Improved Efficiency & Reliability for Data Center Servers Using Immersion Cooling Technology

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DfR Solutions Webinar
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Agenda

- Immersion Cooling Technology Overview
  - News & Competition
- Technology Benefits
- Technology Challenges
- Reliability Opportunities
- Summary
Liquid Immersion Cooling

- Not a new concept!
  - Direct liquid immersion cooling has been used within IBM for over 20 years to cool high powered chips
  - Early supercomputers relied on liquid cooling technologies
    - Cray 2 supercomputer

http://www.electronics-cooling.com/1996/05/direct-liquid-immersion-cooling-for-high-power-density-microelectronics/
### Why Immersion Cooling?

#### TABLE 1. Thermal conductivity and heat capacity of common substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>Thermal Conductivity, ( W/(m \cdot ^\circ C) ) at 25°C</th>
<th>Specific Heat ( (C_p) ), J/(g \cdot ^\circ C)</th>
<th>Volumetric Heat Capacity ( (C_v) ), J/(cm³ \cdot ^\circ C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.024</td>
<td>1</td>
<td>0.001297</td>
</tr>
<tr>
<td>Water</td>
<td>0.58</td>
<td>4.20</td>
<td>4.20</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>0.138</td>
<td>1.67</td>
<td>1.34</td>
</tr>
<tr>
<td>Aluminum</td>
<td>205</td>
<td>0.91</td>
<td>2.42</td>
</tr>
<tr>
<td>Copper</td>
<td>401</td>
<td>0.39</td>
<td>3.45</td>
</tr>
</tbody>
</table>

#### TABLE 2. Power usage for air-cooled versus immersion-cooled data centers

<table>
<thead>
<tr>
<th>Method of Cooling</th>
<th>Power Required to Move 1W of Waste Heat into Chilled Water Loop (W)</th>
<th>Percentage of Technical Load to Power Fan or Pump (at 100%)</th>
<th>Percentage of Technical Load to Power Fan or Pump (at 200%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan-Powered Air</td>
<td>0.13 W</td>
<td>13%</td>
<td>26%</td>
</tr>
<tr>
<td>Pump-Powered Oil Immersion</td>
<td>0.025 W</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>Net savings due to fan removal</td>
<td></td>
<td>10.5%</td>
<td>21%</td>
</tr>
</tbody>
</table>
Single Phase & Two Phase Immersion Cooling Tech

Single-phase immersion cooling
- Oil remains in the liquid phase throughout the cooling cycle

Two-phase immersion cooling
- Cooling liquid is boiled off
- Vapor is captured & condensed before being recirculated
- Phase change from liquid to gas allows for higher heat removal
  - Adds to the complexity
  - Liquid used in two-phase systems costs more than mineral oil
Single Phase: Cooling Using Dielectric Oil

More effective at removing heat than air

Oil costs ~$500 per 55 gallon barrel
Two-Phase: Cooling Using Engineered Fluids

- **3M Novec**
  - Two-phase immersion cooling technology
    - Reduce water consumption and energy use
    - Increase **supercomputer** efficiency
    - Used in fire extinguishing equipment also

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http://solutions.3m.com/wps/portal/3M/en_US/NA-DataCenters/DataCenters/AboutUs/3MInovation/
Tanks can dissipate 40kW of power or more
Immersion Cooling Technology Maturing

- Researchers helped lead the way
  - CERN
  - University of Leeds

- Reaching a more mature level
  - Demands of large, web-scale and cloud operations creating a new market for server & rack-level cooling solutions

Liquid cooling in the rack at CERN

http://www.datacenterdynamics.com/focus/archive/2013/06/viscosity-liquid-cooling&u=2911
Liquid Immersion Cooling Example

- Liquid Submersion Blade Server
  - LiquidCool Solutions
  - Supports High Frequency Trading with Liquid Submersion Cooled Computers
  - Released in 2010
- 2012: World’s 1st **rack-mounted**
  total liquid submerged server

http://www.liquidcoolingsolutions.com/
Liquid-Cooled Supercomputers: Trim the Power Bill

- Prototype supercomputer @ Tokyo Institute of Tech submerged in tank of mineral oil
  - Named in Nov ‘14 in Green500 as the most energy-efficient machine of its kind

- Green Revolution: mineral oil is almost as effective as Novec & costs much less
  - Mineral oil < $10 a gallon
  - 3M Novec 1230 costs ~ $70 a gallon

http://www.nytimes.com/2014/02/12/business/international/improving-energy-efficiency-in-supercomputers.html?_r=0
Rapidly Expanding Options
Iceotope

- Negates the need for air conditioning, chillers, humidity control systems...
- Two-phase cooling
  - Uses 3M™ Novec™ Engineered Fluid
    - Nonconductive
    - Inert
    - Excellent convection properties
    - Provides fire protection at the component level

http://www.iceotope.com/
Ebullient Cooling

- Two-Phase Cooling
  - Uniform device temperatures
  - Reduce maintenance, improve reliability & eliminate risk due to fluid contact
  - Boiling behavior improves the cooling efficiency
    - Even with outside air > 120 F
  - Phase change allows > 2,000 watts cooling per server.

Green Revolution
Cooling

GRC CarnotJet Fluid-Submersion Rack

Oil outlet

Oil inlet

Cold oil jet involves warmer oil around it to increase flow.

http://www.hpcwire.com/2014/02/14/immersion-cooling-floated-green-energy-solution/
Applications for Military & Disaster Relief Operations

- Liquid Cooled Datacenter Containers
  - Deploy data center capacity anywhere and very quickly
  - Temporary computing capacity in war zones
  - 6 countries, 3 continents

http://www.zdnet.com/liquid-cooled-datacenter-containers-7000017881/

Liquid Cool

- Enhancing reliability by eliminating the root causes of failure:
  - Solder joint failures
  - Lower operating temperatures for board & components
  - No oxidation/corrosion of electrical contacts
  - No fretting corrosion of electrical contacts induced by structural vibration
  - No moving parts, like fans, within the device enclosure
  - No exposure to electrostatic discharge (ESD)
  - No sensitivity to ambient particulate, humidity, or temperature conditions

Liquid submersion technology with an eco-friendly di-electric liquid

http://www.liquidcoolsolutions.com/
Early success selling liquid-cooled gaming PCs & desktop workstations
  - > 1.3 million units sold

Now in Data Center Liquid Cooling
  - Drop-in replacements for stock heat sinks
  - No liquid ever comes in contact with the electronics
  - Coolers installed into standard commercial servers
    - Retrofit or on the manufacturing line
    - Tubes exit through PCIe slot


Business Value of Immersion Technology

Redefine how data centers and servers will be built in the future

- Reduced capital and operating expense vs. conventional data centers
- Non-traditional facilities, including transportable “pods”
  - No need for air conditioning, raised floors or chemical fire suppression
- Low impact on software or network infrastructure
  - Retraining of support personnel not required
- “Green” solution
- Reliability Enhancements
Power costs represent 25-40% of monthly operating expenses.

Typical Data Center Operating Costs Profile

- **Servers**: 57%
- **Power**: 13%
- **Power Distribution & Cooling**: 18%
- **Networking Equipment**: 8%
- **Other Infrastructure**: 4%

3 yr. Server; 10 yr. Infrastructure Amortization
Power Usage Efficiency (PUE)

PUE = \frac{\text{Total Facility Power}}{\text{IT Load}}

Any energy expended other than that to drive the IT Load contributes to inefficiency.

Power
- Switchgear
- UPS
- Battery Backup
- Lighting
- Etc.

Cooling
- Chillers
- CRACs
- Etc.

IT Load
- Servers
- Switches
- Storage
- Etc.
## Traditional Data Center vs. Immersion Cooled Data Center

### Identical Processing Capacity Comparison (10,000 servers)

<table>
<thead>
<tr>
<th></th>
<th>Traditional Data Center*</th>
<th>Immersive Cooling Data Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Center Size (sq. ft.)</td>
<td>12,500</td>
<td>4,000</td>
</tr>
<tr>
<td>Power Consumption (MW)</td>
<td>6.88</td>
<td>3.12</td>
</tr>
</tbody>
</table>

*Assumes PUE of 1.8 and Dell PowerEdge R520 servers
Traditional Data Center vs. Immersion Cooled Data Center

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<th>Immersive Cooling Data Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Servers</td>
<td>7,275</td>
<td>16,030</td>
</tr>
<tr>
<td>Data Center Size (sq. ft.)</td>
<td>9,100</td>
<td>6,430</td>
</tr>
</tbody>
</table>

- 120% More Processing Capacity
- 71% Of the Size

Identical Power Comparison (5 MW)

*Assumes PUE of 1.8 and Dell PowerEdge R520 servers
Preparation: Any OEM Server

Prep takes ~ 10 minutes

- Remove fans
- Replace thermal paste
- Use sealed or solid-state drives
Immersion Technology Challenges

- **Skepticism**
  - Changing—Intel's recent positive report
  - SuperMicro Computer is developing SKUs for immersion boards
  - Network gear manufacturers are lagging behind server vendors

- **Disk Arrays**
  - Current hard disks leak, oil crashes the heads
  - Solid State Drives (SSDs) are expensive
  - Newer helium filled, hermetically sealed, drives an option
Immersion Technology Challenges

- **Component specific challenges**
- **Optical components**
  - TTCP transfer times and ping times are very similar crossing the switch network
  - In all cases, no pings were lost
  - Coolant immersion does not appear to adversely affect the error rate on the links.
Immersion Technology Challenges

- **RF components performance**
  - None detected yet
  - Trials underway
  - Image of Ethernet switch which has been running immersed since January 2011
Immersion Technology Challenges

- **Mineral Oil & Health, Flammability, Spills**
  - Class III B liquid with a flammability rating of 1 out of 4
  - Does not require any supplemental fire suppression systems beyond what is normally used in a data center
  - Negligible health effects
  - Spills & leaks considered low probability
**Immersion Technology Challenges**

- How do you work on a server in immersion oil cooling?
  - Pull the server out, wait for it to drain
  - Keep a paper towel nearby
  - If you do get thermal paste into the system, filter it out
    - Thermal paste dissolves in the oil, making it cloudy

- Maintenance
  - Hot-swaps can be done in the oil
  - Server can be lifted out of the tank & drained

- Repair at the circuit board level
  - Clean to remove oil from circuit boards & components
Potential Reliability Enhancements

- Tin Whisker Mitigation
  - Arcing
- Reduction in Corrosion & Electrochemical Migration
  - Corrosive exposure reduction
  - Moisture reduction
- Environmental contaminant reduction
  - Dust, debris, particulates
- More stable and even thermal environment
  - No hot spots
Tin Whiskers

- Hair-like single crystal metallic filaments that grow from tin films
- Unpredictability is the greatest concern
What are the potential failure modes?

- **Direct Contact**
  - Causes an electrical short (arching)
  - Requires growth of sufficient length & in the correct orientation

- **Electromagnetic (EM) Radiation**
  - Emits or receives EM signal & noise at higher frequencies

- **Debris**
  - Whisker breaks off and shorts two leads (primarily during handling)

- Can be mitigated by immersion cooling
Contamination and Cleanliness

- Believed to be one of the primary drivers of field issues in electronics today
  - Induces corrosion & ElectroChemical Migration (ECM)

- Intermittent behavior causes no-fault-found (NFF) returns
  - Driven by self-healing behavior
  - Difficult to diagnosis

- Pervasive

- Will continue to get worse
Future of Contamination / Cleanliness

- Continued reductions in pitch between conductors will make future packaging more susceptible

- Increased use of leadless packages (QFN, land grid array, etc.) results in reduction in standoff
  - Will reduce efficiency of cleaning, which may lead to increased concentration of contaminants

- Increased product sales into countries with polluted and tropical environments (East Asia, South Asia, etc.)
  - ECM occurrence very sensitive to ambient humidity conditions

- Pb-Free and smaller bond pads
  - Require more aggressive flux formulations
Electrochemical Migration Drivers

- Temperature
- Moisture
- Contamination
- Voltage/Electrical Field
- Temperature, moisture, and contamination can all be reduced and/or eliminated with immersion cooling
Sources of Contaminants

- Printed board fabrication process
  - Insufficiently cured polymers
- Rinse water
- Fluxes
- Handling
- Storage and use environment
Contaminants: Handling / Storage / Environment

- **Handling**
  - Salts from human contact (KCl and NaCl)

- **Storage**
  - Cleaning chemicals
  - Outgassing
  - Polymeric materials

- **Use Environment**
  - Dust, Debris
  - Moisture, Evaporated sea water
  - Industrial pollutants

- Immersion cooling prevents these from accumulating on electronics
Influence of Pollutants: Creepage Corrosion

- Recent field issues with printed circuit boards (PCBs) plated with immersion silver
  - Sulfur-based creepage corrosion
- Failures in customer locations with elevated levels of sulfur-based gases
  - Rubber manufacturing
  - Sewage/waste-water treatment plants
  - Vehicle exhaust fumes (exit / entrance ramps)
  - Petroleum refineries
  - Coal-generation power plants
  - Paper mills
  - Landfills
  - Large-scale farms
  - Automotive modeling studios
  - Swamps
- Immersion cooling would prevent this exposure!

P. Mazurkiewicz, ISTFA 2006
Creepage Corrosion Failure of ImAg

- Corrosion product is semi-conductive (resistance of about 1Mohm).
- Resistance decreases as humidity increases.
- Traces sensitive to leakage current trigger the system failure.
- Visual inspection required to identify failures (most are CNDs).
Pollutants: Not Always in Industrial Settings

Drywall Sulfur Fumes Blamed for A.C. & Electrical Equipment failures

- Chinese Drywall Cited in Building Woes
  - The drywall is emitting sulfur-based gases that are corroding air-conditioner coils, computer wiring and metal picture frames.

- Drywall blamed for A.C. failures
  - Air-conditioning coils have turned black, along with wiring, piping and even silver jewelry.
  - "We have definitely identified that a combination of sulfide gases are the cause of the corrosion," said Robert P. DeMott, managing principal of Environ.
  - "Foul odors reported by people living in the homes may also be caused by the combination of sulfur gases being released from the drywall,

- Chinese drywall class action lawsuit
  - LEE COUNTY, Fla. - The Lawsuit was filed against Knauf Plasterboard Tianjin Co., LTD, The Knauf Group, Rothchilt International Limited and the Banner Supply Company.
  - Known as "Chinese Drywall", it was manufactured oversees and was made from waste materials. As a result, it emits sulfur compounds that corrode copper wiring and other metals found in homes.
Infra-Red Thermal Evaluation

- Q16 producing heat when it is supposed to be in an off state - sneak circuit detected
- D11 detected a hot spot that exceeded thermal limit

Expect hot spot reduction and improved thermal uniformity using immersion oil cooling
Intel tests oil immersion to cool servers

“If you are going to add a significant amount of capacity and have systems with a lot of density and don’t have good air flow in your data center, this is worth looking at,” said Mike Patterson, a senior thermal architect for data centers at Intel who supervised the test.

“We asked a lot of tough questions and they had pretty good answers for all of them so we put a pilot together,” said Patterson. “There’s almost an emotional reaction [against oil immersion] at first, so people say they would never do that, but when they see the potential [energy] savings, they see there’s something there,” he said.
Industry Evaluation – Intel Experience

- With all this in mind, Intel plans to start developing motherboards optimized for immersion cooling. Various OEMs involved in server hardware are expected to create modified designs with oil immersion in mind as well. In the future, this technology might even make it to the consumer level in a more official way.

- Intel also found that no computer components — processors, hard drives etc. — were damaged from the yearlong immersion in mineral oil.

Immersion cooling offers significant environmental, cost, performance & reliability advantages

- Reduces potential for failure in:
  - Tin Whisker Mitigation via arcing
  - Corrosion & Electrochemical Migration (ECM)
  - Moisture reduction
  - Environmental contaminant reduction
  - Fretting
  - Provides stable thermal environment
Presenter Biography

- Cheryl has over 20 years of experience in electronics manufacturing focusing on failure analysis and reliability. She is passionate about applying her unique background to enable her clients to maximize and accelerate product design and development while saving time, managing resources, and improving customer satisfaction.

- Throughout her career, Cheryl has had extensive training experience and is a published author and a senior member of both ASQ and IEEE. She views teaching as a two-way process that enables her to impart her knowledge on to others as well as reinforce her own understanding and ability to explain complex concepts through student interaction. A passionate advocate of continued learning, Cheryl has taught electronics workshops that introduced her to numerous fascinating companies, people, and cultures.

- Cheryl has served as chairman of the IEEE Central Texas Women in Engineering and IEEE Accelerated Stress Testing and Reliability sections and is an ASQ Certified Reliability Engineer, an SMTA Speaker of Distinction and serves on ASQ, IPC and iNEMI committees.

- Cheryl earned her Bachelor of Mechanical Engineering degree from Georgia Tech and is currently a student in the UT Austin Masters of Science in Technology Commercialization (MSTC) program. She was drawn to the MSTC program as an avenue that will allow her to acquire relevant and current business skills which, combined with her technical background, will serve as a springboard enabling her clients to succeed in introducing reliable, blockbuster products tailored to the best market segment.

- In her free time, Cheryl loves to run! She’s had the good fortune to run everything from 5k’s to 100 milers including the Boston Marathon, the Tahoe Triple (three marathons in 3 days) and the nonstop Rocky Raccoon 100 miler. She also enjoys travel and has visited 46 US states and over 20 countries around the world. Cheryl combines these two passions in what she calls “running tourism” which lets her quickly get her bearings and see the sights in new places.
Other References


Future Work – Questions & Challenges

- Oil bath monitoring for water (primarily initial equipment insertion) and contaminants (over time, leaching out from cables, plastics, etc).
  - People who use immersion cooling currently are doing things like broadcast RF amplifiers, radars, and similar high voltage applications.
  - In those cases they monitor the resistance of the oil.
  - Wondering about potential electrolyte leakage from capacitors, so been thinking about adding pH monitoring.
Other References


Zinc Whisker References

- http://www.layerzero.com/Innovations/stainless_steel_hardware.html (Data Center & Zinc whisker mitigation)
Zinc Whisker – Data Center Remediation Plan

- Process from Mark at SFIVE
- Step 1. – Power down and REMOVE from the environment any and all equipment that you can. If the whole room can be shut down, do it!
- Step 2. – Power down as many air conditioning units as you can for the remaining load.
- Step 3. – Protect remaining equipment with plastic barrier tents. Create safe envelopes for equipment by sealing plastic sheeting between the ceiling and the floor. If you still have airflow under the floor, you will need to create underfloor barriers as well. This step is critical since these barriers will protect your equipment from zinc-laden airflow during the replacement process. Note: This step is often difficult to perform because of the physical layout of the room. If this step cannot be performed, compensating changes to the work plan must be implemented.
- Step 4. – Remove affected panels by carefully lifting (without sliding or jostling them) and placing them in a plastic bag. Place only one panel in a bag and fold and seal the bag. Remove the panel from the room. Don't reuse the bags!
- Step 5 – Clean the underfloor plenum, flooring understructure, and underfloor infrastructure using HEPA vacuums and wet wiping.
- Step 6 – Clean the underside of unmovable panels (under equipment that cannot be moved) using wet wiping.
- Step 7 – Install replacement panel
- Step 8 – Repeat Steps 4 – 7 throughout remainder of affected area.
- Step 9 – Clean the entire room and its contents. Zinc Whisker contamination does not remain in the underfloor plenum. The whiskers can and do end up on the walls, ceiling, and all items within the room.
- Step 10 – Carefully remove barriers, reinstall equipment. Remember to map or mark panels that were not removed, if any. These panels should be monitored for continued whisker growth and replaced coincident with future equipment moves.