# Liquid Cooling
# Is Hydrophobia Still an Issue?

Over the past decade, we have seen much debate and development on the liquid cooling of electronic equipment. The concept of liquid cooling dates back to the vacuum tube era. But its actual use in modern electronics, other than in space, military and high capacity computing, is a recent phenomenon. With the rapid increase in power dissipation and concentration at the chip and board levels, a slew of new products deploy liquid instead of air for system cooling.

The questions that linger are: What is liquid cooling? And, will the market's hydrophobia remain a point of contention? Let us explore these two issues and attempt to answer whether hydrophobia is a legitimate concern.

The true definition of liquid cooling is represented by Figure 1. Heat generated by PCB components is collected by an attached coldplate, and then transported by coolant to a liquid reservoir. Subsequently, cooler liquid is circulated back into the coldplate. Thus, a liquid loop or cooling system is created. While analogous to using river or sea water to cool a nuclear power plant, this type of true liquid cooling is rarely employed in electronic systems.

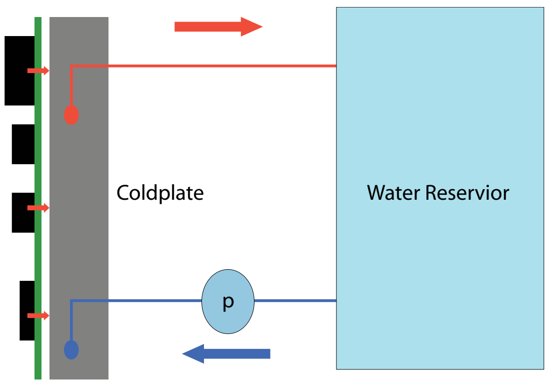


Figure 1. True Liquid Cooling System [1].

Figure 2 shows the cooling system that is traditionally used in electronic systems. It is often mistakenly referred to as liquid cooling.

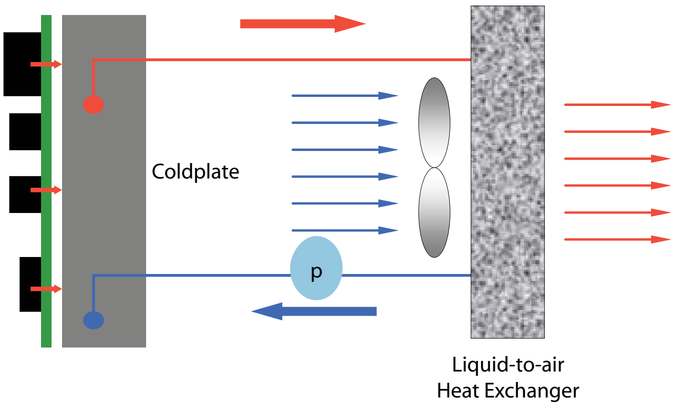


Figure 2. Air-Assisted Liquid Cooling for Electronic Systems.

In this configuration, the liquid is a transport medium that takes heat from the source – component heat transferring into a coldplate – to the air via a liquid-to-air heat exchanger. The cooling capacity of such a system is constrained by the design or performance of the heat exchanger.

When we compare these systems, we find substantial differences. In a true liquid cooling system, (Figure 1), the reservoir is isothermal by its thermodynamic definition. That means its temperature will not change as the result of heat input. The reservoir's volume is massive enough that its average temperature remains constant, and it will ultimately exchange its heat with the atmosphere and space.

Air-assisted cooling is actually an air-cooled system, where liquid is used as the interface between the source and the sink. Engineers must be cognizant of the thermal constraints associated with the design of each system, and the related packaging and internal/external flow (liquid and air) requirements.

In either system, there are some distinct advantages with liquid cooling that are not readily attained with air cooling alone. These benefits include larger transport capacity of heat per liquid volume, and more effective heat spreading.

Let us look at thermal transport in an open system resulting from a change of enthalpy, as shown in Equation 1.

$$Q = \dot{m} C_p (T_{out} - T_{in}) \qquad (1)$$

Where $\dot{m} = \rho VA$, ($\rho$ is the fluid density, V is the velocity, and A is the cross sectional area), and $C_p$ is the specific heat at constant pressure. If we consider the velocity and cross sectional area as constant, the $C_p$ and $\rho$ will dictate the magnitude of heat transfer when different fluids are used.

Table 1 shows the values of $C_p$ , $\rho$, $\mu$ and k for water and air at 300 °K.

Table 1. Thermodynamic Properties of Typical Coolants [2].

| Property | Water | Air | Ratio (Water/Air) |
|---|---|---|---|
| Cp (kJ/kg °C) | 5.73 | 1.001 | 5.7 |
| $\rho$ ($kg/m^3$) | 714.26 | 1.18 | 607 |
| $\mu$ (kg/m-s) | 96.42 | $1.98 \times 10^{-5}$ | $48.7 \times 10^{-5}$ |
| k (w/mK) | 0.54 | 0.026 | 20.8 |

The last column showing the ratios of the two properties is the tell all. It clearly shows the advantage that a fluid with higher density and thermal capacity brings for transporting the heat load. Liquids provide a clear improvement over gases for providing thermal transport in cooling applications.

Liquids can also play an important role in hot-spot thermal management. Local power dissipation at the board and chip levels presents a formidable challenge in designing a successful product. Figure 3 shows examples from Intel and IBM where the heat flux at a given location on the chip exceeds 2500 W/cm².

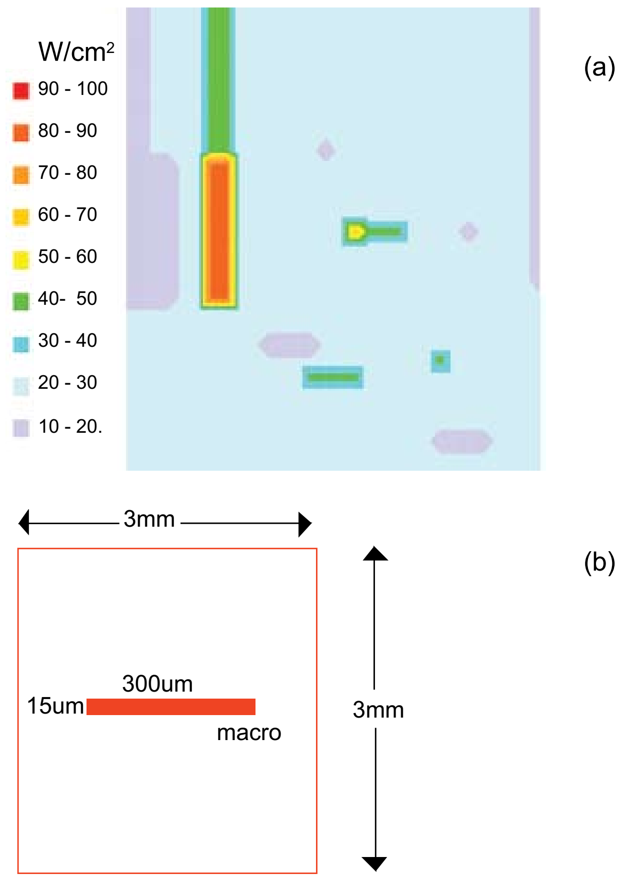


Figure 3. Intel (a) and IBM (b) Microprocessors Showing Heat Flux in Excess of 2500 W/cm² [1].

Clearly, we can more effectively manage local heat fluxes by spreading the heat over larger surface areas. Conduction and convection heat transfer is the backbone of this spreading. High thermal conductivity materials, such as diamond, will assist dramatically in spreading heat more effectively on a larger surface. Barring significant cost for diamond substrates or thermal spreaders, using convective heat transfer will help to attain such wide area spreading.

A look at the Nusselt number (Nu) and heat transfer coefficient shows how effectively liquid can spread heat over a larger surface area. Nu is equal to hL/k, and h, the heat transfer coefficient, e.g. for a flat plate in a laminar flow, is given by Equation 2.

$$h = k/L[0.332\ Re^{0.5} . Pr^{0.33}] \qquad (2)$$

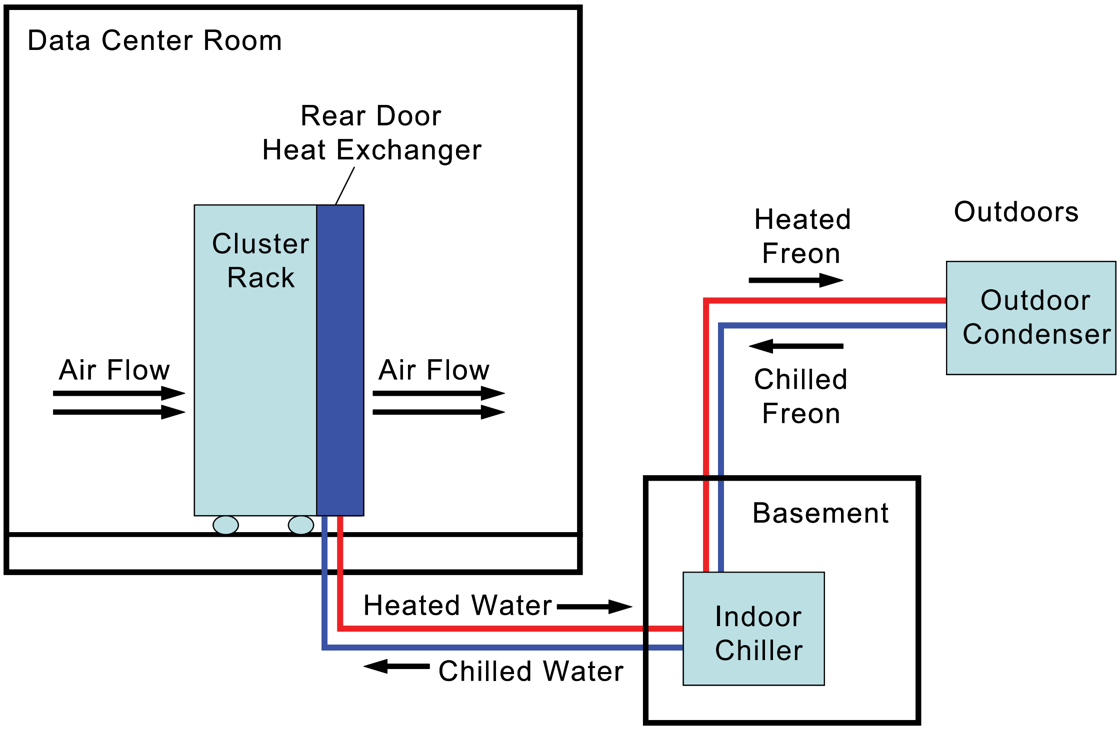


Figure 4. Installation Schematic of a Liquid-Cooled Linux Computer Cluster [3].

Where,

h = Heat transfer coefficient

k = Fluid thermal conductivity

L = Characteristic length

Re = Reynolds number

Pr = Prandtl number

The magnitude of Re is a function of velocity and fluid properties, and Pr is dependent on the viscosity and density of the fluid. Clearly, a fluid with higher properties will have larger Re and Pr and the result will be a higher value of heat transfer coefficient.

Therefore, when we look at Newton's cooling law, $Q = hA_{surface}(T_{surface} - T_{fluid})$, for the same $A_{surface}$ and flow condition, changing the fluid type from gas to liquid (i.e., air to water) yields a significantly higher heat transfer. This will reduce the average surface temperature and may render the design acceptable. The use of liquid cooling, whether pure or air-assisted, can result in higher heat transfer and a better thermally managed system.

However, implementing a liquid-assisted cooling system requires a departure from the conventional air cooling in the field. The majority of deployed equipment is air cooled. Its implementation, barring the lack of reliability of fans, has been easy. Concerns have focused on such issues as fan failure, field service, and acoustic noise. To introduce liquid into this cooling mix means adding a whole new dimension of reliability and safety.

The reluctance to introduce liquid-assisted cooling has been properly referred to as hydrophobia. Whether the cooling method is implemented at the system or site levels, the phobia has been persistent with respect to reliability and cost.

Let us consider a data center. Figure 4 shows a typical liquid cooling system implementation for a computer cluster in a data center.

In this configuration, the electronics are directly coupled to the cooling system (i.e. coldplate or air-to-liquid heat exchanger). This mandates active control and monitoring of the cooling system and the subjected electronics. A failure of the cooling system will require that the electronics be shut down, unless cooling system redundancies

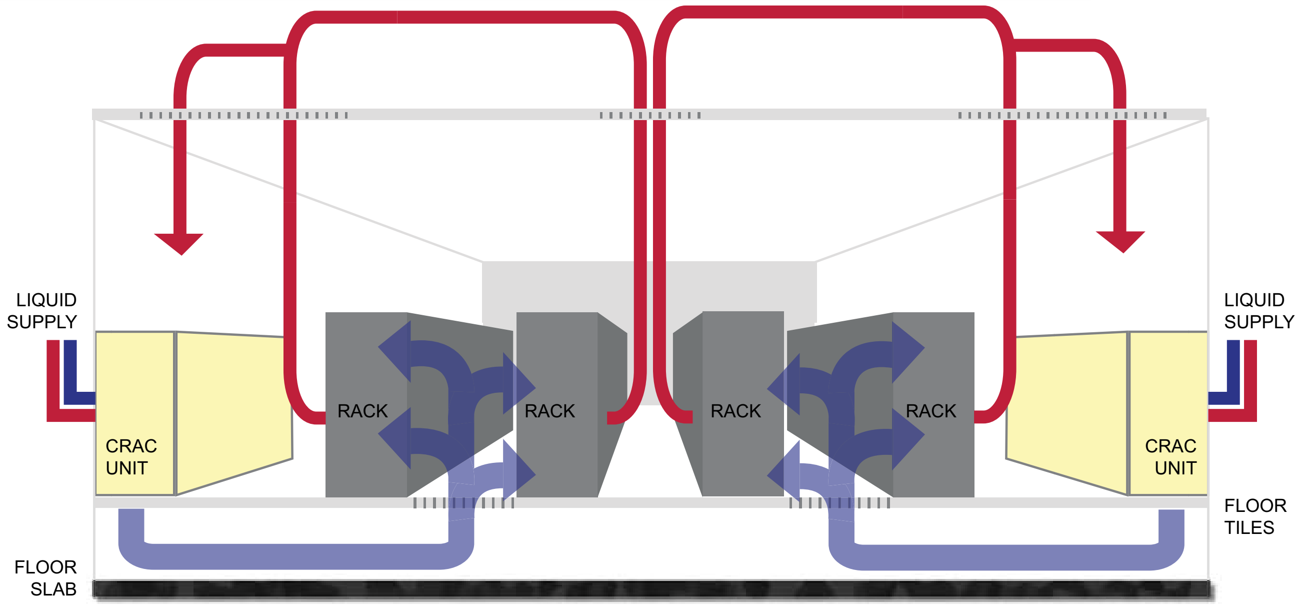


Figure 5. Centrally Air-Cooled Data Center Where CRAC Units Supply Chilled Air to the Electronics [4].

are designed in the overall solution. These safeguards include additional pumps, liquid loops, automatic leak and pressure drop detectors, etc.

When one compares the liquid cooled system, Figure 4, with the traditional air-cooled center, Figure 5, the complexities and concerns for liquid cooled systems become apparent.

One can argue the merits, benefits and weak points of either system, but that is not the intent of this discussion. Any good designer will start from the simplest solution and considers more complex and costly cooling solutions only when a lesser capacity system can not meet the thermal requirements.  The intent is to answer whether hydrophobia is still an issue.

As stated above, the air-cooled system depicted in Figure 5 is a far simpler system from the standpoint of implementation and operation. As depicted in Figures 1 and 2, liquid-cooled systems, by their mere nature, are mechanically more complex and more challenging to maintain than comparable air-cooled systems. Using liquid-cooled systems also poses a significantly higher cost and challenge of their maintenance, operation and control.

Over the past decade, steady rises in power dissipation led to expectations for the broader use of liquid cooling in electronics thermal management. The market responded by improving the reliability of components used in liquid loop systems. But, despite such great strides, and the added heat transfer benefits from liquid cooled systems, the challenges associated with liquid-cooled systems have continued. The market's reluctance to introduce liquid-cooled systems, and the user's fear of high costs and maintenance and operational issues, have rendered the situation hydrophobic. This phobia will persist until we have no other choices or there are many successful implementations that minimize market place fears.

## References:

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3. LaPlante, S., Aubry, N., Rosa, L., Levesque, P., Aboumrad, B., Porter, D., Cavanaugh, C., Johnston, J., Liquid Cooling of a High-Density Computer Cluster, Electronics Cooling, November 2006.
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# RoHS and Electronics Cooling

## History and Purpose

The Reduction of Hazardous Substances (RoHS) directive began nearly 20 years ago as concerns grew in Europe over global pollution and landfill contamination. In 1988, a European Union (EU) council enacted a program to limit cadmium pollution. But it would take another eight years before the RoHS outline was started. This included all six substances that are currently regulated. Over years of debate among politicians, industry representatives, and environmentalists, a total of 50 amendments were proposed, and 10 of these were adopted into law [1].

On July 1, 2006, the RoHS directive was officially enacted to regulate these substances:

Table 1. Limits of Regulated Substances in Homogeneous Materials.

| Material | Concentration Limit | |
|---|---|---|
| Lead | 0.1% | 1000 ppm |
| Mercury | 0.1% | 1000 ppm |
| Cadmium | 0.01% | 100 ppm |
| Hexavalent Chromium | 0.1% | 1000 ppm |
| Polybrominated Biphenyls | 0.1% | 1000 ppm |
| Polybrominated Diphenyl Ether | 0.1% | 1000 ppm |

The following are some of the most common uses for these regulated substances:

lead Pb 82
- Solder
- Paints and coatings
- Coatings on exposed components

mercury Hg 80
- Lightning equipment
- Electrical components, such as switches

cadmium Cd 48
- Plastics
- Solders
- Electroplate coatings

chromium Cr 24
- Hexavalent Chromium
- Corrosion resistant coatings and paints

bromine Br 35
- Flame retardants in plastics
- Polybrominated Biphenyls and Polybrominated Diphenyl Ether

## Exemptions

The RoHS directive covers electronic equipment that uses electricity as its main source of power. There are many exceptions to the directive, several of which are under review but not yet incorporated. For example, the questionable long term durability of low lead solders has exempted mission critical servers, storage arrays, and telecommunications equipment until 2010. Lead is also exempt in glass used to make displays for CRTs, as well as in certain alloys that are discussed below. When used in fluorescent lamps the limit for mercury concentration is relaxed, ranging anywhere from 5-10 mg. Cadmium is allowed on electrical contacts and plated components, except where noted by Directive 76/769/EEC. Finally, hexavalent chromium is exempt when used as a corrosion inhibitor for carbon steel.

Other areas where RoHS offers exemptions are:

- Stationary industrial equipment
- Control and monitoring equipment
- Military and national security applications
- Medical devices

### RoHS in Multi-Part Assemblies

The values stated in Table 1 are the maximum concentrations allowed in a homogenous material, i.e. a single substance that cannot be mechanically separated into different materials. For example, in a wire assembly both the wire and the PVC insulation would have to pass RoHS separately. If the concentration of cadmium was above allowable limits, the assembly would fail RoHS, even if the overall assembly concentration was below allowable limits. A typical semiconductor package has at least six individual materials that must all comply with RoHS. These materials include the silicon chip, gold bond wire, copper lead frame, tin lead frame coating, die attach solder or epoxy, and encapsulation.

### RoHS and Heat Sink Alloys

Modern heat sinks are primarily made from aluminum and copper of various alloys. Heat sink attachment hardware, such as springs and fasteners, are commonly made from steel. These alloys are also covered under the RoHS directive, however they are granted larger concentrations than the materials in Table 1. Steel is allowed up to 0.35% lead, aluminum can contain up to 0.4% lead, and copper alloys can contain up to 4.0% lead.

The two most common aluminum alloys used in heat sinks, AL-6061 and AL-6063, have no significant amounts of lead.

Figure 1. Annodized Heat Sinks from Advacned Thermal Solutions, Inc. in a Variety of Styles and Colors.

### Heat Sink Finishes

It is common practice to give heat sinks anodized or plated finishes to increase their surface emissivity and corrosion resistance. Aluminum heat sinks, as in Figure 1, are commonly anodized to the MIL-A-8625 spec, which is RoHS compliant. Copper heat sinks are usually nickel plated to ASTM-B-733 standards, which are also RoHS complaint. Copper can also be tin plated using a lead free process that conforms to RoHS standards. Most MIL-DTL-5541 Type I chromate finishes are not compliant; however, Type II trivalent chromate does meet the requirements for RoHS.

### Negative Impact of RoHS

When materials and processes are changed to comply with the RoHS directive, there are risks of reduced reliability and performance. These risks are understood by the RoHS committee, which has exempted servers and mission critical equipment until 2010 [2].

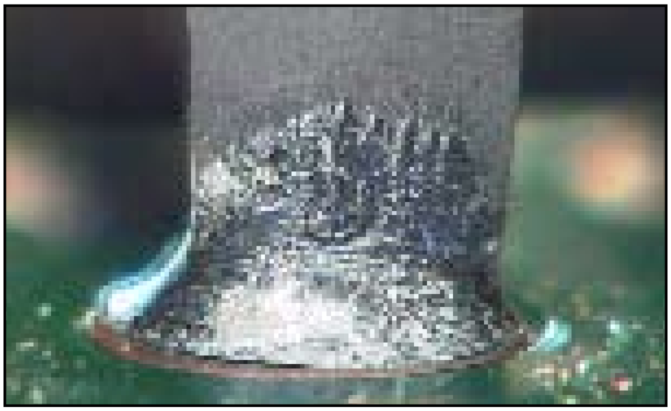

Figure 2. Lead Free Solder Lift-Off [5].

Perhaps the biggest single issue regarding RoHS compliance is the use of lead free solders. These alloys have a higher melting point than lead based solders, which can result in damage to components and PCBs during soldering operations. Further, when surfaces are coated with lead free tin there is a potential for tin whiskers to form. These whiskers are electrically conductive and can cause shorts, as was the case in 2005 at the Millstone Nuclear Power Station in New London, CT [3]. A digital logic card that monitored steam pressure developed a short from a tin whisker and automatically shut down the reactor. The problem was found and regular monitoring of all PCBs is now in place. Another problem was recently encountered at Ford's Lincoln Design Center. Its new computers were failing, whereas the older systems ran without issue. It was found that the new lead free solder was more susceptible to corrosion from the sulfur used in modeling clay.

There are certified agencies  that provide proof of RoHS compliance and every manufacturer needs to provide a certificate that states the hardware and its electronic components comply with the requirements of the EU directive for banned substances.

### Conclusion

U.S. companies that export to Europe must comply with the RoHS standards or risk losing customers to complying competitors. In 2004, the United States exported 124 billion dollars worth of electronics equipment, 18 billion of which was covered by RoHS directives [4]. Going forward, RoHS compliant equipment will dominate overall US electronics sales to European customers.

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My name is Mitch.

I am an applications engineer for a networking equipment provider.

I still call my mother every Sunday.

# I AM HOT

## (AND I'M NOT AFRAID TO ADMIT IT)

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