SOL ENGINEERING SERVICES

Thermal Management Demands of Silicon Carbide Power Electronics in Army Ground Vehicles

Heat loads, coolant conditions and packaging limits for hybrid-electric combat and tactical vehicles

Prepared for DEVCOM Army Research Laboratory, the Ground Vehicle Systems Center, and university and industry partners of the CF-JET effort

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Executive Summary

The binding thermal constraint on silicon carbide (SiC) power electronics in Army ground vehicles is the coolant temperature that the vehicle loop delivers. Die heat flux adds a second constraint. A 2019 briefing from the Ground Vehicle Systems Center (GVSC) lists current hybrid power electronics at 3 kW/L with 85 °C coolant and states a future requirement of 12 kW/L with 105 °C engine coolant.[1] A cold plate that dissipates 1,340 W per half-bridge module with 25 °C coolant retains about 47 percent of that capacity at 105 °C coolant when the junction limit is 175 °C and the thermal resistance is unchanged.[23]

Five findings support the paper's conclusions.

- **Heat load.** A hybrid combat vehicle converts 100 to 400 kW of electrical power through SiC stages. At conversion losses of 2.15 to 3 percent, one stage produces 2 to 12 kW of heat (Table 2). The 1.5 kW module design point is consistent with published modules and corresponds to an inverter rated near 150 to 210 kW built from three modules.
- **Heat flux.** The design point averages 42 W/cm² over a 60 mm by 60 mm footprint. If twelve dies of 0.25 cm² each share the load, the die-level flux is 500 W/cm²; with six dies it is 1,000 W/cm². The highest measured flux in the sources reviewed is about 170 W/cm² (NREL, 2024), and the highest reported die-level flux is above 1,000 W/cm² (Tang et al., 2025).[45]
- **Coolant conditions.** Public Army documents give 65 °C as the current electronics inlet temperature and 80 to 105 °C as the future range.[67] At a 105 °C inlet and a 175 °C junction limit, the allowable junction-to-coolant resistance at the design point is 0.093 K/W per switch position, 36 percent below the 0.145 K/W data sheet value (Table 5).
- **Loop limits.** The engine-oriented Army loop offers 2 to 5 psi (14 to 34 kPa) of pressure drop to electronics.[8] The assumed 4 to 8 L/min at 30 kPa or less fits within that range for a single module. Several modules, motors and a battery share the same budget.
- **Evidence gaps.** GVSC public documents state power density and coolant temperature targets and contain no module-level heat flux, thermal resistance, flow or pressure drop requirement. No public source reviewed gives the mass or volume of cooling hardware on the hybrid vehicles in Table 1, or a silent watch duration.

The paper recommends that the CF-JET effort specify performance as junction-to-coolant resistance at inlet temperatures of 65, 85, 105 and 115 °C, report pressure drop at each condition, and state both footprint and die-level heat flux with the assumed die area.

1. Introduction and Scope

Hybrid-electric propulsion, engine-off operation and exportable power place SiC power electronics in positions on Army ground vehicles that commercial vehicles seldom occupy. Converters on these vehicles are mounted in a hull with limited volume, receive coolant from a loop sized for a diesel engine, and operate at coolant temperatures above those of commercial electric vehicles. This paper describes the resulting thermal demands for the benefit of program managers at the U.S. Army DEVCOM Army Research Laboratory, engineers at GVSC, university co-investigators and industry partners who specify, design and test cooling hardware for these converters.

The scope covers heat generation in SiC and gallium nitride (GaN) inverters, DC-DC converters and motor drives on hybrid-electric combat and tactical vehicles; silent watch and onboard power; and the trade-offs among size, weight and power (SWaP), armor, payload and range. The paper addresses four questions:

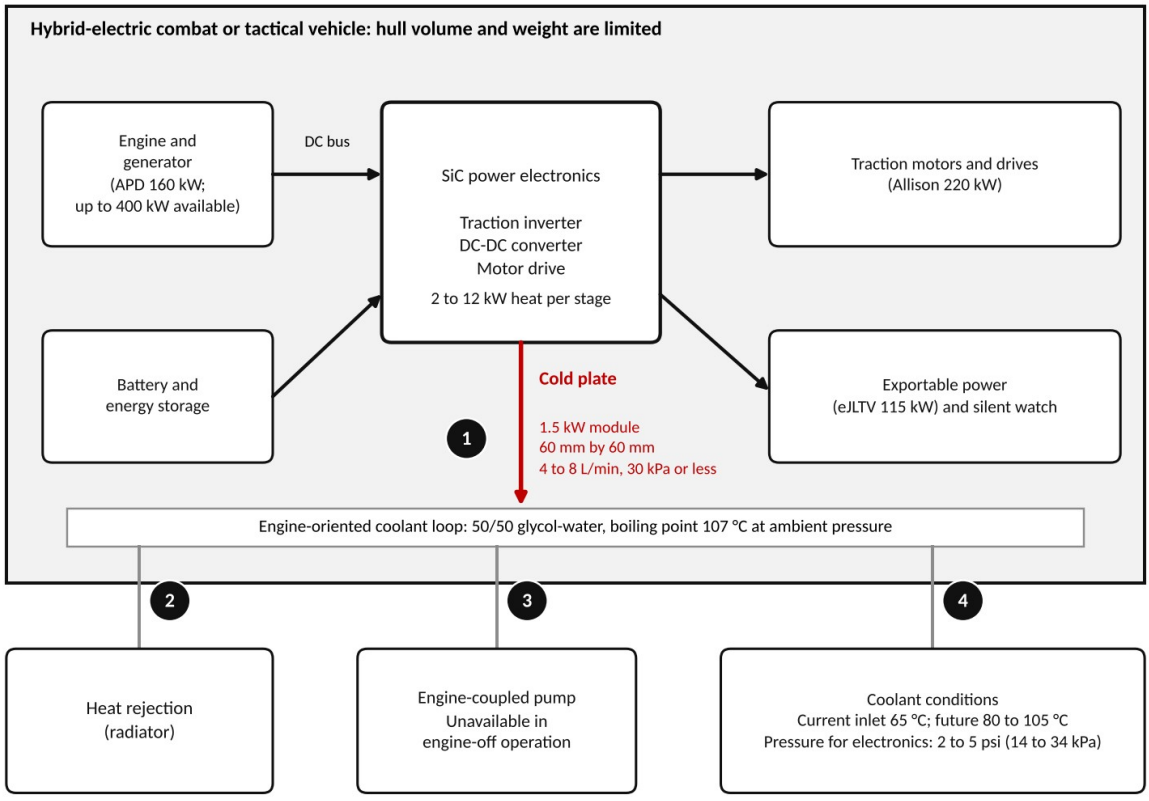
how much heat the converters produce and at what flux; what coolant conditions the vehicle supplies; which Army programs and platforms define the demand; and what GVSC publishes about priorities and gaps.

The documents reviewed for this paper address SiC devices. They contain no GaN device data for Army ground vehicle applications, so GaN enters the analysis only through the shared relationship between power dissipation and die area.

The CF-JET effort, proposed by SOL Engineering Services, LLC, applies an additively manufactured, liquid-cooled jet-impingement cold plate with an optimized carbon fiber target plate to this problem.[9] Its representative module design point is 1.5 kW of heat on a 60 mm by 60 mm footprint, cooled by 50/50 water-glycol at 65 °C inlet temperature, at 4 to 8 L/min and a pressure drop of 30 kPa or less. These values are design assumptions of the proposal. The paper tests each against independently published data in Table 7. Figure 1 shows the operational concept.

Figure 1. Operational concept of SiC power electronics cooling on a hybrid-electric Army ground vehicle

Red marks the CF-JET design point, a proposal assumption. Schematic, not to scale.



1 Heat dissipated at the module 2 Heat rejected to ambient 3 Flow supplied by the engine 4 Conditions the converter must tolerate

Power levels and loop conditions are those reported in the sources cited in this paper. The design point is a proposal assumption.[10] *The diagram is schematic and not to scale.*

2. Army Platforms and the Power Levels That Generate Heat

2.1 Programs define power levels from 100 kW to roughly 400 kW

Army hybrid-electric work spans heavy combat vehicles, tactical wheeled vehicles and onboard power kits. Table 1 summarizes the programs for which public sources state electrification content. The thermal data these sources publish are sparse: they report electrical power levels, fuel savings and signature benefits and give little about coolant temperature, heat load or cooling hardware.

Table 1. Army hybrid-electric platforms and demonstrators with public electrification content

Program	Electrification content in public sources	Power and thermal data published	Status and source type
XM30 Mechanized Infantry Combat Vehicle (General Dynamics Land Systems "Wolf"; American Rheinmetall "Lynx")	Both prototypes use hybrid-electric drive. Both have silent-watch capability and large battery packs that supply exportable power through a NATO power port. The Wolf design has a 10 percent growth margin on all systems. The Lynx cooling stack is located forward in the hull beside the powerplant and also cools the battery packs.	Combat weights in the 50-ton region. Allison announced a 220 kW electric motor and inverter for the Bradley replacement program. No coolant temperature or heat load is published.	Prototypes delivered August and September 2026. The Army declined to sign Milestone B documentation in February 2026 (CRS). Vehicle details come from trade press.
Bradley Hybrid Electric Vehicle (BHEV)	Two retrofitted Bradleys with an upgraded engine, an electric drive motor in place of the transmission, and lithium-ion batteries. Rapid Capabilities and Critical Technologies Office (RCCTO) and BAE Systems, under a 24-month rapid prototyping effort.	About 20 percent lower fuel consumption expected. Army states the hybrid system adds no extra SWaP demand. No thermal data.	Powered on 28 January 2022. Army news article.
Tactical hybrids: Tactical Hybrid Electric Vehicle (THEV), eJLTV, hybrid HMMWV	Three prototype THEVs from three vendors demonstrated in February 2024. Oshkosh eJLTV uses a diesel engine and a lithium-ion battery. Michigan Technological University delivered a series-hybrid HMMWV to RCCTO.	eJLTV: 30 kWh battery and up to 115 kW of exportable power. THEV and HMMWV: exportable power and extended silent watch stated without values.	Army, university and trade press sources. Demonstration stage.
Advanced Powertrain Demonstrator (APD), GVSC	Integrated starter generator, Advanced Thermal Management System, advanced modular battery system and controller for a 45 to 55 ton platform.	Electrical generation rises tenfold to 160 kW. The slide lists the thermal management system and gives no specification.	Undated GVSC briefing slide.
Vehicle Integrated Power Kit (VIPK) and Anti-Idle	Lithium-ion batteries power climate control and communications with the engine off. One slide lists more than 20 percent fuel savings and 50 percent reduced engine run time for hybrid propulsion; the slide layout leaves the system assignment unclear.	110 kW available at 600 VDC on one slide; 30 kW on the move and 120 kW at the halt on another. The two slides conflict.	Industry briefing slides, March 2025.
Robotic Combat Vehicle (RCV)	CRS gives no hybrid or electrification detail. The 2019 GVSC briefing lists a 300-mile silent range as the RCV surrogate target.	Not stated.	Reports in May 2025 stated that the Army would halt work. CRS states the program does not appear cancelled.

Sources: Congressional Research Service reports on the XM30 and RCV;[1112] trade press;[131415] Army news articles;[161718] university release;[19] GVSC briefings;[2021] industry briefing.[22] The Wolf and Lynx cooling arrangements are reported by the cited trade press and are not Army statements.

Three observations follow from Table 1. First, the largest converters belong to the 50-ton class combat vehicles and the 160 to 400 kW class onboard power systems. Second, tactical vehicles export power at roughly 110 to 120 kW, which places a converter of that size on a vehicle with far less hull volume than a tracked platform. Third, the programs state silent watch and exportable power as capabilities and publish

no thermal requirement for the electronics that provide them.

2.2 Conversion losses convert power levels into heat loads

Heat loads follow from power levels and conversion efficiency. Two independent sources bound the efficiency range for a SiC traction inverter. The NREL design target for a 100 kW inverter is 2,150 W of heat, a loss of 2.15 percent.[23] A Virginia Tech inverter rated 100 kW peak measured 503 W of loss per switch at 100 kW output and 97 percent efficiency, which totals about 3.0 kW across six switches.[24] Wolfspeed reports greater than 98 percent efficiency for a 300 kW reference inverter.[25] Table 2 applies the 2.15 and 3 percent loss fractions to the power levels in Table 1.

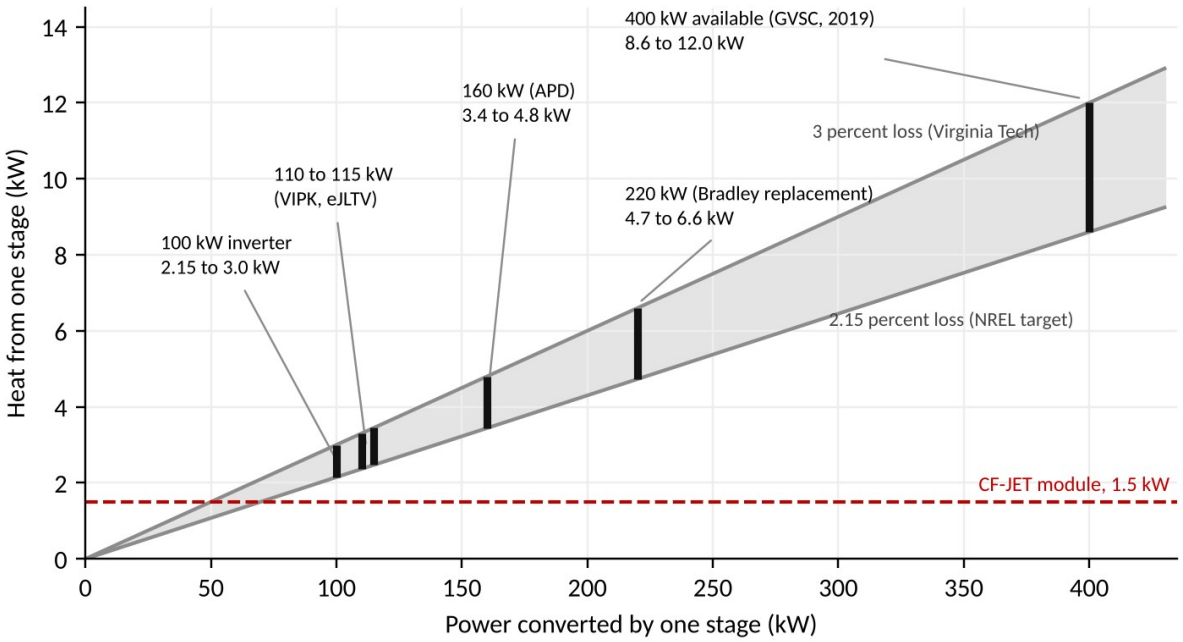
Table 2. Illustrative heat load of one conversion stage at the power levels in Army programs (calculated)

Power level (kW)	Context in public sources	Heat at 2.15 percent loss (kW)	Heat at 3 percent loss (kW)
100	Peak rating of a 100 kW SiC traction inverter (Virginia Tech)	2.15	3.00
110	VIPK available power (one slide of an industry briefing)	2.37	3.30
115	eJLTV exportable power (Oshkosh)	2.47	3.45
160	APD electrical generation (GVSC)	3.44	4.80
220	Allison electric motor and inverter for the Bradley replacement program	4.73	6.60
400	Available electrical power at 100 percent of prime power (GVSC, 2019)	8.60	12.00

Source: calculation in this paper. Each row multiplies the power level by the loss fraction for a single conversion stage. A vehicle that converts power twice, for example a motor inverter followed by a DC-DC stage, produces the sum of the stage losses. The 2.15 percent figure is the NREL design target and the 3 percent figure is the Virginia Tech measurement.[26]

A stage at 220 kW dissipates 4.7 to 6.6 kW. The 1.5 kW module in the CF-JET design point therefore corresponds to an inverter of about 150 kW (at 3 percent loss) to about 210 kW (at 2.15 percent loss) built from three half-bridge modules, one per phase.[27] That range spans the APD and Allison power levels in Table 2 and falls below the 400 kW available-power goal, which a vehicle would divide among several converters. Figure 2 plots the heat of one stage against the power converted.

Figure 2. Heat of one conversion stage against the power converted (calculated)



Calculated as the power level multiplied by 2.15 percent and by 3 percent. The marked power levels are those listed in Table 2.

2.3 Export converters add heat at lower voltage

Exportable power adds conversion stages beyond the traction inverter. A vendor article reports that legacy military export systems supplied 120/240 VAC or 28 VDC at roughly 10 to 30 kW, that delivering just over 10 kW at 28 VDC can require more than 500 A, and that next-generation vehicles use about 300 VDC, which reduces the current for the same power to about 50 A.[28] The article is vendor material. The arithmetic supports the direction: conduction loss in a conductor scales with the square of current, so a tenfold current reduction cuts resistive loss in cabling and bus structure by a factor of one hundred at equal resistance.

At the lower current, resistive heating in cabling falls, and the remaining export-converter loss arises in the SiC switches and magnetics inside the converter enclosure. The thermal path from that enclosure to the vehicle coolant then sets the temperature of the passive components (engineering judgment of this paper).

3. Heat Flux: Footprint Averages Understate Die-Level Demand

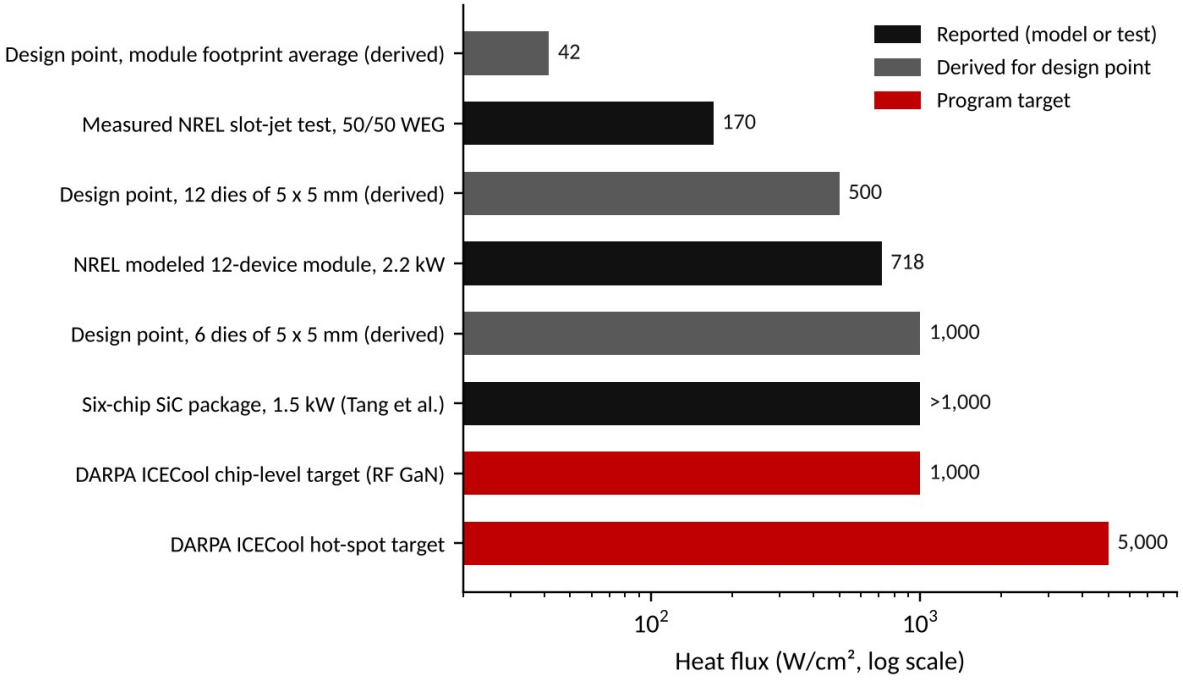
3.1 The design point averages 42 W/cm² and concentrates to 500 to 1,000 W/cm² at the die

The heat flux that the cooling hardware must remove depends on the area chosen as the denominator. The CF-JET design point dissipates 1.5 kW over a 60 mm by 60 mm footprint of 36 cm², an average of 42 W/cm².[29] The dies occupy a small fraction of that footprint. If twelve SiC dies of 0.25 cm² each (5 mm by 5 mm, an assumption of this paper) share the load, each die dissipates 125 W at a flux of 500 W/cm², and the active area is 3 cm², or 8 percent of the footprint. If six dies share the load, each dissipates 250 W and the flux is 1,000 W/cm².[30] The die-level flux therefore exceeds the footprint average by a factor of 12 to 24.

Published designs report fluxes across the same range. Figure 3 compares the values. NREL modeled a slot-

jet cooled module with 12 devices that dissipate 2.2 kW in total and reported 718 W/cm² at a junction temperature near 220 °C.[31] A later NREL experiment on a half-bridge module with four MOSFETs measured about 170 W/cm² at 90 A through the two powered devices.[32] Tang and coauthors report a SiC module with die-level heat flux above 1,000 W/cm² and a module power of 1,500 W.[33] The Army's own 2010 review states that projected device-level fluxes reach upwards of 1,000 W/cm² and lists demonstrated two-phase fluxes of 150 to 200 W/cm² for spray cooling, 840 W/cm² in work by Lee and Mudawar, and about 1,000 W/cm² for a jet-impingement laboratory setup.[34] The Defense Advanced Research Projects Agency (DARPA) set targets of more than 1,000 W/cm² at chip level and more than 5,000 W/cm² for submillimeter hot spots in its 2012 ICECool program.[35]

Figure 3. Heat flux values relevant to the CF-JET design point, on a logarithmic scale



Black bars show values reported in the cited sources, grey bars show values calculated in this paper, and red bars show program targets. The 500 and 1,000 W/cm² bars assume twelve and six dies of 0.25 cm² each. Sources: Moreno et al. (2019, 2024); Tang et al. (2025); DARPA ICECool announcement (2012); calculation in this paper.

The measured value in the sources reviewed (170 W/cm²) is a factor of 3 to 6 below the die-level flux that the CF-JET design point implies for a twelve-die or six-die module. The modeled and reported values (718 W/cm² and above 1,000 W/cm²) bracket the design point. Evidence at the design point flux consists of modeling and one peer-reviewed module design; the NREL measurements reviewed here do not reach that flux.

3.2 Published thermal results use different coolants, temperatures and evidence types

Table 3 lists the published thermal results used in this paper. The entries differ in coolant, inlet temperature, flow rate and evidence type, so their resistance values do not compare directly. The table identifies those differences so that a reader can select a reference value for a given condition.

Table 3. Published SiC module thermal results used as reference points

Source	Device or design	Coolant and temperature	Flow	Pressure drop	Thermal result	Evidence type
Wolfspeed data sheet, 2025	CAB525F12XM3 half-bridge, 1,200 V; package 80 mm by 53 mm	Coolant unnamed; fluid at 60 °C	4 L/min per module	Not stated	Junction-to-fluid 0.145 K/W per switch position (typical)	Vendor data sheet
Wolfspeed 300 kW inverter, 2019	Three CAB450M12XM3 modules on a liquid-cooled cold plate	50/50 water-ethylene glycol; 25 °C	12 L/min for three modules in the reference design specification (4 L/min each)	200 mbar (20 kPa) at 12 L/min	670 W per position, 1,340 W per module, at 25 °C coolant (flow for this test not recorded)	Vendor technical article and reference design data sheet
NREL, 2019	Slot-jet cold plate, 12 SiC devices, 2.2 kW	Modeled fluid at 65 °C inlet	4.1 L/min	2.2 kPa (modeled)	718 W/cm² at about 220 °C junction	Modeled; experiments in progress
NREL, 2024	Half-bridge module with slot jet; four MOSFETs, two powered at 90 A	50/50 water-ethylene glycol; 65 °C	1.7 to 3.3 L/min	5.8 kPa at 3.3 L/min	About 170 W/cm²; 15 mm²·K/W junction to fluid at 3.3 L/min	Measured, conference paper
Virginia Tech, 2022	100 kW peak, 60 kW continuous traction inverter	Water-glycol; 65 °C inlet with 105 °C ambient	10 L/min rated	Not reported	0.16 K/W per switch, measured; 145 °C junction at 100 kW	Peer-reviewed
NREL and John Deere, 2021	SiC inverter, jet flow on mini-channel and mini-manifold cooler	Water-ethylene glycol; 115 °C	Not stated	Not stated	Heat transfer coefficient up to 93,000 W/m²·K; 43 kW/L	Laboratory feature article
Tang et al., 2025	SiC module, 1,500 W	Not recorded in the abstract reviewed	Not recorded	Not recorded	Die-level flux above 1,000 W/cm²; 80 percent lower thermal resistance and 83 percent lower pumping power than the paper's baseline	Peer-reviewed; abstract only

Sources: Wolfspeed;[363738] *NREL;*[394041] *Virginia Tech;*[42] *Tang et al.*[43] *The thermal resistance in the Tang et al. abstract gives an ambiguous unit, so only the relative reductions appear here.*

4. Coolant Conditions: The Junction Budget Compresses at Army Temperatures

4.1 Army sources state coolant temperatures from 65 °C to 105 °C, and commercial work reaches 115 °C

The inlet temperature of the electronics coolant sets the temperature difference available to move heat from the junction to the fluid. Public sources state a range of values (Table 4). A 2010 Army Research Laboratory review states a current Army inlet requirement of about 65 °C with future objectives of 80 to

100 °C, and limits silicon device temperature rise to 25 to 45 °C above the inlet temperature.[44] The 2019 GVSC briefing lists 85 °C as the current coolant reference and 105 °C engine coolant as the future requirement for hybrid power electronics.[45] The slide states "coolant" and does not use the term "inlet," so the 85 to 105 °C range denotes coolant temperature thresholds without defining an inlet specification. NREL and John Deere designed a SiC inverter for 115 °C water-ethylene glycol supplied by an existing diesel engine cooling system.[46]

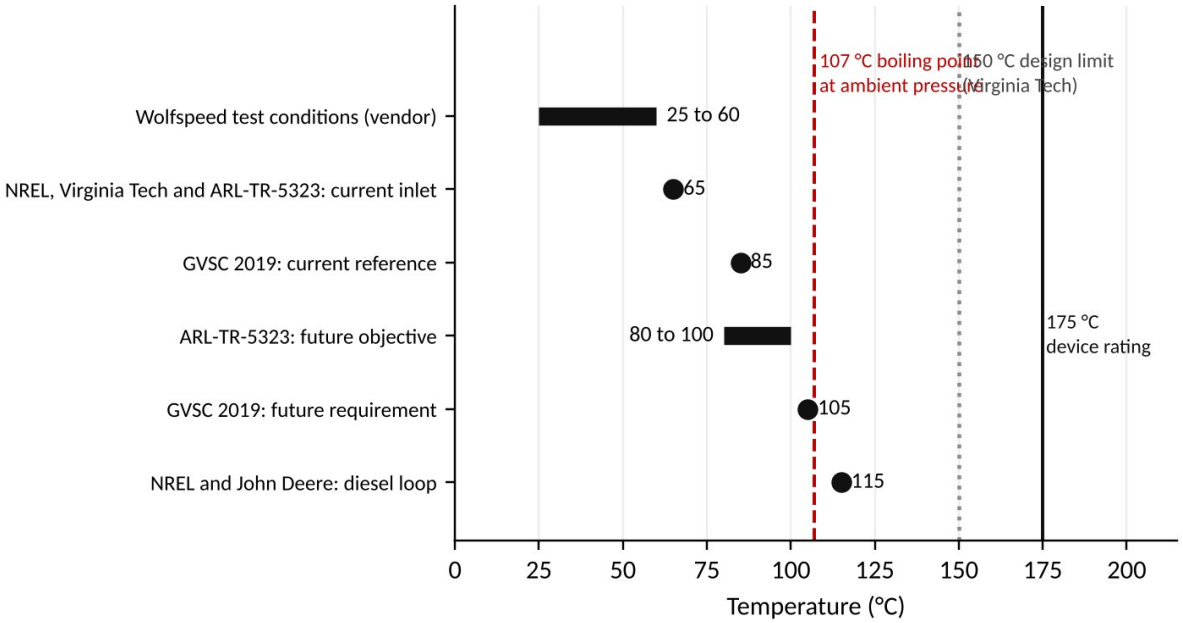
Table 4. Coolant conditions stated in public sources

Source	Coolant	Temperature stated	Context
ARL-TR-5323 (2010)	50/50 ethylene glycol and water	About 65 °C current inlet; 80 to 100 °C future objective	Single engine-coupled pump; boiling point 107 °C at ambient pressure; silicon limit 125 °C
GVSC briefing (2019)	Engine coolant	85 °C current reference; 105 °C future requirement	Hybrid power electronics at 3 kW/L today and 12 kW/L required
NREL and John Deere (2021)	Water-ethylene glycol	115 °C	Existing diesel engine cooling system serves the SiC inverter
Virginia Tech (2022)	Water-glycol	65 °C inlet; 105 °C ambient	Inverter measured at high ambient temperature
NREL (2019, 2024)	Modeled fluid (2019); 50/50 water-ethylene glycol (2024)	65 °C	Slot-jet cold plate, modeled (2019) and measured (2024)
Wolfspeed (2019, 2025)	50/50 water-ethylene glycol	25 °C (reference design); 60 °C (data sheet)	Vendor test conditions

Sources: Sharar, Jankowski and Morgan;[47] *GVSC;*[48] *NREL;*[4950] *Zhang et al.;*[51] *Wolfspeed.*[5253]

The 2010 review predates the GVSC briefing by nine years. The briefing moves the coolant reference from 85 to 105 °C, which is consistent with the review's direction of travel toward higher temperatures. No public Army document reviewed for this paper restates the 65 °C inlet figure after 2010, and no document specifies which temperature (inlet, engine-out or loop average) applies to the electronics. That ambiguity matters because a 20 K change in inlet temperature, from 65 to 85 °C, reduces the temperature difference available at a 175 °C junction limit from 110 K to 90 K, a reduction of 18 percent.[54] Figure 4 places the stated temperatures against the boiling point and the junction limits.

Figure 4. Coolant temperatures stated in public sources against the boiling point and the junction limits

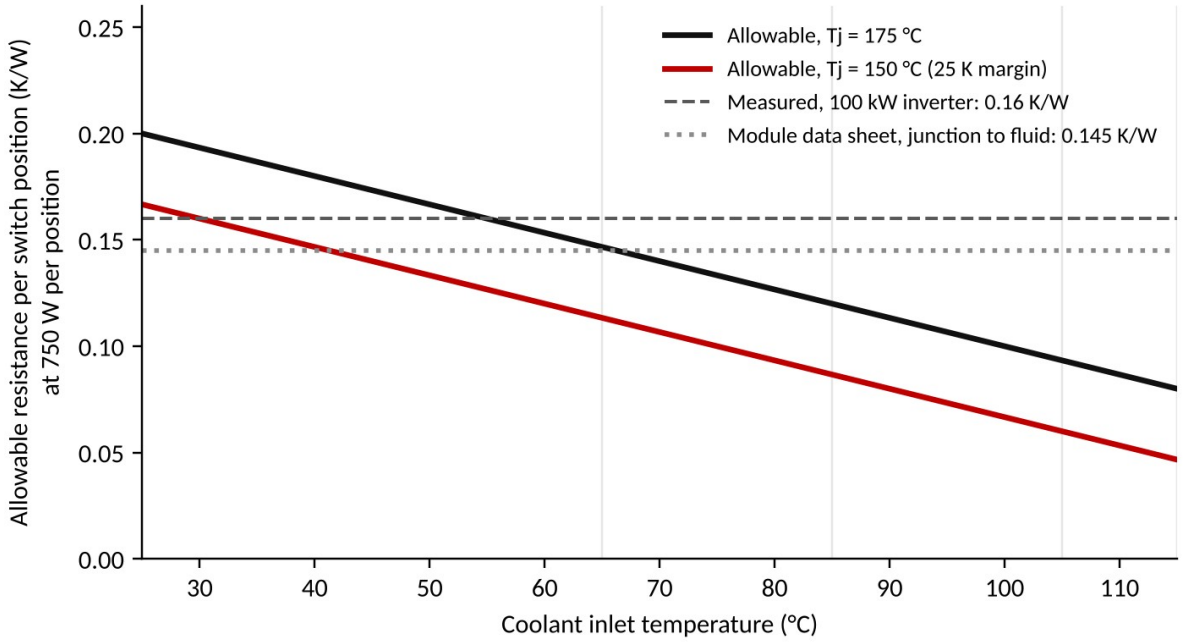


Black marks are values stated in the cited sources.[555657] *The 175 °C value is the device rating and the 150 °C value is the Virginia Tech design limit. The boiling point applies to 50/50 glycol-water at ambient pressure.*

4.2 At a 105 °C inlet the allowable resistance falls 36 to 42 percent below published values

The relationship between inlet temperature and allowable thermal resistance follows from one equation. For a switch position that dissipates power Q with a junction limit Tj and a coolant inlet Tin, the junction-to-coolant resistance must satisfy R ≤ (Tj − Tin) ÷ Q. At the design point, each of the two switch positions in a 1.5 kW half-bridge module dissipates 750 W. Table 5 gives the allowable resistance and the module heat capacity at four inlet temperatures. Figure 5 plots the allowable resistance against two published values: the 0.145 K/W typical junction-to-fluid resistance on the Wolfspeed data sheet and the 0.16 K/W measured by the Virginia Tech group.

Figure 5. Allowable junction-to-coolant resistance per switch position at 750 W, by coolant inlet temperature



Black line: junction limit 175 °C (device rating). Red line: junction limit 150 °C (a 25 °C margin, as used in the Virginia Tech design). Reference lines: 0.16 K/W (measured) and 0.145 K/W (data sheet typical). Source: calculation in this paper; reference values from Zhang et al. and the Wolfspeed data sheet.

Table 5. Allowable resistance and module heat capacity by coolant inlet temperature

Inlet (°C)	Allowable R per position, Tj 175 °C (K/W)	Allowable R per position, Tj 150 °C (K/W)	Module capacity at 0.145 K/W (W)	Module capacity at 0.16 K/W (W)	Module capacity at 0.224 K/W (W)
65	0.147	0.113	1,517	1,375	983
85	0.120	0.087	1,241	1,125	804
105	0.093	0.060	966	875	625
115	0.080	0.047	828	750	536

Source: calculation in this paper. Allowable resistance is (Tj − Tin) ÷ 750 W. Module capacity is 2 × (175 − Tin) ÷ R at a 175 °C junction limit. The 0.145 K/W value is the Wolfspeed typical junction-to-fluid resistance at 60 °C and 4 L/min; 0.16 K/W is the Virginia Tech measurement; 0.224 K/W is the resistance implied by 670 W per position at 25 °C coolant, which assumes a 175 °C junction (150 K ÷ 670 W).[585960]

Three results stand out in Table 5. First, at the 65 °C inlet and a 175 °C limit, the data sheet resistance of 0.145 K/W meets the 0.147 K/W allowable value with 1.25 K of junction margin (the junction reaches 173.75 °C at 750 W).[61] The 1.5 kW design point therefore equals the capability limit of a published module when the coolant is at 65 °C and the junction is allowed to reach its rating. Second, with the 150 °C design limit used in the Virginia Tech inverter, the allowable resistance at 65 °C is 0.113 K/W, 22 percent below the data sheet value. Third, at 105 °C the same module with unchanged resistance dissipates between 625 and 966 W, 36 to 58 percent below the 1.5 kW design point, depending on the resistance reference.[62]

The Virginia Tech inverter illustrates the margin problem. Its group measured 0.16 K/W at a 65 °C inlet with 10 L/min through the inverter, assumed 0.15 K/W in design, and set a 0.23 K/W limit.[63] At 750 W per position, a resistance of 0.16 K/W produces a junction temperature of 185 °C at a 65 °C inlet, which exceeds the 175 °C rating.[64] The Virginia Tech junction temperature of 145 °C at 100 kW corresponds to 503 W per switch, 67 percent of the 750 W per position at the CF-JET design point.[65]

4.3 The 107 °C boiling point constrains the loop and the cooled surface

The 50/50 ethylene glycol and water coolant boils at 107 °C at ambient pressure.[66] A 105 °C inlet leaves 2 K of margin to boiling at ambient pressure, and a 115 °C inlet exceeds the boiling point, which requires a pressurized loop. The NREL and John Deere article does not state the loop pressure.[67] Surface temperature adds a second boiling consideration. At junction temperatures of 150 to 175 °C, the cooled surface is likely to be above 107 °C even after the conduction drop through the substrate, so subcooled boiling may occur on the wetted surface of a jet-impingement cold plate at the design point. Whether boiling raises or lowers the heat transfer coefficient depends on pressure, flow and surface condition. None of the single-phase results in Table 3 addresses this regime.[68]

5. Flow and Pressure Drop: The Engine Loop Limits What Electronics Can Draw

5.1 The pressure budget of 2 to 5 psi accommodates one module and constrains several

The Army loop that serves electronics was designed for the engine. The 2010 review states that the pressure drop available for electronics cooling is typically 2 to 5 psi, that many advanced cooling solutions need roughly 10 to 100 psi, that a single coolant pump drives the loop, and that fluid type, flow rate and pressure generally cannot change for electronics.[69] The range converts to 13.8 to 34.5 kPa. The CF-JET assumption of 30 kPa (4.3 psi) lies near the upper end of that range.[70]

A recent source supports the premise that electronics share the engine loop. NREL and John Deere designed the 115 °C SiC inverter to use the existing diesel engine cooling system and to remove the need for a separate coolant circuit.[71] No source reviewed states whether the hybrid vehicles in Table 1 use a dedicated electronics loop with its own pump. The APD slide lists an Advanced Thermal Management System and gives no specification.[72]

Table 6 gives the coolant temperature rise and the hydraulic power for the assumed flow range. Coolant properties are those of 50/50 ethylene glycol and water near 65 °C: density 1,038 kg/m^3 and specific heat 3,494 J/kg·K.[73]

Table 6. Coolant temperature rise and hydraulic power for one 1.5 kW module (calculated)

Flow (L/min)	Mass flow (kg/s)	Coolant temperature rise across the module (K)	Hydraulic power at 6 kPa (W)	Hydraulic power at 15 kPa (W)	Hydraulic power at 30 kPa (W)
4	0.069	6.2	0.4	1.0	2.0
6	0.104	4.1	0.6	1.5	3.0
8	0.138	3.1	0.8	2.0	4.0

Source: calculation in this paper. Temperature rise is Q ÷ (mass flow × specific heat) with Q = 1,500 W. Hydraulic power is flow × pressure drop.

Hydraulic power remains small: 0.4 to 4 W per module across the table. The binding quantity is the pressure drop, which every component on the loop shares. A cold plate that uses 30 kPa leaves little of a 34.5 kPa budget for motor cooling jackets, the battery cold plate and the connecting hoses. The coolant temperature rise matters as well. When three modules receive coolant in series at 4 L/min, the coolant warms by 6.2 K in each module, and the third module receives coolant at about 77 °C when the first receives 65 °C.[74] That inlet temperature corresponds to a row between the 65 and 85 °C rows of Table 5.

Parallel manifolds avoid the accumulation and add manifold pressure drop.

5.2 Published pressure drops bracket 30 kPa at the upper flow rate

Three published pressure drops apply to the design point. The NREL half-bridge experiment measured 5.8 kPa at 3.3 L/min.[75] The NREL model of the 12-device slot-jet design predicted 2.2 kPa at 4.1 L/min.[76] The Wolfspeed 300 kW reference design specifies 200 mbar (20 kPa) at 12 L/min for three modules at 25 °C coolant, which is a higher viscosity than coolant at 65 °C.[77] The viscosity of 50/50 ethylene glycol and water falls as temperature rises, so the pressure drop at a 65 °C or 105 °C inlet is lower than at 25 °C for the same geometry and flow.

Scaling the NREL measurement to 8 L/min gives a range. Laminar flow scales pressure drop with flow, which yields 14 kPa. Fully turbulent flow scales it with the square of flow, which yields 34 kPa.[78] The 30 kPa limit lies inside that range, so a jet-impingement cold plate at 8 L/min can meet or exceed the limit depending on the flow regime in its manifold and jets. The 4 L/min lower bound gives 2 to 8 kPa by the same scaling and leaves room in the budget.[79]

6. Silent Watch and Onboard Power: Cooling Must Continue When the Engine Stops

6.1 Engine-off operation removes the engine-coupled pump while the electronics keep dissipating heat

The Army states silent mobility and silent watch as enabling capabilities for its electrification efforts. The 2019 GVSC briefing sets silent mobility targets of 3 km on tracks and 6 km off-road at 15 kph, which correspond to 4:1 and 5:1 reductions in detection distance, and states a goal of full-time silent mobility and longer silent watch duration with reduced acoustic and thermal signatures.[80] The APD slide ties a tenfold increase in electrical generation to 160 kW to onboard electrical capability, export power and extended silent watch durations.[81] Army news articles describe silent watch as the ability to observe without being detected, and identify engine starts, exhaust noise and battery depletion as the events that reveal a unit's position.[82]

Silent watch changes the thermal problem in three ways. First, the loop of the 2010 review is driven by a single engine-coupled pump,[83] so a vehicle that shuts down its engine needs an electrically driven source of flow to remove heat from converters that remain energized. The sources reviewed do not state how the hybrid vehicles in Table 1 circulate coolant during silent watch. Second, the heat that must leave the vehicle must do so without raising the thermal signature that silent watch is meant to reduce. The XM30 trade press states that silent-watch capability temporarily reduces thermal signatures,[84] and the Army's VIPK briefing states that the system reduces thermal and acoustic signatures.[85] Third, the pump and fan power for coolant circulation draws from the battery, which forms a parasitic load that scales with the heat to be removed.

The heat to be removed during silent watch is smaller than during mobility, since the electrical load is smaller. As an illustration, a 30 kW electrical load served through one conversion stage at 97 percent efficiency produces 0.9 kW of converter heat.[86] The low heat load permits low coolant flow, which at 4 L/min is the lower bound of the CF-JET flow range. A cold plate that holds its resistance at the low end of its flow range extends silent watch, because less pump power is needed. The Army reports that the Anti-Idle system reduced engine run time by 30 to 40 percent in demonstrations and projects about 30 percent

average fuel savings in large-scale combat operations, which indicates how much operating time the electronics spend with the engine off.[87]

6.2 The temperature limit of passive components affects the usable coolant temperature

The SiC junction limit constrains coolant temperature, and the passive components constrain it as well. A vendor article on military power supplies reports that air inside an enclosure can exceed the coolant temperature by 40 °C or more, that internal air can reach 120 °C or higher with 80 °C coolant, and that passive components lose lifespan above about 100 °C.[88] The article is vendor material about export converters, and it offers no measurement for a vehicle installation. Applying the same 40 K offset to the 105 °C coolant in the GVSC future requirement yields an internal air temperature near 145 °C, which exceeds the vendor's stated 100 °C component threshold.[89] The capacitors, magnetics and gate drivers in a 105 °C coolant environment therefore require a temperature rating or a thermal path beyond what the SiC switches alone demand. The Army documents reviewed give no component temperature requirement.

7. Size, Weight and Power: Higher Power Density Raises Volumetric Heat Density

7.1 Power density targets of 12 to 100 kW/L convert to 0.4 to 3 kW of heat per liter

Power density determines how much heat the cooling hardware must remove from each liter of converter volume. The 2019 GVSC briefing lists current hybrid power electronics at 3 kW/L and a future requirement of 12 kW/L, a fourfold increase, and cites SiC electronics rated at 15 kW/L and 105 °C.[90] Published SiC designs reach higher values. The Wolfspeed 300 kW reference inverter reports 32.25 kW/L at greater than 98 percent efficiency,[91] the Virginia Tech inverter reports 34 kW/L,[92] and the NREL and John Deere inverter reports 43 kW/L at 115 °C coolant.[93] NREL's design for the 2025 U.S. Department of Energy objective of 100 kW/L models a module and cold plate volume of about 120 mL against a target below 240 mL and reports no measured power density.[94]

Volumetric heat density equals the power density multiplied by the loss fraction. At the 3 percent loss that the Virginia Tech measurement gives, 12 kW/L corresponds to 0.36 kW of heat per liter, 32 kW/L to 0.96 kW/L, and 43 kW/L to 1.3 kW/L. At 2.15 percent loss the values are 0.26, 0.69 and 0.92 kW/L.[95] A 220 kW inverter at 12 kW/L occupies 18 L and at 32 kW/L occupies 7 L, so the higher density frees about 11 L of hull volume while it raises the heat released per liter by a factor of 2.7.[96] Cooling hardware that fits within the freed volume determines whether the density gain survives integration.

7.2 Coolant temperature trades radiator size against cold-plate performance

Heat rejection to air scales with the temperature difference between the coolant and the air. For an assumed ambient temperature of 45 °C, a 105 °C coolant provides a 60 K difference and a 65 °C coolant provides 20 K, so the same radiator rejects up to three times as much heat at the higher coolant temperature.[97] The Army's move toward 105 °C coolant is consistent with a smaller cooling stack. The cost appears in Table 5: the cold plate must achieve a junction-to-coolant resistance 36 to 42 percent lower at 105 °C than at 65 °C for the same power at a 175 °C junction limit. The trade between radiator volume and cold-plate performance belongs to the vehicle integrator, and the sources reviewed contain no quantified version of it.

7.3 No public source quantifies the mass and volume of thermal hardware on the hybrid vehicles

The vehicles in Table 1 show how much mass and volume they allocate to cooling only in qualitative terms. The XM30 prototypes weigh in the 50-ton region against the 40-ton Bradley, according to trade press.[98] The APD targets a 45 to 55 ton platform.[99] The Wolf places engine cooling at the rear behind the track so it does not intrude on passenger space, and the Lynx places its cooling stack forward in the hull beside the powerplant.[100] The Army states that the BHEV hybrid system adds no extra SWaP demand.[101] None of these sources gives the mass, volume or parasitic power of the thermal hardware.

An evaluation methodology for military hybrid vehicle thermal management addresses that gap. Jones and coauthors describe performance-based metrics, which test whether a thermal management system meets peak demand at worst-case boundary conditions and which set a design metric for hotel loads, and packaging-based metrics, which address volume and weight.[102] The methodology offers a framework that the CF-JET effort can adopt for reporting cold-plate mass, coolant volume and pump power alongside thermal resistance. The abstract reviewed for this paper reports no test results.

Range and payload follow from efficiency and mass. The Army expects the BHEV to reduce fuel consumption by about 20 percent,[103] and the VIPK briefing reports 3 to 4 days of maneuver endurance before resupply.[104] A converter loss of 3 percent against 2.15 percent costs 0.85 percentage points of the power that passes through it, so the efficiency of the SiC stage adds a second link between thermal design and range: a lower junction temperature reduces conduction loss in the device, and a lower pump power reduces the parasitic load.[105]

8. What GVSC Publishes: Targets for Power Density and Temperature, and No Module-Level Requirement

The public GVSC documents reviewed for this paper state program-level goals. The 2019 briefing states that high-power-density, high-temperature power electronics is a military-unique requirement that industry is not developing, and it identifies SiC as the technology that closes the gap.[106] It lists an Army investment focus on militarized electrification components, a fivefold to sevenfold increase in power density for combat platform packaging, modular or scalable architectures, and fuel cell or mobile recharge capability.[107] The APD slide lists the Advanced Thermal Management System among the demonstrator components and omits specifications.[108] A 2021 National Academies study notes that unmanned vehicles such as the EMAV and the RCV-L can export up to 30 kW, which places the low end of vehicle export power well below the 110 to 400 kW levels in Table 2.[109]

The public record contains four gaps and two conflicts.

- **No module-level thermal requirement.** No GVSC public document reviewed states a heat flux, junction-to-coolant resistance, flow rate or pressure drop requirement for a power electronics cold plate.
- **No inlet definition.** The 85 and 105 °C values in the 2019 briefing denote coolant temperatures and leave the inlet temperature at the electronics undefined.[110]
- **No mass, volume or parasitic power data.** The thermal hardware on the vehicles in Table 1 has no public mass, volume or pump power values.
- **No silent watch duration or electrical load.** The Army articles describe silent watch capability and

omit duration and power draw.[111]

- **Conflicting power density figures.** The 2019 briefing gives SiC electronics at 15 kW/L on one slide and the current industry baseline at 3 kW/L with a 12 kW/L requirement on another; the 15 kW/L value appears to be a demonstrated capability.[112]
- **Conflicting power figures.** The VIPK briefing lists 110 kW available on one slide and 30 kW on the move with 120 kW at the halt on another.[113]

The Army's priority in the XM30 prototypes, as trade press reports it, is margin for future requirements. Contractors state that the Army is not prioritizing external power for command posts, and the Wolf design has a 10 percent growth margin on all systems.[114] A cooling system sized at the design point therefore needs headroom in heat capacity, which Table 5 shows is erased by a 20 K increase in inlet temperature.

9. Implications for the CF-JET Effort

9.1 The design-point assumptions find support at 65 °C and require margin analysis at higher inlet temperatures

Table 7 compares each CF-JET design-point assumption with the evidence reviewed. The assumptions are those of the proposal, and the evidence is independent of it.[115]

Table 7. Assessment of the CF-JET design-point assumptions against published evidence

Assumption	Evidence reviewed	Assessment
1.5 kW heat per module	Tang et al. report a 1,500 W module. Wolfspeed reports 1,340 W per module with 25 °C coolant. NREL modeled 2.2 kW for a 12-device module. The Virginia Tech inverter dissipates about 3.0 kW at 100 kW across three modules.	Supported. The value corresponds to an inverter of about 150 to 210 kW built from three modules.
60 mm by 60 mm footprint (36 cm²)	The XM3 package measures 80 mm by 53 mm, or 42.4 cm². The average flux at the design point is 42 W/cm².	Consistent with a smaller module or with the die-bearing area of a substrate. The footprint is 15 percent smaller than the XM3 package outline.
50/50 water-glycol at 65 °C inlet	ARL-TR-5323, NREL and Virginia Tech use 65 °C. The GVSC briefing states 85 °C as the current coolant reference and 105 °C as the future requirement. NREL and John Deere use 115 °C.	Supported for the 2010 Army requirement and for commercial test practice. Contradicted in part by GVSC values. A sweep from 65 to 115 °C is required.
4 to 8 L/min	Wolfspeed specifies 4 L/min per module. NREL used 1.7 to 3.3 L/min (measured) and 4.1 L/min (modeled). The Virginia Tech inverter uses 10 L/min for three modules.	Supported. The range lies at or above published per-module flows.
Pressure drop of 30 kPa or less	The Army range is 13.8 to 34.5 kPa for all electronics. NREL measured 5.8 kPa at 3.3 L/min. Scaling to 8 L/min gives 14 to 34 kPa.	Within the Army range at 4 L/min. At 8 L/min the result depends on flow regime. The budget is shared with other components.

Sources: as cited in Tables 3 to 6 and the surrounding text.

9.2 Five risks follow from the evidence

- **Inlet temperature uncertainty.** The Army inlet condition lies between 65 and 115 °C in public sources. A design validated at 65 °C loses 36 to 58 percent of its module capacity at 105 °C if its resistance is unchanged (Table 5).

- **Junction margin.** At 65 °C inlet and a 175 °C limit, the published data sheet resistance leaves 1.25 K of margin at 750 W per position. A design limit of 150 °C, as in the Virginia Tech inverter, requires a resistance of 0.113 K/W at 65 °C and 0.060 K/W at 105 °C.
- **Shared pressure budget and coolant temperature rise.** A 30 kPa cold plate uses most of a 34.5 kPa loop budget, and series connection of three modules at 4 L/min raises the third module's inlet temperature by about 12 K.
- **Boiling on the cooled surface.** A 105 °C inlet is 2 K below the ambient-pressure boiling point, and wetted surfaces at 150 to 175 °C junction conditions are likely to exceed it. Single-phase results in the sources reviewed do not cover this regime.
- **Passive component limits.** Capacitors, magnetics and gate drivers may impose a lower coolant temperature limit than the SiC switches, and no Army source states that limit.

9.3 Six design implications apply to the specification and test plan

- **Specify resistance together with heat flux.** State junction-to-coolant resistance per switch position at inlet temperatures of 65, 85, 105 and 115 °C, with the junction limit stated. The values in Table 5 give the targets: at 105 °C and a 175 °C limit, 0.093 K/W or lower; at a 150 °C limit, 0.060 K/W or lower.
- **Report pressure drop at each inlet temperature and at both flow limits.** Viscosity falls as temperature rises, so a 65 °C result requires re-measurement at 105 °C. Report 4 L/min and 8 L/min at each condition.
- **Report heat flux on both bases.** State the footprint average and the die-level flux, and state the die area assumed. The die-level value is 12 to 24 times the footprint average at the design point.
- **Test the series and parallel arrangements.** Quote the coolant temperature rise per module (Table 6) and the manifold pressure drop for three-module installations.
- **Report mass, coolant volume and pump power with the thermal result.** Follow the performance and packaging metric structure of the military hybrid thermal management methodology.[116] The sources reviewed give no baseline for comparison, so the CF-JET results will establish one.
- **Test engine-off conditions.** Report resistance at 4 L/min and at the lowest flow that an electric pump can supply, because silent watch removes the engine-coupled pump.

9.4 Six research questions remain open

- What inlet temperature, and at what point in the loop, applies to electronics on the XM30 prototypes and on the tactical hybrids? The public documents do not define it.
- How does a jet-impingement cold plate with an additively manufactured surface perform at inlet temperatures from 65 to 115 °C, and how much of the 36 to 42 percent resistance reduction required at 105 °C can it supply? The sources reviewed contain no measurement of a carbon fiber target plate with water-glycol jets.
- Does subcooled boiling occur on the wetted surface at the design point, and does it raise or lower the heat transfer coefficient and the pressure drop?
- What pressure does a 115 °C loop operate at, and what does that pressure add to hose, fitting and pump requirements?
- What temperature limits apply to capacitors, magnetics and gate drivers in a 105 °C coolant environment, and what thermal path keeps them within those limits?

- What do the thermal systems on the Table 1 vehicles weigh, occupy and consume? A public baseline would allow a quantified comparison of any new cold plate.

10. Conclusion

Army hybrid-electric vehicles apply SiC converters at power levels from 100 to 400 kW, where one conversion stage produces 2 to 12 kW of heat. The CF-JET design point of 1.5 kW per module corresponds to an inverter of 150 to 210 kW and has support in published module data at a 65 °C coolant inlet. At 105 °C, the temperature that GVSC states for future engine coolant, the same module with unchanged resistance dissipates 625 to 966 W, and the allowable junction-to-coolant resistance falls 36 to 42 percent below published values.

The loop adds a pressure budget of 14 to 34 kPa that all electronics share, an engine-off requirement for electric coolant circulation, and passive component limits that no Army source quantifies. The public record gives power density and coolant temperature targets and omits module-level heat flux, resistance, flow, pressure drop, mass and volume requirements. The CF-JET effort can address that omission by reporting resistance, pressure drop, heat flux on both bases, mass and pump power at inlet temperatures of 65, 85, 105 and 115 °C.

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[33]Tang et al., “Integrated Thermal Management.”

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[35]“DARPA Asks Industry to Develop Microelectronics with Cooling Built Right into the Chip,” *Military & Aerospace Electronics* (trade press), 12 June 2012, https://www.militaryaerospace.com/articles/2012/06/darpa-asks-industry-to-develop-microelectronics-with-cooling-built-right-into-the-chip.html.

[36]Wolfspeed, *CAB525F12XM3 Data Sheet*, vendor data sheet, February 2025, https://assets.wolfspeed.com/uploads/2025/02/Wolfspeed_CAB525F12XM3_data_sheet.pdf.

[37]Wolfspeed, “300 kW 3-Phase SiC Inverter.”

[38]Wolfspeed, *CRD300DA12E-XM3 300 kW High Performance Three Phase Reference Design with Three CAB450M12XM3 1200 V, 450 A SiC Half Bridge Modules*, vendor data sheet, Rev. A, 1 June 2019, https://www.farnell.com/datasheets/2838125.pdf.

[39]Moreno et al., “Power Electronics Thermal Management,” slides 9, 10 and 12.

[40]Moreno et al., “Half-Bridge Power Module.”

[41]National Renewable Energy Laboratory, “Advanced Thermal Management Design Boosts Performance of Silicon Carbide Inverters for Heavy-Duty Vehicles,” feature article, 2021, https://nrel.gov/news/features/2021/advanced-thermal-management-design-boosts-performance-of-silicon-carbide-inverters-for-heavy-duty-vehicles.html.

[42]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[43]Tang et al., “Integrated Thermal Management.”

[44]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[45]GVSC, “CVEMP,” slide 7.

[46]NREL, “Advanced Thermal Management Design.”

[47]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[48]GVSC, “CVEMP,” slide 7.

[49]NREL, “Advanced Thermal Management Design.”

[50]Moreno et al., “Half-Bridge Power Module.”

[51]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[52]Wolfspeed, *CAB525F12XM3 Data Sheet*.

[53]Wolfspeed, *CRD300DA12E-XM3 Reference Design*.

[54]Calculation in this paper: 20 K ÷ (175 °C − 65 °C) = 0.18.

[55]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[56]GVSC, “CVEMP,” slide 7.

[57]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[58]Wolfspeed, *CAB525F12XM3 Data Sheet*.

[59]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[60]Wolfspeed, “300 kW 3-Phase SiC Inverter.”

[61]Calculation in this paper: 65 °C + 750 W × 0.145 K/W = 173.75 °C.

[62]Calculation in this paper: (1,500 − 966) ÷ 1,500 = 0.36; (1,500 − 625) ÷ 1,500 = 0.58.

[63]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[64]Calculation in this paper: 65 °C + 750 W × 0.16 K/W = 185 °C.

[65]Calculation in this paper: 503 W ÷ 750 W = 0.67; 65 °C + 503 W × 0.16 K/W = 145 °C.

[66]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[67]NREL, “Advanced Thermal Management Design.”

[68]Engineering judgment of this paper. The conduction drop between junction and wetted surface is not reported in the sources reviewed.

[69]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[70]Calculation in this paper: 30 kPa ÷ 6.895 kPa/psi = 4.35 psi.

[71]NREL, “Advanced Thermal Management Design.”

[72]GVSC, “APD.”

[73]Property values are standard engineering approximations assumed for this calculation and should be confirmed against the coolant supplier’s data at the operating temperature.

[74]Calculation in this paper: 65 °C + 2 × 6.2 K = 77.4 °C.

[75]Moreno et al., “Half-Bridge Power Module.”

[76]Moreno et al., “Power Electronics Thermal Management,” slide 12.

[77]Wolfspeed, *CRD300DA12E-XM3 Reference Design*.

[78]Calculation in this paper: 5.8 kPa × (8 ÷ 3.3) = 14.1 kPa; 5.8 kPa × (8 ÷ 3.3)² = 34.1 kPa. The scaling applies to the NREL geometry only and gives bounds, not a prediction for another geometry.

[79]Calculation in this paper: 5.8 kPa × (4 ÷ 3.3) = 7.0 kPa; 5.8 kPa × (4 ÷ 3.3)² = 8.5 kPa.

[80]GVSC, “CVEMP,” slides 8 and 16.

[81]GVSC, “APD.”

[82]“Advantage of Silence.”

[83]Sharar, Jankowski, and Morgan, *Review of Two-phase Electronics Cooling*, sec. 1.2.

[84]“Test Plans Change.”

[85]Roberts, “Integration,” slides 3 and 4.

[86]Calculation in this paper: 30 kW × 0.03 = 0.9 kW. The 30 kW load is an assumption chosen for illustration. No source reviewed states a silent watch electrical load.

[87]Roberts, “Integration,” slide 4.

[88]Astrodyne TDI, “Thermal Management of Military Power Supplies.”

[89]Calculation in this paper: 105 °C + 40 K = 145 °C. This extrapolation applies a vendor-reported offset outside the temperature range in the article and has no support from a measurement.

[90]GVSC, “CVEMP,” slides 5 and 7.

[91]Wolfspeed, “New SiC Power Modules.”

[92]Zhang et al., “Liquid-Cooled Electric Vehicle Traction Inverter.”

[93]NREL, “Advanced Thermal Management Design.”

[94]Moreno et al., “Power Electronics Thermal Management,” slides 3, 6 and 10.

[95]Calculation in this paper: 12 × 0.03 = 0.36; 32 × 0.03 = 0.96; 43 × 0.03 = 1.29; 12 × 0.0215 = 0.26; 32 × 0.0215 = 0.69; 43 × 0.0215 = 0.92 kW/L. The volumes in the sources include different boundaries (module, inverter or system), so the values indicate scale only.

[96]Calculation in this paper: 220 ÷ 12 = 18.3 L; 220 ÷ 32 = 6.9 L; 32 ÷ 12 = 2.7.

[97]Calculation in this paper: (105 − 45) ÷ (65 − 45) = 3.0. The 45 °C ambient is an assumption. Radiator performance also depends on airflow and on the temperature limits of other components on the loop.

[98]“Test Plans Change.”

[99]GVSC, “APD.”

[100]“Test Plans Change.”

[101]Jones-Bonbrest, “First Hybrid Electric Bradley.”

[102]S. Jones, J. Mendoza, G. Frazier, and G. Khalil, “Developing a Methodology for the Evaluation of Military Hybrid Electric Vehicle Thermal Management Systems,” SAE Technical Paper 2024-01-3099 (SAE posting dated 15 November 2024),

https://saemobilus.sae.org/papers/developing-a-methodology-evaluation-military-hybrid-electric-vehicle-thermal-management-systems-2024-01-3099.

[103]Jones-Bonbrest, “First Hybrid Electric Bradley.”

[104]Roberts, “Integration,” slide 5.

[105]Engineering judgment of this paper. SiC MOSFET on-resistance rises with junction temperature; the sources reviewed do not quantify the effect for the modules in Table 3.

[106]GVSC, “CVEMP,” slide 7.

[107]GVSC, “CVEMP,” slides 10 and 14.

[108]GVSC, “APD.”

[109]National Academies of Sciences, Engineering, and Medicine, *Powering the U.S. Army of the Future* (Washington, DC: National Academies Press, 2021), chap. 8, https://doi.org/10.17226/26052.

[110]GVSC, “CVEMP,” slide 7.

[111]“Advantage of Silence.”

[112]GVSC, “CVEMP,” slides 5 and 7.

[113]Roberts, “Integration,” slides 3 and 5.

[114]“Test Plans Change.”

[115]SOL Engineering Services, *CF-JET*, Rev Final 2.

[116]Jones et al., “Evaluation of Military Hybrid Electric Vehicle Thermal Management Systems.”