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Evaporative Spray Cooling Guide

for

Electronic Assemblies and Systems

Electronic devices traditionally produce heat. While there have been great strides to reduce the power consumption of devices, newer computers and many other densely packaged electronic items still produce enough heat to destroy themselves if that heat is not removed. It seems that advancements in low-power, low-voltage designs are accompanied by greatly increased circuit density, with much larger processors (more transistors) and more memory. The new electronic devices enable substantial performance improvements, yet the resulting overall system dissipates as much power as ever, sometimes even more. Therefore, a systematic approach to selection and application of adequate thermal management (usually cooling) is required for all electronic products. Fortunately there are many choices.

This paper is written to help the user make an informed decision on selection of the most appropriate cooling approach for their system design and application. This guide does not attempt to perform the engineering required to apply a particular cooling technique, but offers a basic overview of various choices, and list of considerations to assist in the selection of cooling approach. And for evaporative spray cooling, offers numerous nuggets of advice, considerations, and things to watch out for.

For this paper, the term “evaporative spray cooling” means a cooling approach that uses some sort of cooling fluid, sprayed via nozzles or spray caps, onto components to remove heat. The spray mist changes phase (evaporates from a liquid to a vapor) to carry away heat. There are many other types of liquid- and air-based cooling approaches discussed below in comparison and contrast to evaporative spray cooling.

Cooling Choices

There are many ways the thermal environment for electronics can be managed. Many benign office-like environments may not require any special approach. Simply allowing ambient air to circulate around the electronics will often suffice to keep the components within allowable temperature limits, usually 0-70°C for commercial grade ICs.

Operating in less-friendly environments, such as a factory floor, or uncontrolled space, forces the design to have some sort of cooling mechanism other than natural convection. The typical approach is to force convection by use of fans to move air through the equipment enclosure and around the components to remove the generated heat. This works up to a point. Air can only hold a finite quantity of heat. Removing more heat with airflow requires either moving more air, or cooling the air before it enters the system, or both. A large enclosure full of power-hungry electronics often has several fans roaring away to maintain adequate airflow. If the available ambient air reaches a high enough temperature, this approach fails. Increasing circuit density by use of large, multi-million transistor chips adds yet another dimension to the heat removal problem.

Designers have long recognized that changing the heat-carrying medium from air to a liquid holds the potential for vast improvements (as much as 10X or more) in heat removing capacity. The biggest problem with liquids is that it adds complexity to the overall system design. Using air is easy by comparison. After all, the system is already immersed in it, and moving it around can be done by using fans and blowers. Leakage is no big deal. With a liquid, moving it around not only requires a pump, but plumbing as well. Leaks are not only intolerable, they could often lead to system failure or damage to nearby items that are not tolerant of the cooling fluid.

To sum up all the cooling options available, Figure 1 offers a cooling "family tree" for consideration.

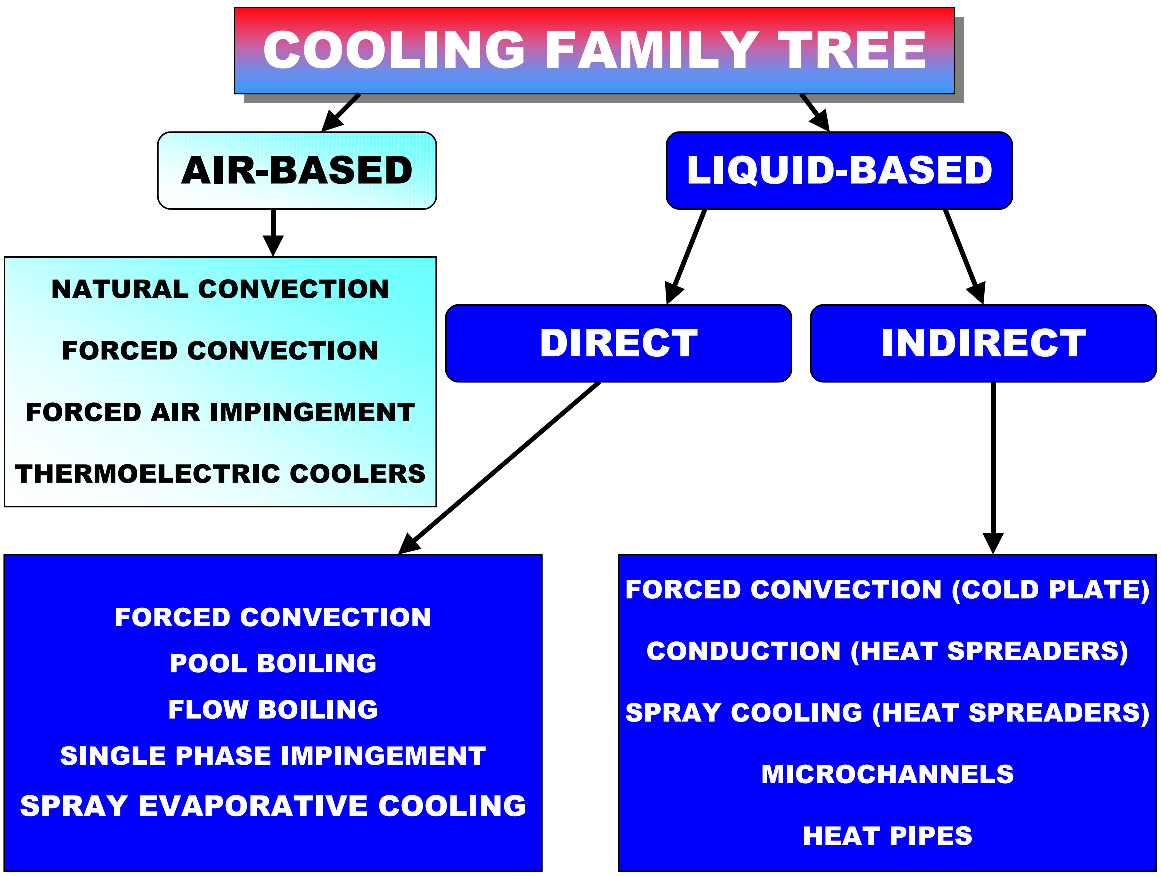

Figure 1. Cooling "Family tree"

The terms "Direct" and "Indirect" used above means that the cooling fluid comes into contact with the components to be cooled (Direct), or contacts another surface that in turn conducts heat out of the components (Indirect).

AIR vs. LIQUID

Cost – Air-based cooling is typically much less expensive than liquid-based. More enclosures are designed around air-cooling, and fans are typically not very expensive. Liquid cooling enclosures usually cost significantly more, and the requisite pumps, atomizers, nozzles, and plumbing add costs and complexity to the overall design. Evaporative spray cooling, or other novel cooling approach, may enable use of lower-cost COTS circuit boards in an otherwise harsh environment, which may offset some of the added integration cost.

Reliability – A fan failure on an air-cooled enclosure can often be tolerated, especially if some redundancy is designed in. The higher operating temperatures of dense, heat-generating components in air-cooled designs may lower overall system reliability. Liquid cooled system pumps tend to be about as reliable as fans, however a pump failure may be a more catastrophic event if redundancy or adequate controls and "fail-safes" are not designed in. Liquid cooling of dense, heat-generating components tends to lower operating temperatures on the hottest parts, which may boost overall system reliability. In some liquid-cooled systems the temperature is about the same throughout (an isothermal design), which has led to much debate about whether this helps or hurts system reliability (some low-power parts actually *run hotter* than in a comparable air-cooled system).

Maintenance – Maintenance of air-cooled designs is very straightforward and familiar to most technicians. There are no fluids to drain, plumbing to unhook, or seals to check. The liquid cooling designs add extra steps to system maintenance procedures. There is debate on whether the improved reliability and environmental isolation of liquid cooled designs offsets the added maintenance needs, since the fluid helps keep internal components cleaner and cooler (leading to less corrosion, contamination, and operating failures). Most engineers have concluded that organizational or even interim depot-level maintenance is not suitable for evaporative spray cooling. Most suggest using only a well-equipped depot operation.

Performance – Air-cooled systems have a much lower total heat capacity than liquid-cooled systems of the same size. While additional space must be devoted to a heat exchanger in a liquid-cooled design, this exchanger may be located separately from the functional system, allowing for some flexibility. This may actually be considered a benefit of liquid-cooled designs, since the collected heat is transferable to a remote location. In air-cooled designs, the system produces local area heating, which may put additional strain on area air conditioning. This is often not calculated in considering the overall space needs of air-cooled designs, as the air conditioning system of the room the system is in may need to be larger. Liquid-cooled systems can be environmentally isolated easier than air-cooled designs, which may permit their use in severe operating conditions without much change. Air-cooled designs, since they draw in large quantities of external air, cannot be used in hot, dirty, or water-soaked areas without careful adaptation to deal with the poor quality intake air. A liquid-cooled system could potentially be used in a complete vacuum, such as outer space.

Table 1. Comparison of various Air- and Liquid-based Cooling Approaches

Air-Based

COOLING TYPE	Description	Fan or Pump Required	Complexity	Cost
Natural Convection	Components lose heat to ambient air. As air heats, it creates a convection flow. Enclosure must have adequate ventilation ports.		**Lower**	**Lower**
Forced Convection	Components transfer heat to air, which is forced to flow through enclosure by fans, or a pressurized source.		**Lower**	**Lower**
Forced Air Impingement	Cooling air is blown directly on hottest components. Other parts are cooled by residual airflow.		**Medium**	**Medium**
Forced Convection	A cooling liquid is pumped across components.		**Medium**	**Medium**
Pool Boiling	Components immersed in pool of cooling fluid, which gives up heat by boiling. Vapor is condensed on sidewalls of enclosure, removing heat.		**Lower**	**Medium**
Flow Boiling	Similar to pool boiling, only cooling fluid is circulated over components.		**Medium**	**Medium**
Single Phase Impingement	Fluid is pumped directly onto hot components, warms, but remains in liquid state, collected and cooled.		**Higher**	**Higher**
Spray Evaporative Cooling	Cooling fluid is sprayed as a fine mist, evaporates, which forms a vapor, then is collected and condensed, which releases heat.		**Higher**	**Higher**
Forced Conduction (Cold Plate)	Cooling fluid is pumped through a plate upon which component assemblies are mounted.		**Higher**	**Higher**
Forced Convection (Heat Spreaders)	Components are mounted to a heat spreader, which acts as a heat conduit to the cooling fluid.		**Higher**	**Higher**
Spray Cooling (Heat Spreaders)	Similar to direct spray cooling, only heat spreader is cooled by evaporative spray cooling.		**Higher**	**Higher**
Microchannels	A complex cold plate built into the component mounting assembly. Small channels circulate cooling fluid around select components.		**Higher**	**Higher**

Liquid-Based

Decision Tree

- ***If air-based cooling will meet your requirements, it is probably the best way to go. It is by far the less expensive and easiest to implement. The simplest is natural convection. Next is use of fans to force convection.***
- ***If air cannot meet all your requirements, then a liquid-based approach may work, but be prepared for additional costs, some additional design considerations and limited system layout and construction options.***
- ***The most complex liquid cooling options - evaporative spray and microchannel – are the most costly and difficult, yet provide the highest cooling capacity.***
- ***A combination of approaches for a larger system may be the optimum solution, applying the complex and costly techniques only where needed, and using traditional air cooling for the balance of the system.***

Various Liquid Cooling Issues

There are numerous choices to make in selection of a liquid-cooling approach. Below, some of the many considerations are discussed, along with some suggestions.

Direct or Indirect Fluid Contact?

Also called an “open” (direct fluid contact with electrical components) or “closed” (fluid kept separate from components) system. With direct liquid cooling, the cooling fluid contacts the components to be cooled. With indirect, the cooling fluid does not contact the components, but conducts heat away from a cold plate or heat spreader the components are mounted on. As one can guess, a direct contact fluid must be a dielectric fluid. Indirect fluids do not have to be non-conductive, and can even include water.

Some issues to consider –

- ☞ Direct contact possibly eliminates the need for a heat sink or cold plate. Many commercial boards designed for air convection cooling can be adapted to direct cooling by removal of the heatsinks. With indirect, the air-based heatsinks may need to be changed to ones compatible with the indirect fluid cooling approach – a likely expensive and difficult step. A custom circuit board design with an integral heat sink or cold plate may be required in some approaches, such as microchannel.

- ☞ Direct contact means fluid compatibility issues. Some cooling fluids may react with (dissolve or weaken) the component packaging materials, such as plastic, epoxies, or metals. Indirect cooling usually keeps the fluid separated from sensitive materials. Keeping the fluid contained also means potentially less filtering and contamination problems.

- ☞ If an open system is not intended to run for extended periods of time there are additional things to consider. It may be less expensive and lighter to have a pressurized reservoir to deliver the fluid to the electronics to be cooled versus a pump and reservoir. The fluid may not even need to be collected if the electronics being cooled have a limited lifetime, this could potentially eliminate a heat exchanger and other components, resulting in space and weight gains as well as a reduction in cost.

Evaporative Spraying (change-of-phase), or Single-phase Liquid?

Evaporative spray cooling uses nozzles to direct a fine mist of coolant onto selected components. The heat from the components is removed by the evaporation of the coolant mist into a vapor. The vapor is then condensed and reused or simply removed from the immediate area.

Single phase cooling involves spraying or pumping a liquid coolant directly over hot components. The idea is to provide a fast-moving stream of cooled inert liquid directly on a high heat-dissipating device to literally flush away the heat. The coolant is then collected and re-circulated. Some spraying approaches are also called jet impingement, since the coolant spray resembles a jet blast in miniature.

Some issues to consider –

- ☞ The use of evaporation (change-of-phase from a liquid to a gas) to collect heat from power-dissipating components yields significant increases over the use of single-phase fluid conduction. This approach is discussed in detail in the section below on evaporative spray cooling.
- ☞ With jet impingement, there are problems in properly positioning the jet spray and the erosion of delicate components by the high-speed fluid jet.
- ☞ With either approach there is extra equipment required for pumping, collecting, and filtering all the coolant, unless the coolant can be discarded by some means outside of the system.

Pool Boiling and Flow Boiling

These techniques involve total immersion of the electronics in a specially designed dielectric fluid. The fluid is designed such that the boiling point is sufficiently low to have the heat transferred away from the hot components when the fluid boils near them. These techniques are rarely used for computers, and find most applications in power systems.

Conduction Cooling (Conduction to a "Cold" Plate)

Chilled water cabinets have been in use for years in the Navy, using conduction cooled electronic boards that move the dissipated heat out via metal frames, cold plates, and heat pipes, rather than by moving air directly over the boards. The ship provides a chilled water source that is plumbed through large electronics enclosures, and returned to the chiller for heat removal. High power dissipation devices such as TWTs in radar systems and rectifiers in large power microwave transmitters are similarly cooled. At the microcircuit level, the heat dissipating components are mounted on a frame designed as an integral part of the printed circuit board. This metal frame, usually an aluminum or copper alloy, conducts the heat to side rails that fit tightly into the cabinet slot. The enclosure is built with cold plates constructed with channels for circulation of the chilled water within. There is little need for air circulation inside the enclosure as the heat conducts through the metal parts and into the chilled water.

Alternatives to water include PAO (Poly-alphaolefin), Ethelyne Glycol & Water mix (EGW), and other "engineered" fluids, including 3M's Fluorinert. Designs for aircraft and other applications, where chilled water is not available out of a tap, often use a closed system filled with one of these alternative coolants.

Some issues to consider –

- ☞ The move to COTS has pretty much squelched designing with this approach for some systems because many COTS boards today are designed to use air-based cooling. "Rugged" COTS products offer extended temperature range operation using a conduction cooling approach, but many still depend on air convection cooling. There are limited COTS boards that make use of a frame compatible with conduction cooling, and these tend to be much more expensive than their air-cooled cousins.

☞ Chilled coolant promotes water condensation in humid environments, so drips and puddles of condensed water must be expected. Most chilled cabinets use a drip tray to route the condensation to a collection point. One fix for this is to keep the coolant at a reasonably warm temperature, although that may be unsuitable if the electronics generate too much heat.

Evaporative Spray Cooling – Special Design Considerations

Evaporative spray cooling has found its way into several applications to cool high-power, or heat-dense components such as power diodes and transistors, large processor multi-chip arrays, and tightly packed circuit cards. While spray cooling can be applied to numerous other designs, the increased design and equipment cost, added size and weight, and loss of maintenance flexibility usually tilts cooling designs toward more traditional air-based cooling where possible. For these reasons, spray cooling is typically considered only if traditional air simply cannot meet requirements.

Designing an effective evaporative spray cooled system must include all aspects of the total system, not just the spraying equipment. Assembled below are sections that address these concerns, and the various items to consider are discussed to illustrate the potential problems that must be overcome before a successful evaporative spray cooling design can be achieved.

A Hermetic or Non-Hermetic System?

A hermetic system is completely sealed against infiltration from outside contaminants, such as water, dirt, or gas. A non-hermetic system may allow some infiltration, and the system is usually tolerant of the contaminants, or has some means to deal with them. Any type of fluid cooled design can be made hermetic, a characteristic with which air-based cooling has difficulty.

Some issues to consider –

Hermetic System	***Non-Hermetic System***
Costs more	Costs less
Maintenance is hampered by additional seals and control of access	Maintenance access is simpler
Needed for control of gas or moisture infusion	Cooling fluid prone to buildup of contaminants over time
Controlled pressure inside (usually positive vs external)	Lower cooling capability than hermetic
Heat exchanger design easier	Heat exchanger design more difficult

A Gravity-Dependent or -Independent System?

With a gravity-dependent system the orientation is fixed, and gravity helps draw fluid down into a reservoir for collection and redistribution. A gravity- (or orientation-)

independent design can be positioned in any orientation, and fluid spray and collection become bigger problems.

Some issues to consider –

Gravity-Dependent	***Gravity-Independent***
Fluid collection aided by gravity, system orientation must be somewhat fixed.	Space and airborne applications, no gravity needed for fluid control.
Simpler fluid collection and spray nozzle design.	More complex fluid collection and spray nozzle designs.
Pressure of vaporization assists in the removal of fluid from the area being cooled.	Useful when the design does not allow for pressure of vaporization to aid in the removal of coolant from the area being cooled.

Pressurized (Gas saturated) or Non-Pressurized System?

Pressurizing the system has a few advantages, but can also lead to a bit more cost and complexity. By maintaining a positive pressure inside the system enclosure, external contaminants tend to be kept out. Also, a pressurized system can be used to more accurately control the component operating temperature.
One way to control the system pressure is though the use of nitrogen (or air if corrosion is not an issue). Part of the nitrogen gas saturates into the fluid while the rest remains in a gas form in the void space of the closed system. The additional pressure that the nitrogen gas exerts on the fluid causes a state of "gas subcooling." The pressure of the nitrogen can be adjusted, there-by adjusting the boiling point of the working fluid. The are also other effects that occur as the nitrogen levels in the fluid decrease as the fluid is heated when it comes in contact with the hot surface. The over-all effect is that the fluid can remove higher heat fluxes but the surface temperature also increases for a given heat flux.

Some issues to consider –

Pressurized System	***Non-Pressurized System***
Needed to carefully control system operating temperatures.	Use when precise system operating temperature control is not required.
Use when positive internal pressures or positive head is required on pumping system.	Use if positive pump head is not needed.
Positive pressure works to keep air and gas infiltration down.	Use when evaporation temperature effects on operating pressure of no concern.

- ☞ There are UL requirements for a pressurized system for safety and operation purposes for commercial applications. The military typically adheres to these same requirements. An overpressure safety release valve is typically required on pressurized systems.

Pump and Nozzle Selection

Selecting the right pumps and nozzles to use involves a large tradeoff between mechanical, thermal, and electrical power properties. The pumps must supply adequate pressure to the nozzles to achieve the desired coolant flow and spray patterns. Controlling the coolant flow to the nozzles, meeting sufficient thermal efficiency, while also keeping electrical power use and noise to a minimum is a very involved problem. There are numerous pump designs to choose from, three of which are compared below.

The quantity of nozzles needed, the capacity of the pumps to supply adequate pressure and fluid flow, and the electronics layout that is to be cooled all affect the combined nozzle/pump design. The electronic packaging and layout of the system design might preclude or limit certain spraying approaches. For example, a circuit board with only a large BGA style package to be cooled may only require a single spray nozzle, while a multi-chip module may require a custom spray plate consisting of several nozzles. The spray pattern needed for coverage of the area to be cooled must also be factored into the nozzle design. Spray cooling packaged single chips such as a processor must be approached differently than customized multi-chip modules.

Spray cooling is less effective at reducing operating junction temperatures in a packaged chip than if the spray can be directed on the bare die. *The best spray cooling advantages are realized when the spray cooling design can be integrated in the total chip and system packaging scheme. Adding spray cooling to an existing enclosure design cannot possibly achieve similar efficiencies.*

Some issues to consider –

- ☞ Pumps and nozzles, just like many electronic devices, are often single source items. In fact, numerous designs would be considered custom or proprietary, and substitution with a different supplier's pump or nozzle may be out of the question.
- ☞ Overall fluid control is heavily dependent on proper pump and nozzle combinations. The pump may cavitate if there is improper fluid pressure, leading to gas in the fluid lines and a drop in flow.
- ☞ Pump Selection and Requirements: What parameters to control?
    - Flow rate
    - Pressure differential
    - Temperature
    - Heat exchanger performance
    - Current draw
    - Pump speed
    - Is there positive head on the pump?
    - Seals and fitting compatibility
    - Pump control features

Pump Types

	Advantages	Disadvantages
Gerorotor Pump	Size, Delivery Pressure, Control	Thermal Load, Cost
Gear Pump	Delivery Pressure, No Thermal load, Control, Reliability, Fluid compatibility	Size, Cost, Contamination
Centrifugal Pump	Cost, NoThermal load	Reliability, Sealing, Control

☞ Larger system designs employing spray cooling across more than one chassis may want to consider a "common pump network", where a single set of pumps supply cooling fluid to each chassis. This approach may reduce system complexity, but fluid metering and regulation must be employed to keep all chassis operating within temperature.

☞ Spray Plate Design Considerations
- What are the Heat Flux requirements?
- What is the operating heat flux range?
- What is the maximum chip heat flux?
- Is this a gravity assisted fluid removal spray plate?
- If more than one chip, what are the interacting dependencies?
- Is a single nozzle or multiple nozzles required?
- What is the distance between the nozzle and the cooling surface?
- Is the fluid that is being atomized saturated with a gas?
- Is flow rate a concern or consideration?
- Equal flow to nozzles in a multiple nozzle configuration
- Is full field coverage required? This is the pattern of the spray, either shaped a certain way (such as a hollow cone shape) or a solid coverage spray pattern.

Filtering Requirements

There are several conditions that require filtering the coolant. Most relate to keeping the coolant's operating characteristics within specifications, preventing pump clogging and wear, and preventing the buildup of unwanted chemicals or contaminants in the coolant. Most spray cooling designs make use of at least a particulate filter to remove abrasive, clog-forming particles. The need for filters adds to maintenance concerns, but going without them may lead to severe performance and safety problems.

Gas Filtering Requirements
- Prevent the buildup of non-condensable gasses in the system
- Prevent corrosion
- Infusion of air and gases is not permissible
- Material compatibility issues

Moisture Filtering
- Prevent the buildup of non-condensable
- Prevention of moisture associated corrosion
- Prevent heat transfer performance reducing effects from occurring

Organic Filtering

- Removal of contaminates such as finger oils, machine oils, plasticizers and elastomers that can affect filtering performance and cause corrosion

Particulate Filtering

- Prevent the fouling of the spraying devices (atomizers and such)
- Reduce wear of pump
- Prevent the plugging of other filter types
- Prevent reduction of heat exchanger performance

Decomposition Filtering

- Prevent the buildup of hazardous byproducts, such as Perfluoroisobutylene (PFIB) from Fluorinert, in the system. (Safety regulation – PFIB can be very harmful if inhaled or otherwise contacted)
- Remove hydrofluoric acid to prevent corrosion.
- Prevent performance reducing effects from occurring from due to fouling

Fluid Selection Factors

There are many factors to consider when selecting the proper cooling fluid. Most spray-cooled systems use a version of Fluorinert by 3M, but there are alternatives, such as HFE (Novec).

The selection of the cooling fluid should consider the following topics:

- Safety - Obviously the fluid must have the desired properties of boiling point, specific gravity and the like to be useable, but some accommodation of undesirable events must also be considered. If a system operates long enough, a component inside is likely to fail. Sometimes this failure may be an unspectacular dead chip, but others may literally "go out in a blaze of glory". The fluid must not support a fire (some coolants are actually fire suppressants), and should not decompose such that it poses a health hazard to the technician who has to open the enclosure and fix the problem.
- Material compatibility – Much work has been done in this area, but obviously no one has tested every material and device for compatibility with every cooling fluid. 3M has offered to "certify" any design for material compatibility with the fluid, but this can be an added expense. Individual testing or verification of material compatibility of selected components in the system design with the selected cooling fluid should be done. Other factors to consider: Virgin fluid to material compatibility; Contaminated fluid to material compatibility issues; Material absorption characteristics; Material long term property changes; Service requirements; Contamination and filtering issues Filtering requirements
- Operational parameters – Most cooling fluids come with some technical parameters that the fluid has been tested to. The boiling point, specific gravity, density, and so forth, all can be selected to optimize performance. Remember that the fluid freezing point may be high enough to require system pre-heaters in order to start the system during cold temperatures.
- Operating life – A fluid that is expected to last for a long period of time will likely need maintenance to retain operating parameters.

- Regulations and governing laws – Some applications do not permit some of the chemicals used in the cooling fluids. Better be sure before trying to use them in the application.
- Environmental release issues – Disposal of the fluid is also regulated in some cases. Unless you are using pure water, it is likely that disposal of used fluid will require certain procedures and special handling.
- Design application – Engineered fluids for specific design applications may not be suitable for use in other applications.
- Heat Transfer requirements
- Surface temperature requirements
- Heat Flux requirements
- Evaporation temperature
- Filtering requirements – See the "Filtering Requirements" section above
- Reliability
- Cost
- Availability

Heat Exchanger Design

The heat exchanger can be the external walls of the system enclosure itself, an internal unit, or an entirely separate enclosure. Fluid management between the cooled system and the heat exchanger must be carefully engineered to make sure the fluid transfer doesn't generate too much pressure or temperature loss. In any case, the heat exchanger must effectively remove the collected heat from the system and deposit it in the desired medium, air or water or something else entirely.

Some issues to consider –

- Material selection should be based on fluid selection and performance requirements
- Non-condensable in the system determines heat exchanger design
- Water cooled or air used as heat transfer medium
- Fluid management in heat exchanger
- Fluid management in system plumbing
- Material compatibility issues
- Serviceability

Summary

If you have read this far, you can see that there are many options for cooling electronic equipment, and many issues to consider under each. If evaporative spray cooling appears to be the most suitable option, hopefully this paper sheds a little light on the subject and helps to bring up all the concerns that you should answer before committing to the approach.