Two-Phase Cooling Method Using R134a Refrigerant to Cool Power Electronic Devices

Jeremy B. Campbell, *Member, IEEE*, Leon M. Tolbert, *Senior Member, IEEE*, Curt W. Ayers, Burak Ozpineci, *Senior Member, IEEE*, and Kirk T. Lowe

*Abstract** — **This paper presents a two-phase cooling method using R134a refrigerant to dissipate the heat energy (loss) generated by power electronics (PE) such as those associated with rectifiers, converters, and inverters for a specific application in hybrid-electric vehicles (HEVs). The cooling method involves submerging PE devices in an R134a bath, which limits the junction temperature of PE devices while conserving weight and volume of the heat sink without sacrificing equipment reliability.**

First, experimental tests that included an extended soak for more than 850 days were performed on a submerged insulated gate bipolar transistor (IGBT) and gate-controller card to study dielectric characteristics, deterioration effects, and heat-flux capability of R134a. Results from these tests illustrate that R134a has high dielectric characteristics and no deterioration of electrical components.

Second, experimental tests that included simultaneous operation with a mock automotive air-conditioner (A/C) system were performed on the same IGBT and gate-controller card. Data extrapolation from these tests determined that a typical automotive A/C system has more than sufficient cooling capacity to cool a typical 30 kW traction inverter.

Last, a discussion and simulation of active cooling of the IGBT junction layer with R134a refrigerant is given. This technique will drastically increase the forward current ratings and reliability of the PE device.

Index Terms – **Power electronic cooling, two-phase cooling, thermal management.**

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I. Introduction

As the cost of oil increases and oil stockpiles diminish, consumers recognize the importance of alternatively fueled vehicles. Presently, the most promising of these vehicles are hybrid-electric vehicles (HEVs) because of the latest technology advances in power electronics (PEs) that improve energy usability and efficiency. PEs provide the interface between the energy sources such as batteries and the traction drive motor.

The typical location for these PE packages is in the engine compartment. While this location offers some environmental protection (rain, debris, etc), space for mounting, and minimizes stray inductance for the PE, the ambient temperatures can be as high as 140°C. Unfortunately, PEs are highly temperature dependent. Typically, the junction temperature of Silicone (Si) power devices is limited to 150°C, and it is directly proportional to reliability. As a rule of thumb, the failure rate for semiconductor devices doubles for each 10–15°C temperature rise above 50°C [1]. Therefore, PEs must meet strict automobile manufacturers' design criteria when used in HEVs. The four most import design criteria for the automotive industry are weight, size, reliability, and cost [2–4].

The thermal management system for PE devices plays an important role for all four criteria. Typical thermal management systems occupy one-third of the total volume for a power converter and in many cases weigh more than the converter itself [5]. Presently, HEVs use a liquid-cooled heat sink where ethylene glycol is circulated separately from the internal combustion engine (ICE). This system provides adequate cooling fluid at 65–70°C, but requires an additional coolant loop, coolant, coolant hoses, a pump, and a radiator which is an increase in vehicle weight [4].

However, with slight modification to existing air-conditioner (A/C) systems in automobiles, they can be used to cool PE devices. The Oak Ridge National Laboratory (ORNL) has developed a system that shares a vehicles A/C condenser while providing refrigerant for PE cooling. The additional loop does not require the compressor to run continuously and does not affect the performance of the existing A/C. It can also be integrated with minimal impact on vehicle weight and components [6–7]. A study of PE compatibility with R134a and the utilization of the existing A/C system for cooling PEs is presented in this paper as a means to help meet the design criteria described previously.

II. Energy Dissipation of Silicon Devices

Si-based insulated gate bipolar transistor (IGBT) PE devices dissipate heat energy during the turn-on, turn-off, and conduction periods shown in Fig. 1. Energy dissipation (loss) in semiconductors increases as the junction temperature increases, and this can cause catastrophic failure if the thermal energy is not managed within specification.

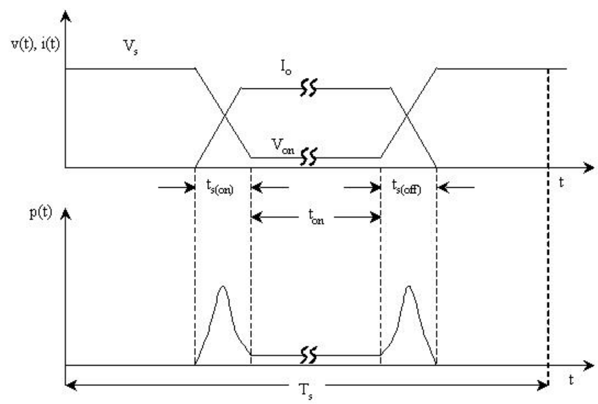


Fig 1. IGBT switching characteristics [1].

Total average power dissipation in semiconductors during switching can be calculated by Eq. (1):

$$P_t = \frac{1}{T_s}\int_0^{T_s} v(t)\cdot i(t)dt \qquad (1)$$

where T_s denotes the period of one complete cycle, *v(t)* is the voltage across the collector-emitter, and *i(t)* is the current through the collector. The equation consists of power dissipated during turn-on, turn-off, conduction, and blocking.

III. Refrigeration Properties

Cooling by nucleate boiling is one of most efficient means of removing heat from a component [8–13]. The typical working fluids for boiling research are water and FC-72 (Fluorinert). The latter is more common in electronic applications because FC-72 was specifically developed as a dieletric fluid. Until now, R134a was not intended to cool electrical equipment. It was designed for automobile passenger climate control; however, R134a has exceptional thermal characteristics that are useful in cooling semiconductors.

A comparison of R134a, FC-72, and water are shown in Table 1. Even though water has a latent heat value that is an order of magnitude higher than R134a, it is corrosive and a poor dielectric which make it an unfavorable choice for this type of system. Its large vapor-to-liquid volume ratio also makes water undesirable, but it is used here as a comparison with the other fluids.

Table 1. Comparison of refrigerant characteristics at 25°C and saturation pressure

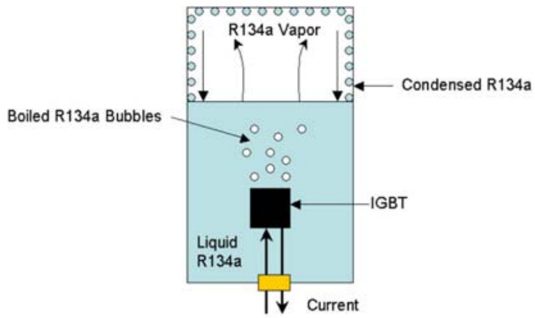
	Latent Heat [kJ/kg]	Vapor Flowrate per kW [l/s]	Boiling Point @ 1ATM [°C]	Saturation Pressure [kPa]	Vapor/Liquid Volume Ratio	Dielectric Properties [kV/mil] Liquid/Vapor
R134a	176	0.1	-26.6	660	36	7.2/6.7
FC-72	88	1.7	56	31	408	3.8/na
Water	2440	17.8	100	3.2	43200	na

R134a has the lowest vapor-to-liquid volume ratio. This property implies that for a closed system the amount of volume needed to contain the vapor at a desired pressure is much smaller than competitor working fluids. It also means the working pressures will be more reasonable, which has many safety implications. Furthermore, R134a can hold more energy per unit of vapor volume than either water or FC-72, which should require less pumping power than the other fluids.

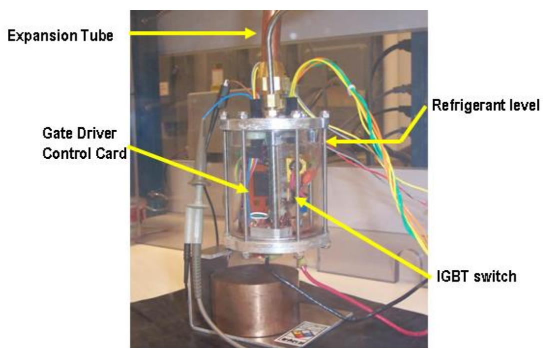
Despite its intended purpose, FC-72 requires more system volume at the boiling point and circulation power for similar effects. Also, its environmental affect will soon cause it to be discontinued on the market. Since R134a is already available on a vehicle, is environmentally friendly, and has good heat transfer and dielectric properties, it is considered a nearly ideal refrigerant for cooling PEs such as those found in HEVs.

IV. Experimental Setup

The experimental two-phase, R134a-based cooling system is shown in Figs. 2(a) and 2(b). The vessel is a closed system because the run time and power losses were expected to be low during these tests. The top flange has a condensing tube attached to keep pressure increases in the container to a minimum. The experimental components are comprised of a glass vessel with aluminum top and bottom flanges, IGBT, gate-controller card, and associated snubber components. The electrical connections for the dc-bus and gate-controller card are feed-through pins that are held in place using potted epoxy for a leak-proof seal. The IGBT is an International Rectifier IRGBC20UD2 configured in a simple chopper circuit with a pure resistive load as shown in Fig. 3. The IGBT was cycled on and off at 1 kHz with a 50% duty cycle and a gate voltage of 13.0 V. The voltage V_{dc} applied was 480 V and a fixed load resistance R_L of 140 Ω drew an average current of 6 A.



(a) Submerged R134a cooled technique.



(b) Test vessel including PE devices.

Fig. 2. Experimental refrigerant system.

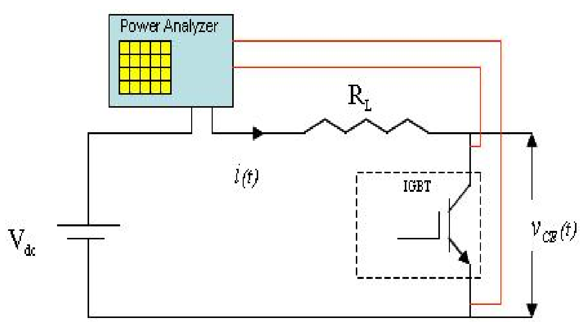


Fig. 3. Experimental circuit.

V. Dielectric Test Results

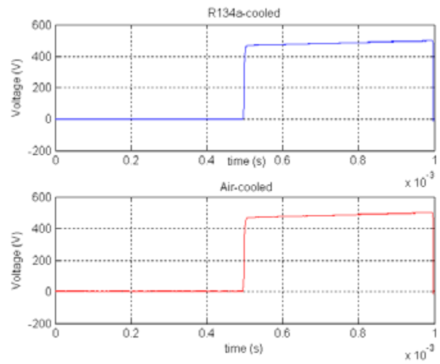
The same experimental IGBT was tested in both air-cooled and R134a bath environments to investigate whether R134a has high dielectric characteristics and no adverse physical effects on electronic components. The air-cooled configuration was tested at 21°C, and the R134a bath was tested at 21°C and 590 kPa. Figures 4(a) and 4(b) are views of voltage and current transitions during one switching period. The voltage and current waveforms are identical in both the air-cooled and R134a-cooled cases. Figure 4(c) is an expanded view of the voltage and current turn-off transitions. These waveforms indicate R134a does not change the IGBT turn-on and turn-off transition by introducing additional capacitance across the IGBT terminals or the gate-controller card. Figure 4(d) is a graph of instantaneous and average power for both tests. The average power loss for the R134a-cooled test was 24.73 W using Eq. (1) while the air-cooled test was 22.21 W. The difference in data is determined to be from power supply variances and data collection/reduction procedure. The data from Fig. 4 is enough to indicate no major switching discrepancies. These electrical components have been submerged in the refrigerant for over 850 days during which the test was repeated regularly with no evidence of damage.

The power loss for each IGBT state of operation (conduction, blocking, turn-on, and turn-off) is shown in Table 2. Conduction loss is the largest power loss while the IGBT is operating within rated switching frequency (1 kHz for this experiment).

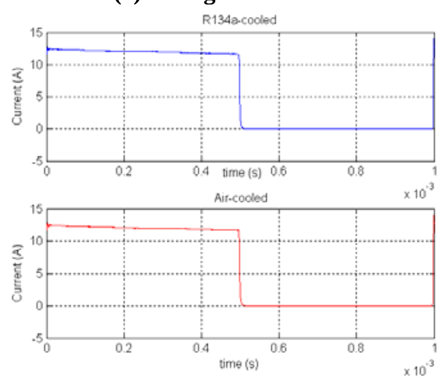
Table 2. Power dissipated from tested IGBT and PWL comparison

	P_{total} (W)	$P_{blocking}$ (W)	$P_{s(on)}$ (W)	$P_{s(off)}$ (W)	P_{cond} (W)
Air	22.12	2.65	0.38	5.85	13.24
R134a	24.73	2.26	0.41	5.75	16.32

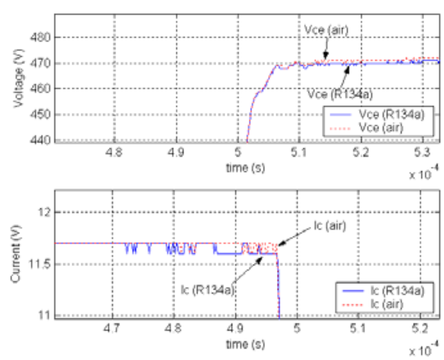
For this specific configuration, the IGBT was determined to have a heat flux of 114 W/cm^2 (rate of heat flow per unit area) in the R134a. This calculation is determined from the mounting case surface area. The mounting case surface area is where the majority of the heat flow path is directed. The small remaining heat flow is through the plastic enclosure surrounding the junction.



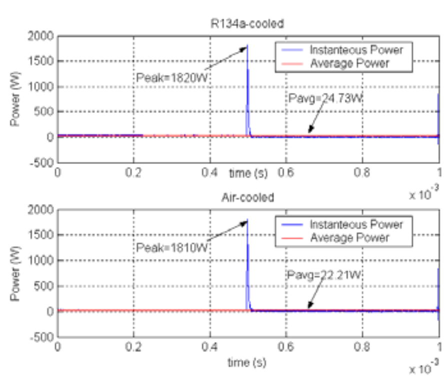
(a) Voltage waveforms.



(b) Current waveforms.



(c) Expanded voltage and current device turn-off.



(d) Instantaneous and average power loss.

Fig. 4. Experimental results for R134a-cooled and air-cooled power systems.

VI. Mock Automotive R134a A/C Results

The results from the air-cooled and R134a-cooled experiments demonstrated that the R134a provides no interference with normal operation of the power circuit. Switching characteristics of the IGBT were not affected; therefore, to take full advantage of the thermal characteristics of R134a, the circuit is operated in parallel with an evaporator of a mock automotive A/C system shown in Fig. 5. The mock automotive A/C system is constructed from components that comprise a 2003 Buick Park Avenue A/C system which includes a compressor, condenser, evaporator, and control system. Two service ports are placed in parallel with the evaporator refrigeration circuit to provide external mounting and operation for the test vessel. The automotive A/C system has 9320 W of cooling capacity for cooling the cabin, as well as to provide ample capacity for cooling the IGBT [14]. A special note needs be given to the placement of the test vessel. In the introduction, the means for cooling via an automotive A/C was described by a parallel path to the condenser. The following experiments were run prior to the development of the ORNL floating loop. Since these initial tests, others have been run on the parallel condenser set up with noted success. The primary difference between this test and the floating loop is the bulk fluid temperature.

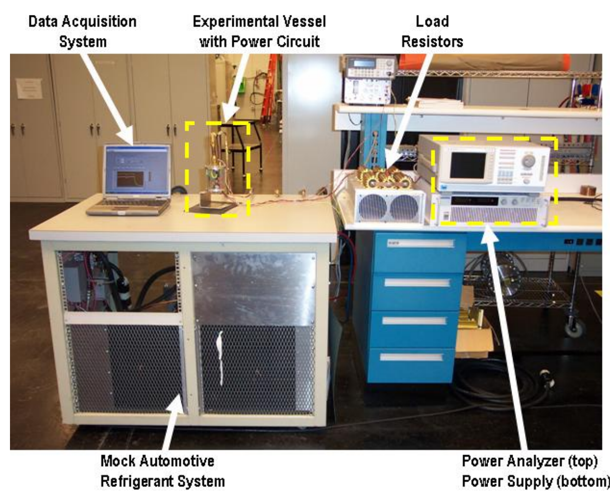


Fig. 5. Mock automotive R134a A/C system including experiment.

Realistically, the experiment discussed is a best case scenario. The specific results would not change with an increase in ambient temperature because the evaporator operates at a near constant temperature throughout a large range of ambient temperatures.

The objective of this experiment is to observe the IGBT case and vessel refrigerant temperatures, IGBT voltage and current waveforms, and A/C system behavior during an increase in forward current. The forward current is increased by 1 A increments at 30 minute intervals beginning with 6 A. The test results from the mock A/C test are shown in Fig. 6.

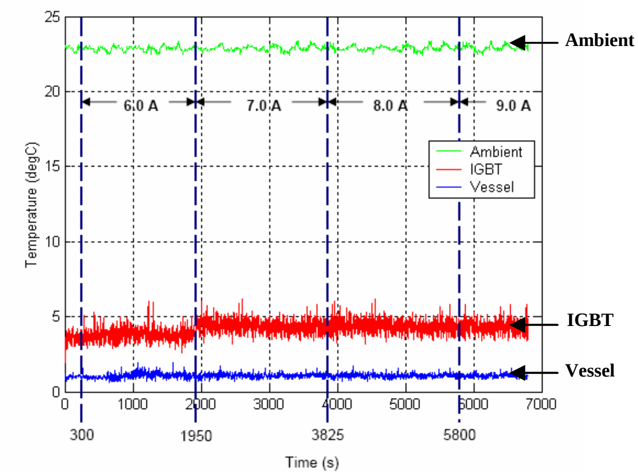


Fig. 6. Experimental temperature vs. time.

Figure 6 is a plot of the ambient, IGBT case, and vessel refrigerant temperatures versus time. The IGBT case, vessel refrigerant, and ambient temperatures remain nearly constant throughout the average forward current levels of 6, 7, 8, and 9 A. The IGBT case temperature was calculated to be 4.2°C, while the vessel refrigerant was on average 1.1°C, and the ambient temperature was 22.9°C external to the test vessel. The IGBT failed at the beginning of the 10 A interval, at which point the IGBT was conducting a peak current of 20 A which exceeded its rating.

Conclusions from the data in this test indicate the automotive A/C system has more than sufficient cooling capacity to cool the single test IGBT. The temperature of the IGBT case remained well below ambient temperature, thus it can be concluded that the A/C system can dissipate more heat from multiple PE devices.

VII. Three-Phase Inverter

One requirement of the FreedomCAR Program is that the electric propulsion system, including the inverter as shown in Fig. 7, must be capable of delivering 30 kW of continuous power [2]. The efficiency of the inverter is an important factor because it is an indicator of wasted power converted into heat by the PE devices. The wasted power robs the power from the motor and draws extra power from the batteries. Efficiency for an inverter is based on many variables such as semiconductor ratings, switching frequency, supply voltage, phase current, stray inductance, etc. Typically, an inverter's efficiency is 96%; therefore, an estimated loss for a 30 kW inverter is 1200 W continuous.

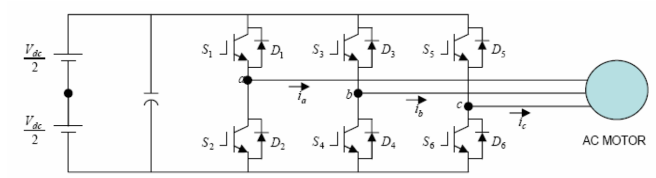
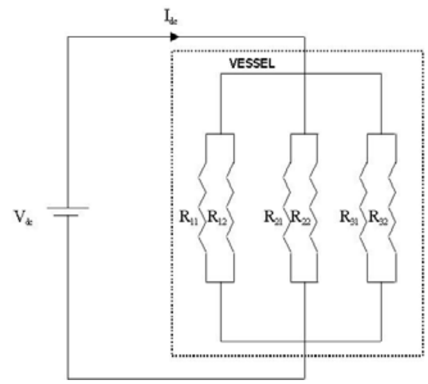
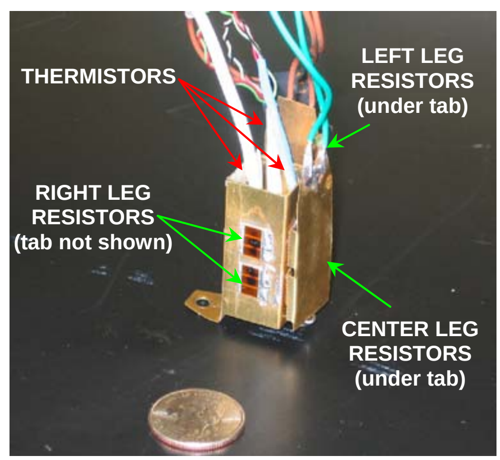


Fig. 7. Three-phase inverter driving an A/C machine.

The inverter was simulated using six thin-film resistors as the PE devices shown in Fig. 8. Resistors were used to emulate heat from an inverter because of time constraints to build an inverter. The resistors were submerged and cooled by the mock automotive A/C system described previously in Section VI.



(a) Circuit diagram.



(b) Resistor assembly.

Fig. 8. Thin-film resistor circuit.

The test procedure was to supply the resistors with a dc voltage from which the resistors draw 16 A of current. The current was increased by 1 A every 30 minutes of operation.

Each branch temperature represented the case temperature of the IGBT device in that branch. A plot of the resistor temperatures of each branch versus time is shown in Fig. 9. At first look, the resistor temperatures are different because of the configuration of the resistors (see Fig. 8 (b)). During this experiment, the R134a fluid temperature remained 1.5°C. The center resistor branch receives heat energy from the two neighboring resistor branches conducted by the metal substrate to which the resistors are mounted, thus increasing the center branch resistor temperature. The left branch is the coolest because it is placed nearest to the inlet refrigerant tube, where a fresh supply of refrigerant is being forced across this branch.

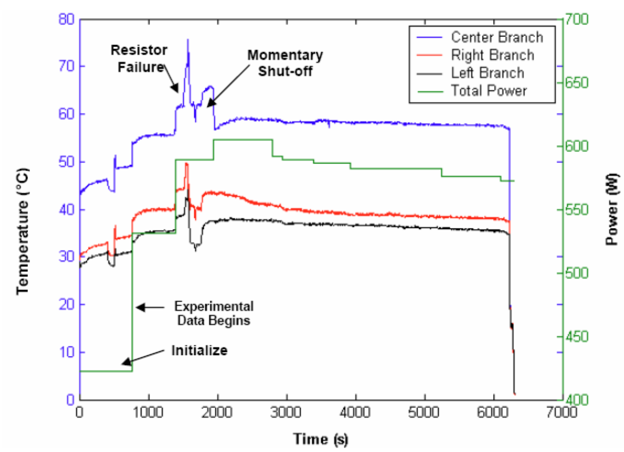


Fig. 9. Resistor temperature and power dissipation vs. time.

Initially the resistors dissipate 422 W at 16 A as illustrated in Table 3, which shows each interval of power dissipation. During this period, temperature fluctuations are present due to adjustments of the bulk refrigerant level within the vessel. Once the liquid level settled, the current was increased to 18 A, and the total power dissipated was 531 W. The center, right, and left branch temperatures reached steady state temperatures of 56.6°C, 40.9°C, and 36.0°C, respectively. The current level was then adjusted to 19 A, and the total power dissipated was 589 W. After 100 seconds, a portion of the center branch resistor failed at a temperature of 61.8°C. The center, right, and left branch temperatures reached a peak of 75.6°C, 49.7°C, and 44.0°C respectively; at which point the power supply was deactivated for 80 seconds. A decision was made to continue the experiment, and the power supply was again activated.

The results of the experiment demonstrate that the automotive A/C is capable of cooling the resistors up to 605 W. The power ratings and thermal properties of the resistors are unknown because they were custom built by Vishay Electro-thin-films to match the footprint of a PE device and no specifications were given. However, a reasonable conclusion based upon an extrapolation of the experimental temperature versus forward current results is that if the resistors have a larger current rating, the automotive A/C could sustain the resistor temperatures below 125°C at power levels up to 1200 W as shown in Table 4.

Table 3. Thin-film resistor experimental results

		Branch Temperature (°C)		
I_{avg} (A)	P_{total} (W)	Center	Right	Left
16.0	422	55.5	39.7	35.4
18.0	531	56.6	40.9	36.0
19.0	589	61.8	43.9	38.5
18.4	605	58.9	41.0	37.7
18.0	592	58.8	40.8	37.5
17.9	589	58.3	38.7	36.9
17.8	586	58.3	39.2	36.8
17.7	582	58.1	38.7	36.5
17.5	576	57.5	37.8	35.5
17.4	572	57.5	37.7	35.4

Table 4. Extrapolated thin-film resistor results

		Branch Temperature (°C)			
I_{avg} (A)	P_{total} (W)	Center	Right	Left	Fluid
0.0	0	0.0	0.0	0.0	0.0
10.0	165	17.8	13.1	14.5	10.0
20.0	659	61.5	43.9	38.4	26.3
27.0	1201	107.1	75.5	60.0	40.8
30.0	1483	130.5	91.6	70.5	47.9
34.0	1905	165.2	115.6	85.6	58.0

VIII. Active Cooling of the IGBT Junction

Experimental results in Sections VI and VII demonstrate that the removal of heat energy away from the generating area is a major limiting factor for large forward current capabilities in PE devices. As an example, the tested IGBT junction-to-case thermal resistance is 2.1°C/W. For conduction, thermal resistance is determined by geometry and a material's thermal conductivity or experimentally from temperatures and heat flux data. For a given heat flux, temperature differences increase with increasing resistance. Resistances larger than one translate into significant differences in temperature between the case and the junction. Presented in this section, the plastic enclosure is theoretically removed from the junction, and a simulation is performed in which the IGBT junction is actively cooled by an automotive R134a A/C system.

Theoretically separating the plastic enclosure from the junction and case will expose the junction layer to the ambient. Knowing that exposing the junction to the ambient will potentially pollute the Si die, a special coating should be applied to shield the Si from contaminates. The special coating is estimated to be a few thousandths of an inch applied to the surfaces of the junction layer, and it should have a thermal resistance of 0.5 °C/W or less, similar to a thermal interface material (TIM), which is applied between a PE device and a heat sink to provide even heat conduction.

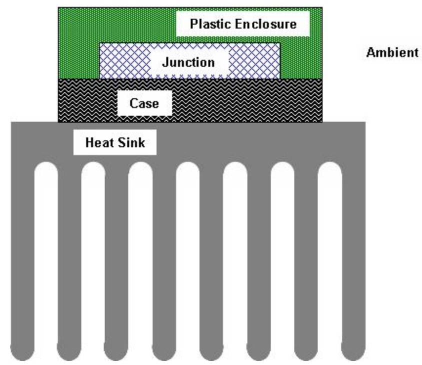
The junction layer temperature of a single exposed junction IRGBC20UD2 IGBT is simulated and compared to an enclosed IRGBC20UD2 IGBT. These IGBTs are operated under identical switching frequency, duty cycle, and refrigerant temperature. The simulation incorporates the steady state thermal circuit model of the IGBT and cooling system, described in Fig. 10, where simple steady state thermal equations can be used. Unlike the enclosed IGBT where heat flow has one path (junction-case-ambient), the exposed junction IGBT has two heat flow paths (junction-case-ambient and junction-TIM-ambient). The first heat flow path is identical to conventional IGBTs; however, the latter path has a much lower thermal resistance because of the direct proximity to the R134a refrigerant. Due to the lower thermal resistance, the junction-case-ambient heat flow path shall be ignored in the simulation.

The simulation results are shown in Fig. 11. As the forward current increases, the junction temperature increases for both IGBTs. With a manufacturer limit on the junction temperature of 125°C, the IGBT with the attached case experiences a maximum junction temperature at 8.5 A; however, the exposed junction IGBT can operate at 17.5 A before meeting the maximum junction temperature. At 17.5 A, the junction temperature of the IGBT with a case was estimated to be 423°C by simulation, which is unachievable in a practical Si semiconductor.

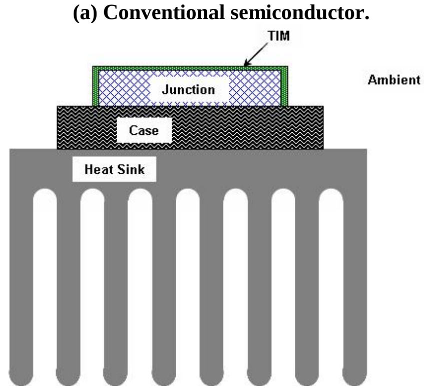
HEVs would be an ideal application for an inverter built from exposed junction IGBTs because the inverter would be smaller, lighter, and more reliable than present designs that have a bulky case. The IGBTs would have a greater current capability and would not have to be overrated.

IX. Conclusions

PEs are vital to the operation and performance of HEVs because they provide the interface between the energy sources and the traction drive motor. As with any practical system, PE devices have losses in the form of heat energy during normal switching operation which has the ability to damage or destroy these devices. Thus, to maintain reliability of the PE system, the heat energy produced must be removed. Present HEV cooling methods provide adequate cooling effects, also these techniques are bulky, heavy, and require extra mechanical components.



(a) Conventional semiconductor.



(b) Exposed junction semiconductor.

Fig. 10. Semiconductor packaging.

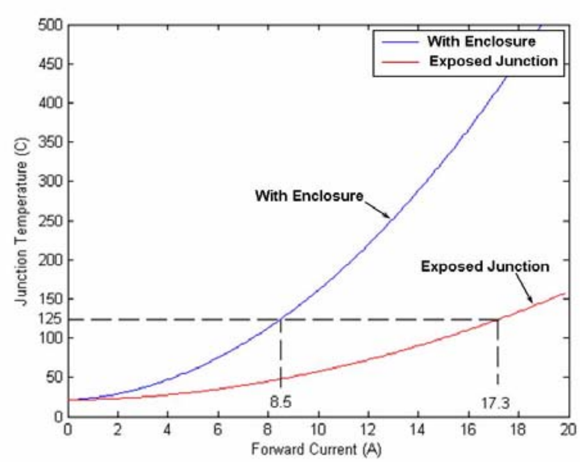


Fig. 11. IGBT junction temperature vs. forward current.

The technique described in this paper incorp
R134a refrigerant and the on board A/C system tc
PE devices in a reliable range of temperatures. P
by experimentation, R134a has no damaging effe
the normal operation for 850 days on a subm
IGBT, gate-controller card, and snubber circuits.
IGBT circuit was operated in an air-cooled and I
environments where the voltage and current wave
were compared. Results indicate R134a induc
additional delay or switching losses on the
circuit. The automotive A/C system provic
constant case temperature of 4.2°C.

The automotive A/C system was shown to have
than adequate cooling capacity to cool a six-
30 kW inverter with 96% efficiency. Base... FreedomCAR specifications, normal operation of the inverter IGBTs will dissipate 1200 W of heat energy. The thin-film resistor experiment proved that the automotive A/C could keep the junction temperature below 62°C while dissipating 600 W. After extrapolating the results, the A/C system is expected to be able to dissipate 1200 W of heat energy and keep the junction temperature below the 150°C target.

In addition, experimental data proved that the thermal resistance of the case limits a PE device's ability to remove heat energy from the junction layer. A simulated comparison of an IGBT with the plastic enclosure attached and an exposed junction IGBT was performed that incorporated experimental results. The results from the simulation indicate the exposed junction IGBT technique would result in reduced junction temperature, increased forward current ratings, and increased reliability of the device.

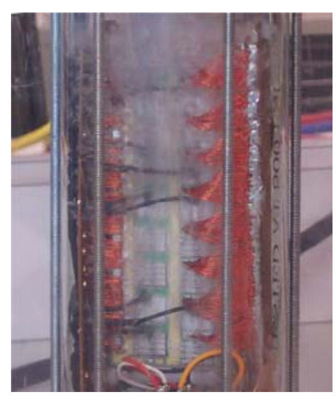
X. Continuing Work

As mentioned earlier, ORNL is improving on this work with the floating loop shown in Fig 12. The floating loop is a novel approach to heat removal by using the condenser side of the R134a refrigerant loop to cool PEs. The condenser is the highest pressure zone in the A/C system. Unlike a system running in parallel with the evaporator which requires the compressor to function continuously, the floating loop can function independently with the existing A/C system as well as jointly. The system consists of a heat/cooling zone and a small pump to motivate the fluid in the proper direction while sharing the condenser with the existing A/C system. The floating loop is able to remove several kilowatts of heat energy [6].

Fig. 12. Floating loop experimental setup.

Additionally, further research is being conducted using active junction cooling. IGBTs from a commercially available inverter are directly cooled using R134a refrigerant (see Fig. 13). These studies are focusing on the coefficient of thermal expansion (CTE) of the Si dies and bonding surfaces, wire bonding fatigue, soldering, and soldering techniques. This research may give greater insight into reliability improvement techniques and smaller packaging of PE.

(a) Inverter card with exposed junction IGBTs.



(b) IGBT card dissipating 1 kW in R134a.

Fig 13. Preliminary experimental IGBTs for direction junction cooling using R134a.

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