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Two-phase Fluid Selection for High-temperature Automotive Platforms

by Darin Sharar, Nicholas Jankowski, and Avram Bar-Cohen

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14. ABSTRACT

High-temperature environments and device self-heating are pushing the thermal limits of power electronics. This is particularly true in automotive applications, where there is a transition from internal combustion architectures to hybrid electric and full electric vehicles. In general, two-phase cooling has emerged as an attractive solution to meeting the high-temperature, high-power cooling needs of the aforementioned electronics. However, it is important to understand the benefits and limitations of various fluids when designing a two-phase cooling system. To aid in the selection process and add to the current knowledge base, this report briefly discusses the current state of high temperature electronics, reviews platform considerations when selecting a fluid, and introduces a two-phase Figure of Merit (FOM) to analyze over 110 different fluids for cooling high-temperature electronics up to 500 °C.

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1. Introduction

The last several decades have witnessed a dramatic increase in the use of electronics on a variety of deep-well drilling, geothermal, aircraft, power generation, automotive, and other high-temperature systems. This trend continues due to the availability of powerful microelectronic devices, and the enhanced system functionality and performance associated with improved system integration. Table 1 shows several predominant markets, their temperature ranges, and expected lifetimes.

Table 1. High temperature electronic markets and performance metrics (*1*).

Market	**Temp (°C)**	**Life (KHrs)**	**TTM (yrs)**
Down Hole Instruments			
- MWD & gages	175–225	>2	1–2
- Perm. monitoring	150–225	40	1–2
- Geothermal	250–300	≤8	2–3
Turbine Engine			
- Aircraft	200–300	40–80	5–10
- Power generation	225–250	8–40	2–5
Int. Comb. Engine			
- ABS sensor	>150	5	4
- Drive train module	>150	5	4
- Heavy engine	>150	20	4

1.1 Automotive Applications

High temperature electronics and sensors are used for internal combustion engine control applications such as engine control units (ECUs), camshaft position sensing, and in-cylinder pressure sensing. These measurements directly affect emissions and system power efficiency. Accuracy is an inherent feature of the sensor, but the precision of the measurements can be improved by sensor and signal conditioning close to, or inside of, the engine components. Similar efficiency/measurement precision tradeoffs can be observed in anti-lock braking systems (ABS) and vehicle drive trains. Consequently, integrated microelectronic sensors for internal combustion engine applications can exceed 150 °C (see table 1).

There has also been a growing trend towards the use of vehicle electric platforms in the commercial and military sectors. Platform proponents have demonstrated that replacing the traditional mechanical power, propulsion, and control systems with full-electric or hybrid-electric equivalents improves system design flexibility and functionality, while also reducing system size, weight, and power (SWaP) requirements. Figure 1 schematically shows an electric vehicle architecture complete with battery bank, power electronics, electric motor, and transmission (*2*). Aligned efforts aimed towards increasing component power while reducing component size has led to improved power density, but has also exacerbated the task of removing waste heat. Future integration of power transistors and smart power devices will require operation from 175 °C to 200 °C (*3*).

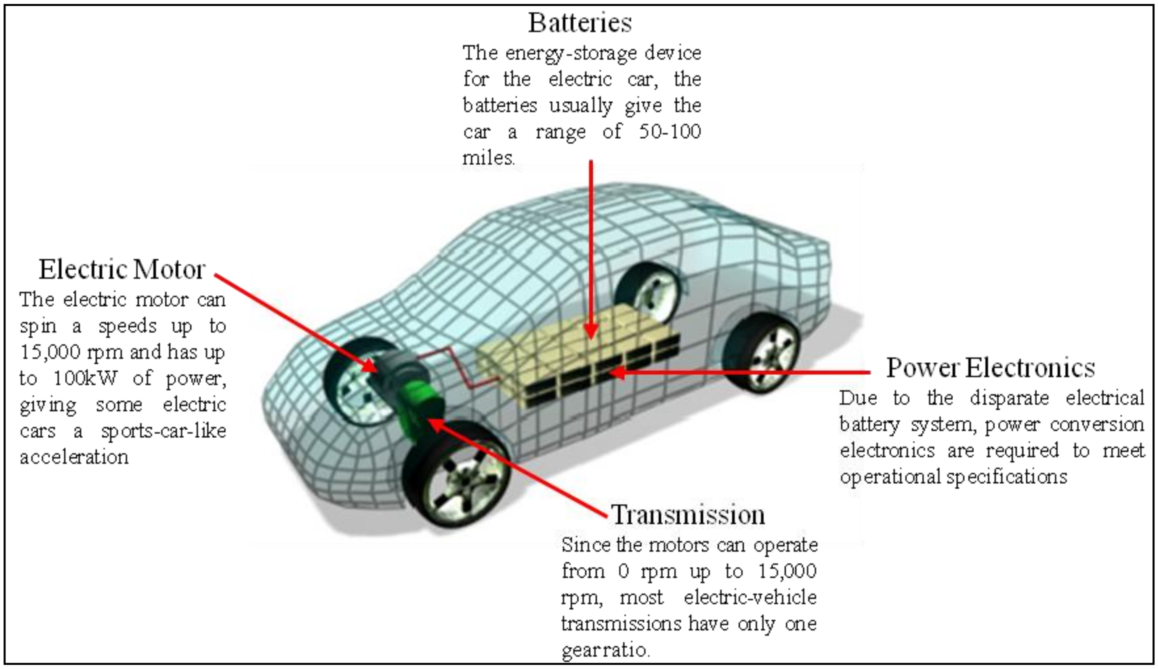
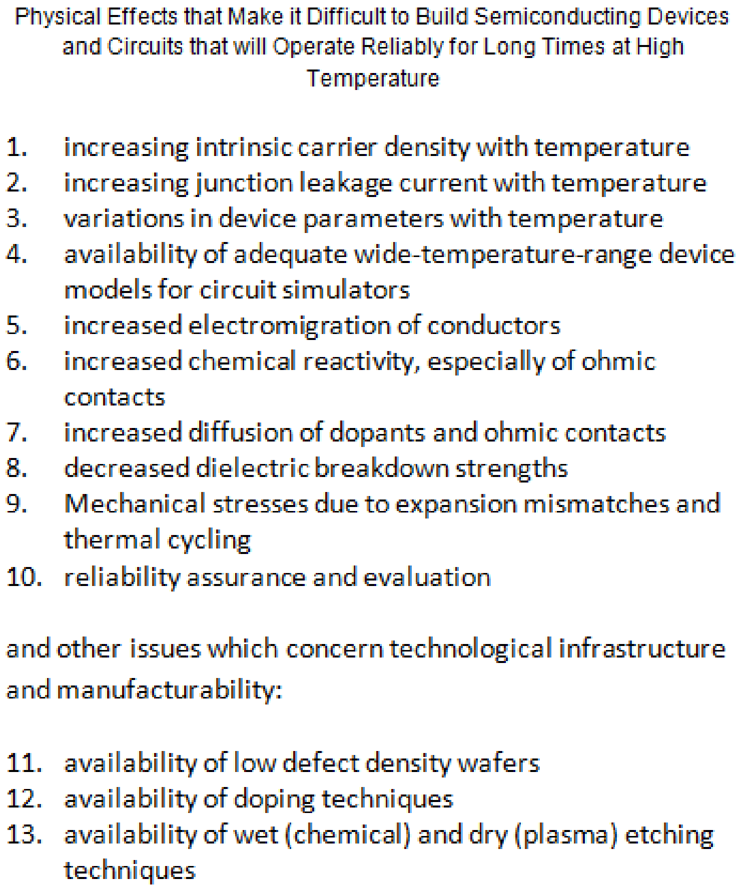


Figure 1. Major components of an electric vehicle – (*2*) adjusted from Howstuffworks.com high temperature operation concerns.

High temperatures, >125 °C, are inherent to the operation of many of these systems. However, practical operation of silicon electronics at these elevated temperatures is problematic, especially when considering power electronics, which can experience significant self-heating and further increased device junction temperatures. The most fundamental thermal limit to semiconductor device operation is due to the exponential increase of intrinsic carrier concentration as temperature increases (*4, 5*). As a silicon (Si) device approaches 125 °C, the device becomes “intrinsic” and, as a result, inoperable as a switching device. Other failure mechanisms exacerbated by increased junction temperature include: p-n junction leakage, degraded carrier mobility, time dependent dielectric breakdown, and electromigration (to name a few). Table 2 gives a fairly comprehensive list of the major technical issues facing high-temperature electronics, both inside and outside the device.

Table 2. Major technical issues facing high-temperature electronics (*6*).



Physical Effects that Make it Difficult to Build Semiconducting Devices
and Circuits that will Operate Reliably for Long Times at High
Temperature

1. increasing intrinsic carrier density with temperature
2. increasing junction leakage current with temperature
3. variations in device parameters with temperature
4. availability of adequate wide-temperature-range device models for circuit simulators
5. increased electromigration of conductors
6. increased chemical reactivity, especially of ohmic contacts
7. increased diffusion of dopants and ohmic contacts
8. decreased dielectric breakdown strengths
9. Mechanical stresses due to expansion mismatches and thermal cycling
10. reliability assurance and evaluation

and other issues which concern technological infrastructure and manufacturability:

11. availability of low defect density wafers
12. availability of doping techniques
13. availability of wet (chemical) and dry (plasma) etching techniques

The high-temperature limits of Si devices are, however, not without reprieve. In some cases, extra work by researchers can be done to uprate the device, either by parameter conformance, parameter re-characterization, or stress balancing. However, this process can become very time-consuming and costly, and there is no guarantee that any method will work for a give device. Higher temperature Si devices can also be realized with the silicon on insulator (SOI) layout schematically shown in figure 2. Compared to a standard Si MOSFET, shown on the left in figure 2, which consist of n-type channels in a p-type substrate, SOI devices consist of a p-type channel between two n-type channels with a layer of silicon oxide (SiO_2) underneath. The result is a decreased n-p leakage area by a factor of ~100 and an associated reduction in leakage current. This enables SOI devices to operate in the 200–300 °C temperature range (*7*). However, one drawback of the SOI technology compared to bulk Si is the difficulty in implementation. From an economic standpoint, the mass production of high-quality silicon on top of high-quality insulator has proven a nontrivial technical challenge (*7*). Furthermore, SOI devices are particularly prone to failure at temperatures above 300 °C due to gate oxide degradation and threshold voltage shifting (*5*), electromigration (*8*), and, to one degree or another, the failure mechanisms discussed in table 2.

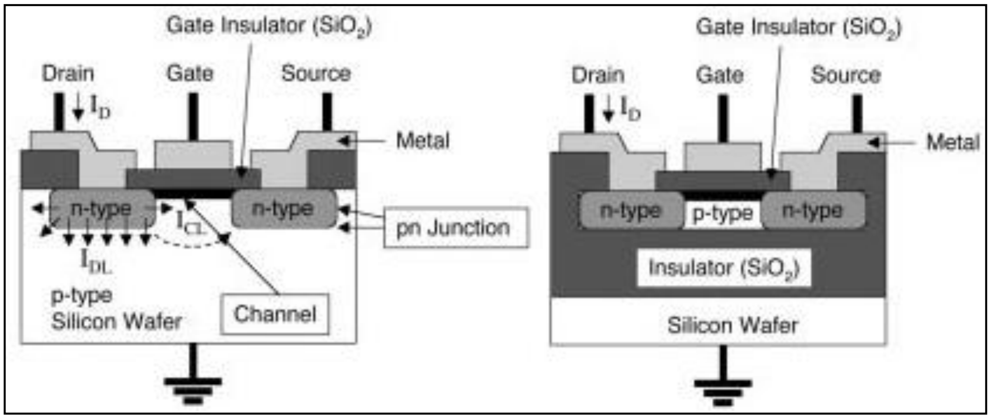


Figure 2. Schematic diagram of n-channel Si MOSFET (left) and n-channel SOI MOSFET (right) (*7*).

Beyond 300 °C, wide bandgap electronics like silicon carbide (SiC), and the Group III-Nitrides (such as GaN) are promising candidates to replace Si technology. As shown in table 3, wide bandgap materials have bandgaps larger than bulk Si. The result of larger bandgap energy is a reduced quantity of intrinsic carriers for a given temperature. As a result, wide bandgap materials can operate at much higher temperatures, 300–600 °C (*9–12*). However, wide bandgap device fabrication is not as mature as Si fabrication, resulting in technical difficulties and higher cost. Crystal growth and quality challenges are still a major concern in wide bandgap materials (*13, 14*), which results in discontinuities and large leakage currents at very high temperatures. Similarly, the reliability of metal-semiconductor interconnects is a major concern at high temperatures. Not unlike Si devices, electromigration, chemical reactivity, noble metal oxidization, intermetallic growth, CTE mismatch and other failure mechanisms are an issue with wide bandgap materials at very high temperatures.

Table 3. Bandgap energy for common semiconductor materials.

Semiconductor	Band Gap @ 302K
Germanium	0.67 eV
Silicon	1.11 eV
Gallium Arsenide	1.43 eV
Silicon Carbide	2.86 eV
Gallium Nitride	3.4 eV
Diamond	5.5 eV

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2. High Temperature Electronic Thermal Management

Bulk silicon devices are typically cheaper than SOI devices, which in turn are cheaper than wide bandgap devices. An effective thermal management scheme would allow cooler device operation and the use of lower temperature (cheaper) semiconductor devices. Furthermore, it is apparent that there is also a need for thermal management to alleviate the failure mechanisms and losses associated with high device temperatures for all three of the technologies.

2.1 Two-phase Cooling

Traditionally, electronics have relied on air-cooled heat sinks or liquid-cooled cold plates to manage electronic waste heat; however, cooling schemes using liquid-vapor phase change (hereafter referred to as “two-phase cooling”) have been examined as a practical and cost-conscious next step beyond single-phase cooling. In fact, the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) have already distinguished two-phase cooling as a favorable solution to meeting the strict demands for some emerging cooling requirements (*15, 16*).

Two-phase cooling refers to intentionally using a cooling fluid in a manner where at least a portion of the fluid is transformed into vapor upon heating, thereby resulting in a gas/liquid mixture in a portion of the cooling loop. The boiling event generally occurs when the temperature of the heat acquisition surface exceeds the liquid’s saturation temperature, or boiling point. At this temperature, the vapor pressure of the liquid is equal to the pressure of the environmental surroundings, thus allowing vapor bubbles to form at the solid-liquid interface, grow, and eventually detach from the surface. After this point, multi-phase flow exists in the system until the vapor is either separated from the liquid flow or is cooled to the point of condensing back into a liquid; schematically, the components typically used (the filter and vapor/liquid separator are optional) to achieve a two-phase loop are presented in figure 3.

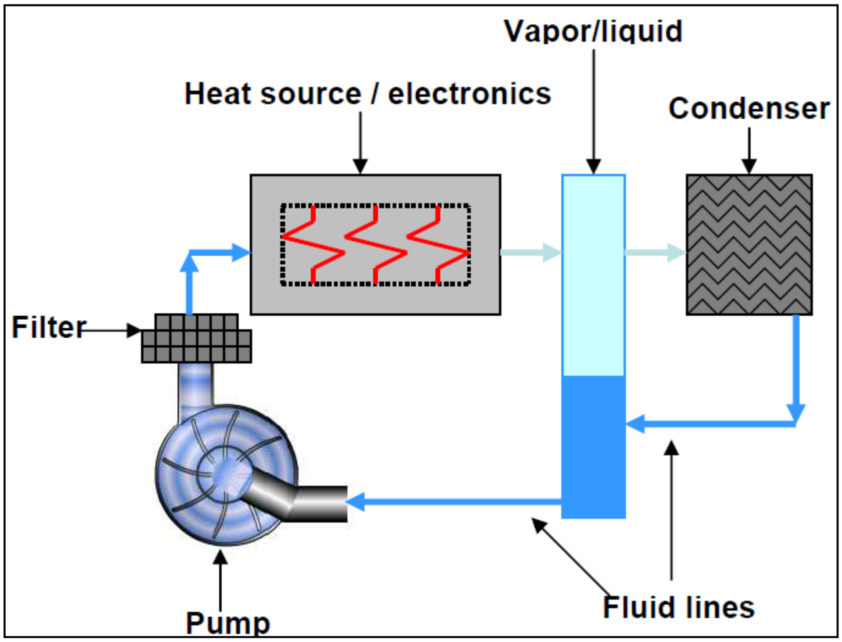

Figure 3. Primary components of a two-phase coolant loop.

Compared to single-phase cooling, two-phase cooling provides improved heat dissipation for a given volume or mass of fluid due to the fact that the latent heat of a fluid can be orders of magnitude larger than the specific heat. This effect can be seen by comparing equation 1 for single-phase heat transfer with water and equation 2 for two-phase heat transfer using water:

$$q = \dot{m} C_p dT = \dot{m} \times 4186 \times 20 \sim \dot{m} \times 84000 \tag{1}$$

$$q = \dot{m} h_{lg} x = \dot{m} \times 2257000 \times 0.5 \sim \dot{m} \times 1130000 \tag{2}$$

Where q is dissipated heat, $\dot{m}$ is mass flowrate, C_p is specific heat, dT is the change in fluid temperature, h_{lg} is the latent heat of vaporization, and x is the vapor quality. Here, we assumed a moderate 20 °C single-phase temperature rise and a conservative quality of 0.5, which means that 50% of the fluid has been vaporized. Obviously, the more fluid you vaporize, the more dramatic the effect would be. Two-phase cooling also has the benefits of increased heat transfer coefficients, flowrate reduction, pressure drop reduction, improved temperature uniformity, and order-of-magnitude improvement in heat dissipation for a fixed pumping power (*17*).

Based on these benefits, the remainder of this report will explore the use of two-phase cooling to mitigate temperature concerns in high-temperature electronic components. First, platform considerations for two-phase cooling will be addressed. Next, an analysis of conventional and unconventional two-phase cooling fluids will be performed; a two-phase figure of merit (FOM) will be introduced to assist in the selection process. Finally, conclusions will be drawn and recommendations for future research will be recommended.

2.2 Platform Considerations

The focus here will be practical implementation of a two-phase coolant loop on a vehicle platform. Specific to Army vehicle applications, designs have relied on 80–100 °C fluid bypassed from the antifreeze-based automotive liquid coolant loop to manage waste heat (*18*). The use of engine coolant removes the need for additional condensers, pumps, and fluid reservoirs. However, in practice, other vehicle platforms have adopted the use of multiple coolant loops; the Chevy Volt hybrid vehicle is equipped with four independent cooling loops. A power electronics loop is devoted to cooling the battery charger and power inverter module. A battery loop regulates the 360 V high voltage battery. An engine cooling loop cools the gasoline engine and, when required, doubles as a heater for the passenger compartment (*19*).

There are definite disadvantages involved with implementing secondary loops; the most obvious of these are the additional SWaP required for the extra loop components such as pumps, hoses/tubing, and heat exchangers/condensers. However, while there are possible drawbacks of such a multi-loop system, the overall potential for cooling performance improvement in an optimized multi-loop system may be able to offset those negative elements. Four potential benefits lie in the ability to design optimized coolant loops for the specific heat loads and temperature requirements in the system:

- Flexibility of working fluid, including refrigerants in some cases.
- Possibility to implement a vapor compression refrigeration cycle to deliver coolant to the electronics at specified temperatures.
- Pump autonomy to optimize system pressure, flow, and temperature to match specific heat loads.
- Potential for hermetically sealed systems to reduce contamination and clogging/fouling potential.

3. Two-phase Fluid Selection

It is important to understand the benefits and limitations of coolant fluids when designing a two-phase cooling system (or any cooling system for that matter). Knowledge of this information will lead to more informed design choices when developing new systems or modifying existing ones. To aid in this process and add to the existing knowledge base, the remainder of the report will discuss the critical specifications when selecting a two-phase coolant fluid based on fluid limits, such as saturation temperature/pressure and a two-phase critical heat flux (CHF) FOM.

3.1 Critical Heat Flux (CHF) and Figure of Merit (FOM)

There are inherent benefits of two-phase cooling. A poorly designed two-phase cooling system, however, can fail catastrophically due to CHF. Figure 4 shows the transition from natural convection to nucleate boiling (A), column and slug boiling (P), and critical heat flux (C) for water at 1 atm. Critical heat flux (C) is marked by an excessive rise in device temperature that can result in overheating or physical melting of system components (E). When designing a two-phase cooling system, CHF should generally be as large as possible to allow dissipation of high power density electronics; if the electronic power density if larger than the fluid CHF, overheating and potential failure are likely.

Typically, CHF can occur at wall superheats (temperature rise over the saturation temperature of the fluid) between 15 and 25 °C, placing a lower limit on the fluid boiling temperature for a given electronic device temperature before failure occurs. For example, cooling a 250 °C SOI device with 100 °C saturated water at 1 atm would be prone to failure—a minimum fluid saturation temperature of ~225 °C would be recommended to avoid CHF. Similarly, a fluid saturation temperature close to 250 °C would not provide sufficient temperature overhead to effectively cool the device before reaching its temperature limits. These criteria are used in the following sections to choose the saturation temperatures, and associated fluid properties, of two-phase fluids for various temperature ranges. After selecting the appropriate saturation temperatures and fluid properties, equation 3 can be used to predict CHF for flow boiling with and without subcooled fluid (*21*):

$$CHF = 0.0742\left(\frac{u^{0.27}}{L^{0.365}}\right)\left(\rho_g^{0.239}\rho_f^{0.396}\sigma^{0.365}h_{fg}\right)\left[1 + 0.952\left(\frac{\rho_f^{0.118}C_p^{1.414}}{\rho_g^{0.118}h_{fg}^{1.414}}\right)\Delta T_{sub}^{1.414}\right] \qquad (3)$$

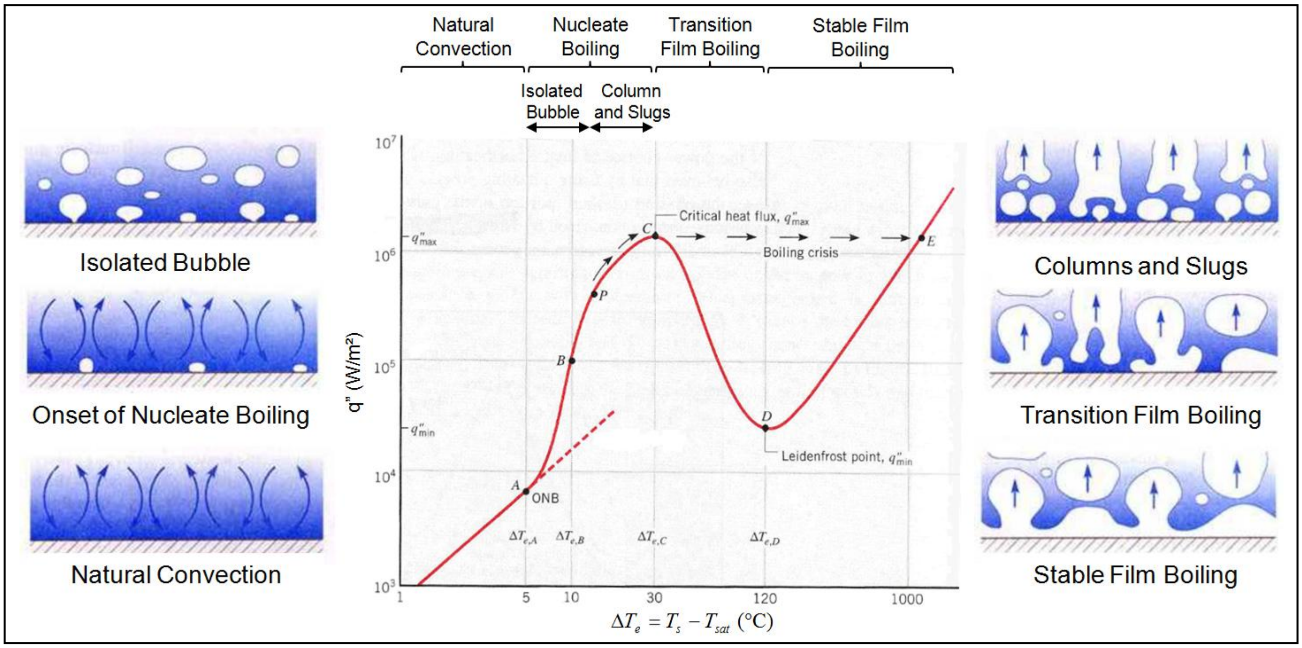

Figure 4. Two-phase failure mechanism –CHF for water at 1 atm (*20*).

where u is the fluid velocity, L is the heated length, ρ_g is the vapor density, ρ_f is the fluid density, σ is the surface tension, h_{fg} is the latent heat of vaporization, C_p is the specific heat, and ΔT_{sub} is the amount of liquid subcooling below saturation. This correlation may be used in cooling of small heated regions such as electronic devices; it was developed for heated lengths from 0.25 to 5 mm and bulk velocities from 1 to 15 m/s. From equation 4, a two-phase saturated flow boiling CHF FOM can be obtained by ignoring geometric (L), velocity (u), and subcooling effects (ΔT_{sub}). The result is (*22*):

$$FOM_{CHF,FB,S} = \left(\rho_g^{0.239} \rho_f^{0.396} \sigma^{0.365} h_{fg}\right) \tag{4}$$

The aforementioned two-phase saturated flow boiling CHF FOM will be used to analyze the relative value of different coolant fluids in the following sections.

3.2 Saturation Temperature and Pressure

A liquid may be induced to boil over a range of temperatures, depending on the pressure of the environment, where increasing system pressure will increase the nominal boiling temperature of the fluid. This provides an additional benefit for a system using two-phase cooling, whereby the boiling and condensation temperatures of enclosed coolant loops may be tailored by controlling system pressurization. This is especially important when considering the proceeding discussion, where superheats greater than ~25 °C can lead to premature CHF.

3.3 Standard Fluids from NIST REFPROP7 (*23*)

Table 4 shows material properties for a variety of standard refrigerants/coolants at a saturation temperature of 100 °C. This temperature was chosen because it represents 25 °C below the maximum operating temperature of bulk Si, or the maximum superheat before CHF typically occurs. The pressure required to obtain these saturation temperatures, as well as calculated FOMs from equation 4 are shown. These values were obtained from isoproperty tables using NIST REFPROP7 (*23*). A variety of other fluids were available in the NIST REFPROP7 library for analysis: argon, carbon dioxide, ethane, methane, nitrogen, oxygen, propane, propylene, R115, R116, R12, R124, R125, R13, R134a, R14, R143a, R152a, R218, R22, R227ea, R23, R236fa, R32, R41, RC318, R401A, R401B, R401C, R402A, R402B, R403A, R403B, R404A, R405A, R406A, R407A, R407B, R407C, R407D, R407E, R408A, R409A, R409A, R409B, R410A, R410B, R411A, R411B, R412A, R413A, R414B, R500, R501, R502, R503, R504, R507A, R508A, R508B, and R509A. However, these materials were '*undefined*' for 100 °C and the associated pressure required to achieve this saturation temperature. Presumably, this is because the defined operation conditions are outside the practical (above the critical temperature) or historically significant limits of these fluids. It is also worth noting that HFO-1234yf, a refrigerant that has been identified by Honeywell and DuPont as the preferred low-GWP (Global Warming Potential) refrigerant (*24*), has a critical temperature of 94 °C (*25*) and is probably not suitable for cooling high temperature electronics. However, due to the similar performance to R-134a, low toxicity, and excellent environmental properties, HFO-1234yf is being pursued as a direct substitution for R-134a refrigeration applications.

Table 4. Material properties and FOMs for standard coolants at 100 °C saturation temperature, from (*23*).

Fluid	**Pressure (MPa/psi)**	**Liquid density (kg/m³)**	**Vapor density (kg/m³)**	**Latent heat (kJ/kg)**	**Surface tension (N/m)**	**FOM**
Water	0.101/15	958	0.6	2256	0.0589	10761
R11	0.824/119	1275	43.3	147	0.0087	1087
R113	0.437/63	1369	29.9	125	0.0091	890
R114	1.42/206	1170	109.1	88	0.0032	549
R123	0.785/114	1247	46.9	134	0.0068	920
R141b	0.677/98	1073	29.7	185	0.0095	1208
R142b	2.08/302	869	101.7	131	0.0029	690
R236ea	1.57/228	1128	109.7	103	0.0031	621
R245ca	0.928/134	1165	50.3	151	0.0070	1038
R245fa	1.26/183	1093	71.9	135	0.0047	855
Ammonia	6.25/907	456	56.1	716	0.0051	3096
Butane	1.52/221	467	39.3	258	0.0038	929
Isobutane	1.99/288	430	56.8	211	0.0023	672

From table 4, water appears to be the most favorable fluid for cooling high temperature Si devices around the upper limit of 125 °C. The FOM of water (10761) is more than three times larger than the second best fluid, ammonia (3096), and 8.5 times larger than the third best fluid, R141b (1208). As seen from table 4 and equation 5, this is a direct result of the order-of-magnitude larger latent heat and surface tension of water compared to the other fluids. The only restoring factor that prevents water from completely dominating is the large liquid-vapor density difference.

An additional benefit of using water is that it boils at 100 °C at atmospheric pressure, compared to 6.25 and 0.677 MPa for Ammonia and R141b, respectively. Some of the saturation pressures for other fluids may seem prohibitively high; however, most stainless steel tubing is capable of multiple thousands of psi and Swagelok tube fittings can be purchased capable of 60,000 psi without customization. One disadvantage of water is its inherent corrosive, electrically conductive nature. In contrast, many of the refrigerants are non-corrosive and have dielectric properties, thus allowing direct cooling of electronic components (*26*). Direct cooling provides the potential to eliminate conduction layers in the thermal package and thermal interface materials (TIM), which can hinder thermal performance. Therefore, under certain operation conditions, one could justify using a non-water fluid based on the referenced knowledge.

A similar study was performed for the fluids in the REFPROP7 (*23*) library for saturation temperatures of 275 °C and 575 °C. These temperatures represent 25 °C below the practical upper limits of SOI (300 °C) and wide bandgap semiconductors (600 °C) to avoid CHF. Table 5 shows the results for saturation temperatures of 275 °C. The only fluid that was defined by NIST REFPROP7 was water at a pressure of 205 psi. All other fluids, including those that were '*undefined*' for 100 °C, were '*undefined*' for 275 °C. None of the fluids, including water, were defined for a saturation temperature of 575 °C.

Table 5. Material properties and FOMs for water at 275 °C saturation temperature.

Fluid	**Pressure (MPa/psi)**	**Liquid density (kg/m³)**	**Vapor density (kg/m³)**	**Latent heat (kJ/kg)**	**Surface tension (N/m)**	**FOM**
Water	1.41/205	759	30.5	1574	0.0201	11848

Comparing the results for water at 100 °C and 275 °C shows a 10% increase in the FOM. Upon inspection, this is due primarily to a sharp increase in the vapor density (from 0.6 to 30.5 kg/m^3). A decrease in the latent heat of vaporization (from 2256 to 1574 kJ/kg) and surface tension (from 0.059 to 0.020 N/m) inhibited further FOM improvement.

3.4 3M Thermal Management Fluids

It is important to realize that there are a variety of alternative dielectric coolant fluids available that are not in the NIST REFPROP7 library. Table 6 shows material properties for 3M thermal management fluids (*27*), also sold as 3M Novec Engineered Fluids and 3M Fluorinert Electronic Liquids, at 1 atm and 25 °C. The material properties as a function of temperature and pressure are not readily available, but the boiling and condensation temperatures of these coolants may be tailored by controlling system pressurization.

Table 6. Material properties and FOMs for 3M engineering fluids at 1 atm.

Fluid	Boiling point (˚C)	Pour point (˚C)	Liquid density (kg/m³)	Vapor density (kg/m³)	Latent heat (kJ/kg)	Surface tension (N/m)	FOM
Novec 7000	34	–122	1400	N/A	142	0.0124	N/A
Novec 7100	61	–135	1510	N/A	112	0.0136	N/A
Novec 7200	76	–138	1420	N/A	119	0.0136	N/A
Novec 7300	98	–38	1660	N/A	102	0.015	N/A
Novec 7500	128	–100	1614	N/A	89	0.0162	N/A
Novec 7600	131	–98	1540	N/A	116	0.0177	N/A
Novec 649	49	–108	1600	N/A	88	0.0108	N/A
FC-40	155	–57	1850	N/A	68	0.016	N/A
FC-43	174	–50	1860	N/A	70	0.016	N/A
FC-72	56	–90	1680	N/A	88	0.010	N/A
FC-84	80	–95	1730	N/A	90	0.012	N/A
FC-770	95	–127	1793	N/A	86	0.015	N/A
FC-3283	128	–50	1820	N/A	78	0.015	N/A
FC-3284	50	–73	1710	N/A	105	0.013	N/A

These fluids provide a broad range of boiling points (34 °C up to 175 °C) and freezing points (–38 °C down to –138 °C) at ambient conditions. They offer excellent dielectric properties, good material compatibility, low toxicity, non-flammability, and zero Ozone Depletion Potential (ODP). As before, the dielectric properties and non-corrosive nature of 3M fluids provide the potential for direct cooling and thermal stack reductions. Furthermore, the relatively high boiling points of some of these fluids demonstrate the potential for high temperature operation with elevated system pressures.

The vapor density values necessary for FOM calculations are not readily available online; direct comparison based on this metric is not possible. However, a quick comparison of surface tension, latent heat of vaporization, and fluid density indicates that 3M Engineering Fluids at 1 atm would have FOMs (and thermal performance) close to or slightly worse than the refrigerants discussed in table 4—assuming, of course, the vapor densities are not starkly different. For example, the FOM of Novec 7000 (ignoring the vapor density term) would be:

$$FOM_{CHF,FB,S} = \left(\rho_f^{0.396}\sigma^{0.365}h_{fg}\right) = (1400^{0.396} \times 0.0124^{0.365} \times 142 = 503 \tag{5}$$

And the FOM of R141b (ignoring the vapor density term) would be:

$$FOM_{CHF,FB,S} = \left(\rho_f^{0.396}\sigma^{0.365}h_{fg}\right) = (1073^{0.396} \times 0.00952^{0.365} \times 185) = 537 \tag{6}$$

3.5 Additional High-temperature Fluids

We have discussed the fluids suitable for cooling 125 °C electronics and the potential for cooling with water and possibly 3M fluids, for 300 °C electronics. However, it seems unlikely that any of the fluids previously discussed will be able to operate at temperatures as high as 575 °C. Table 7 shows a list of notable fluids that boil at temperatures exceeding 100 °C. While most of these fluids are flammable, extremely corrosive, explosive, or harmful (or all four), three of these fluids may be suitable as a high-temperature coolant—Dowtherm (boiling point 258 °C), ethylene glycol (boiling point 197 °C), and propylene glycol (boiling point 187 °C). Dowtherm is a heat transfer fluid developed by Dow Chemical Company. It is a eutectic mixture of two stable compounds, biphenyl ($C_{12}H_{10}$) and diphenyl ($C_{12}H_{10}O$). These compounds have practically the same vapor pressure, so the mixture can be handled as a single compound rather than a binary mixture. Propylene Glycol ($C_3H_8O_2$) and Ethylene Glycol ($C_2H_6O_2$) are organic compounds that are widely used as automotive antifreezes.

Table 7. Boiling points of various fluids at 1 atm.

Fluid	Boiling point (˚C)
Acetic acid anhydride	139
Alcohol	97-117
Aniline	184
Butyric acid n	162
Carbonic acid	182
Dowtherm	258
Glycerin	290
Ethylene bromide	131
Ethylene glycol	197
Iodine	184
Jet fuel	163
Kerosine	150–300
Mercury	359
Napthalene	218
Nitric acid	120
Nitrobenzene	210
Nonane-n	150
Octane-n	125
Olive oil	300
Petroleum	210
Propionic acid	141
Propylene Glycol	187
Toluene	110
Turpentine	160
Xylene-o	142

Shown in table 8 are the material properties, boil/freeze temperatures, and FOM for the -glycol and Dowtherm fluids at 1 atm. As can be seen, the glycol fluids have melting temperatures below –10 °C, while the Dowtherm fluid melts at 12 °C. This could make application of Dowtherm fluids difficult. However, as discussed above, the boiling point of Dowtherm is

258 °C, the highest of the three fluids, which provides hope for cooling high-temperature electronics. It is interesting to point out that this is very close to the practical upper limit of SOI before CHF (275 °C). Dowtherm could potentially boil at 275 °C upon pressurizing the coolant loop.

Table 8. Material properties and FOMs glycols and dowtherm fluids at 1 atm (*28–30*)

Fluid	**Boiling point (˚C)**	**Pour point (˚C)**	**Liquid density (kg/m³)**	**Vapor density (kg/m³)**	**Latent heat (kJ/kg)**	**Surface tension (N/m)**	**FOM**
Ethylene glycol	197	–13	1115	2.1	800	0.048	5075
Propylene glycol	187	–57	1038	2.62	914	0.036	5350
Dowtherm A	258	12	854	3.8	297	0.040	1829

As shown in the last column of table 8, propylene glycol and ethylene glycol have very similar FOMs (5350 and 5075), but Propylene Glycol is slightly better due to a larger latent heat of vaporization and vapor density. Dowtherm A has the worst FOM of the three (1829) due to the low latent heat and liquid density, but remains a promising fluid due to the high boiling temperature. These FOMs are worse than water but generally better than the refrigerants and 3M dielectric fluids studied.

4. Conclusions and Future Work

Enhanced system functionality and performance for deep-well drilling, geothermal, aircraft, power generation, automotive, and other high-temperature systems have resulted from improved electronic system integration. However, the environments inherent to these systems pose temperatures >125 °C, which causes device performance degradation.

A variety of two-phase coolant fluids were explored in the course of this study to determine what options were available for a thermal engineer trying to address these temperature concerns. Water demonstrated the highest figure of merit out of all of the fluids tested. By changing the pressure of water, from atmospheric pressure to 205 psi, two-phase electronic cooling from 125 °C to 300 °C was demonstrated. From table 1, this covers the entire range of high-temperature electronics for the down hole instruments, turbines, and automotive applications.

It was found that standard refrigerants, such as R141b, could be pressurized to cool 125 °C electronics, albeit not as well as water. Furthermore, 3M thermal management fluids provide FOMs similar to refrigerants and a wide range of boiling points (34 °C up to 175 °C). Unlike water, which is electrically conductive and corrosive, the refrigerants and 3M fluids are non-corrosive dielectric fluids. As a result, a system engineer could justify using the lower-FOM fluids for direct cooling.

Three other fluids—ethylene glycol (boiling point 197 °C), propylene glycol (boiling point 187˚C), and Dowtherm (boiling point 258 °C)—were studied. These three fluids had performance worse than water but typically better than the refrigerants and 3M fluids. Furthermore, they possess higher boiling points which could allow higher-temperature two-phase cooling.

The results presented in this report serve only as a tool for choosing a high-temperature two-phase coolant. A detailed system-level cost and benefit study would need to be conducted before choosing one fluid over the next. For instance, the choice of fluid will depend on temperature limits (both high and low), choice of direct or indirect cooling, single vs. multi-loop architecture, and material compatibility, to name a few. Based on the platform specific limits and the current unknowns, the following research directions are recommended for achieving the two-phase thermal performance necessary for future systems:

1. Study vehicle architectures compatible with two-phase cooling—examining the system-level costs and benefits of various fluids, as well as single and multi-loop architectures, would help identify potential cooling solutions.
2. Compile properties for 3M thermal management fluids, ethylene glycol, propylene glycol, Dowtherm, and others for various temperatures and pressures.
3. Continue searching for and engineering new high-temperature two-phase fluids.
4. Explore the absolute upper two-phase temperature limits for various fluids based on the idea of “critical temperature.”
5. Explore cooling schemes using “supercritical” refrigerants.

5. References

1. Geortz, J. High Temperature Electronics for Sensor Interface and Data Acquisition. *Sensors Expo.*, 1998
2. Nice, K.; Layton, J. "How Hybrid Cars Work," available at <http://auto.howstuffworks.com /hybrid-car1.htm>
3. Johnson, R. W.; Evans, J. L.; Jacobsen, P.; Thompson, J. R.; Christopher, M. The Changing Automotive Environment: High-Temperature Electronics. *IEEE Trans. On Electronics Packaging Manufacturing* **2004**, *27* (3), 164–176.
4. Pierret, R. F. Advanced Semiconductor Fundamentals. Reading, MA: Addison-Wesley, **1987**, *6*, ch. 4, 91–134.
5. Sze, S. M. *Physics of Semiconductor Devices* 2nd ed. New York: Wiley, 1981.
6. Dreike, P. L; Fleetwood, D. M.; King, D. B.; Sprauer, D. C.; Zipperian, T. E. An Overview of High-Temperature Electronic Device Technologies and Potential Applications *IEEE Trans. Comp. Pack. And Manuf. Tech. Part A* **1994**, *17*, 594–609.
7. Neudeck, P. G.; Okojie, R. S.; Chen, L. Y. High-Temperature Electronics – A Role for Wide Bandgap Semiconductors? *Proc. of IEEE* **2002**, *90* (6), 1065–1076.
8. Grovenor, C.R.M. Grovenor, Microelectronic Materials. in Graduate Student Series in Materials Science and Engineering, Bristol, UK: Hilger, pp. 250–263, 1989.
9. Brown, D. M.; Downey, E.; Ghezzo, M.; Kretchmer, J.; Krishnamurthy, V.; Hennessy, W.; Michon, G. Silicon Carbide MOSFET Circuit Technology. *Phys. Stat. Sol.* **1997**, *162* (1), 459–479.
10. Neudeck, P. G.; Beheim, G. M.; Salupo, C. S. 600 °C Logic Gates Using Silicon Carbide JFETs. in *Proc. Government Microcircuit Applications Conf.*, Anaheim, California, 2000, pp. 421–424.
11. Sheppard, S. T.; Slater, Jr., D. B.; Lipkin., L. A.; Das, M. K.; Suvorov, A. V.; Palmour, J. W. High-temperature Demonstration of CMOS Operational Amplifier Using 6H Silicon Carbide N-well Tchnology and ONO Dielectrics. in *Proc. 5th Int. High-Temperature Electronics Conf.*, Albuquerque, NM, 2000, pp. XI.3.1–XI.3.8.
12. Pearton, S. J.; Zolper, J. C.; Shul, R. J.; Ren, F. GaN: Processing, Defects, and Devices. *J. Appl. Phys.* **1999**, *86* (1), 1–78.

13. Ericsen, T. Future Navy Application of Wide Bandgap Power Semiconductor Devices. *Proc. IEEE* **2002**, *90*, 1077–1082.

14. Davis, R. F.; Roskowski, A. M.; Preble, E. A.; Speck, J. S.; Heying, B.; Freitas, J. A.; Glaser, E. R.; Carlos, W. E. Gallium Nitride Materials – Progress, Status, and Potential Roadblocks. *Proc. IEEE* **2002**, *90*, 993–1005.

15. Kuszewski, M.; Zerby, M. Next Generation Navy Thermal Management Program. CARDIVNSWC-TR-82-2002/12, 2002.

16. Ponnappan, R.; Donovan, B.; Chow, L. High Power Thermal Management Issues in Space-based Systems. *Space Technology and Applications International Forum – STAIF* 2002, Albuquerque, NM.

17. Sharar, D. J.; Morgan, B.; Jankowski, N. J. Two-Phase Minichannel Cold Plate for Army Vehicle Power Electronics. *ASME InterPACK2011*, July 6–8, 2011, pp. 133–142.

18. Jones, S. T.; Mendoza, J.; Frazier, G.; Kahlil, G. Developing a Methodology for the Evaluation of Hybrid Vehicle Thermal Management Systems. *NDIA's Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, Troy, Michigan, 2009.

19. The Chevrolet Volt Cooling/Heating Systems Explained. available at < http://gm-volt.com /2010/12/09/the-chevrolet-volt-coolingheating-systems-explained/>

20. Incropera, F.; Dewitt, D.; Bergman, T.; Lavine, A. *Fundamentals of Heat and Mass Transfer: Sixth Edition*; John Wiley and Sons, Inc.: Hoboken, NJ 2007.

21. Lee, Y.; Simon, T. W.; Bar-Cohen, A. An Investigation of Short-heating-length Effects on Flow Boiling Critical Heat Flux in a Subcooled Turbulent Fow. in *Proc. Int. Symp. On Cooling Technology for Electronic Equipment*, 1989, pp. 358–373.

22. Saylor, R.; Ber-Cohen, A.; Lee, T. Y.; Simon, T. W.; Tong, W.; Wu, P. S. Fluid Selection and Property Effects in Single- and Two-Phase Immersion Cooling. *IEEE Trans. on Components, Hybrids, and Manufacturing Tech.* **1988**, *11* (4), 557–565.

23. Lemmon, E. W.; Huber, M. L.; McLinden, M. O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties – REFPROP, Version 7.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg.

24. Spatz, M.; Minor, B. HFO-1234yf: A low GWP refrigerant for MAC – Honeywell/DuPont Joint Collaboration. *SAE World Congress*, Detroit, MI, April 14–17, 2008.

25. Higashi, Y. Thermophysical Properties of HFO-1234yf and HFO-1234ze(E). *International Symposium on Next-Generation Air Conditioning and Refrigeration Technology*, Tokyo, Japan, February 17–19, 2010.

26. Campbell, J. B.; Tolbert, L. M.; Ayers, C. W.; Ozpineci, B. Two-Phase Cooling Method Using R134a Refrigerant to Cool Power Electronic Devices. in *Applied Power Electronics Conference and Exposition* 2005, pp. 141–147.

27. "3M Thermal Management Fluids," available at < http://multimedia.3m.com/mws/mediaweb server?mwsId=tttttvW9lEgUmy7VPZA_qZ0t2XW62EW9iXut2Xut2tttttt--&fn=bro_heattrans.pdf>

28. "Product Information: DowthermA" available at <http://msdssearch.dow.com/PublishedLiteratur eDOWCOM/dh_0040/0901b80380040b89.pdf>

29. "Technical Data Sheet – Dow Propylene Glycol USP/EP," available at < http://msds search.dow. com/PublishedLiteratureDOWCOM/dh_0048/0901b80380048696.pdf?filepath=propyleneglycol/pdfs/noreg/117-01619.pdf&fromPage= GetDoc>

30. " Ethylene Glycol: Product Guide – ME Global," available at <http://www.meglobal.biz/media product _guides/MEGlobal_MEG.pdf>

List of Symbols, Abbreviations, and Acronyms

ABS	anti-lock braking systems
CHF	critical heat flux
DoD	Department of Defense
ECUs	engine control units
FOM	figure of merit
NASA	National Aeronautics and Space Administration
ODP	Ozone Depletion Potential
Si	silicon
SiC	Silicon Carbide
SiO_2	Silicon Oxide
SOI	silicon on insulator
SWaP	size, weight, and power
TIM	thermal interface materials

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