU's off has a major impact on the power draw of the system. The fans ramping up from 7,000 RPM to around 23,000 RPM causes a spike in power of 69 Amps or 57kW.

**Table 1: Attaway Test Data**

| | | 11:51AM Linpack | 1:58PM Idle | 2:32PM CDU's Off |
|---|---|---|---|---|
| **Data Points** | **Test State 1: 11:10AM Idle** | **Test State 2: 1:25PM Linpack** | **Test State 3: 2:10PM Idle** | **Test State 4: 2:42PM Idle No CDU's** |
| **CDU Readings** | | | | |
| CDU 1 Supply Temp (°F) | 68.9 | 71.8 | 71.8 | 69.3 |
| CDU 1 Return Temp (°F) | 73.9 | 85.1 | 76.8 | 68.5 |
| CDU 1 Supply Pressure (PSI) | 80 | 88 | 90 | |
| CDU 1 Return Pressure (PSI) | 56 | 62 | 66 | |
| CDU 1 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| CDU 1 Power Draw L1 (Amps) | 4.6 | 4.6 | 4.6 | 0.5 |
| CDU 1 Power Draw L2 (Amps) | 3.3 | 3.3 | 3.3 | 0.5 |
| CDU 1 Power Draw L3 (Amps) | 5.1 | 5.1 | 5.1 | 0.5 |
| | | | | |
| CDU 2 Supply Temp (°F) | 69.8 | 72.9 | 72.3 | 70.7 |
| CDU 2 Return Temp (°F) | 74.7 | 85.5 | 77.4 | 70.5 |
| CDU 2 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| | | | | |
| CDU 3 Supply Temp (°F) | 68.5 | 70.9 | 70.7 | 68.7 |
| CDU 3 Return Temp (°F) | 73.9 | 85.1 | 76.6 | 68.9 |
| CDU 3 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| | | | | |
| **Computer Readings** | | | | |
| Low Flow Tile Flow (CFM) | 195 | 300 | | |
| High Flow Tile Flow (CFM) | 240 | 400 | | |
| Attaway North Power (Amps) | 152 | 389 | 152 | 156 |
| Attaway South Power (Amps) | 151 | 387 | 151 | 155 |
| | | | | |
| **Data Center Readings** | | | | |
| Air Handler 1 Flow (CFM) | 12250 | 18000 | 18950 | 15590 |
| Air Handler 2 Flow (CFM) | 12150 | 18520 | 21000 | 20040 |
| Air Handler 3 Flow (CFM) | 12000 | 18110 | 17740 | 15820 |
| Total Air Handler Flow (CFM) | 36400 | 54630 | 57690 | 51450 |
| Chilled Water Coil Flow (GPM) | 64.8 | 64.8 | 40.8 | 40.8 |
| Process Water Supply Temp (°F) | 67.1 | 69.7 | 69 | 67.4 |
| Process Water Return Temp (°F) | 67.6 | 70.1 | 69.4 | 67.6 |

Table 2: Attaway Test Data (Continued)

| | | 3:06PM Linpack | | 3:14PM CDU's On |
|---|---|---|---|---|
| Data Points | Test State 5: 2:50PM Idle No | Test State 6: 3:10PM Linpack No CDU's | Test State 7: 3:13PM Linpack | Test State 8: 3:16PM Linpack CDU's On |
| **CDU Readings** | | | | |
| CDU 1 Supply Temp (°F) | 69.3 | | | 70 |
| CDU 1 Return Temp (°F) | 68.5 | | | 93 |
| CDU 1 Supply Pressure (PSI) | | | | |
| CDU 1 Return Pressure (PSI) | | | | |
| CDU 1 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| CDU 1 Power Draw L1 (Amps) | 0.5 | 0.5 | 0.5 | |
| CDU 1 Power Draw L2 (Amps) | 0.5 | 0.5 | 0.5 | |
| CDU 1 Power Draw L3 (Amps) | 0.5 | 0.5 | 0.5 | |
| | | | | |
| CDU 2 Supply Temp (°F) | 70.9 | | | 72.7 |
| CDU 2 Return Temp (°F) | 70.7 | | | 83.3 |
| CDU 2 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| | | | | |
| CDU 3 Supply Temp (°F) | 68.9 | | | 69.1 |
| CDU 3 Return Temp (°F) | 69.1 | | | 89.4 |
| CDU 3 CW Valve Position (% Open) | 100 | 100 | 100 | 100 |
| | | | | |
| **Computer Readings** | | | | |
| Low Flow Tile Flow (CFM) | | | | 350 |
| High Flow Tile Flow (CFM) | | | | 450 |
| Attaway North Power (Amps) | 158 | 423 | 423 | 389 |
| Attaway South Power (Amps) | 157 | 419 | 422 | 388 |
| | | | | |
| **Data Center Readings** | | | | |
| Air Handler 1 Flow (CFM) | 15800 | 17000 | 19410 | 20700 |
| Air Handler 2 Flow (CFM) | 19260 | 21000 | 23500 | 22400 |
| Air Handler 3 Flow (CFM) | 16440 | 17500 | 18000 | 19500 |
| Total Air Handler Flow (CFM) | 51500 | 55500 | 60910 | 62600 |
| Chilled Water Coil Flow (GPM) | 40.8 | 40.8 | 40.8 | 40.8 |
| Process Water Supply Temp (°F) | 67.6 | | | 68.5 |
| Process Water Return Temp (°F) | 68 | | | 69 |

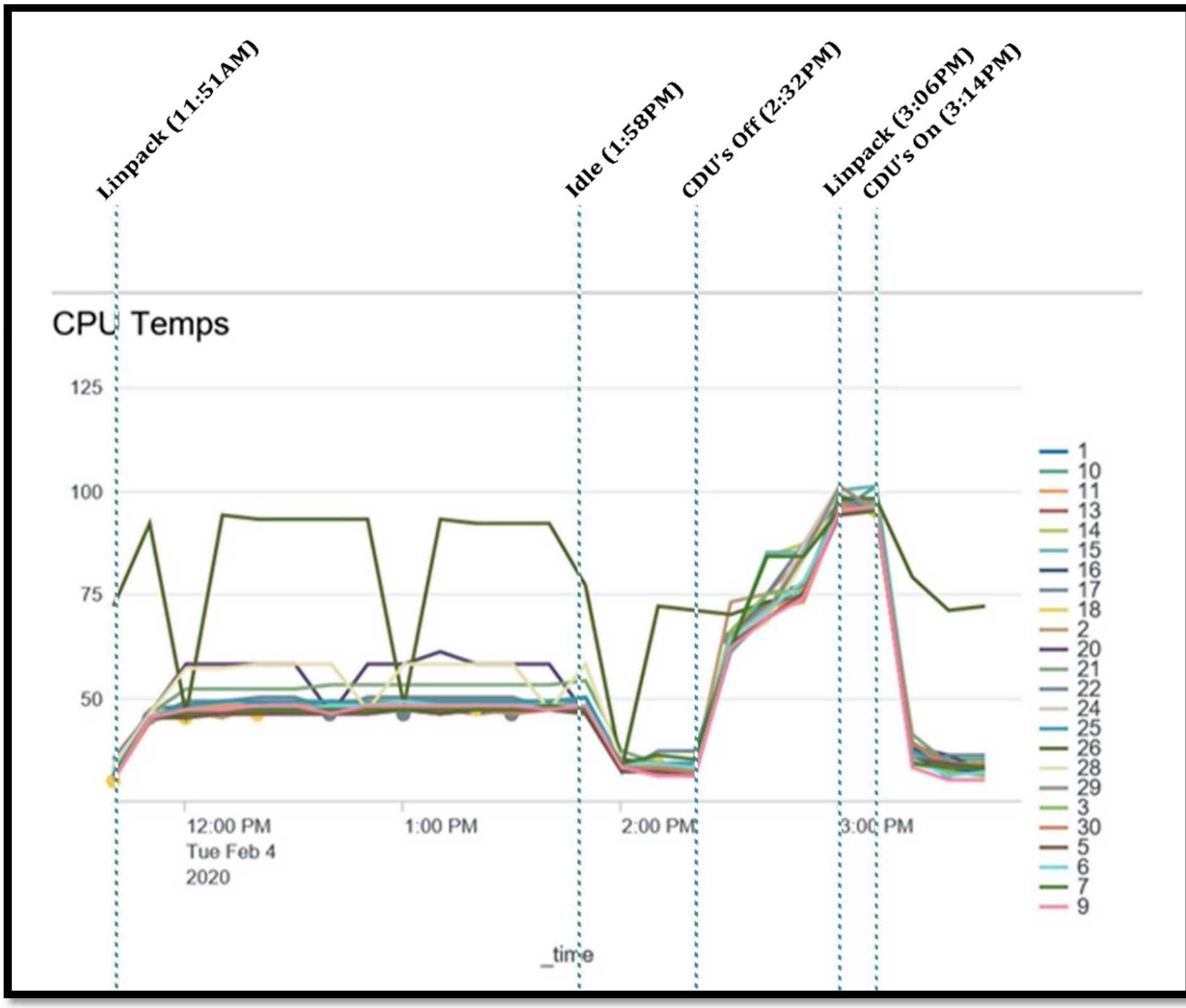


**Figure 13: CPU Temperatures (°C) on Attaway**

In Figure 16, the CPU temperatures can be seen during different test states. When Linpack was started on a normally function system with CDU's on, the CPU's increased in temperature until leveling off around 48°C. The system had a few CPU's that behaved erratically, increasing in temperature more than others, one of which dramatically increased to nearly 100°C.

The few CPU's that operated at a temperature greater than 46°C, reaching temperatures of around 52°C-58°C suggest a lack of cooling due to poor contact between the CPU, the heatsink, and thermal compound joining the two. Other possible causes of high temperatures on these CPU's are miscalibrated temperature sensors or a lack of water flow due to blockage in the lines.

The single CPU which is seen hitting temperatures in excess of 90°C is likely overheating as the result of a similar problem to the other CPU's, but to an exaggerated extent. This CPU has no water-cooling happening and is being cooling by only fans/air-cooling. When Linpack is started at 3:06PM without CDU's, the temperatures of all of the CPU's match that of the single, overheating CPU during the normal test state.

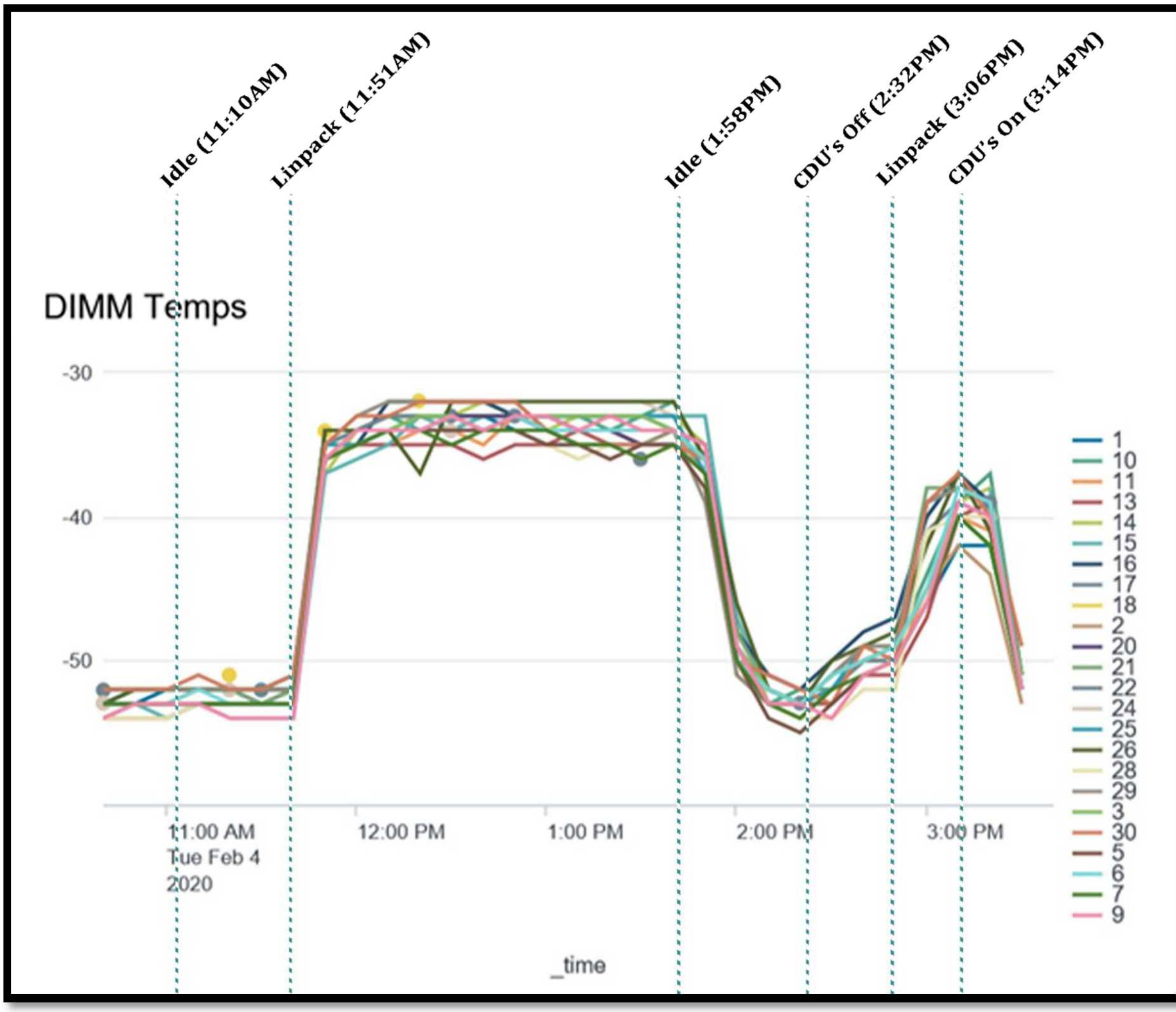


**Figure 14: Memory DIMM Temperatures (°C) on Attaway**

In Figure 14, the DIMM temperatures throughout the testing process can be seen. When Linpack is started, the DIMM's increase in temperature by roughly 20°C. This increase happens very rapidly, and it is important to note the rate of this increase compared to the rate of increase during Linpack while the CDU's are turned off.

When Linpack is started while the CDU's are off, the DIMM's increase in temperature less rapidly than when the CDU's are on. When the CDU's are off, the fans in the compute nodes are spinning at much higher speeds, moving much more air in order to keep the CPU's cool. This additional air movement causes the DIMM's to heat up more slowly and to reach lower peak temperatures. Although the CPU's are operating at much higher temperatures without CDU's, the DIMM's are operating at lower temperatures.

A small increase in DIMM temperature is seen when the CDU's are initially turned off but Linpack is not yet started. While Attaway is idling but the CDU's are turned off, the fans do not need to increase in RPM to reject the additional heat. The heat which would normally be rejected from the CDU to water is now being rejected to air and causing the DIMM's to heat up from the warmer air.

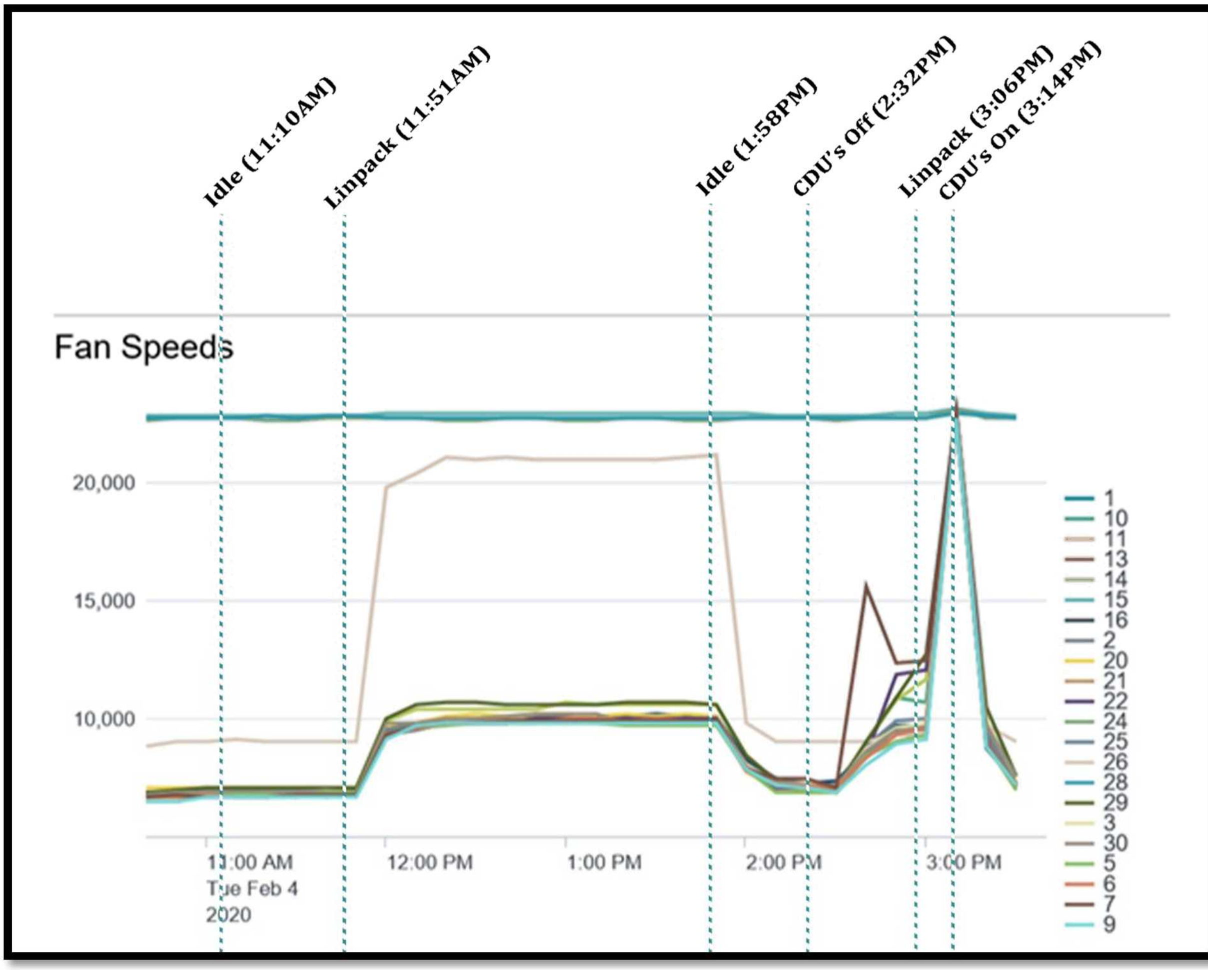


**Figure 15: Fan Speeds in RPM on Attaway**

The fan speeds within the individual nodes of Attaway maintain a steady 7,000RPM while the machine is at idle. When Linpack is started on the machine with the CDU's running, the fans increase in speed up to 10,000 RPM. When Linpack is started on the machine without the CDU's running, the fans quickly increase in speed up to 23,000 RPM to make up for the lack of water-cooling.

In Figure 14, there are two nodes (Nodes 10 and 28) with fans running at 23,000 RPM regardless of which state the machine is in. These two nodes have fans spinning at the max RPM constantly even though from Figure 12 we know that nodes 10 and 28 are at 48°C. This data suggests that there is an issue with the fan control, never reducing the fan speed although the temperature is within the expected range. Node 26 (the tan line at 21,000 RPM during Linpack) also appears to have an issue with fan control since its temperature is within a normal range in Figure 13.

# 4. CONCLUSION

After compiling data from various test states on Attaway it is possible to see how well the Chilldyne cooling systems reacts to system changes. The system is always flowing water, ready for high-heat loads from heavy compute jobs such as Linpack. When the CDU's are shut off during Linpack the fans are able to carry the load but the CPU's run at a much higher temperature, some of which even throttle due to temperature. Although the CPU's throttle, the system is able to continue its compute processes but with an added energy use of 57kW due to added fan energy. This is a large improvement over past water-cooled systems in which a complete shutdown occurs with the loss of water flow.

The fear of utilizing direct liquid cooling on HPC components has reduced over the years. Many question the reliability of direct liquid cooling, being concerned with leakage on system components as well as reliability and redundancy. The Chilldyne negative pressure system has taken liquid cooling to a new, safer stage. The Chilldyne system allows for greater redundancy than seen in other liquid-cooled systems as well as leak-free operation for the past 9 months of operation at SNL.

## REFERENCES


[1] Carter, Thomas, Zan Liu, David Sickinger, Kevin Regimbal, and David Martinez. 2017. “Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Modeling and Installation (NREL/CP-2C00-66690), Presented at the 2017 ASHRAE Winter Conference, Las Vegas, Nevada, January 28–February 1, 2017. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/66690.pdf.

## APPENDIX A. ADDITIONAL FIGURES

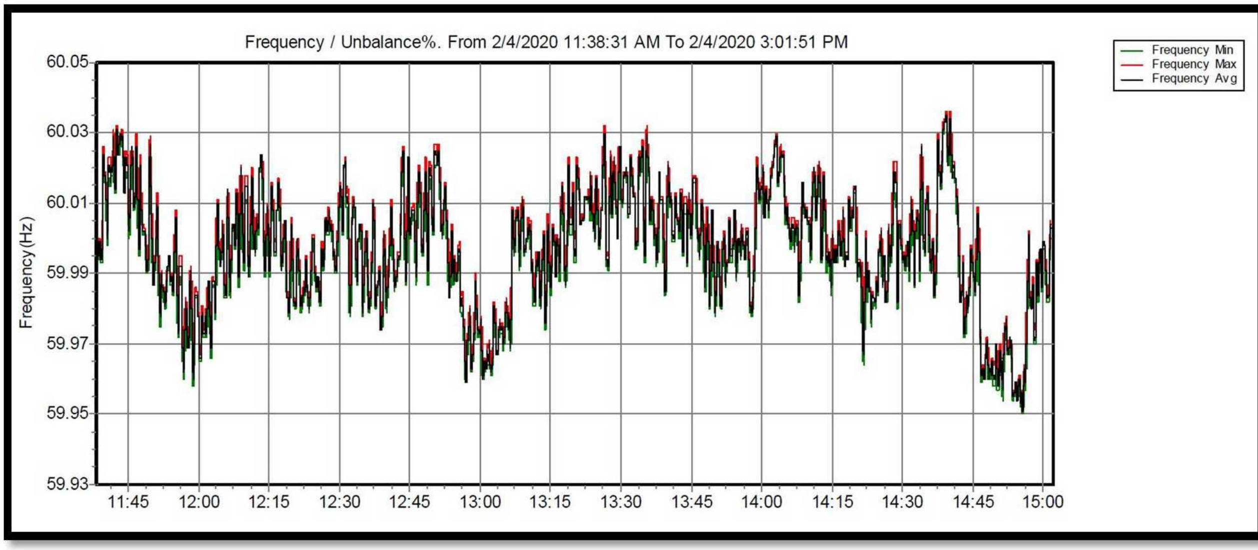


**Figure 16: CDU Power Frequency (Hz)**

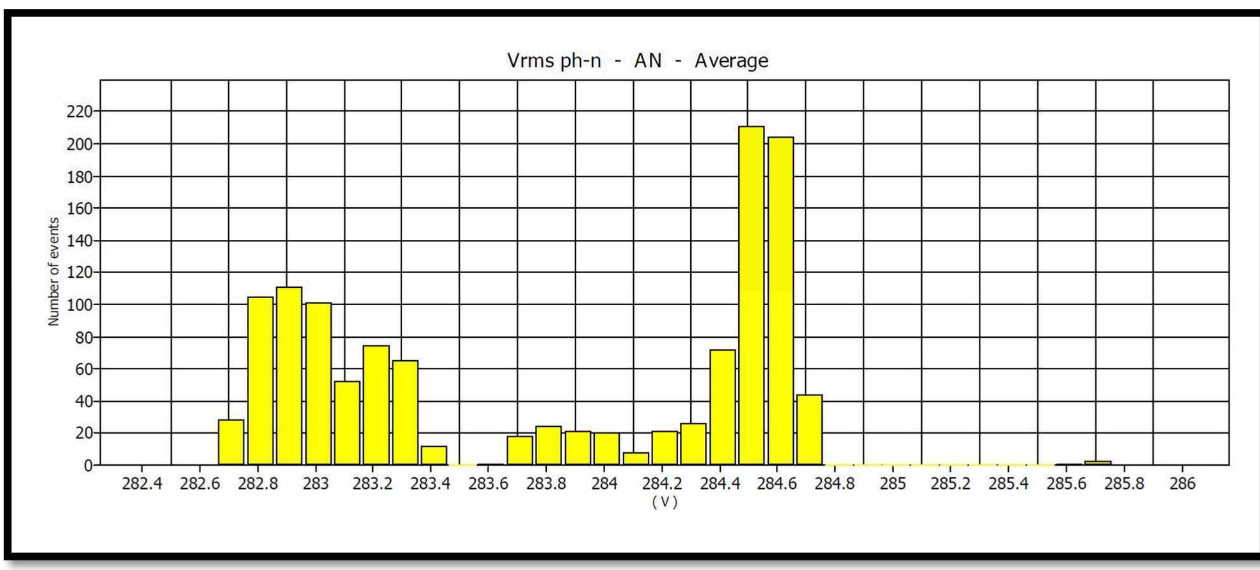


**Figure 17: CDU Average Voltage Readings**

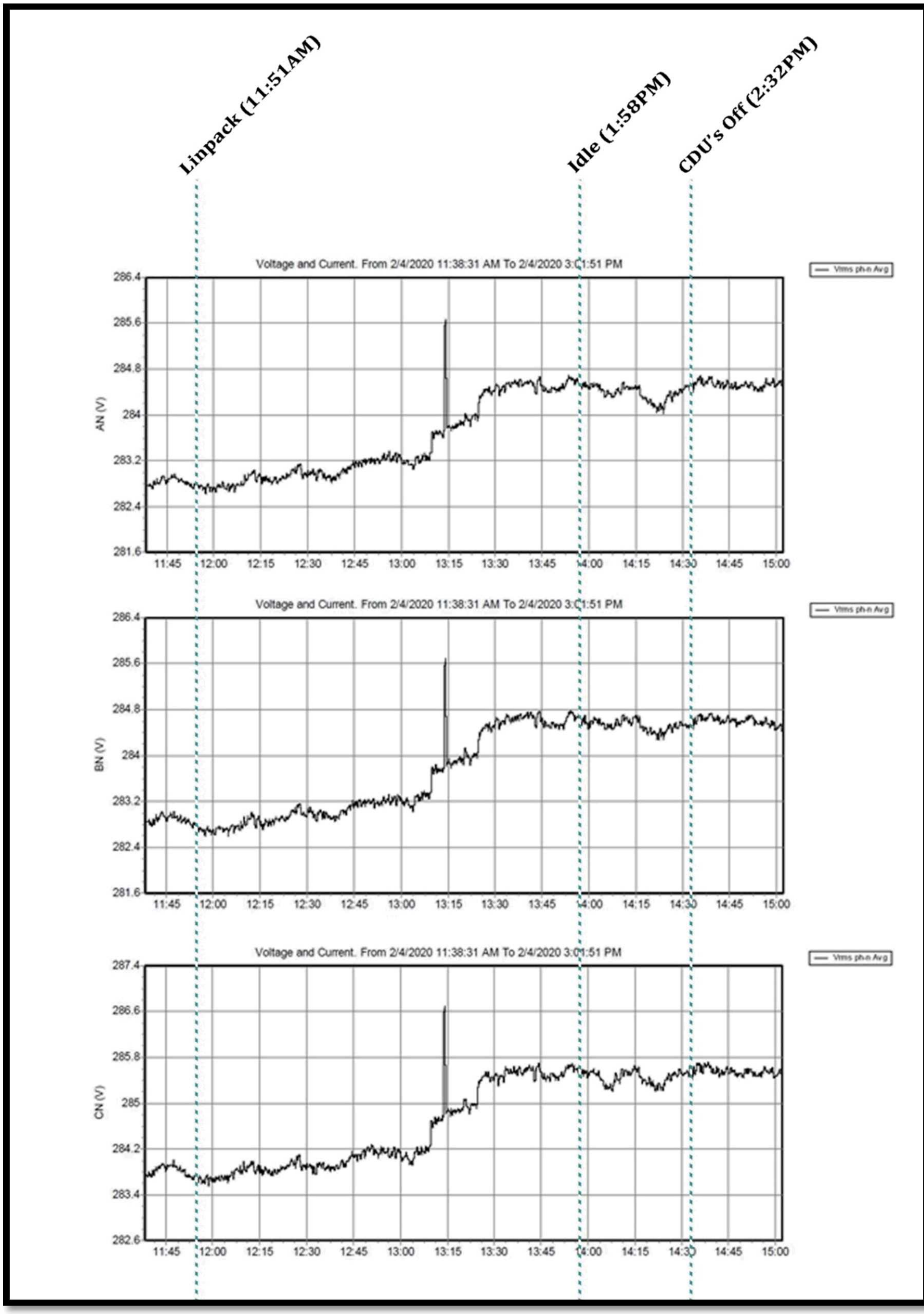


**Figure 18: CDU Voltage on All Phases**

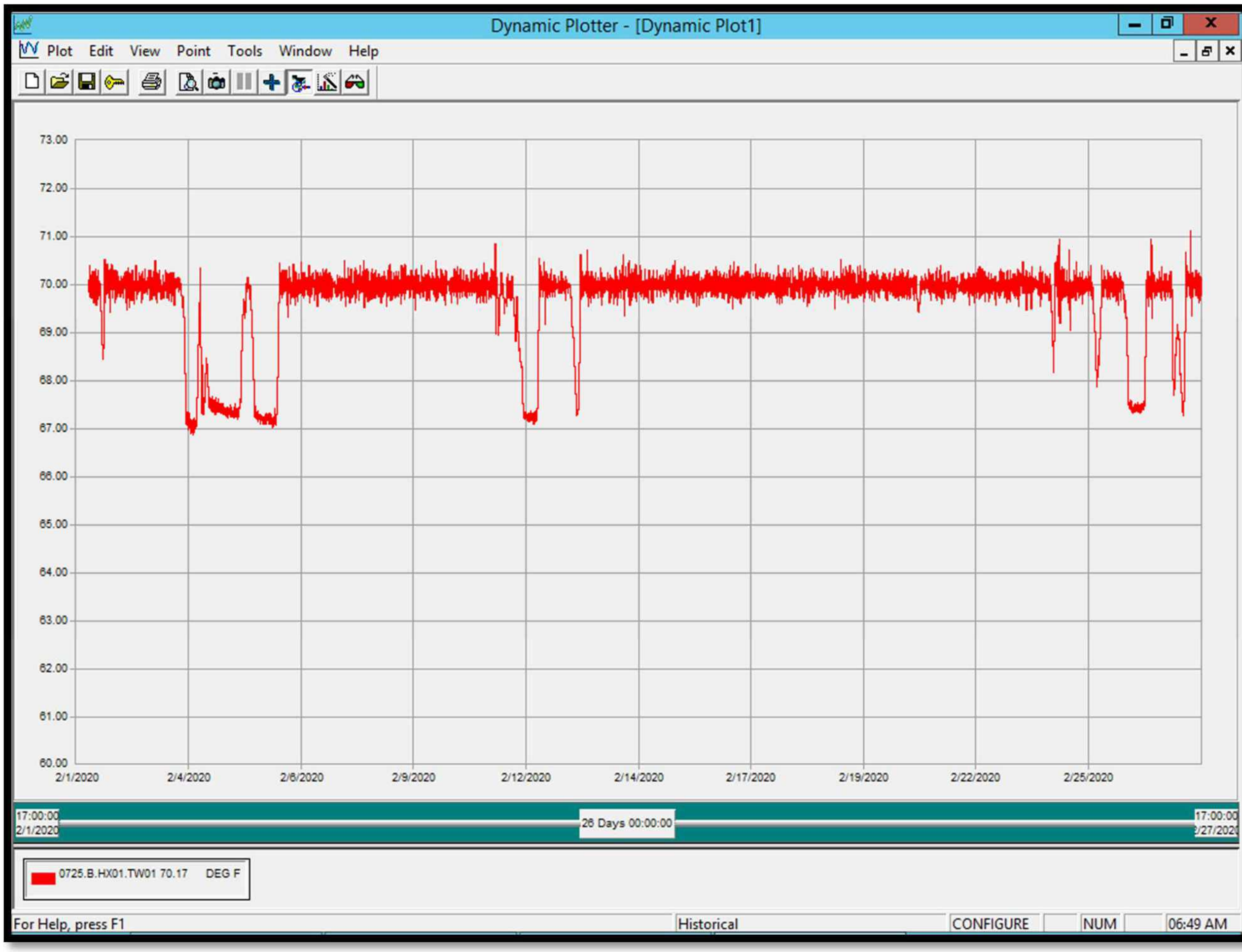


**Figure 19: Chilled Water Temperature (°F) During Month of February**

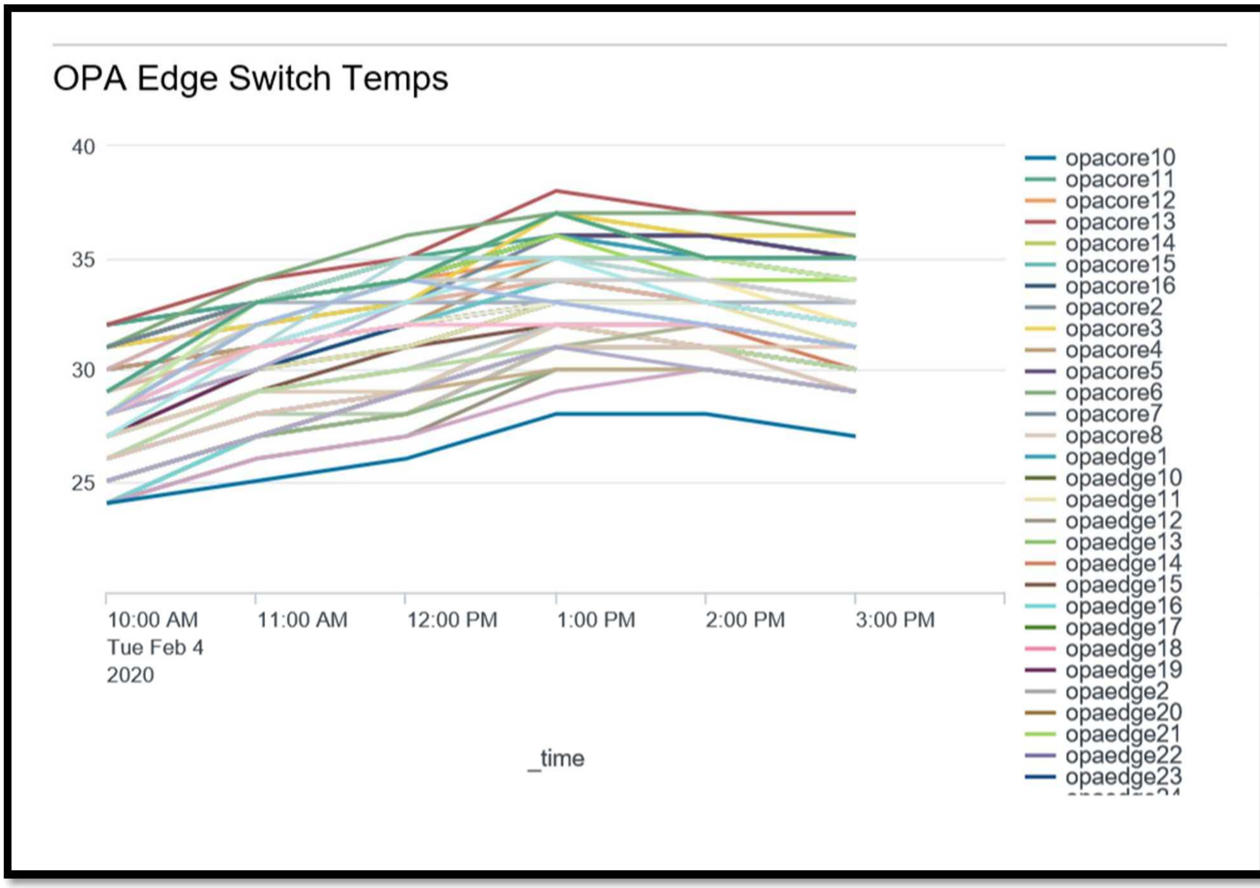


**Figure 20: OPA Switch Temperatures (°C) on Attaway**