

# NEXT GENERATION MILITARY VEHICLE POWER CONVERSION MODULES

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## About the Authors

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Gary Mulcahy is Chief Technology Officer and Co-CEO of TDI. He received his BE-EE from New York University followed by graduate study at the Polytechnic Institute of New York. Mr. Mulcahy is a recognized authority in power conversion technology and the design, development and production of power systems for maximum performance and reliability with minimal life cycle cost of ownership.

### **JOHN SANTINI**

John Santini is Vice President of Engineering of TDI. He received his BS-EE from Cornell University. Along with a career that includes founding and running his own company which provided high end power conversion equipment for military and commercial systems, Mr. Santini is a noted authority on hybrid vehicle systems. Among his long line of technological achievements, John once converted a 1967 Corvette into a fully electrical vehicle.



## **Executive Summary**

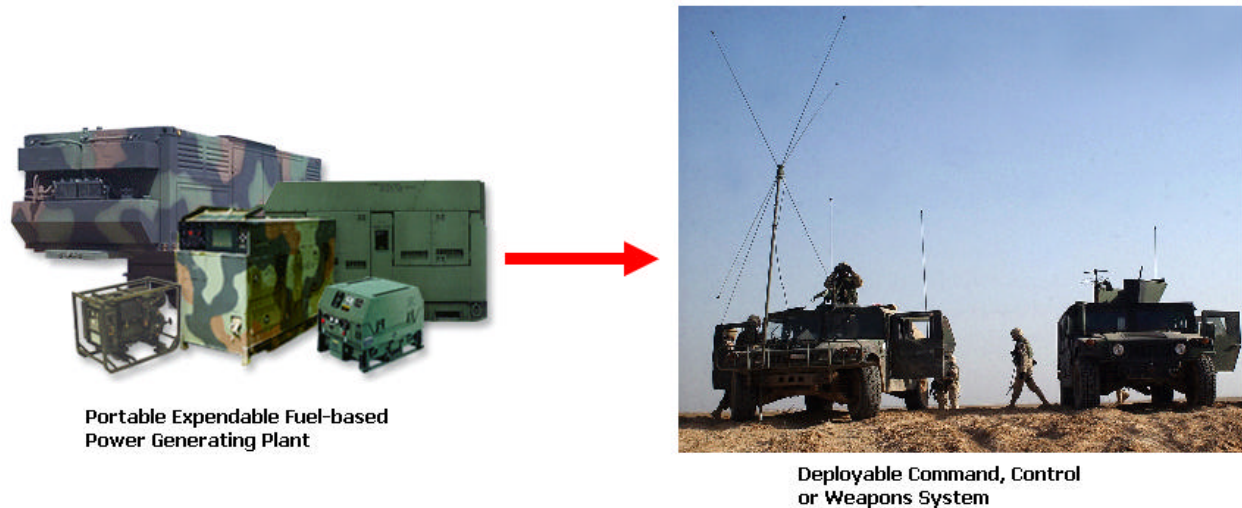
**Next generation military vehicles will be providing unprecedented levels of export power and standardization. Analysis has shown that conventional design techniques will come up short in terms of power density, reliability and cost for these applications.**

**TDI has developed alternative equipment design and construction techniques for highly reliable power conversion that will provide these applications new levels of standardization and performance.**



## Background

As depicted in Figure 1, present generation deployable land-based systems generally derive their power from vehicle engines or portable generators. These typically provide 120/240VAC or 28VDC at power levels from 10kW up to 30kW.

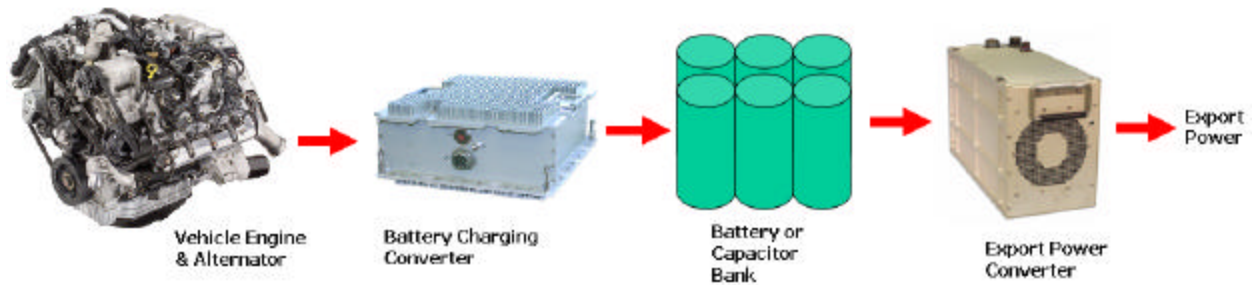


**Figure 1 – Present Generation Power for Deployable Systems**

Problems associated with the present practice include excessive audible noise, thermal signature and fuel usage. All of these lead to increased risk for the war fighter, as well as increased pressure on logistics. New generation military vehicles which employ electric hybrid technology present an opportunity to significantly address these issues by providing “Export Power” that is sourced by the vehicles’ on board energy storage plant and provided to systems outside the vehicle.

On present generation systems, more often than not export power is sourced from the vehicle’s 28VDC alternator. At the typical power levels being demanded by today’s export power loads (many times significantly greater than 10kW) operating currents can easily top 500A, presenting problems with expensive, large conductors and especially with the overload protection components required to break this much current.

New generation vehicles will employ higher voltage energy storage plants such as Nickel-Metal Hydride or Lithium-Ion Batteries, or Super Capacitors. These will typically operate at around 300VDC to optimize hybrid motor operation. Along with the ability to provide significant amounts of power with drastically reduced audible and thermal signatures, the availability of this higher voltage power presents some significant advantages to the export power conversion system. As illustrated in Figure 2, distribution currents are reduced by 90% (for example from 500A to 50A) from the 28V case, and components within the power converter can be reduced in size due to reduced operating currents.

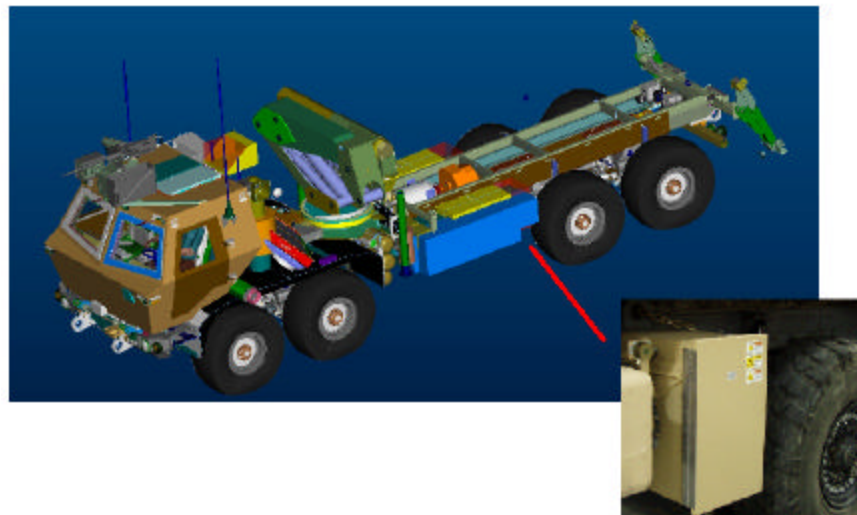


**Figure 2 – Export Power Configuration on Electric Hybrid Vehicle**

### Challenges to Vehicle On-Board Power Conversion Units

Military vehicles present challenges to power conversion assemblies due to the severe environment they must operate in, and the mission critical nature of their deployment. By their very nature, they will be operating in remote areas where maintenance may be limited and unanticipated failures catastrophic.

As depicted in Figure 3, which shows a TDI converter mounted to the underside of a military transport vehicle, more often than not export power converters will be located outside the crew space, fully exposed to the elements. Many times they can be located below the fording plane of the vehicle, requiring the assembly to be immersion compatible. Operating temperatures generally range from  $-46$  to  $+54^{\circ}\text{C}$ . Mechanical vibration and shock requirements are typically characterized by MIL-STD-810F, Methods 514.5 and 516.5.

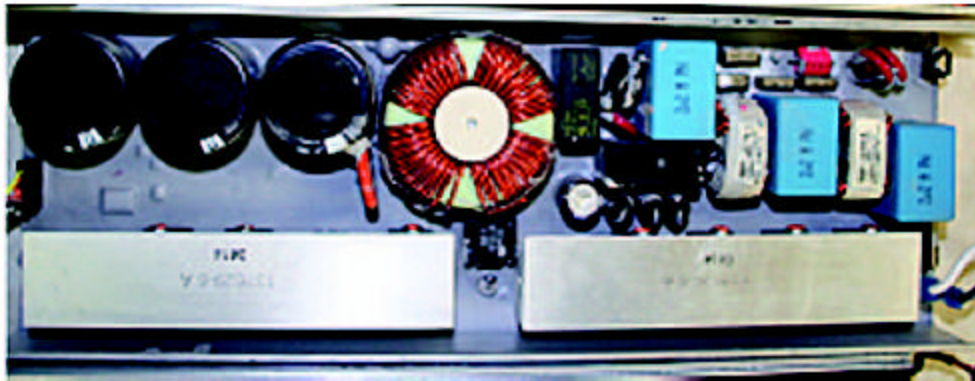


**Figure 3 – Typical Installation Location of Export Power Converter**

A survey of required power conversion density requested by various vehicle manufacturers indicates a range from  $3.4\text{W}/\text{in}^3$  to as high as  $10.3\text{W}/\text{in}^3$ . Typical cooling requirements call for either forced air cooling or liquid cooling. The choice of cooling methodology is absolutely critical in the successful deployment of this type of equipment. The remainder of this paper will focus on the various choices available, highlighting the attributes of each.

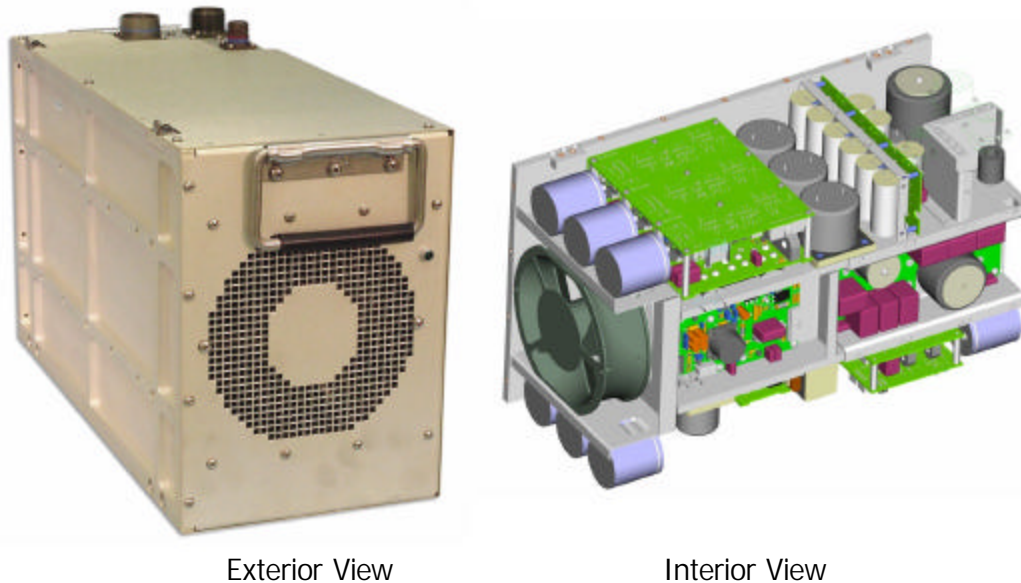
## Cooling Choices – Forced Air Cooling

In dealing with severe environments in both the commercial and military markets, TDI has a great deal of experience with both sealed and unsealed equipment solutions. We have issued a companion white paper [Environmentally Sealed Power Modules](#) regarding the use of air cooled power conversion equipment in compromising environments. The highest power conversion density is achieved through the use of direct fan cooling, circulating air throughout the inside of the power conversion assembly. However, this is only advisable if the unit is mounted in a protected location where relatively clean air is available. Otherwise, the solution is prone to dust and dirt buildup on internal components and the addition of moisture can form conductive “mud”, which can precipitate failures. Given the tactical nature of these vehicles, extreme conditions of dust and dirt buildup will overcome even the extra protection measures shown in page 9 of the above mentioned white paper, repeated below in Figure 4.



**Figure 4 – Environmentally Hardened Air Cooled Assembly**

The best chance for success for an externally mounted, air-cooled converter in a military vehicle is an indirect system where there is no direct air impingement on internal components. This arrangement (usually referred to as a “wind tunnel” design) uses fans to cool heat sinks and allows the electronic components to be protected from the environment by locating them on the other side of the aluminum heat exchanger. While this approach offers more protection, it also results in a larger package. Figure 5 shows a typical wind tunnel design that has been deployed by TDI in both airborne and ground based applications.



**Figure 5 – Wind Tunnel Design Approach**

The unit depicted in Figure 5 is a 10kW DC-AC inverter that meets military requirements. Package size for this state-of-the-art unit is 20" x 8.17" x 12", and it delivers approximately 5W/in<sup>3</sup> at 10kW from an input voltage of 360VDC. (Note that if this unit were to be redesigned for 28VDC input, power conversion density would drop to approximately 3W/in<sup>3</sup>.)

While the wind tunnel approach fully isolates electronic components from the external environment, there are some limitations associated with it that should be noted.

- Requires a fan that is exposed to the environment. This is a wear out mechanism that has to be taken into account.
- If the air inlet or outlet is blocked, operation may be compromised.
- Not compatible with full immersion unless contained in an additional water-tight vessel.
- Designs tend to be fully customized, providing little opportunity to leverage solutions into different applications.

## Liquid Cooling

The use of liquid cooling allows the electronics package to remain sealed, while also allowing the heat exchanger to be located in a potentially more convenient location, such as the front of the vehicle. Typically, the cooling liquid employed is either water or a mixture of water and ethylene glycol (a.k.a., antifreeze).

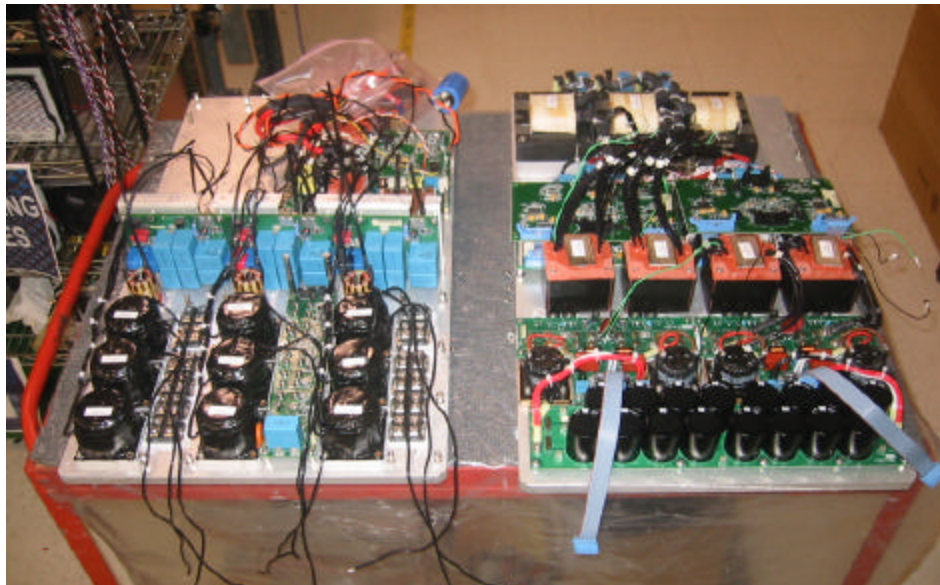
The most common approach to liquid cooled systems has all heat producing components mounted to a flat cold plate, which has liquid circulating through it. The liquid is then routed through an external heat exchanger to cool it. Figure 6 presents a unit TDI has designed and

deployed with this approach. This is an immersion compatible, vehicle mounted converter that produces 21kW of 28VDC and 110VAC power from a 300VDC input, while being cooled with 80°C coolant delivered from the vehicle.



**Figure 6 – Liquid Cooled Power Inverter with internal Cold Plate**

While this can be an efficient cooling system, it requires a large amount of engineering time to design, keeping all the heat producing components in contact with the cold plate as well as maintaining good electrical connections to a printed circuit board. Figure 7 depicts the typical complexity of this type of approach.

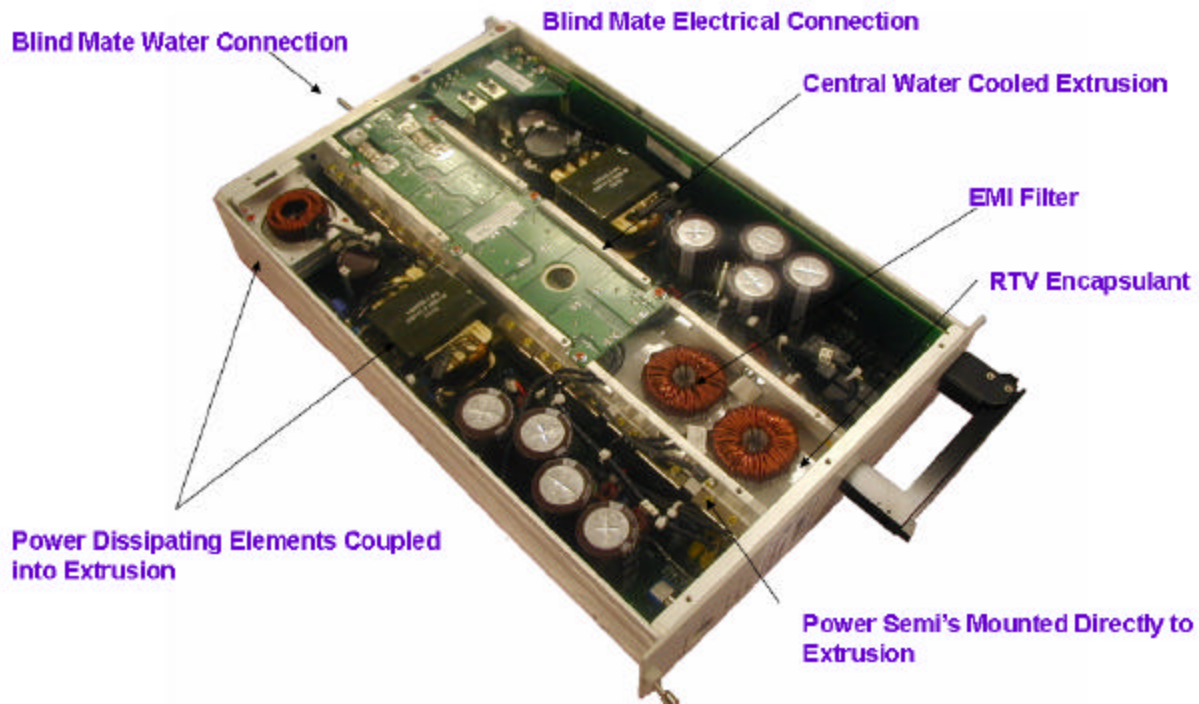


**Figure 7 – Internal Assemblies with Cold Plate Approach**

One of the limitations of the cold plate approach is that it depends on flat shapes for heat transfer. Often times, this results in an assembly that is spread out over a larger than ideal

physical area, which can result in electromagnetic noise containment issues. Likewise, this type of assembly generally requires an excess of wiring, resulting in higher cost and potentially reduced reliability due to the increased number of interconnects.

Beyond a simple cold plate, more exotic and integrated liquid cooling structural members can be deployed. For example, the unit shown in Figure 8 is produced by TDI for industrial applications. It provides 7kW of DC output power and utilizes a central liquid cooled extrusion that is highly customized to provide cooling for a number of both flat and irregularly shaped components.



**Figure 8 – Power Converter with Extruded Liquid Cooled Central Structure**

While this type of design addresses some of the limitations presented by a flat cold plate, it requires a higher level of engineering design, resulting in a completely customized unit that is not adaptable to other applications.

## Next Generation Liquid Cooled Products

In determining a strategy to address new generation liquid cooling requirements, TDI has built upon our experience to date in the above mentioned approaches. In order to provide the best performance in on-vehicle applications, this technology must be able to meet the following objectives.

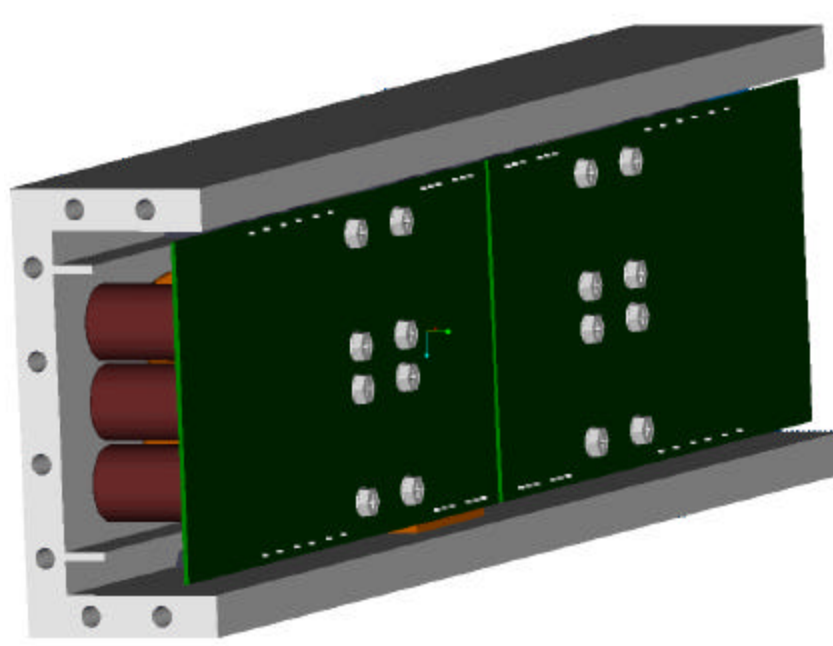
1. Meet the environmental requirements of vibration, mechanical shock and liquid immersion.
2. Work with coolant temperatures much higher than was dealt with in the past (up to 80°C in some instances).
3. Meet the EMC requirements of MIL-STD-461
4. Provide solutions that are not so highly customized as to jeopardize development timelines or cost budgets.
5. Provide a good basis for reliability expectations.

Taken together, items 2 and 5 present a particularly challenging requirement. Analysis of existing units shows that while it is not too difficult to control the temperatures of components with the larger share of power losses, it can be very difficult to control temperatures of components with relatively low losses, but which don't have a good connection to the heat transmission path. It is not unusual for the internal ambient air temperature inside water cooled units to be 40°C, or higher, than the coolant temperature. If the coolant is 80°C, then internal ambient air temperature can easily reach over 120°C. This presents some real problems for certain component types. For example, integrated circuits contained in PC board mounted SMT packages may dissipate a few hundred milliwatts. These depend on the ambient air that surrounds them to carry this heat away, and with an effective ambient of over 120°C, reliability is compromised. Likewise, there are many passive components whose reliability quickly falls off as temperatures increase above 100°C.

Methods for controlling this effect include reducing the internal ambient temperature rise above coolant temperature, or improving the thermal path from the component to the coolant. Internal air temperature rise can be reduced by circulating air inside the box and employing an air-to-liquid heat exchanger. However, this generally takes up a significant amount of room and adds the reliability impact of a circulating fan.

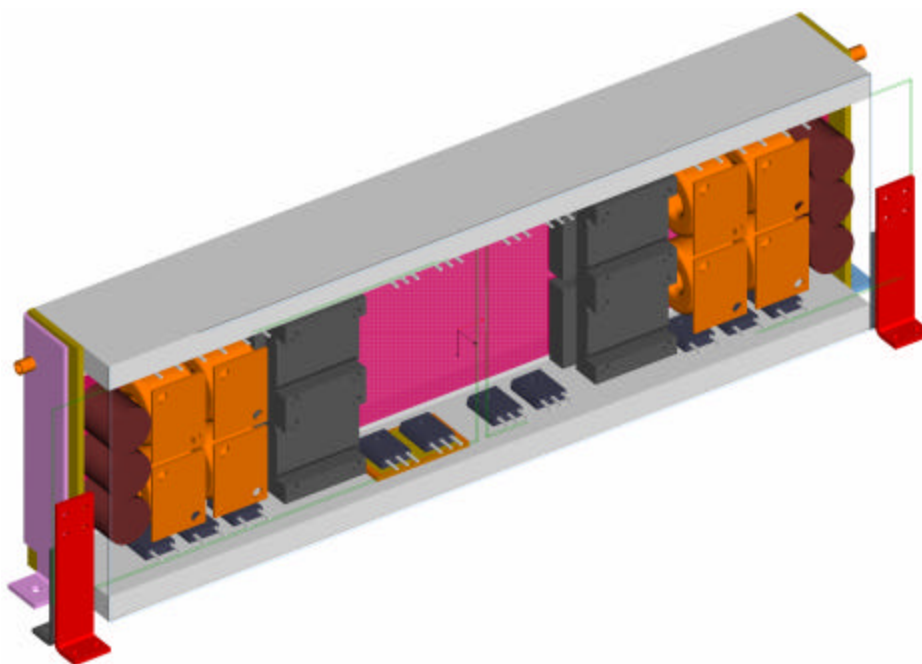
Improvement of the thermal path can be achieved by surrounding the sensitive components with a thermally conductive compound that ultimately contacts with a liquid cooled surface. While this method is effective, the design needs to comprehend this need from the very beginning, otherwise a short path from the component to the coolant might not be achievable.

Given these considerations, TDI considers a modularized liquid cooled approach as a good fit for military vehicle applications. A concept of this approach is presented in Figure 9.



**Figure 9 – “LiquaCore” Water Cooled Building Block Concept**

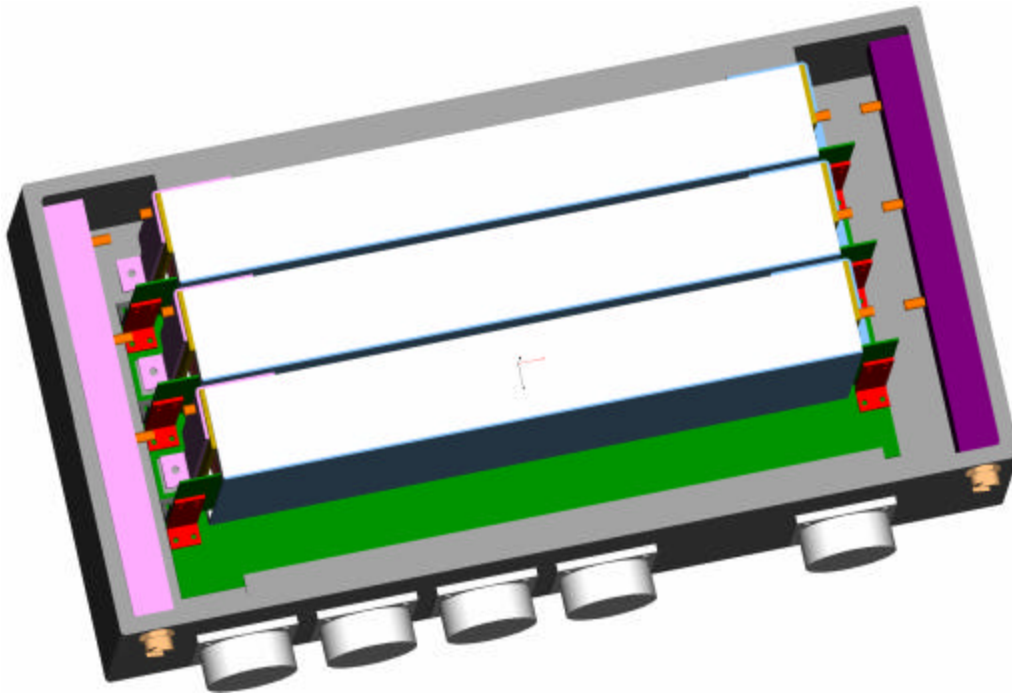
The building block presented in Figure 9, which we refer to as TDI’s “LiquaCore” technology, is approximately 5” x 2”, and utilizes a water cooled extruded “U” shape that can accommodate a number of different power conversion board assemblies, such as DC-DC converter blocks, or DC-AC converter blocks, or PFC converter blocks. The extruded shape is set up to have coolant circulating through the holes shown around its three sided perimeter. Figure 10 presents a view of this sub-module with the printed wiring board rendered transparent.



**Figure 10 – “LiquaCore” Water Cooled Sub-Module Detail**

As shown in Figure 10, the extruded shape allows for very short thermal paths between the high heat components and the coolant. In addition, this design allows for the use of PC board mounted power semiconductors, eliminating the need for wire harnesses to remotely located parts. Heat from irregularly shaped components is extracted by embedding these components in a layer of thermally conductive RTV potting that is poured into the base of the “U” shaped extrusion. Most important with this approach is the fact that the coolant completely surrounds the printed wiring board, limiting the ambient temperature rise that components on the board will be exposed to.

As depicted in Figure 11, these power blocks are connected in parallel to realize the overall converter.



**Figure 11 – Overall Power Converter Construction**

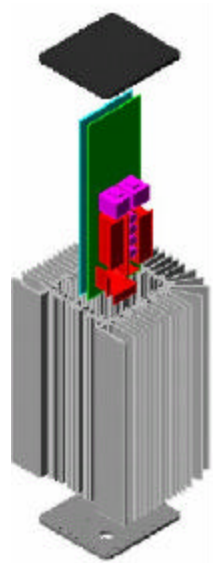
Coolant is distributed to the water cooling jackets via a distribution manifold on one side of the box, and a collection manifold on the opposite side of the box. Input and output power is distributed to the modules via connections from a power distribution mother board at the bottom of the unit. The entire enclosure is environmentally sealed, employing conventional techniques.

The modularized liquid cooled approach also presents some advantages with regard to design for electromagnetic compatibility. By partitioning assemblies, the EMI filter can be fully isolated and shielded from noise generating assemblies, thereby simplifying filter design.

## Non-conventional Liquid Cooling Technologies

TDI has developed a new technology that utilizes oil to encapsulate electronic components so as to provide a highly thermally conductive path between these components and the ultimate heat dissipater. As detailed in the companion white paper [Environmentally Sealed Power Modules](#), the initial deployment of this technology is in convection cooled, environmentally sealed products for commercial, industrial and military use.

The advantage of oil in these applications is that it is an insulator, so it can be used in direct contact with the electronic components. Complete circuit board assemblies are immersed in the oil, and this produces a relatively isothermal environment that greatly increases component reliability. Figure 12 presents a typical assembly that utilizes this technique, while Figure 13 shows these modules in a typical application.

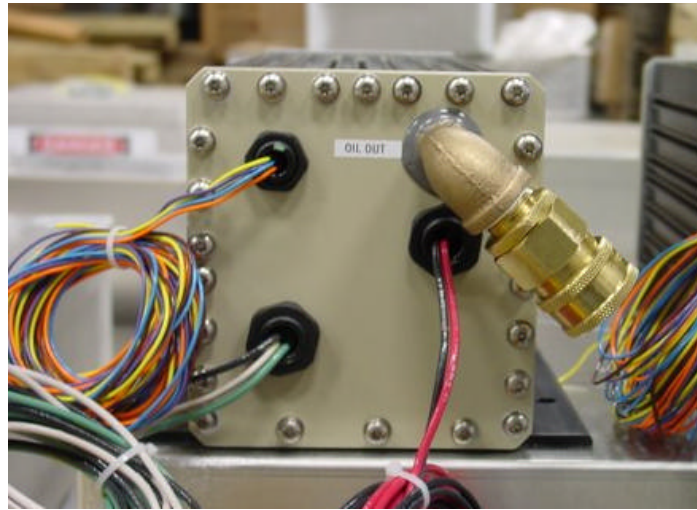


**Figure 12 – Exploded View of Oil-Filled, Environmentally Sealed Power Converter**



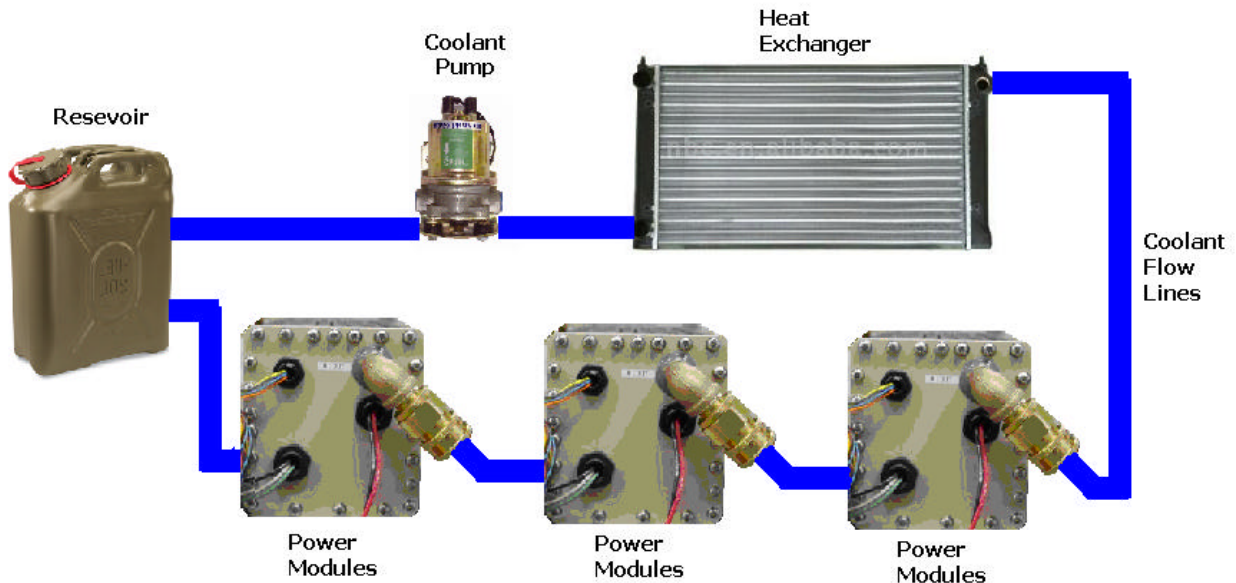
**Figure 13 – Typical Application Deployment of Environmentally Sealed Products**

Recently this technology has been expanded to include heat dissipation through circulating oil. TDI has deployed this technique on commercial hybrid vehicle components such as battery chargers and DC/DC converters. Figure 14 shows a DC-DC converter that employs circulating oil cooling.



**Figure 14 – Converter with Circulating Oil Cooling**

The oil used is typically a UL approved, environmentally friendly, vegetable-based transformer oil. However, hydrocarbon-based mineral oil has also been successfully tested and we believe that diesel fuel could also be used in this application. The advantage of diesel fuel would be that it is already used on the vehicle and is logistically an excellent choice. Figure 15 presents a conceptual power system cooling loop that circulates the coolant through the power converters.



**Figure 15 – Circulating Oil Coolant Loop**

Advantages of circulating coolant directly to electronic components include the following.

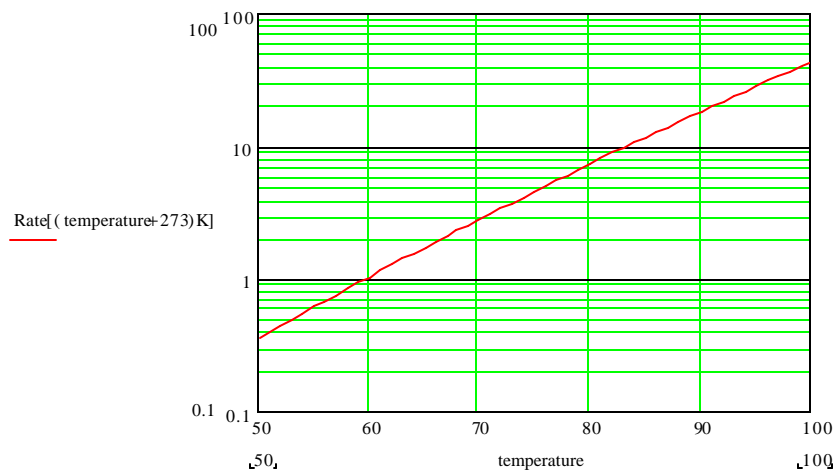
- Extreme protection from exterior environmental effects
- Buffering from shock and vibration effects
- The ability to utilize existing air-cooled assemblies with little or no changes

Perhaps the biggest advantage that can be achieved with this method of cooling is the reduction of overall operating temperatures. Since most liquid cooling technologies that have been considered to date share the coolant loop with other heat sources, power electronic components end up operating at unusually high temperatures. These higher operating temperatures will ultimately have a deleterious effect on system reliability. By cooling the power electronics with a lower temperature coolant that comes in direct contact with the components, their operating temperature will be significantly reduced, resulting in a significant improvement in reliability.

A general rule of thumb in most systems is that as temperature increases, reliability decreases. The Arrhenius Model is generally accepted as an accurate predictor of semiconductor, and other device reliability. This model covers many of the non-mechanical (or non material fatigue) failure modes that cause electronic equipment failure. It is particularly useful in describing failure mechanisms that depend on chemical reactions, diffusion or migration processes. The model suggests the rate a reaction occurs is given by the following equation:

$$R(t) = A * e^{-(E_A / \kappa T)}$$

Where A is a constant,  $E_A$  is the activation energy of the reaction,  $\kappa$  is Boltzman's Constant and T is temperature in degrees Kelvin. The model predicts that as temperature increases, the rate to failure increases, as depicted in Figure 16.



**Figure 16: Rate to Failure versus Temperature based on the Arrhenius Model**

Once the activation energy for a specific failure mechanism is known, the effects of increased temperature on the rate of reaction can be expressed as:

$$\text{Failure Rate @ Temp T1} / \text{Failure Rate @ Temp T2} = \exp^*(E_A / \kappa) (1/T2 - 1/T1))$$

The typical activation energy for failure mechanisms of components found within electronic power supplies is on the order of 0.5 to 1.5 electron volts. Thus, a 10°C increase in temperature can correlate to a two to eight times increase in various component failure rates.

In the case of Export Power Converters, if the converter is cooled via 70°C coolant, we can expect component operating temperatures as high as 100°C, or higher, and these temperatures will be spread across the vast majority of components in the converter.

In the case of Circulating Oil Cooling, temperatures can be expected to drop significantly, perhaps as low as 70°C. A 30°C reduction in operating temperature can very easily result in a 100X increase in component reliability.

## **Conclusions**

Great opportunities for reduced design cycle time and improved performance are presented through the use of standardized cooling topologies that can be employed across various power conversion assemblies. Further, extremely significant gains can be made through the use of direct circulating coolant on component approach.