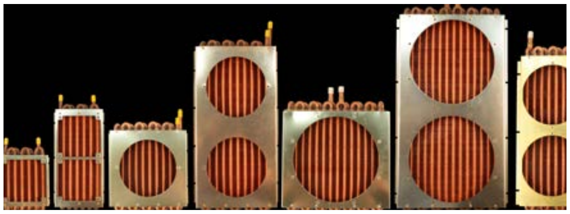
ATS Liquid Cooling eBook

Select Technical Articles on Liquid Cooling and its Various Roles in the Thermal Management of Electronics



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Calculating The Loads For A Liquid Cooling System

This article presents basic equations for liquid cooling and provides numerical examples on how to calculate the loads in a typical liquid cooling system. When exploring the use of liquid cooling for thermal management, calculations are needed to predict its performance. While it is often assumed that a liquid coolant itself dissipates heat from a component to the ambient, this is not the case. A closed loop liquid cooling system requires a liquid-to-air heat exchanger. Because of its structure, several equations must be calculated to fully understand the performance and behavior of a liquid cooled system.

For this article we consider a liquid cooling system as a closed loop system with three major components: cold plate, heat exchanger and pump. The cold plate is typically made from aluminum or copper, and is attached to the device being cooled. The plate usually has internal fins which transfer heat to the coolant flowing through them. This fluid moves from the cold plate to a heat exchanger where its heat is transferred to the ambient air via forced convection. The final part of the cooling loop is the pump, which drives the fluid through the loop.

Equation 1, below, was derived to predict the final temperature of the device being cooled [1]:

$$T_{mod} = q_L \bullet R_{cp} + T_{w1}$$

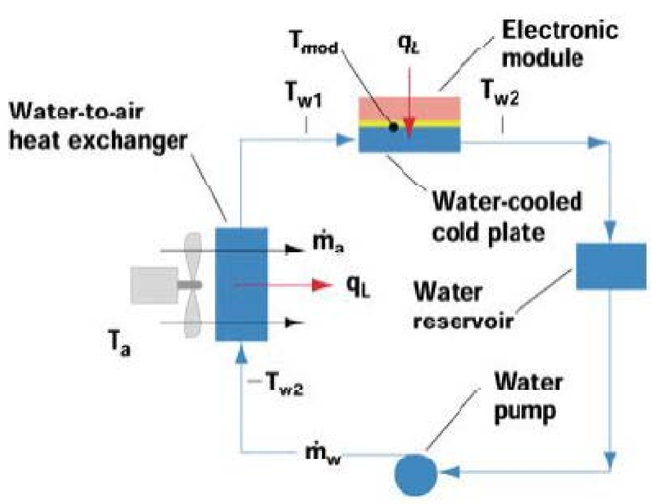

Figure1. Closed Loop Liquid Cooling System [1] .

Where:

T_{mod} = surface temperature of the device being cooled
q_L = power dissipated by the device
R_{cp} = thermal resistance of the cold plate and TIM
T_{w1} = water temperature entering the cold plate

In an open loop cooling system, the value of Tw_1 is known and controlled by the supply system. Calculating Tw_1 in a closed loop system is more involved. This is because the water temperature is both rising from the power transferred from the device and dropping while transferring heat to the ambient in the heat exchanger.

The temperature rise of the water due to the device power is given by:

$$T_{w2} - T_{w1} = \frac{q_L}{C_w} \qquad (2)$$

Where:

Tw_2 = temperature of the water exiting the cold plate and entering the heat exchanger

C_w = heat capacity rate of water
The heat capacity rate is found by multiplying the mass flow rate and the specific heat of water.

Once the liquid enters the heat exchanger it transfers heat into the air. The amount of heat transfer, at steady state, is equal to the heat produced by the component.

$$q_L = \varepsilon \bullet C_{min} (T_{W2} - T_a) \qquad (3)$$

Where:

Ta = temperature of the air entering the heat exchanger
ε = effectiveness of the heat exchanger
C_{min} = heat capacity rate of water (C_w) or air (C_a), whichever is smaller

Next, we solve Equations 2 and 3 for Tw_1

$$T_{w1} = q_L \left(\frac{1}{\varepsilon \bullet C_{min}} - \frac{1}{C_w} \right) + T_a \qquad (4)$$

Finally, we combine Equations 1 and 4 to solve for T_{mod}

$$T_{mod} = q_L \left(R_{cp} + \left(\frac{1}{\varepsilon \bullet C_{min}} - \frac{1}{C_w} \right)\right) + T_a \qquad (5)$$

Several factors must be known to effectively use this equation as a design guide. First, we must determine the cold plate's thermal resistance. This can be obtained from a computational fluid dynamic (CFD) analysis of the cold plate using software such as CFDesign or Flotherm. It is also important to understand the manufacturing limits before starting the mechanical design. Typically a cold plate's design is driven by these limits, which control the minimum width of its internal channels and fins. A cold plate's thermal resistance is usually in the range of 0.05 to 0.25°C/W, depending on size and material.

Next, the performance of the heat exchanger must be specified. A heat exchanger's performance is the product of its efficiency (ε) and the total specific capacity rate flowing through it (C_{min}). The performance specifies, in units of W/°C, the amount of heat removed from the heat exchanger at a given difference between the water and air temperatures. A typical heat exchanger used for electronics cooling, with a 120 mm fan, provides performance values of 11 to 20 W/°C [3].

As an example, consider the design of a liquid-cooled loop for cooling an Intel Xeon X5492 processor.

Where:

q_L = 150 W
$T_{mod, Max}$ = 63°C
T_a = 25°C
M_w = 0.032 L/s (0.5 gpm)
R_{cp} = unknown
Heat exchanger performance = 16.7 W/°C
Equation 5 is used to solve for the device temperature (T_{mod}) as a function of cold plate resistance. Figure 2 shows that to cool an X5492 processor in a 25°C environment a cold plate resistance of less than 0.18°C/W is required.

Figure 2 illustrates the basic steps needed to properly design a liquid cooling loop. It also shows the importance of characterizing all the components within a system. The cold plate, heat exchanger, and pump must all be selected and designed as a group to ensure acceptable performance.

The heat exchanger is often the limiting factor in a compact system due to its relatively large size. Packaging and other mechanical concerns for the heat exchanger dictate that it should be considered first. The cold plate and pump are typically easier to optimize. For example, if a heat exchanger's size is limited, a copper micro fin cold plate and a high volume pump may be needed. If a sufficiently-sized heat exchanger is available, a lower cost cold plate and pump may be used with sufficient results.

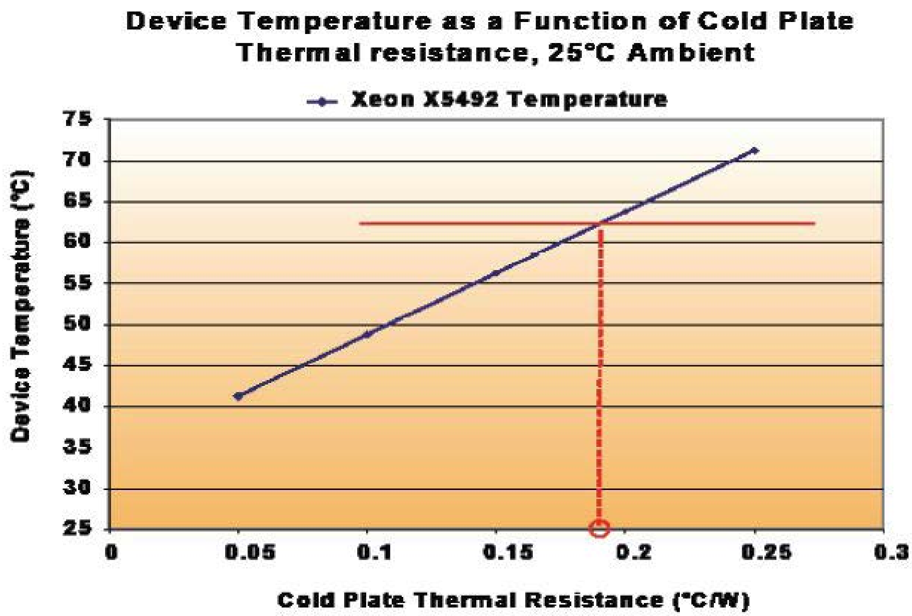

Figure 2. Device Temperature as a Function of Cold Plate Thermal Resistance.

In summary, liquid cooling loops are an important part of the electronics industry, and their use will continue into the future.

It is important to understand the impact on performance of all three major parts of liquid cooling loops (cold plate, heat exchanger and pump) to ensure an acceptable level of performance at the lowest cost. It is also critical to address the design of the heat exchanger as it can be the limiting factor in many systems.

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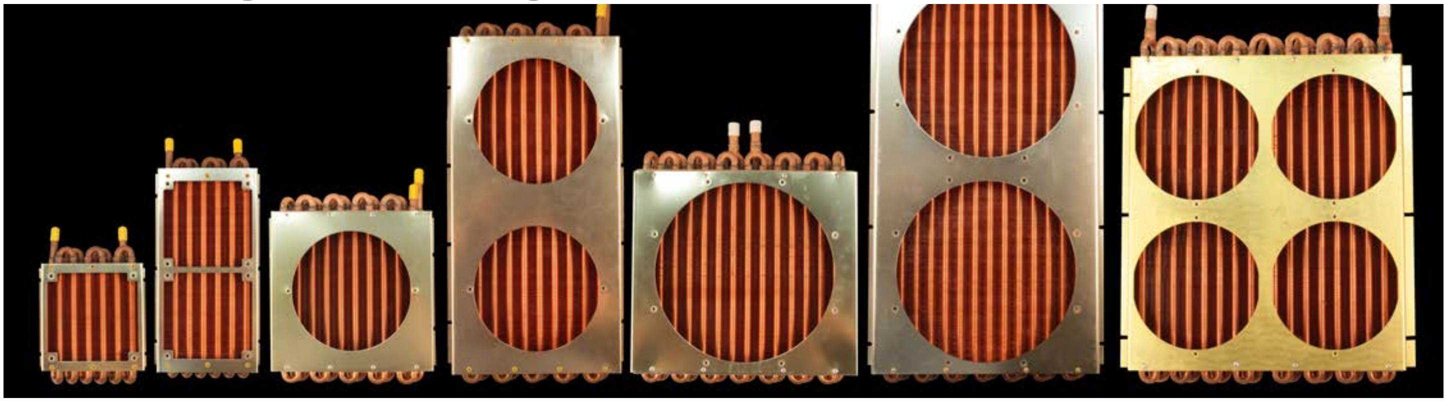
Heat Transfer Analysis of Compact Heat Exchangers Using Standard Curves



Introduction

In previous issues of Qpedia Thermal eMagazine [1,2], we covered some fundamental and practical aspects of heat exchangers. In this issue, we will concentrate on compact heat exchangers and how to use standard curves for heat transfer analysis. Compact heat exchangers are a class of heat exchangers which features at least one of the fluids, on one side, as a gas. They generally have a very large heat transfer area per unit volume (>700 m2/m3) [3]. Most of the applications of compact heat exchangers are in the area of electronics cooling, because space for a cooling device is typically at a premium. Generally, the heat exchangers used in electronics cooling are of the air-to-liquid type. The heat transfer coefficient on the air side is significantly smaller than the liquid side, hence increasing the surface area on the air side can compensate for the low value of the heat transfer coefficient. Compact heat exchangers can come in different shapes and forms [3].

They can be made as:

- Flat tubes (liquid) – continuous plate (air)
- Round tube (liquid) – continuous flat plate (air)
- Round tube (liquid) – round disks (air)
- Flat plate (liquid) – folded fin (air) single pass or multi-pass

Flow passages are generally very small (hydraulic diameter Dh < 5 mm) and the flow is considered laminar. Kays and London [4] have compiled a large volume of data for different heat exchanger configurations. The data plotted is in the form of the Colburn factor (JH) and friction factor as a function of Reynolds number (Re), as shown in figure 1.

The Colburn JH factor is defined as: $J_H = StPr^{2/3}$

Where,

The Stanton number is defined as:

$$St = \frac{Nu}{RePr}$$

Nu, Re and Pr are Nusselt, Reynolds and Prandtl numbers, respectively.

After considering all of the constraints and identifying the heat exchanger type, the engineer must look at the graphs and match the heat exchanger configuration to the available data, if it is available, and extract the information from there.

The following example shows how to use curves to solve a heat exchanger problem:

Consider a circular tube-circular fin compact heat exchanger as shown in figure 1.

The liquid water transfers the heat from hot components through the aluminum tube. Ambient air is blown through the fins attached to the tubes to remove the heat from hot fluid. Calculating the overall heat transfer coefficient on the air side:

The geometrical dimensions of this heat exchanger and other information are as follows:

Tube outside diameter = 9.65 mm

Fin pitch = 343 per m

Flow passage hydraulic diameter = 3.929×10^{-3}m

Fin thickness = 0.46×10^{-3}m

Free flow are/frontal area = $\frac{A_{ff}}{A_{ff}}$ α = 0.524

Heat transfer area/total volume = α = 0.524

Fin area/total area = $\frac{A_f}{A}$ = 0.91

Inside tube diameter = 6 mm

$\dot{m}_c$ = air mass flow rate (cold side) = 0.45 Kg/s

$\dot{m}_h$ = water mass flow rate (cold side) = 0.1 Kg/s

T_{air} = air flow temperature = 20°C

A_{fr} = frontal area = 0.0225 m^2

The properties of air at 20°C are as follows:

C_p = 1007 J/Kg.K

μ = 180 x 10^{-7} N.s/m^2

Pr = 0.709

The overall heat transfer coefficient for a heat exchanger is written as:

$$\frac{1}{UA} = \frac{1}{(\eta_0 hA)c} + R_w + \frac{1}{(\eta_0 hA)h} + R''_f$$

The fin effectiveness η_0 can be written as:

$$\eta_0 = 1 - \frac{A_f}{-A}(1-nf) \quad (2)$$

Where,

A_f = fin area

A = total heat transfer area

η_f= fin efficiency

h = heat transfer coefficient

Rw = conduction resistance due to tube walls

R''_f = fouling resistance

Subscripts c and h stand for cold and hot side, respectively.

Neglecting the fouling resistance

$R''_f = 0$

Since there are no fins inside the tubes $\eta_{0,h}$=1, the subscript h means water is the hot fluid. The overall heat transfer coefficient, for the air which is directed to the cold side, can then be written as:

$$\frac{1}{U_c} = \frac{1}{\eta_{0,c} h_c} + R_w A_c + \frac{1}{h_h (A_h / A_c)}$$

$$A_h / A_c \approx D_i / D_o (1 - A_f / A)$$

Di = inner diameter of the tube

D0 = outer diameter of the tube

The conduction resistance is calculated as:

$$R_w A_c = \frac{Ln(\frac{D_o}{D_i})}{2\pi Lk / A_c} = \frac{D_i Ln(D_o / D_i)}{2KA_h / A_c} = \frac{6\times10^{-3} Ln(9.65/6)}{2(200)(0.0559)} = 0.127x10^{-3}\, m^2.K/W$$

The heat transfer coefficient of the water flow inside the tube is calculated as:

$$U_{water} = \dot{m} / \rho A = \frac{0.1}{1000\times\pi/4\times(6\times10^{-3})^2} = 3.5\, m/s$$

$$Re = \frac{\rho U_{water} D_h}{\mu} = 3.5(6\times10^{-3})/352\times10^{-6} = 59$$

This shows the flow is laminar.
Assuming it is also fully developed:

Nu = Nusselt number = 4.26

h_{water} = kNu/D = 0.67(4.26)/6X10^{-3} = 486 W/m^2 • K

Now calculate the air side heat transfer coefficient:

$$Re_{air} = \frac{\rho U_{air} D_h}{\mu}$$

U_{air} is the air flow velocity in the free flow area

$$\rho U_{air} = \frac{\dot{m}_{air}}{A_{ff}} = \frac{\dot{m}_{air}}{\sigma A_{fr}} = \frac{0.45}{0.524(0.0225)} = 38.16\ Kg/m^2.S$$

$$Re_{air} = \frac{38.16(3.929\times10^{-3})}{180\times10^{-7}} = 8329$$

From figure 1 [4], the Colburn factor JH is found as:

$$J_H = 0.006$$

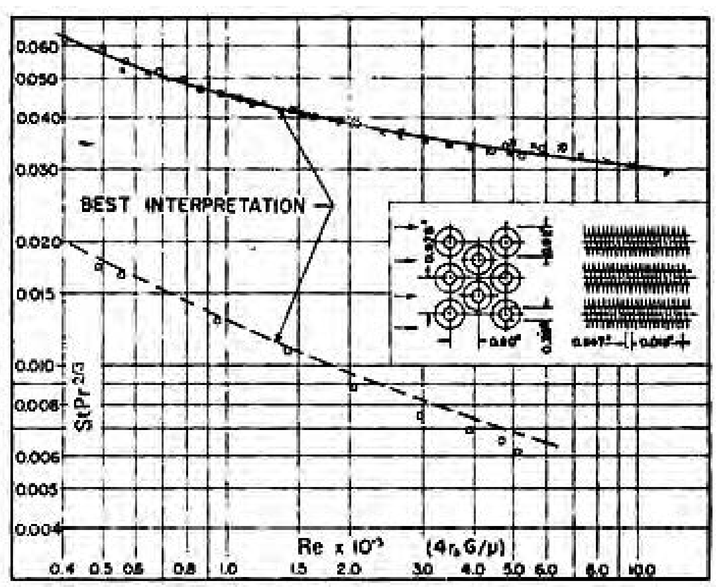


Figure 1. Colburn JH Factor as a Function of Reynolds Number for Circular Tubes, Surface CF-8.72 [4].

The air side (cold side) heat transfer coefficient is then calculated as:

$$h_c \approx 0.006\frac{GC_p}{Pr^{2/3}} = 0.006\frac{38.16\times1007}{0.709^{2/3}} = 289\,W/m^2.K$$

Where,

G = Volumetric flow rate

Cp = Heat capacity

Calculate the fin effectiveness from Equation 2.

First we need the fin efficiency. Referring to figure 2:

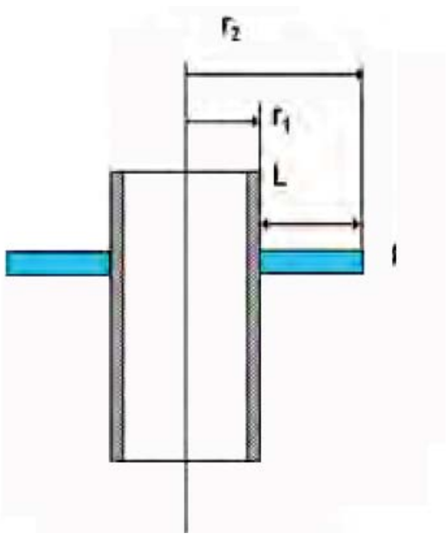


Figure 2. Schematic of Annular Fins of Rectangular Profile.

From figure (3.19) in reference [3], we can find the fin efficiency as a function of $LC^{3/2}(h/KA_p)^{1/2}$ for different values of r_{2c}/r_1.

The variables are defined as:

$r_{2c} = r_2 + t/2 = 11.914$ mm
$L_c = L + t/2 = 7.089$ mm
$A_p = L_c t = 1.63\times10^{-6}$
$Lc^{3/2}(h/KA_p)^{1/2} = 0.561$ and $r_{2c}/r_1 = 2.46$
$\eta_{0,c} = 1 - Af/A(1-\eta_f) = 0.772$

Finally the overall heat transfer coefficient is calculated as:

$$\frac{1}{U_c} = \frac{1}{486\times0.0559} + 0.127\times10^{-3} + \frac{1}{0.772\times289}$$

Overall heat transfer coefficient on the air side (cold side):

$$U_c = 23.5W/m^2.K$$

In future articles we will show analytical techniques for heat exchangers, with geometries that are not referenced in any available literature, especially compact heat exchangers with very dense fins on the air side. Also, the above procedure simplified the analysis by ignoring the fouling factor. Fouling is the process of accumulation of particles on the fins or inside the liquid tubes. It depends on the fluid velocity, length of service and the type of fluid. In future articles, we will devote the topic to Fouling.

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What Fluids Can Be Used With Liquid Cold Plates in Electronics Cooling Systems

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Liquid cooling systems transfer heat up to four times better than an equal mass of air. This allows higher performance cooling to be provided with a smaller system. A liquid cooled cold plate can replace space-consuming heat sinks and fans and, while a liquid cold plate requires a pump, heat exchanger, tubing and plates, there are more placement choices for cold plates because they can be outside the airflow. [1]

One-time concerns over costs and leaking cold plates have greatly subsided with improved manufacturing capabilities. Today's question isn't "Should we use liquid cooling?" The question is "What kind of liquid should we use to help optimize performance?"

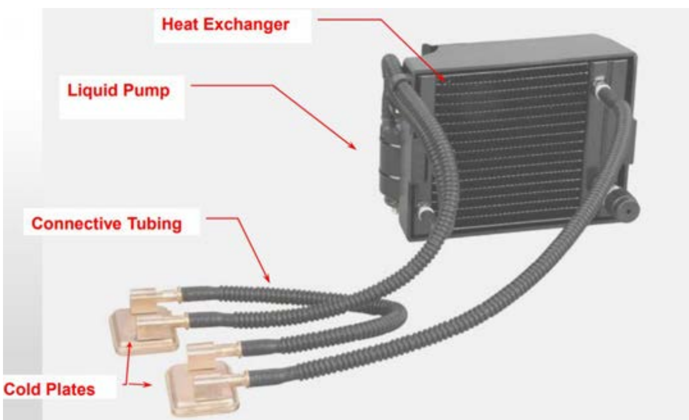

Figure 1. A Liquid Cooling System for a Desktop PC with Two Cold Plates. [2]

For liquid cold plates, the choice of working fluid is as important as choosing the hardware pieces. The wrong liquid can lead to poor heat transfer, clogging, and even system failure. A proper heat transfer fluid should provide compatibility with system's metals, high thermal conductivity and specific heat, low viscosity, low freezing point, high flash point, low corrosivity, low toxicity, and thermal stability. [3]

Today, despite many refinements in liquid cold plate designs, coolant options have stayed relatively limited. In many cases, regular water will do, but water-with-additives and other types of fluids are available and more appropriate for certain applications. Here is a look at these coolant choices and where they are best suited.

Basic Cooling Choices

While water provides superior cooling performance in a cold plate, it is not always practical to use because of its low freezing temperature. Additives such as glycol are often needed to change a coolant's characteristics to better suit a cold plate's operating environment.

In fact, temperature range requirements are the main consideration for a cold plate fluid. Some fluids freeze at lower temperatures than water, but have lower heat transfer capability. The selected fluid also must be compatible with the cold plate's internal metals to limit any potential for corrosion.

Table 1 below shows how the most common cold plate fluids match up to the metals in different cold plate designs.

	Technology	Water	Glycol/Water	De-ionized Water	Oil	Dielectric Fluids (e.g. Flourinert)	Polyalphaolefin (PAO)
Standard	Copper Tube Cold Plate	X	X	X	X	X	X
	Stainless Tube Cold Plate	X	X	X	X	X	X
	Aluminum Blister Cold Plate		X		X	X	X
Extended Surface	Copper AavTube Cold Plate	X	X	X	X	X	X
	Aluminum AavBlister		X		X	X	X
	Alum AavFin Cold Plate		X		X	X	X

Table 1. Compatibility Match-ups of Common Cold Plate Metals and Cooling Fluids [1]

The choices of cold plate coolants will obviously have varied properties. Some of the differences between fluids are less relevant to optimizing cold plate performance, but many properties should be compared. Tables 2 and 3 show the properties of some common coolants.

Properties of Typical Electronic Coolants

Coolant	Thermal Conductivity (W/m-K)	Thermal Expansion Coefficient (K^{-1})	Specific Heat (J/kg-K)	Boiling Point (°C)	Freezing Point (°C)	Reference Temperature (°C)
Water	0.600	0.0003	4279	100	0	25
Ethylene Glycol/Water (50%)	0.404	0.0016	3341	107.2	-34	25
Propylene Glycol/Water (50%)	0.382	0.0023	3640	222	-28	25
3M™ Novec™ HFE-7100 (HFE)	0.069	0.0018	1183	61	<-38	25
R-134a	0.0824/0.0145 Liquid/vapor[1]	N/A	1400	-26.1[7]	-103	25

Table 2. Comparisons of Properties of Typical Electronic Coolants. [4]

Properties of Typical Electronic Coolants

Coolant	GWP (GWP)	Flashpoint (°C)	Vapor Pressure (kPa)	Dielectric Constant (@1kHz)	Prandtl Number	Liquid Density (kg/m³)	Reference Temperature (°C)
Water	0	None	3.2	78.5	6.2	997	25
Ethylene Glycol/Water (50%)	Low	111	2.3	N/A	29	1076	25
Propylene Glycol/Water (50%)	Low	99.1	N/A	N/A	46	1034	25
3M™ Novec™ HFE-7300	210	None	5.9	7.4	N/A	1660	25
R-134a	1300	None 750[2]	661.9[1]	9.5	N/A	1210	25

Table 3. Comparisons of Properties of Typical Electronic Coolants. [4]

An excellent review of common cold plate fluids is provided by Lytron, an OEM of cold plates and other cooling devices. The following condenses fluid descriptions taken from Lytron's literature. [5]

The most commonly used coolants for liquid cooling applications today are:

- Water
- Deionized Water
- Inhibited Glycol and Water Solutions
- Dielectric Fluids

Water – Water has high heat capacity and thermal conductivity. It is compatible with copper, which is one of the best heat transfer materials to use for your fluid path. Facility water or tap water is likely to contain impurities that can cause corrosion in the liquid cooling loop and/or clog fluid channels. Therefore, using good quality water is recommended in order to minimize corrosion and optimize thermal performance.

If you determine that your facility water or tap water contains a large percent of minerals, salts, or other impurities, you can either filter the water or can opt to purchase filtered or deionized water. [5, 6]

Deionized Water – The deionization process removes harmful minerals, salts, and other impurities that can cause corrosion or scale formation. Compared to tap water and most fluids, deionized water has a high resistivity. Deionized water is an excellent insulator, and is used in the manufacturing of electrical components where parts must be electrically isolated. However, as water's resistivity increases, its corrosivity increases as well. When using deionized water in cold plates or heat exchangers, stainless steel tubing is recommended. [5, 7]

Inhibited Glycol and Water Solutions – The two types of glycol most commonly used for liquid cooling applications are ethylene glycol and water (EGW) and propylene glycol and water (PGW) solutions. Ethylene glycol has desirable thermal properties, including a high boiling point, low freezing point, stability over a wide range of temperatures, and high specific heat and thermal conductivity. It also has a low viscosity and, therefore, reduced pumping requirements. Although EGW has more desirable physical properties than PGW, PGW is used in applications where toxicity might be a concern. PGW is generally recognized as safe for use in food or food processing applications, and can also be used in enclosed spaces. [5, 8]

Dielectric Fluid – A dielectric fluid is non-conductive and therefore preferred over water when working with sensitive electronics. Perfluorinated carbons, such as 3M's dielectric fluid Fluorinert™, are non-flammable, non-explosive, and thermally stable over a wide range of operating temperatures. Although deionized water is also non-conductive, Fluorinert™ is less corrosive than deionized water. However, it has a much lower thermal conductivity and much higher price. PAO is a synthetic hydrocarbon used for its dielectric properties and wide range of operating temperatures. For example, the fire control radars on today's jet fighters are liquid-cooled using PAO. For testing cold plates and heat exchangers that will use PAO as the heat transfer fluid, PAO-compatible recirculating chillers are available. Like perfluorinated carbons, PAO has much lower thermal conductivity than water. [5, 9]

Conclusion

Water, deionized water, glycol/water solutions, and dielectric fluids such as fluorocarbons and PAO are the heat transfer fluids most commonly used in high performance liquid cooling applications.

It is important to select a heat transfer fluid that is compatible with your fluid path, offers corrosion protection or minimal risk of corrosion, and meets your application's specific requirements. With the right chemistry, your heat transfer fluid can provide very effective cooling for your liquid cooling loop.

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Cold Plates and Recirculating Chillers for Liquid Cooling Systems

ATS cold plates and recirculating chillers can be used in closed loop liquid cooling systems for high-powered electronics.

The miniaturization of high-powered electronics and the requisite component density that entails have led engineers to explore new cooling methods of increasing complexity. As a result, there is a growing trend in thermal management of electronics to explore more liquid cooling systems and the reintroduction, and re-imagining, of cold plate technology, which has a long history that includes its use on the Apollo 11 space shuttle. [1]

Thermal management of high-powered electronics is a critical component of a design process. Ensuring the proper cooling of a device optimizes its performance and extends MTBF. In order for a system to work properly, engineers need to establish its thermal parameters from the system down to the junction temperature of the hottest devices. The use of cold plates in closed loop liquid cooling systems has become a common and successful means to insure those temperatures are managed.

Cold plate technology has come a long way since the 1960s. At their most basic level, they are metal blocks (generally aluminum or copper) that have inlets and outlets and internal tubing to allow liquid coolant to flow through. Cold plates are placed on top of a component that requires cooling, absorbing and dissipating the heat from the component to the liquid that is then cycled through the system.

In recent years, there have been many developments in cold plate technology, including the use of microchannels to lower thermal resistance [2] or the inclusion of nanofluids in the liquid cooling loop to improve its heat transfer capabilities. [3]

An article from the October 2007 issue of Qpedia Thermal eMagazine detailed the basic components of a closed loop liquid cooling system, including:

- A cold plate or liquid block to absorb and transfer the heat from the source
- A pump to circulate the fluid in the system
- A heat exchanger to transfer heat from the liquid to the air
- A radiator fan to remove the heat in then liquid-to-air heat exchanger

The article continued, “Because of the large surface involved, coldplate applications at the board level have been straight forward…Design efforts for external coldplates to be used at the component level have greatly exceeded those for PCB level coldplates.”

Exploring liquid cooling loops at the board or the component level, according to the author, requires an examination of the heat load and junction temperature requirements and ensuring that air cooling will not suffice to meet those thermal needs. [4]

Chillers provide support for liquid cooling loops

In order to increase the effectiveness of the cold plate and of the liquid cooling loop, recirculating chillers can be added to condition the coolant before it heads back into the cold plate. The standard refrigeration cycle of recirculating chillers is displayed in Fig. 1.

Several companies have introduced recirculating chillers to the market in recent years, including ThermoFisher, PolyScience, Laird, Lytron, and ATS. Each of the chiller lines has similarities but also unique features that fit different applications.

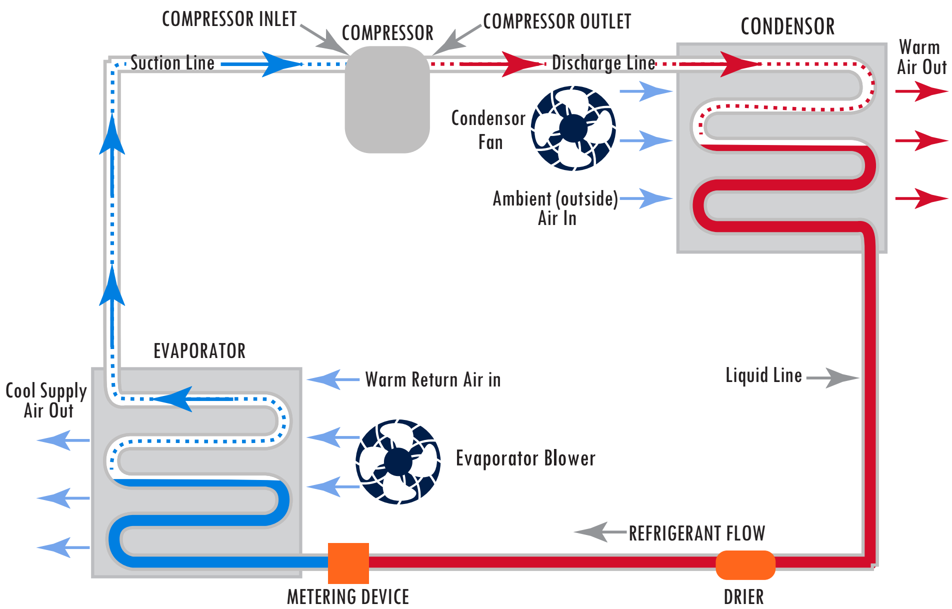

Fig. 1. The standard refrigeration cycle for recirculating chillers.

First, determine the change in temperature (ΔT), then the BTU/hour (Gallons per hour X 8.33 X ΔT), then calculate the tons of cooling ([BTU/hr]/12,000), and finally oversize by 20 percent (Tons X 1.20). [6]

Not every application will require industrial capacity, so for smaller, more portable chillers, Julabo.com had a secondary calculation for required capacity (Q).

Q=[(rV cp)material+(rV cp)bath fluid]ΔT/t

In the above equation, r equals density, V equals volume, cp equals constant-pressure specific heat, ΔT equals the change in temperature, and t equals time. “Typically, a safety factor of 20-30% extra cooling capacity is specified for the chilling system,” the article continued. “This extra cooling capacity should be calculated for the lowest temperature required in the process or application.” [7]

In order to select the right chiller, Process-Cooling.com warns that it is important to avoid “sticker shock” because of testing conditions that are ideal rather than based on real-world applications. The site suggests a safety factor of as much as 25% on temp ranges to account for environmental losses and to ensure adequate cooling capacity. [5]

The site also noted the importance of speaking with manufacturers about the cooling capacity that is needed, the required temperature range, the heat load of the application, the length and size of the pipe/tubing, and any elevation changes.

“Look for a chiller with an internal pump-pressure adjustment,” the article stated. “This feature enables the operator to dial down the external supply pressure to a level that is acceptable for the application. Because the remaining flow diverts internally into the chiller bath tank, no damage will result to the chiller pump or the external application.”

When trying to decide on the right size chiller for your particular application, there are several formulas that can help make the process easier. Bob Casto of Cold Shot Chillers, writing for CoolingBestPractices.com, gave one calculation for industrial operations.

Comparison of Industry Standard Recirculating Chillers

	ATS – Chill150V	ATS-Chill300V	ATS-Chill600V	Lytron Kodiak© RC006	Thermo-Fisher ThermoChill I	PolyScience LS Series	Laird MRC300
Temp. Range	0-40°C	5-35°C	5-35°C	5-35°C	5-30°C	-20°C- +40°C	2-40°C
Temp. Stability	±0.1°C	±0.1°C	±0.1°C	±0.1°C	±0.1°C	±0.1°C	±0.16°C
Cooling Capacity (Q_{max} at 20°C)	150W	300W	600W	825W	700W	900W	299W
Pump Pressure	0.4 BAR	0.6 BAR	0.6 BAR	n/a	n/a	43.40 PSI	n/a
Water Tank Capacity	1.0 L	4.5 L	4.5 L	4.0 L	9.5 L	2.65 L	0.45 L
Overall Dimensions (W x D x H)	230 x 260 x 380 mm (9.1 x 10.2 x 14.9”)	235 x475 x 490 mm (9.3 x 18.7 x 19.3”)	235 x 475 x 490 mm (9.3 x 18.7 x 19.3”)	318 x 483 x 559 mm (12.5 x 19.0 x 22.0”)	605 x 356 x 585 mm (23.8 x14.0 x 23.0”)	607 x 254 x 483 mm (23.9 x 10 x 19”)	213.40 x 337.80 x 345.40 mm (8.40 x 13.30 x 13.60”)
Weight	10 kg (22.1 lbs.)	23 kg (50.7 lbs.)	23 kg (50.7 lbs.)	44 kg (97.0 lbs.)	40.8 kg (90.0 lbs.)	46.3 kg (102.0 lbs.)	13.6 kg (29.9 lbs.)
Power-Failure Mode	Protects against over-pressure and compressor overload	Protects against over-pressure and compressor overload	Protects against over-pressure and compressor overload	Pressure relief factory-set at 90 PSI (6.2 BAR)	Temperature alarms	Low flow shutoff and alarm	n/a
Power Supply Required	AC 220V	Switch Selectable 120/220Vac	Switch Selectable 120/220Vac	Varies per customer choice	230Vac	120/240VAC	100-240Vac

Applications for liquid cooling systems with chillers

Recirculating chillers offer liquid cooling loops precise temperature control and coupled with cold plates can dissipate a large amount of heat from a component or system. This makes chillers (and liquid cooling loops in general) useful to a wide range of applications, including applications with demanding requirements for temperature range, reliability, and consistency.

Chillers have been part of liquid cooling systems for high-powered lasers for a number of years to ensure proper output wavelength and optimal power.viiiix To ensure optimal performance, it is important to consider safety features, such as the automatic shut-off on the ATS-Chill 150V that protects against over-pressure and compressor overload. Other laser-related applications include but are not limited to Deep draw presses, EDM, Grinding, Induction heating and ovens, Metallurgy, Polishing, Spindles, Thermal spray, and Welding. [10]

Machine hydraulics cooling and semiconductors also benefit from the inclusion of chillers in liquid cooling loops. Applications include CVD/PVD, Etch/Ashing, Wet Etch, Implant, Inductively Coupled Plasma and Atomic Absorption Spectrometry (ICP/AA), Lithography, Mass Spectroscopy (MS), Crystal Growing, Cutting/Dicing, Die Packaging and Die Testing, and Polishing/Grinding. [11]

One of the most prominent applications for liquid cooling, heat exchangers, cold plates, and chillers is in medical equipment. As outlined in an ATS case study,xii medical diagnostic and laboratory equipment requires cyclic temperature demands and precise repeatability, as well as providing comfort for patients. For Harvard Medical School, ATS engineers needed to design a system that could maintain a temperature of -70°C for more than six hours. Using a cold plate with a liquid cooling loop that included a heat exchanger, the engineers were able to successfully meet the system requirements.

Liquid cooling with chillers are also being used for medical imaging equipment and biotechnology testing in order to provide accurate results.

Conclusion

Closed loop liquid cooling systems are not new but are gaining in popularity as heat dissipation demands continue to rise. Using cold plate technology with recirculating chillers, such as the ATS-Chill150V, ATS-Chill300V, and the ATS-Chill600V, to condition the coolant in the system can offer enhanced heat transfer capability.

Portable and easy to use, ATS vapor compression chillers are air-cooled to eliminate costly water-cooling circuits and feature a front LED display panel that allows users to keep track of pressure drop between inlet and outlet and the coolant level. They each use a PID controller.

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Measuring The Thermal Resistance of Microchannel Cold Plates

The trend towards ever higher power dissipation rates has pushed liquid-cooled cold plate designers to look for more effective methods and structures to transfer heat from device to liquid. The heat dissipation level of a liquid-cooled cold plate is determined by the heat conduction in solids and the heat convection in fluids. Normally convection is the dominant factor for reducing the thermal resistancewhen highly conductive material is used to fabricate the heat sinks. In most cases, the single-phase flow inside microchannels is a laminar flow.

For a fully developed laminar flow in a square channel, with constant wall temperature or constant wall heat flux, the Nusselt number is a constant. The heat transfer coefficient can be calculated by the following equation,

$$h = \frac{Nuk}{D_h} \Rightarrow \frac{h\ 1}{D_h}$$

The heat transfer coefficient is inversely proportional to the channel hydraulic diameter. Microchannels can be directly etched on silicon or ceramics or they can be machined on metal. Different materials have different properties. For example, the copper cold plates are widely used in personal computers to cool the CPUs. Silicon/ceramic microchannels have potential applications in integrating on-chip cooling.

This paper studies how the channel size and material affects the overall thermal resistance of cold plate. The cold plate studied is illustrated in Figure 1. The cold plate has base size of 40 X 40 mm. The channel width is a and channel height is b. The cold base thickness is t. The water is chosen as the working fluid.

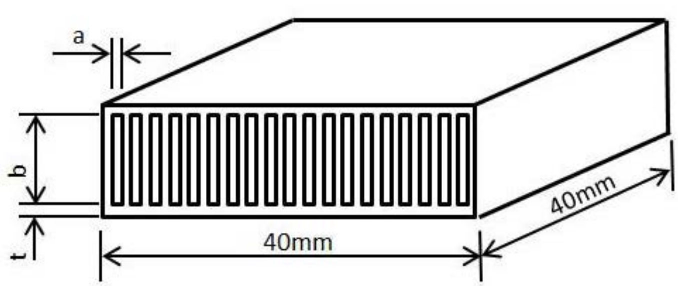

Figure 1. Cold Plate Configuration

Four typical materials are used to study the effect of thermal conductivity on cold plate performance. The properties of these four materials are listed in Table 1.

Material	Density (kg/m^3)	Thermal Conductivity (W/°C.m)	Specific Heat (kJ/kg°C)
Silicon	2330	148	0.71
Aluminum Nitride	3200	270	0.76
Copper	8933	398	0.39
Diamond	3500	2000	0.55

Table 1. Typical Cold Plate Material Properties

The overall thermal resistance of a microchannel cold plate is defined as

$$R = \frac{T_{cp} - T_{w\_inlet}}{q}$$

Where T_{cp} is the cold plate base temperature, T_{w_inlet} is the water temperature at the cold plate inlet, and q is the heat flux dissipated by the cold plate. The overall thermal resistance of a microchannel cold plate can be calculated by the following equation,

$$R = R_{spreading} + R_{conduction} + R_{convection} + R_{caloric}$$

Where,

$R_{spreading}$ is the heat spreading resistance between heat source and cold plate

$R_{conduction}$ is the conduction resistance of cold plate base

$R_{convection}$ is the convection resistance between microchannel fins and water

$R_{caloric}$ is the liquid caloric thermal resistance due to temperature rise of water

To simplify the analysis, the heat source base is assumed to be the same size as the cold plate. So, the heat spreading resistance between the heat source and the cold plate is zero. For calculating the heat spreading resistance due to the size difference between the heat source and cold plate base, please refer to a previous Qpedia paper entitled "Spreading Resistance of Single and Multiple Heat Sources" in the September, 2010 issue [1].

The base conduction resistance is affected by material, base size and base thickness,

$$R_{conduction} = \frac{t}{kA}$$

Where k is solid thermal conductivity, t is cold plate base thickness, and A is cold plate base area.
For the studied cold plate, the base size is 40 X 40 mm, the conduction thermal resistance for different material and base thickness is shown in Table 2. The conduction thermal resistance is very small and is only a small portion of overall cold plate thermal resistance, even for a silicon-made cold plate.

	$R_{conduction}$ (W/°C)			
Base Thickness (mm) / Material	0.25	0.5	0.75	1
Silicon	0.00106	0.00211	0.00317	0.00422
Aluminum Nitride	0.00058	0.00116	0.00174	0.00231
Copper	0.00039	0.00079	0.00118	0.00157
Diamond	0.00008	0.00016	0.00023	0.00031

Table 2. Cold Plate Conduction Thermal Resistance

The liquid caloric thermal resistance is inversely proportional to the fluid volumetric flow rate,

$$R_{calotic} = \frac{1}{2\dot{m}C_p}$$

Where $\dot{m}$ is the water mass flow rate, and C_p is the water specific heat. Table 3 shows the calculated liquid caloric thermal resistance at different flow rates. At an operating condition of 2 LPM (liter per minute), the resistance is around 0.0036°C/W.

Water Flow Rate (LFM)	0.5	1	2	4
$R_{calotic}$ (W/°C)	0.0143	0.0071	0.0036	0.0018

Table 3. Liquid Caloric Thermal Resistance

The convection thermal resistance is dictated by the following equation,

$$R_{convection} = \frac{1}{\eta h A}$$

Where η is the fin efficiency, h is the heat transfer coefficient of the fin, and A is the total fin surface area. Three different fin configurations (CP1, CP2, and CP3) are studied. The channel aspect ratio is kept at a constant of 15. All three fin configurations have similar fin surface areas, but their hydraulic diameter D_h is different, which leads to a different fin heat transfer coefficient. The smaller the hydraulic diameter, the larger the heat transfer coefficient. The detailed information for the three different configurations is listed in Table 4.

	Fin Thickness (mm)	Fin Height (mm)	Channel Width (mm)	Base Thickness (mm)	# of Fins	A (mm^2)	D_h (mm)	h (W/m^2.°C)
CP1	0.75	11.25	0.75	1	26	23400	1.406	2987
CP2	0.5	7.5	0.5	1	40	24000	0.938	4480
CP3	0.25	3.75	0.25	1	80	24000	0.469	8960

Table 4. Three Fin Configurations

For cold plates made of silicon, the calculated thermal resistance is shown in Table 5; all results are for 2 LPM flow and 0.5 mm base thickness. The fin efficiency of the silicon cold plate is relatively low (<40%) due to the low conductivity of silicon. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is 81% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.376	0	0.0021	0.0381	0.0036	0.0438
CP2	0.377	0	0.0021	0.0247	0.0036	0.0304
CP3	0.378	0	0.0021	0.0123	0.0036	0.0180

Table 5. Thermal Resistance of Silicon Cold Plate

The calculated thermal resistance for the aluminum nitride cold plate is shown in Table 6. Compared to silicon cold plate, its fin efficiency is higher (~49%) and the overall thermal resistance is low. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is still around 79% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.492	0	0.0012	0.0291	0.0036	0.0338
CP2	0.494	0	0.0012	0.0188	0.0036	0.0236
CP3	0.495	0	0.0012	0.0094	0.0036	0.0141

Table 6 Thermal Resistance of Aluminum Nitride Plate

The calculated thermal resistance for the copper plate is shown in Table 7. Its fin efficiency increases to around 57% and the overall thermal resistance is 13% lower than that of the aluminum nitride cold plate. In the case of the 0.5 mm channel (CP2), the convection thermal resistance is around 79% of the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.574	0	0.0008	0.0249	0.0036	0.0293
CP2	0.576	0	0.0008	0.0162	0.0036	0.0205
CP3	0.577	0	0.0008	0.0081	0.0036	0.0124

Table 7 Thermal Resistance of Copper Plate

The calculated thermal resistance for the diamond plate is shown in Table 8. Its fin efficiency jumps to 86% and the overall thermal resistance is 29% lower than that of the copper cold plate. As for the 0.5 mm channel (CP2), the convection thermal resistance is around 74% of the overall thermal resistance. In the case of the 0.25 mm channel (CP3), the convection thermal resistance drops to 59% of the overall thermal resistance. Here, the $R_{caloric}$ starts to have a larger impact on the overall thermal resistance.

	η	$R_{spreading}$ (°C/W)	$R_{conduction}$ (°C/W)	$R_{convection}$ (°C/W)	$R_{caloric}$ (°C/W)	R (°C/W)
CP1	0.858	0	0.0002	0.0167	0.0036	0.0204
CP2	0.859	0	0.0002	0.0108	0.0036	0.0146
CP3	0.859	0	0.0002	0.0054	0.0036	0.0091

Table 8. Thermal Resistance of Diamond Cold Plate

From the above data, it is obvious that by using good material and a microchannel structure, cold plates can achieve amazingly low thermal resistance rates. For example, the copper cold plate with 0.5 mm wide channels can display a thermal resistance of 0.0205°C/W for a 40 X 40 mm size, which translates to a unit thermal resistance of 0.33°C/W/cm^2. If the heat source has a heat flux of 100W/cm^2, the temperature rise caused by the cold plate is only 2.1ºC. Through the above comparisons, it is clear that materials with higher thermal conductivity will have better thermal performance.

Diamond is the best but there is no feasible way to justify its cost for cooling commercial products. Copper is a very good choice for cold plates used to transfer heat from higher power chips to water.

On the other hand, reducing the hydraulic diameter of the channel will dramatically decrease the convection resistance. However, there are two drawbacks for reducing the hydraulic diameter of the channel. First, it will greatly increase the pressure drop across the channel, which leads to more pumping power required for the pump. Second, the smaller channel size will have more chance of clogging due to particles inside the working fluid, which requires finer filtering system. For high performance cold plates, the Rcaloric will be an important factor on overall thermal resistance, besides convection thermal resistance. The only way to reduce it is by increasing the liquid flow rate, which will lead to more pressure drop and this then requires a better pump. When designing a cutting edge cold plate, engineers should pay a lot of attention to pressure drop, pumping power, system complexity and reliability while pursuing high performance.

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