CASE STUDY

GREEN REVOLUTION COOLING

The Immersion Cooling Authority®

U.S. AIR FORCE

United States Air Force: Modular Data Center

Small Business Innovation Research (SBIR) AF112-205

Test Plan Developed by:
Air Force Testing Authority

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Background of the Problem

The United States Air Force has a need for a modularize data center which:

- Is capable of being deployed in a wide range of environments and temperatures with minimal modifications.
- Can be deployed rapidly (under 24 hours) with minimal personnel.
- Reduces the overall amount of support equipment required.
- Reduces overall cost of operation and maintain optimum operational environment.
- Increases reliability with reduced maintenance cost.
- Can be remotely monitored and controlled as needed.
- Reduces and minimalizes harsh environmental effects on equipment found in various deployment areas.
- Is viable as a standalone data center or to augment existing data centers.

The suggested technology replaces air conditioning and air-handling infrastructure with a semisealed liquid cooling solution.

Data centers and the information processing capability they deliver are indispensable to warfighting missions. Much of the current generation of Air Force data centers do not meet strict specifications for redundancy (Core Data Center Reference Architecture) and efficiency (AFI 90- 1701, Executive Order 13693). The cost to retrofit existing facilities to meet these requirements is exorbitant, both in terms of dollars and time.

Green Revolution Cooling (GRC), an Austin-based developer and manufacturer of immersion cooling systems which provide high-efficiency and high-performance data centers, aims to produce a commercially viable, fully-integrated modularized data center and cooling solution, called the ICEtank™, for the US Air Force.

The ICEtank uses a proprietary coolant called ElectroSafe™. ElectroSafe is an odorless, non-toxic, single phase coolant that is both electrically and chemically inert. The proprietary blend of high-performance fluids is the result of years of development, testing, and deployments across the globe. ElectroSafe ensures maximum performance and material compatibility, enabling your servers to run efficiently and reliably.

ElectroSafe NFPA 704
Fire Diamond

The benefit to the Air Force will be the capability to deploy cost-effective and expedited data center build-out and expansion. Featuring total immersion of computer equipment in ElectroSafe, the technology replaces air conditioning and air-handling infrastructure with liquid cooling.

Summary of Research

Two modular data centers were designed with feedback from the Air Force, allowing several design optimizations and significant improvements based on field tests.

The Air Force Test Authority created a test plan to verify all stated functionality and energy savings and found the performance was even greater than claimed.

- **100% uptime** for both modular units since installation (now approaching nearly 3 years of cumulative testing.)
- Modularized data centers functioned as expected in both **extreme cold and warm environments.**
- **18.1% less power required to** run servers using off-the-shelf servers commonly used by the Air Force.
- Servers Designed for Immersion (SDI) work **reliably** in ElectroSafe and have increased density and efficiency over air cooled counterparts.
- **93.1% PUE reduction** in cooling power from 1.45 to 1.037.
- **41.4% overall reduction in total power usage** (computers and required cooling.)
- **Power per rack unit increase of 314%** due to ability to operate more compute in denser space.
- **Allowing smaller data center footprint** requirements for the Air Force. One 40ft ISO modul with four immersion cooling racks can provide the same compute as 153 air cooled racks.

Task 1: Definition of Specifications

Task 1.1 Kick-Off Meeting (complete)

Throughout the grant, Air Force and GRC employees have collaborated in taking suggestions and feedback to address issues or concerns and make the most relevant product to fulfill the mission for the USAF.

Task 1.2 Detailed Design Specification (complete)

Cooling performance was specified with a maximum heat rejection; each specification was based upon a certain environmental condition. The testing at Hill proved even greater capacity than specified due to conservative modeling.

Environmental Resilience: The ICEtank ("C3") is expected to remain operational in extreme environmental conditions. GRC will quantify operating and storage temperatures, as shown in later testing; performance was verified.

GRC designed two different versions of specifications. C3 One (Hill AFB) and C3 Two (Tinker AFB) The specifications vary in the following ways:

- Number of racks per module (2-4)
- Final Heat Rejection Method - cooling tower (C3 One) vs dry cooler (C3 Two)
- Heat exchanger redundancy

The second unit (C3 Two) with a dry cooler has the advantage of greater range of extreme cold environmental operational temperatures: with the ability to run between – 40 F and 95 F with minimal changes.

- Lower maintenance, higher reliability: with fewer components, the systems are less likely to fail.
- Faster installation time: deployed at any location and setup in less than one day. The net result is a design which will enable the Air Force even greater flexibility and speed during deployment.
- The lowest installation cost of any modularized data center.
- Highest efficiency of any product made by GRC.
- Advanced remote monitoring and controls
- The second unit delivered will also be the first data center to achieve high efficiency
- (PUE <1.25) with **zero** water usage and without any requirement for a chiller.

Task 1.3 Code Compliance (Complete)

While code compliance does not apply to non-permanent buildings, GRC engaged code compliance engineers to design the module to meet code: including electrical system design, OSHA guidelines for ingress and egress, and mechanical ergonomics.

Task 2 Design

Task 2.2 CAD Work and Layout (Complete)

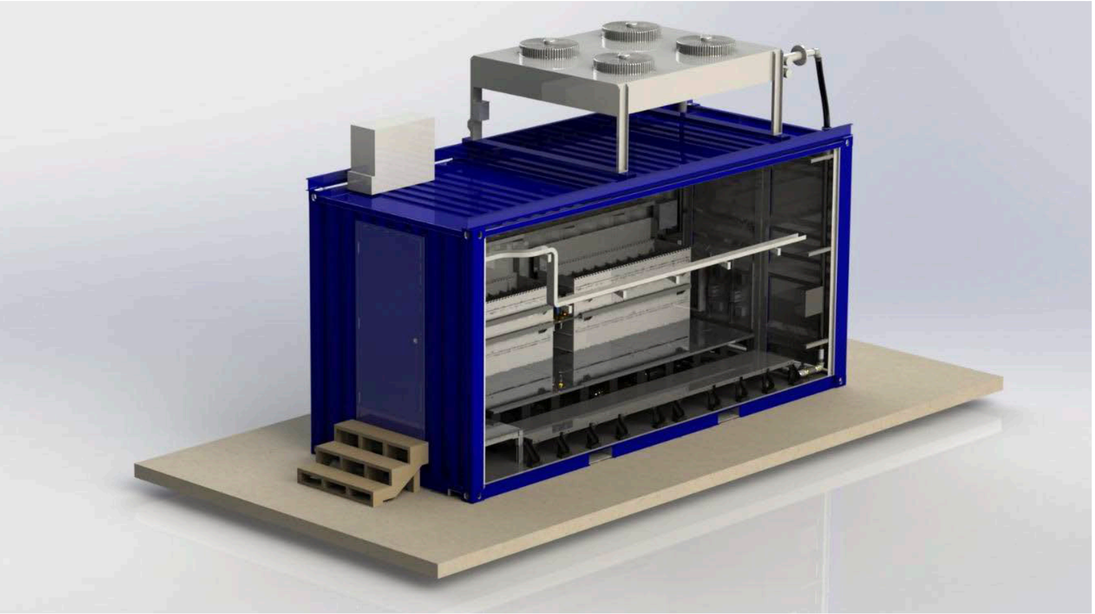

Image 1: (C3 Two – Tinker)

Task 2.3 ICEtank Integration (Complete)

GRC previously manufactured low-profile CDUs (Coolant Distribution Units) with a custom floor for use in raised floor environments, using the same concept, most of the supporting infrastructure was placed underneath the walking surface (See Image 1). The design focused on making the structure possible to securely ship, while being a quick and repeatable manufacturing process.

Image 2: (C3 Two – Tinker)

Task 2.4 Stress Analysis (Complete)

The modules and micro-modular racks were designed to handle a seismic event, suitable for installation in seismic zones such as California.

Task 2.5 Connection Integration (Complete)

The module is designed for expedient installation, including making the necessary external connections: electrical, network, and water/drain. All electrical infrastructure downstream of the exterior cutoff is prewired, making for a plug-and-play installation. The only electrical connections required on site is wiring to the external cut off (arching conduit to the large box mounted on face on module) (See Image 2). Network connections are passed through the front wall.

In the module at Hill (C3 One), water and drain connections were made through the floor for secure water use and freeze prevention. The C3 Two modules, with a dry cooler, has fewer connection requirements by not requiring a drain or water supply.

Task 2.6 Safety and Fire Detection (Complete)

GRC used the expertise of fire and code compliance professionals to create a safe environment. 2N redundant fire detection alerts both GRC and a local relay system. Various floors were tested to find a surface that maintains a safe, non-slip surface regardless of fluid being present. All lights are motion detecting and if power is lost, the exit sign and an emergency light illuminates the exit path to an easy egress path.

Task 2.7 Lift Mechanism (Complete)

A two-axis electric crane integrated into the module makes maintenance of the servers quick and easy. The crane is mounted onto the ceiling, allowing for full clearance when lifting servers. The hook (triangular bar) connects a server to the hoist where it can be lifted with a button push. This allows any size or weight of server to be used in the system without the need to be fully supported by personnel (See Image 3).

Image 3: (C3 Two – Tinker (Similar to C3 One – Hill)

Task 2.8 Cooling Tower (Complete)

A cooling tower and dry cooler model have been designed, constructed, and installed; both have advantages and disadvantages.

The cooling tower used in C3 One was designed to handle extreme temperature and has insulation, line heaters and an indoor storage tank. Early designs had minimum temperature of 10° F, final design can handle as low at -4° F. The cooling towers must also be able to perform reliably in extremely hot conditions, handling maximum expected temperatures, not just in Utah, but most any environment in the world.

GRC developed controls which previously did not exist in the market to fully automate and monitor the datacenter in a reliable manner. Most cooling towers rely on a traditional method of using a float valve which is prone to breakage. The design was changed to use an electronic water level sensor, fed into a control computer to monitors levels and activates a solenoid automatically to refill the tower when needed. In the event of electronic failure, a redundant analog system prevents overflow. A pressure regulator at the module input sets the pressure to a consistent level. This allows a range of supply pressures to be connected safely without concern of connection availability.

Image 4: (C3 One – Hill)

Task 3: Fabrication

Two modules were fabricated; small design changes to the second module resulted in dramatic improvements in assembly time. Overall, assembly time was reduced by nearly 60%. Pieces were designed to be pre-assembled, then installed within the module.

Task 4: Testing and Installation

4.1: C3 One (Hill AFB) Functional Testing (Complete)

While GRC had existing quality control and testing for the standard rack and pump module, new functional testing procedures were developed for the new product to detect any quality control issues before leaving the manufacturing area. Before shipping, all pressure, temperature, voltage, current, etc. sensors are tested for accuracy and an operating test completed. Due to the advanced monitoring system, the multitude of sensors allow diagnostics of the system's functionality.

4.2 Installation of C3 One (Hill AFB) at DoD Facility (Complete)

The unit was shipped on a standard flatbed truck with an ancillary load of exterior insulation panels. It had some nonstandard sized items that were at risk for shipping damage. Module Two addressed these deficiencies by simplifying the design.

4.3 C3 One (Hill AFB) Operational Testing

A battery of tests were developed by the Air Force Testing Authority to definitively test specifications and energy savings. A brief summary of findings:

- Extreme cold testing: tests the insulation, automatic heating elements and remote water sump can successfully operate in the winter environment on Ogden, UT. Operated successfully at 2 F.
- Hot weather testing: a module is rated for a specific heat rejection (kW) at a certain environmental condition. The validation test confirms the capacity. The module surpassed design specifications on heat rejection capability. At a world record temperature of 33.4° C WB the system is calculated to maintain a coolant temperature of 48.3° C; an acceptable temperature for liquid immersion.
- Electrical System Verification: the electrical system verification tested maximum loads of pumps and fans operating simultaneously. All systems operated without issue.
- Server efficiency: a server in air datacenter ran a software test using Linpack and its power use measured. The exact same server had its fans removed and immersed in the module's racks, ran the software test again using Linpack and its power use measured. Power usage decreased 7.2% on stress test, 18.1% less power in Air Force application.
- Cooling system efficiency: the average PUE of the module was measured at 1.037. The reduction in server power for the same server in ElectroSafe as compared to servers in air used 41.4% less total power compared to HEDC datacenter with a PUE of 1.45.
- SDI (Servers Designed for Immersion): these purpose built servers are designed without spacing for fans or air flow shrouds and eliminate the typical server case, allowing denser configurations reducing capital costs. A 40 x 8ft module with eight racks of SDIs can compute the equivalent of 153 racks of air-cooled servers, currently in use. Running the same computing task with existing servers and infrastructure would use 6.5x the power as what is consumed using SDIs in the module.

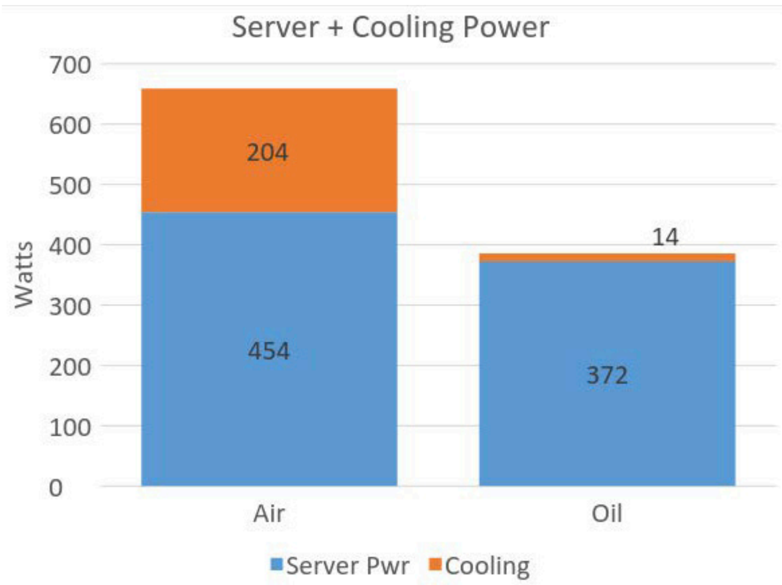

Figure 1: Server Power vs. Cooling Power (More details in appendix)

4.4 C3 Two (Tinker AFB): Functional Testing

The C3 two was functionally tested at GRC Headquarters. Due to the simpler system, and reduced part count, the quality control became easier. A new brand of PDUs were tested providing higher functionality including remote shutoff; useful to cut power if the temperature becomes too hot.

4.5 C3 Two (Tinker AFB): Installation and Operational Testing at DoD Facility

The module, final heat rejection, and ElectroSafe coolant was transported on a standard flatbed truck with no shipping damage.

Due to improvement in the design, the amount of time spent to install the module onsite was reduced by more than 90%+. In total, the unit installation at Tinker took a single person less than 20 man-hours total. The unit has had 100% uptime since installation.

Image 5: C3 Two - Tinker

In Summary:

These initial two ICEtank Data Centers have allowed for many design improvements to create the most automated, efficient, easy to transport and low cost modular data center. The improvements made between the two units provided dramatic improvements in simplicity, assembly time, and aesthetic appearance.

These improvements should also help with deployment within the Air Force. Without external insulation and with significantly reduced infrastructure on the roof, the unit can be transported just like any standard 40 ft. ISO container.

Image 6: Shipping the C3 Two using standard methods designed for ISO container movement.

Future Research:

The research and engineering done for the first two modules showed great progress towards making a viable production unit for the Air Force. Both modules are functional, but additional research is needed to make the unit as robust and fully featured as the Air Force would need for a production unit. Research topics for the third module include:

- Increased reliability of the cooling system and increasing environment operating range while increasing redundancy
- Easier to maintain, including research to reduce water usage and treatment requirements.
- Improved manufacturing, further modularizing the manufacturing to increase output speed and quality.
- Reduced assembly time at destination with a target of one day installation
- Easier shipping logistics with all components on ISO skid
- Integration of UPS for servers to allow simplified servers and less redundant electrical infrastructure for same level of resilience.
- Integration of a fire suppression system
- Increase reliability and functionality of monitoring system

Appendix – Testing Results of C3 One (Hill)

This attachment may be read standalone; more details on testing methods detailed in main section.

Objective 1.1: Verify Functionality at Extreme Temperatures

1.1A Cold Temperature Testing

Metric: To avoid pipe freezing during expected winters, water temperatures must maintain at least 19.6° C higher than ambient temperature, with a 10kW or higher heat load, on the coldest day (-16.2° C dry bulb (DB)).

Result: PASSED. The lowest ambient temperature recorded was -16.7° C, and the corresponding water pipe temperature was 36° C higher, better than required 19.6 °C delta. The ICEtank remained functional and no damaged occurred.

Details: The ICEtank's specification states no freezing will occur at -16.2° C with a minimum 10kW load. Testing with less than 10kW indicates a better than specified performance. The coldest temperature recorded for this test was on 01 January 2016: -16.7° C. The heat load was 2.6kW, 74% lower than the specified 10kW. The lowest temperature recorded on the water piping was 19.3° C, a 36.0° C delta. The test results were that the ICEtank remained functional with no damage occurring.

Time	1/1/2016 7:53
Ambient (°C)	-16.7
Basin Temp (°C)	27.2
Exterior Water Line (°C)	19.3
Heat Exchanger Output (°C)	28.3
Minimum Delta (°C)	36.0
Heat Load (W)	2600

Table 1: C3 One Cold Temp Testing Results

1.1B High Temperature Testing:

Metric: Ensure system equivalently meets performance specification of 45° C (max) ElectroSafe temperature at 20° C peak wet bulb (WB). Performance is only attainable with cooling towers, heat exchangers, and entire system working in tandem. Therefore, all systems must function well for test to pass.

Result: PASSED. The ICEtank performs at or better than specification.

Details: A 20 °C wet bulb is an extreme condition for the region of Ogden, UT and has not yet been reached this year. Hence, performance data from lower wet bulb temperatures and 25kW load was used to calibrate models to extrapolate performance at 20° C WB and 50kW as per specification. Wet bulb is based on temperature achieved after evaporation and is the temperature relevant to cooling towers. ASHRAE1 developed the model to correlate heat load to cooling tower performance with resulting water temperatures. Water temperature data, along with varying wet bulb metrics were recorded with this system at 25kW and showed a linear relationship which can be extrapolated to 20° C WB. The model correlated performance at 50kW load to data at 25 kW. Using the model, performance is better than required to meet specifications.

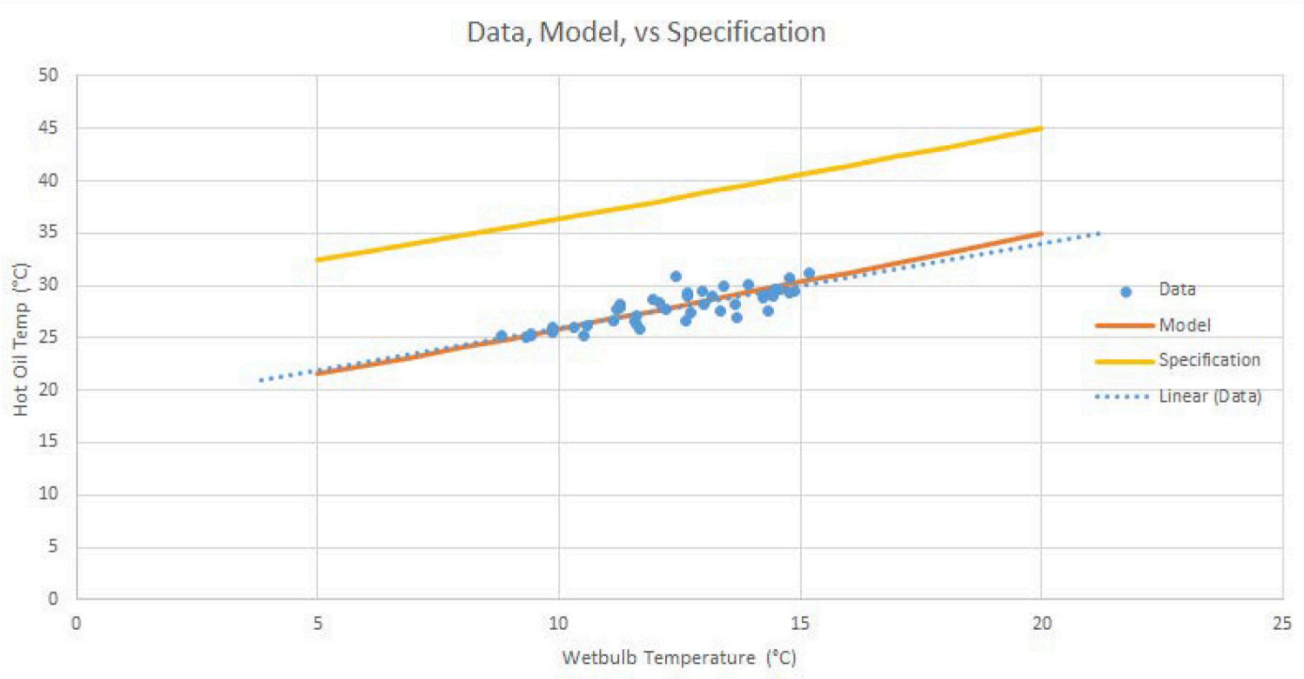

Figure 1: C3 One Hot Temp Testing Results

1.2 Electrical System Verification:

Metric: Breakers must not trip under max load.

Result: PASSED. No breakers tripped during the test. Remote monitoring alerts received upon PDU overloading.

Details: The purpose of this test was to ensure functionality of the ICEtank's electrical systems at maximum electrical load. Without enough resistive elements to test the entire system at 100% load, the test was conducted one immersion rack at a time. The metrics for this test were a pass/fail based on breakers tripping or not using the following procedures:

- Connect all available heating elements into a single rack, loading the Power Distribution Units (PDU) between 80-100% of breaker rating.
- For each PDU branch, balance phases within +/- 2A, as is common practice.
- Distribute heating elements to ensure at least 25 kW of heat, the maximum rack rating.
- Record electrical loads using meters in PDU.
- Switch load to other PDU electrical feeds. Run for at least 4 hours.

[1] Schwedler, Mick. 2014. Effect of Heat Rejection Load and Wet Bulb on Cooling Tower Performance. ASHRAE Journal, 2014, pp16

The ICEtank's CDU, and evaporative cooling tower ran at 100% capacity while overloading the PDU to test if the breakers would trip.

Breaker	Breaker size (amps)	80% of breaker per NEC (amps)	Peak amps measured at max possible load
PDUs	60	48	52.3-53.9 (measured per phase)
Primary CT Fan and Pump	20	16	16.6*
Secondary CT Fan and Pump	20	16	17.1*
Primary Coolant Pump	15	11.25	9.0
Secondary Coolant Pump	15	11.25	5.8

*Peak only possible with manual control. Automatic control maxes at fewer amps than 80% rating.

Table 2: C3 One Electrical Testing Results

2.1 Server Efficiency

Metric: Server must use equal or less power per computation cycle immersed in ElectroSafe as compared to air.

Result: PASSED. Servers use 18.1% less power.

Details: Initially, several air-cooled servers were to be tested to compare immersion to air. However, preliminary measurements show server power varies significantly between adjacent servers.

	Power (watts)
Air-Cooled Server #1 in Air at Idle	454
Air-Cooled Server #2 in Air at Idle	480
Air-Cooled Server #3 in Air running production load	446

Table 3: C3 One Power use Test Results

With this discrepancy in mind, power measurements were taken from an air-cooled server; then the exact same server was modified (remove fans and thermal paste) for immersion in ElectroSafe and retested in same manner. The same "Wattsup" power meter is connected to the same power strip connected to the same power supplies in the same server running the same program; only difference is the cooling environment.

According to Air Force staff, the servers are programmed to maintain CPU readiness and therefore idle power is not minimized. A server used in Air Force production was measured and its power is approximately the same at idle. The measured power savings at idle will be representative of savings from converting the current datacenter.

The important metric is power per computational cycle and not just power usage, the software Linpack was used to calibrate computational speed. Linpack was run with the following configuration/settings; NB: 128, N 16,384. The problem required approximately 500 seconds to run. Computational speed in air vs immersion was equal within 0.2% so the computational speed is not affected per cooling type. Typically, computational speed is unchanged except for overclocking scenarios. Power savings identified Linpack represent a reduction in peak power, which can be used to downsize electrical infrastructure.

The power usage difference was especially significant at idle as fan power is a higher percentage of total power at low loads. Most data centers operate at near idle, the majority of time.	Air (W)	Dielectric Fluid (W)	Difference (W)	Difference (%)
Idle	454.4	372.1	-82.3	-18.1%
Linpack	697.4	647.3	-50.1	-7.2%

Table 4: C3 One Electrical Testing Results

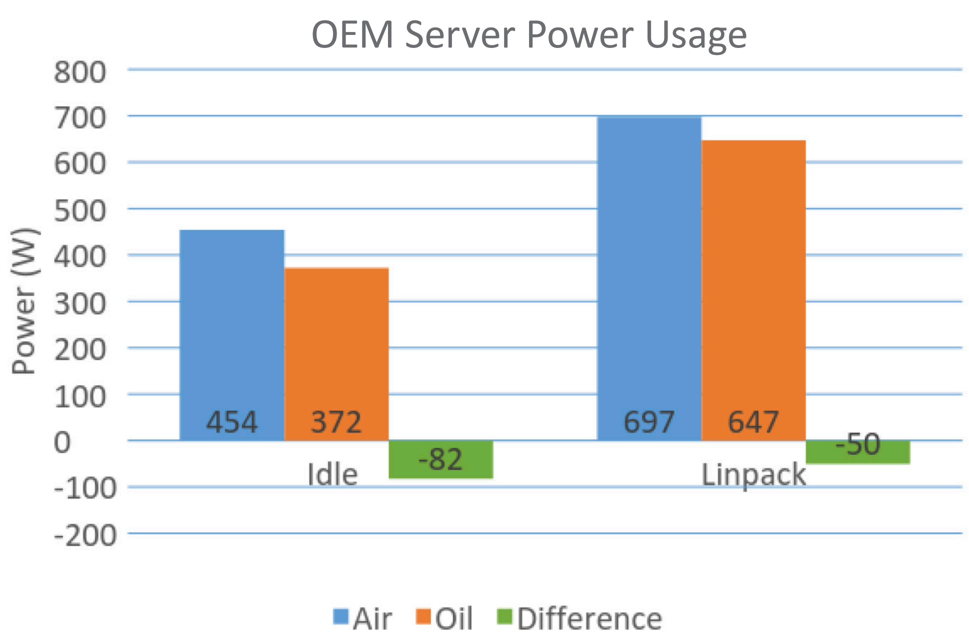

Figure 2: C3 One Power Usage Test Results

2.2 Module Cooling Efficiency

Metric: Cooling system must have a Power Utilization Effectiveness (PUE) of 1.15 or lower.

Result: PASSED. 93.1% reduction in cooling power from 1.45 PUE to a measured PUE of 1.037.

Details: Total cooling power usage includes CDU (including control computer, coolant pump, water pump) and cooling tower. Power measurements were taken over a 24-hour period than averaged.

Load	Average Power (W)watts
Control Computers	50
Coolant Pump	398
Water Pump	276
Cooling Tower	233
Total Cooling Power (sum of controls, fan, pumps)	958
IT Load	25687
PUE	1.037

Table 5: C3 One Power Consumption

2.3 Total Power Usage

Metric: Reduce total power.

Result: PASSED. Total power savings of 41.4% compared to same server in current datacenter.

Details: The reduction in server power and the low PUE combine to form the most important metric - total power usage. Total power usage was reduced by 41.4% compared to the air cooled datacenter; the total power usage is found by multiplying PUE by the individual server power.

	Air (W)	Oil (W)	Δ (W)	Δ (%)	Equation
Server Power	454	372	-82	-18.1%	Measured (low utilization)
Cooling Power	204	14	-191	-93.2%	Measured: Server Power * (PUE-1)
PUE	1.45	1.037			(Cooling Power + Server Power)/Server Power
Total Power	659	386	**-273**	**-41.4%**	Server Power * PUE

Table 6: C3 One Total Power Usage

* An immersion-cooled server plus cooling power is less than the air-cooled server alone.

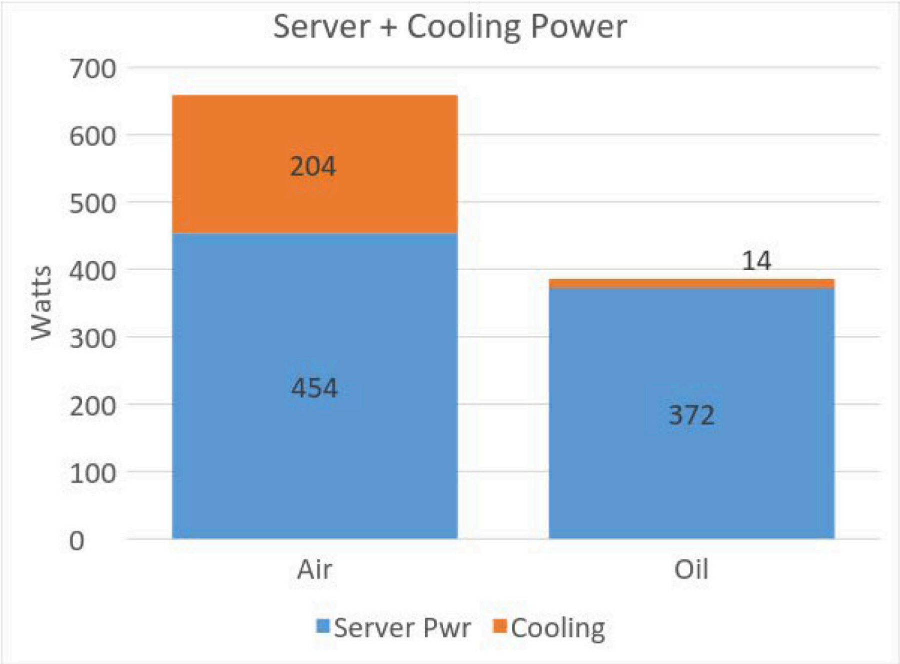

Figure 3: C3 One Server vs. Cooling Power

Addendum A - SDI Testing

Servers Designed for Immersion (SDIs) were chosen to reduce purchase price through eliminating the need for fans or a complicated chassis. Removing the unnecessary air components, the servers can be made denser, using less data center space for the same computational power.

New servers have more computational power in many metrics; they are packaged tighter, taking up less space and increasing rack density. The processing speed is increased per component, and the power to complete a computation is reduced.

Server Model	Immersed OEM vs. SDI	Immersed OEM	SDI	OEM in Air	OEM in Air vs. SDI
Space (U)	-88%	4	0.5	4	-88%
Linpack (W)	-44%	647	361	697	-48%
Idle (W)	-73%	372	99	454	-78%
FLOPS	139%	298	712	298	139%
Power/U	346%	162	722	174	314%
FLOPS/U	1811%	75	1,424	75	1811%
W/FLOP	-77%	2.17	0.51	2.34	-78%
Power/ 42U Rack	346%	6,794	30,324	7,319	314%
PUE	0%	1.04	1.04	1.45	-28%
Total: PUE* W/FLOPS	-77%	2.3	.53	3.4	**-84%**

Table 7: C3 One Immersion vs. Air Comparison of Servers

The power per U increased 314% so a 42U using the old servers would reject 7.3kW, SDIs will reject 30.3kW. With the increase in Power/U, new methods of cooling are necessary. The density of the new servers surpasses air cooling capabilities.

With increase in Floating Point Operations/Unit (FLOPS/U), the datacenter can become smaller. For the same task, modular data centers could provide equivalent computational power as large data centers have provided. To complete an equivalent task, the SDI servers require **1811% less space (i.e. air-cooled servers use 19 times the space). A 40 x 8ft module with 8 racks of SDIs can compute the equivalent of 153 racks of air-cooled servers, currently in use.**

With the increase in efficiency, Floating Point Operations per second/Watt (FLOPS/W), the total power to compute a task is reduced. As the SDI do not come with fans to reduce purchase price, they cannot be run outside of an immersed environment and therefore cannot test the same air vs immersion comparison. The OEM server demonstrated an 18.1% decrease in idle power, when immersed. Idle power of an SDI compared to the OEM server in air was reduced by 78%.

The efficiency upgrade by using the SDI in ElectroSafe compared to the the OEM server in air is significant. To compute the same task, the **SDI require 78% less energy** than the the OEM server in air.

Tying all the efficiency components together; the air-cooled server running in standard infrastructure will use 3.4W/FLOPS, an SDI in the immersion datacenter used 0.5W/FLOPS. Changing from the air-cooled data center using the existing server to SDI in ElectroSafe will use **84% less power (i.e. 6.5x the power for the OEM servers)** for the same compute.

Glossary

ICEtank: Liquid immersion cooling system for servers designed and manufactured by GRC.

C3: ICEtank (C3-one is at Hill AFB; C3-two is at Tinker AFB) ISO compliant

COTS: Commercial Off the Shelf. Standard servers designed for air-cooling that may be optimized for immersion.

DELTA: Difference between two things. E.g. the delta between 12 and 18 is 6.

ElectroSafe: GRC's proprietary coolant. ElectroSafe is an odorless, non-toxic, single phase coolant that is both electrically and chemically inert. The proprietary blend of high-performance fluids is the result of years of development, testing, and deployments across the globe. ElectroSafe ensures maximum performance and material compatibility, enabling your servers to run efficiently and reliably.

DRY-BULB: (DB) Ambient temperature, our normal understanding of temperature. Traditionally measured by expansion of mercury. Assume a temperature implies dry-bulb unless noted.

FLOPS: Floating-point operations per second is the number of operations the computer can execute. The most common measure of computational output.

HEDC: Hill Enterprise Data Center. The reference data center.

LINPACK: The most common benchmarking software to measure FLOPS. It measures how fast a computer solves a dense n by n system of linear equations Ax = b, which is a common task in engineering. Scores consistently when programmed the same but typically ran multiple times to ensure caching does not affect performance.

PDU: Power Distribution Unit. A big power strip that may have power metering capability.

PUE: Power Usage Effectiveness: Anything that isn't considered a computing device in a data center (i.e. lighting, cooling, etc.) falls into the category of facility energy consumption. PUE= (IT Equipment Energy + Facility Energy)/ IT Equipment Energy. PUE can be misleading: reducing energy use of a server while keeping the same cooling power calculates to a worse PUE, even though total energy use is lessened. The average PUE of US datacenters is 1.73, HEDC 1.45, GRC ICEtank 1.037, ideal PUE is 1.0.

SDI: Server Designed for Immersion (sometimes referred to as Built for Immersion)

WET-BULB: (WB) Coldest temperature reached by evaporation. Most relevant temperature to cooling towers. WB=DB at 100% humidity. WB is lower than DB at less than 100% humidity. Traditionally measured by measuring a wet temperature probe with air moving across it.

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