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FY 2007

DC-DC CONVERTER FOR FUEL CELL AND HYBRID VEHICLES

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DC-DC Converter for Fuel Cell and Hybrid Vehicles

Final Technical Report

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Appendices

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2 OBJECTIVES

The goal of this project is to develop and fabricate a 5kW dc-dc converter with a baseline 14V output capability for fuel cell and hybrid vehicles. The major objectives for this dc-dc converter technology are to meet:

- Higher efficiency (92%)
- High coolant temperature,e capability (105°C) ,
- High reliability (15 Years/150,000miles),
- Smaller volume (5L),
- Lower weight (6kg), and
- Lower cost ($75/kW).

3 TECHNICAL APPROACHES

The key technical challenge for these converters is the 105°C coolant temperatures. The power switches and magnetics must be designed to sustain these operating temperatures reliably, without a large cost/mass/volume penalty. The following key technologies are proposed to break through technical barriers to achieve high temperature, high power density, and lower cost design.

3.1 Converter Topology

A novel interleaved dc-dc converter topology is proposed for this high power conversion, as shown in Figure 1. The key merits of the converter are:

- Lower RMS current stresses on components due to interleaving,
- Reduced ripple current on capacitors due to interleaving,
- Lower power losses due to low Rds_on and soft-switching,
- Smaller magnetics due to high switching frequency, and
- Low EMI due to integrated power devices and magnetics.

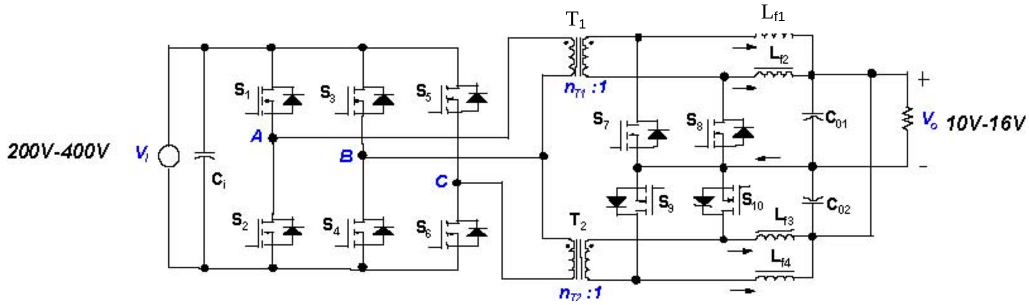
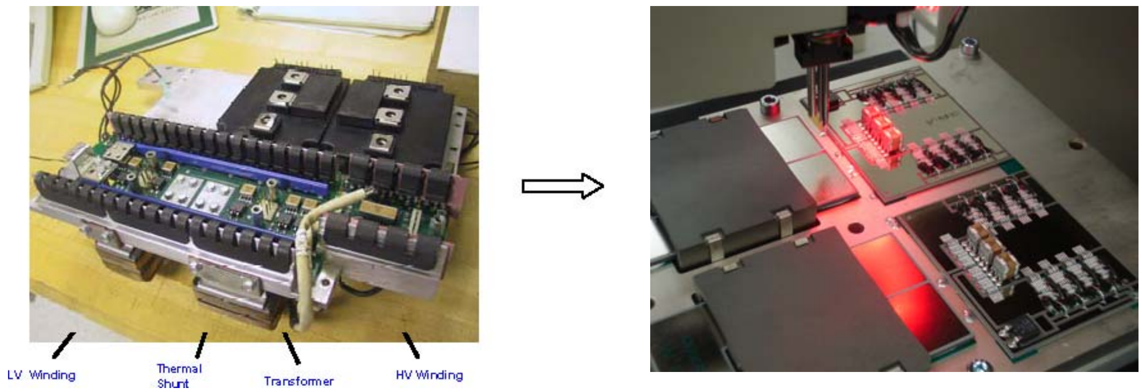


Figure 1. A novel interleaved dc-dc converter topology

3.2 Integrated Module-Based dc-dc Converter

The power module-based integration technology has been employed in this design. The thermal is a challenge. The coolant temperature is 105°C. In order to meet the design criteria of junction temperature at 125°C, the thermal impedance has to be very small. Power module integration simplifies thermal stack-up layers, obtaining smaller thermal resistance. Furthermore, customized power module enhances the high current interconnection path. The conduction loss is reduced. By removing the bolt connections in transformer winding and busbar by using wire bond, the reliability is also improved. Figure 2 shows a traditional dc-dc converter packaging and a power module-based design approach adopted by this project. The major advantage of the power module based dc-dc converters are:

- Enhanced thermal performance
- Reduced number of devices
- Increased reliability
- Higher level of integration



(a) Conventional design. **(b) Power module based design.**

Figure 2. A traditional dc-dc converter packaging vs. power module based packaging.

3.3 Planar Magnetics with Enhanced Cooling

This converter has also been designed using planar magnetics, a technology that Ballard believes is critical for reliable and cost effective high volume production of such products. The benefits from this technology are:

- Lower leakage inductance due to shorter winding termination and smaller circuit paths,
- Elimination of discrete contacts' ohmic loss,
- Reduction of ohmic loss due to shorter conduction paths,
- Lower ac loss due to flat winding structure,
- Higher core window utilization ratio,
- Smaller core volume and weight,
- Higher surface to volume ratio for improved heat conduction,
- Direct cooling of core by direct contact to heatsink, and
- Higher power density.

The planar transformer winding structure is shown as follows:

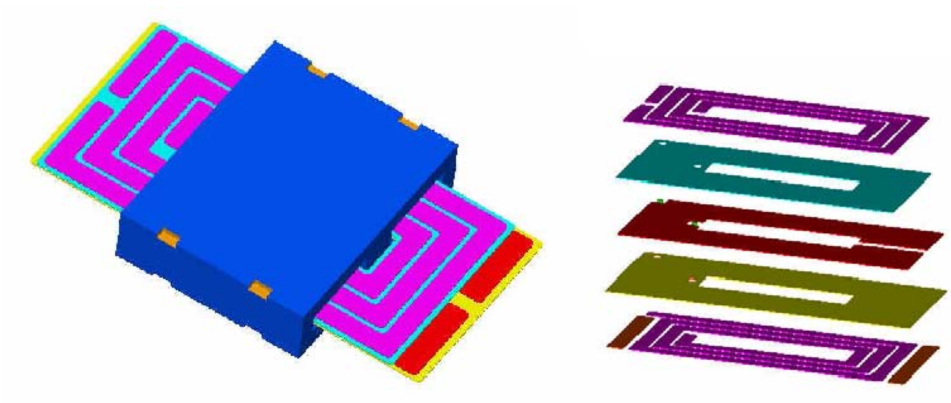


Figure 3. A planar transformer winding structure

4 MAJOR ACCOMPLISHMENTS OF FISCAL YEAR 2004–2007

Figure 4 shows the technical road map over three years of development periods starting from the second half of year 2004. During the second half of FY2004, a segmented dc-dc power module (2.5kW) was developed to investigate the feasibility of power module design and integrated planner transformer. During FY2005, a full 5kW dc-dc power module was developed with the proposed dc-dc converter topology to prove to full function of the dc-dc converter with full power and voltage range. This is Alpha design and is meant to prove the functionality. During FY2006, a beta version of the dc-dc converter was designed to meet high temperature and reliability requirement. During FY2007, the major tasks were focused on manufacturing process and final test.

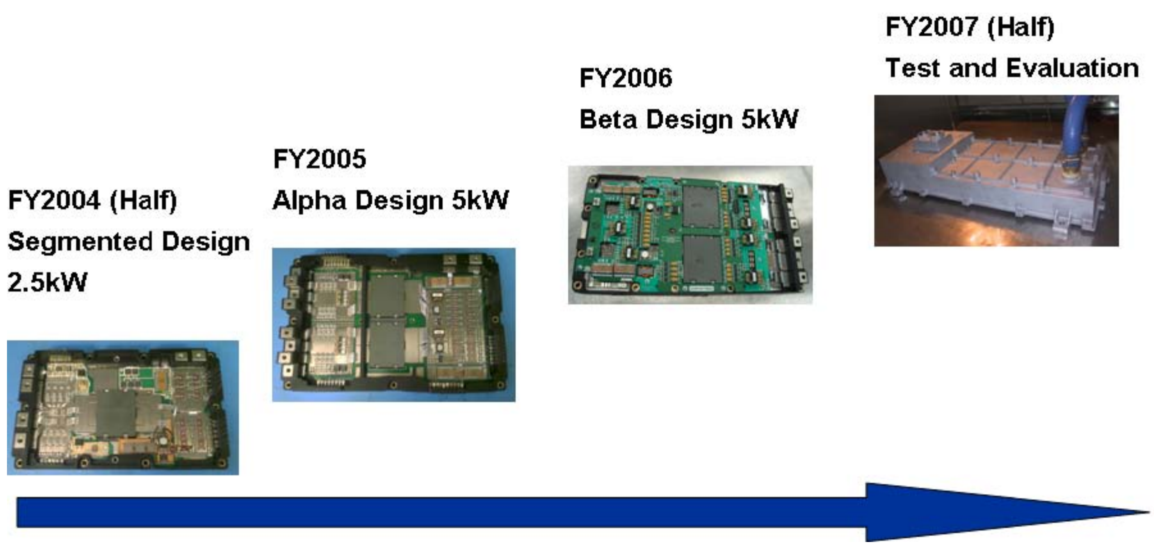
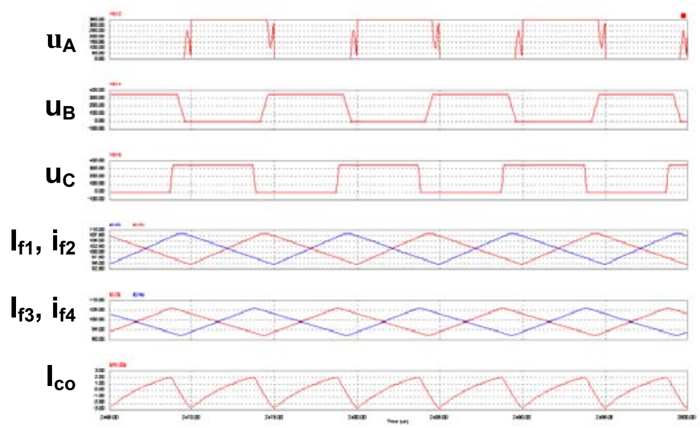


Figure 4. Technical development road map.

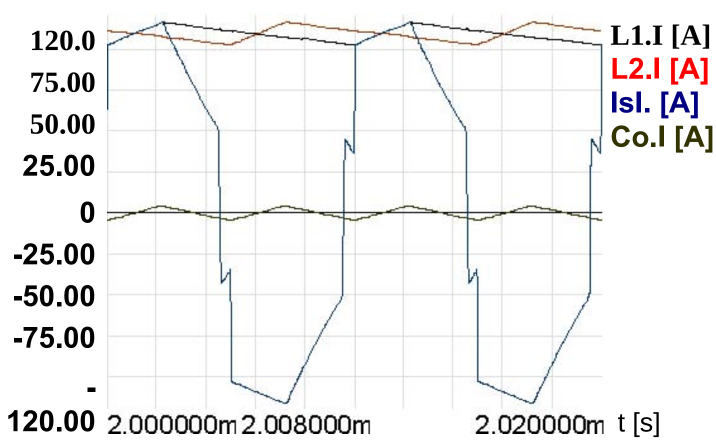
4.1 Technical Achievements Highlights in FY2004

4.1.1 Topology simulation

Figure 5 shows the simulation waveforms of the primary bridge output voltage, four inductor current waveforms and the ripple current flowing into the output capacitors, and the secondary transformer winding current. The operation condition is 5kW/500A. The result shows each inductor takes a quarter of the load current and the ripple current to output capacitor is less than 10A.



a) u_A, u_B, u_C: Primary inverter bridge waveforms; I_{f1}, I_{f2}, I_{f3}, I_{f4}: Secondary four inductors current waveforms; I_{co}: Ripple current of output capacitor



b) L1.I, L2.I: Inductor L1, L2 current; Is.I: Secondary transformer winding current; Co.I: Ripple current of the output capacitors

Figure 5. Simulation waveforms (Po = 5kW).

4.1.2 Parameter design and component selection

Selected dc-dc parameters are designed as:

- Turns ratio: 6:1 Note:Vi = 200V, Vo = 14.5Vmax(not 16V),
- Switching frequency: 100kHz,
- Primary side Mosfet: (3+4+3) x 550V, 0.11 Ohm Rds(on) (total 20),
- Secondary side Mosfet: 8 x 100V, 0.009 Ohm Rds(on) (total 32),
- Planar transformer,
- Core size 50 x 100mm with 30mm window width,
- 6 oz copper, multiple layers, and
- Core flux density 0.14T.

4.1.3 Efficiency calculation

Po=2.5kW per CH	Vi=200V, Vo=10V	Vi=350V, Vo=10V	Vi=400V, Vo=10V	%
LV mosfet loss (W)	84.4	70.8	68.6	21%
HV mostet loss (W)	66.6	66.6	66.6	21%
LV winding loss (W)	34.3	34.3	34.3	11%
HV winding loss (W)	39.8	39.8	39.8	12%
Magnetic core loss (W)	20.4	20.4	20.4	6%
Control power (W)	20.0	20.0	20.0	6%
Switching Loss (W)	5.0	10.0	20.0	6%
Misc (2%)	50.0	50.0	50.0	16%
Total Loss (W)	320.5	311.9	319.7	100%
Efficiency (Est.)	88.6%	88.9%	88.7%	

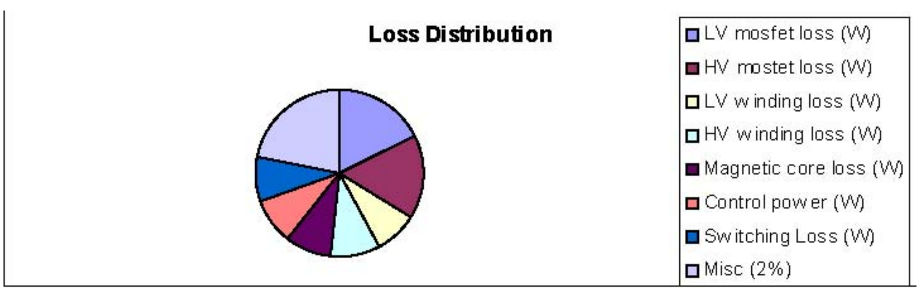


Figure 6. The calculated efficiency and the loss.

4.1.4 Planar transformer design

Planar transformer parameter:

- Turns ratio: 6:1,
- Core size 50x100mm with 30mm window width,
- 6 oz copper, multiple layers, and
- Core flux density 0.14T.

A thermal simulation is performed to estimate the planar winding temperature, as shown in Figure 7. The simulation parameters and results are:

- Voltage output: 10V,
- LV winding loss: 34.3W,
- HV winding loss: 39.8W,
- Coolant Temperature: 105ºC, and
- Winding temperature: 139ºC.

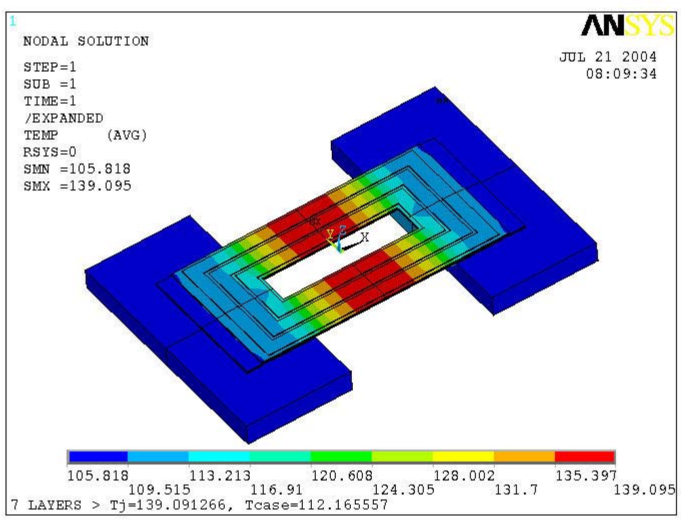


Figure 7. Thermal simulation result for planar transformer winding.

4.2 Technical Achievements Highlights in FY2005

4.2.1 Key technologies proven out

A 2.5 kW segmented dc-dc power module was developed at the beginning of FY2005 to verify key technologies adopted in this project. Figures 8, 9, and 10 shows the photo of the preliminary power module as well as the test results. Through this first design iteration, the following technologies have been verified and implemented:

- DBC transformer winding design and manufacture feasibility
- Identified key variables affecting the performance
- Wirebond diagram and Rds-on packaging efficiency
- Non-interleave planar transformer vs. interleaved planar transformer
- Mosfet die selection with low Qrr
- Snubber circuit optimization
- Transformer ratio
- Exercised the power module fabrication process with larger DBCs and lead frames

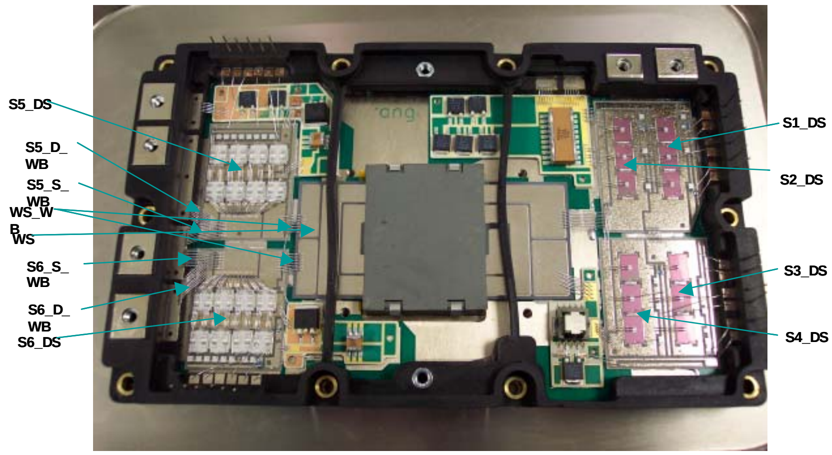


Figure 8. A segmented preliminary 2.5kW DC-DC power module

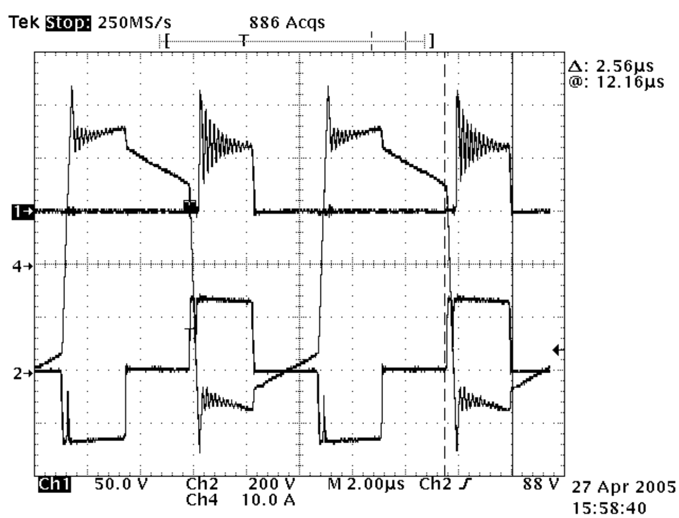


Figure 9. Tested waveforms at Vi=300V, Vo=13.35V/197A, Po=2627W, I_rr=35A,

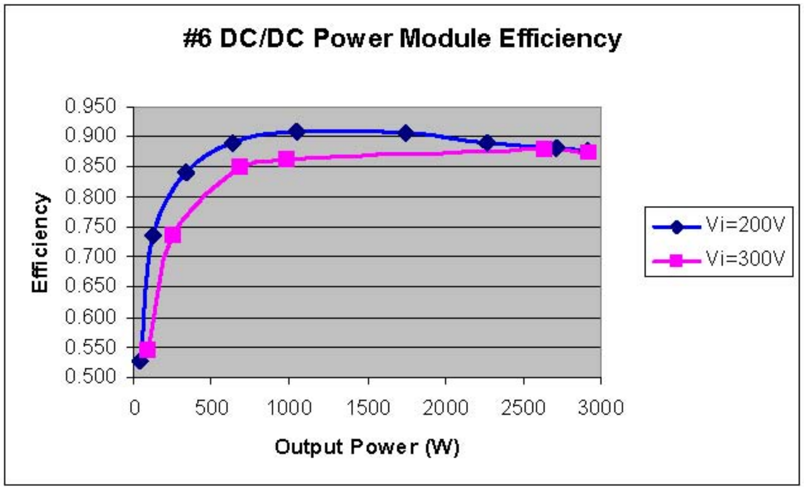


Figure 10. The efficiency testing results of the segmented dc-dc power module.

4.2.2 Fully-functional, Alpha unit prototype design and fabrication

A 5kW converter with the selected topology, shown in Figure 10 above, has been designed during this phase. The following major tasks have been accomplished:

- Power module design, including: DBC, lead frame, and module baseplate,
- DC-DC converter packaging: Housing plate, seal, busbar, etc.,
- Control board, EPLD program and simulation,
- High temperature components selection,
- Design release and components purchasing,
- Power module process development, and
- Fabrication and assembly.

Figures 11 and 12 show the designed Alpha 5kW power module and completed dc-dc converter. This design level incorporated the lesson-learned in the 2.5kW segmented power module (described above), with the goal to verify full electrical function against the specification. To reduce prototyping time the leadframe was made from urethane and the baseplate was made from aluminum. Plastic and AlSic, respectively, shall be used in the final design.

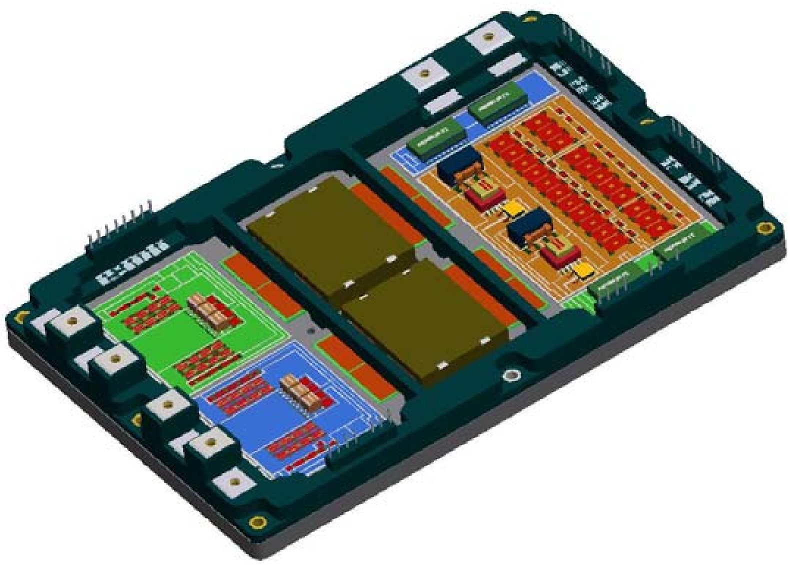


Figure 11. A 5kW full functional dc-dc power module–Alpha design.

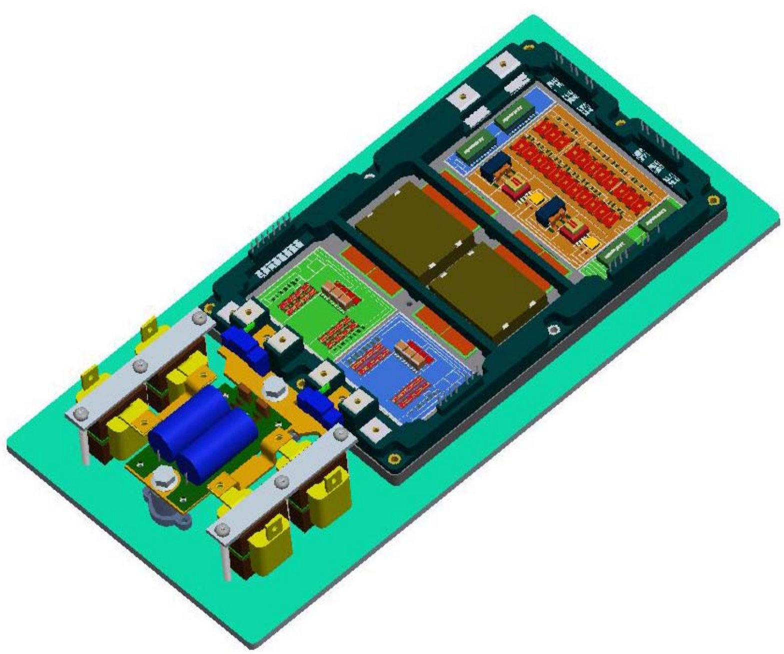


Figure 12. A completed 5kW dc-dc converter–Alpha design.

4.2.3 High volume cost estimation

Based on the bill of material (BOM) generated in the Alpha version dc-dc converter design, a unit cost at high volume has been estimated, as illustrated in Table 1 below. The current cost estimate for this module is $545/per unit, 45% higher than the DOE target of $375/per unit.

Table 1. Alpha dc-dc converter BOM and cost estimation at 1000K volume

#	Level	Part Description	Tooling Cost	Tooling Type	Part Unit Price (@1KK)	# Per Uint	Part Cost
1	1	ORNL 5kW dc-dc Power Module	$166,000		$320	1	$320
2	1	LV Busbar Positive	$15,000	Stamping die	$2	1	$2
3	1	LV Busbar Positive	$15,000	Stamping die	$2	1	$2
4	1	Converter Housing	$80,000	Die cast	$15	1	$15
5	1	Housing Cover	$50,000	Stamping die	$8	1	$8
6	1	LV Studs	$30,000	Insert mold	$5	2	$10
7	1	HV Connector			$20	1	$20
8	1	Inductor	$10,000		$9	4	$35
9	1	LV Capacitor Board Assembly			$10	1	$10
10	1	Signal Connector			$8	1	$8
11	1	Control Board	5000		$80	1	$80
12	1	Current Sensor			$8	2	$16
13	X	MFG, F&T					$18

Tooling Cost	$371.000

Part Cost Per Unit @1000K	$545	145%
DOE Target	$375	

The power module is the major cost in the dc-dc converter, composing 59% of the total cost. Table 2 and Figure 13 contain a detailed study of the power module cost.

Table 2. DC-DC power module cost spreadsheet

1	Lead Frame	$10.00	3%
2	AlSic Baseplate	$50.00	17%
3	DBC Substrates	$57.86	20%
4	DBC XFMR Wingding	$36.50	13%
5	HV mosfets	$22.00	8%
6	LV mosfets	$32.00	11%
7	Chip Resistors	$10.80	4%
8	HV Caps	$32.00	11%
9	LV Caps	$12.00	4%
	Sub Total	$263.16	90%
	Total Cost	$291.00	100%

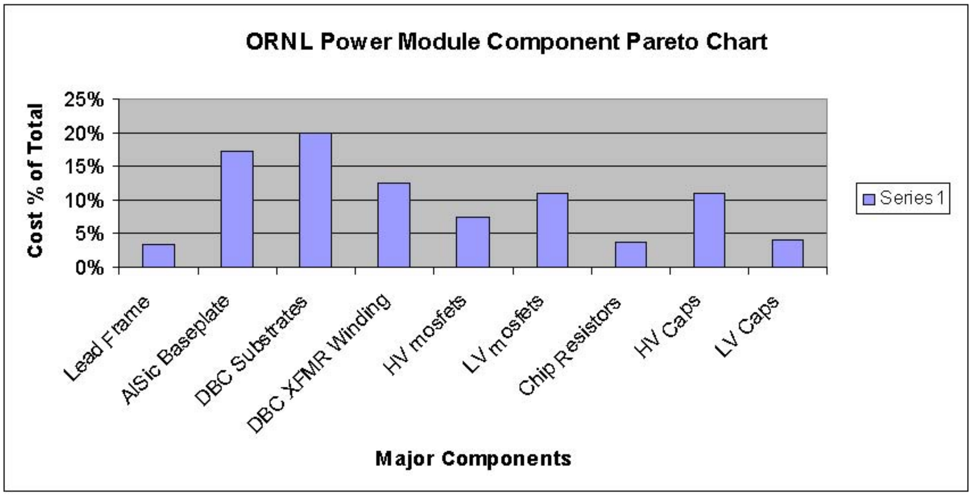


Figure 13. DC-DC power module cost distribution.

4.2.4 Alpha prototype test results

Figure 14 shows the ORNL Alpha dc-dc converter test setup. The tests are still on-going. Currently the converter attains 5.0 kW output (full power) and achieves a peak efficiency of 95%. From the test waveform shown in Figure 15, the Irr loss is eliminated compared to the segmented dc-dc converter tested earlier this year. The Alpha unit efficiency map is shown in Figure 16. Comparing these results to the segmented dc-dc converter efficiencies shown in Figure 10, overall efficiency in the Alpha design has been improved by 5%.

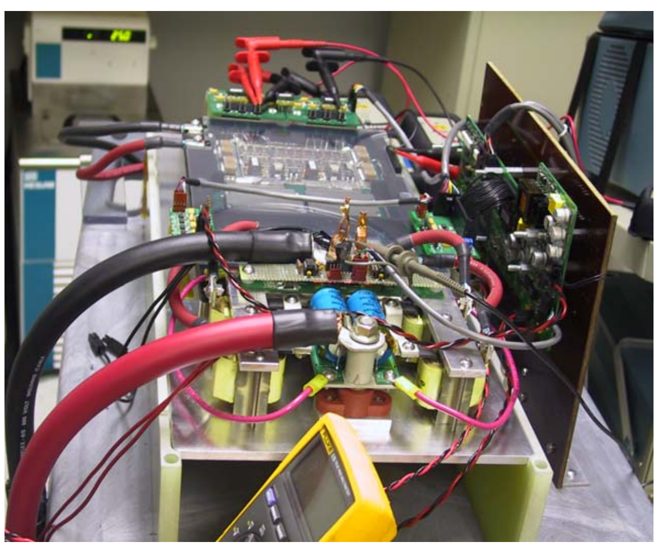


Figure 14. Alpha dc-dc converter under test.

The measured volume of the Alpha unit approaches 6.5 liters, approximately 1.5 liters over the DOE target of 5 liters. The measured pressure drop of this module is approximately 2.3 psi, exceeding the DOE target by 1.57 psi.

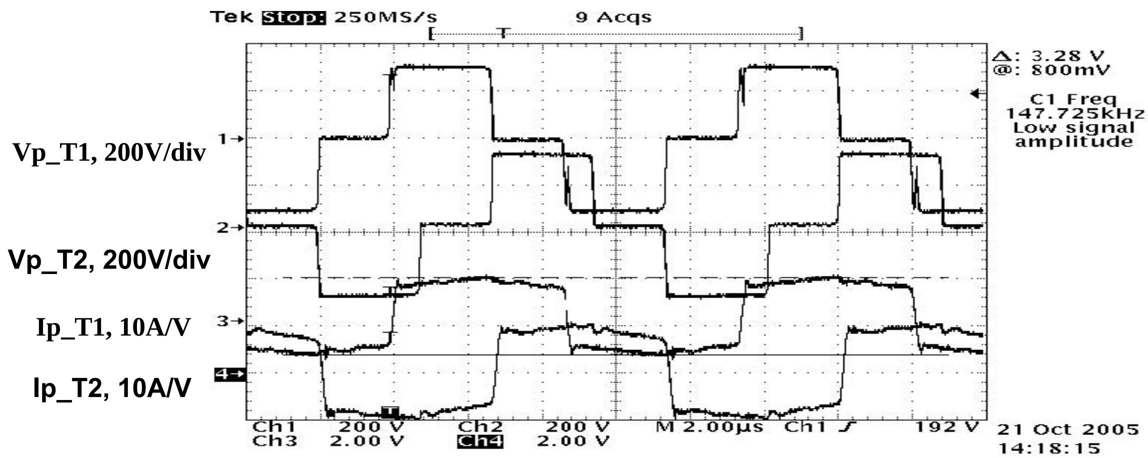


Figure 15. Alpha unit tested waveforms at Vi = 300.6V, Vo = 13.31V, Po = 5.1kW, η = 93.3%.

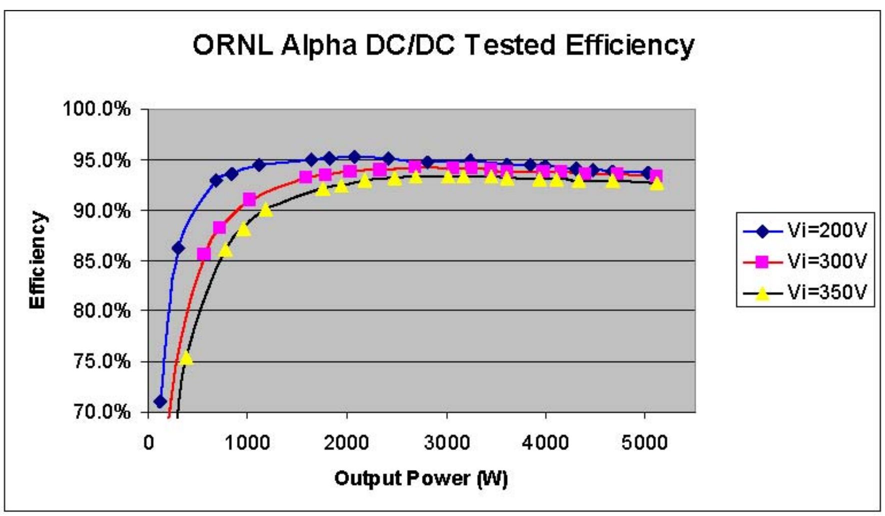


Figure 16. Alpha unit tested efficiency at Vi = 200V, 300V, 350V, and up to 5kW.

4.2.5 Technical discussion

The Alpha level prototype successfully verified the operation of the proposed topology and the improvement of the power module layout. The efficiency has been improved by 5% compared with the preliminary design and achieved a peak efficiency of 95%, exceeding the DOE target of 92%.

However, we have found several issues that must be improved in the final Beta level design. These issues include:

- High volume cost target,
- Power density improvement towards the DOE target,
- Large DBC size (87mmX112mm) exceeds the supplier's zone of comfort and has reliability, implications (thermally cycling),
- Large lead frame results in excessive tooling costs,
- Large module baseplate approaches limit of production facility capabilities, and
- Higher pressure drop than target.

4.2.6 Conclusion for FY2005

- The key technologies have been proven out in Phase I,
- Alpha converter prototype has been designed in Phase II,
- All components have been received and the system has been assembled,
- High volume cost estimates have been developed,
- Achieved full power output (5kW),
- Efficiency has been improved by 5% compared to preliminary design,
- Volume and pressure drop of the Alpha design has been tested, and
- The up-to-date status from the Alpha design is summarized in Table 3.

Table 3. Up-to-date status summary from the Alpha design

	Alpha Design	DOE Goal	% Target
Output Power	5.1kW	5kW	102%
Efficiency	93%	92%	101%
Cost Estimation	$545	$375 total, ($75/kW)	69%
Coolant Temperature	90 Deg C	105 Deg C	86%
Volume	6.5 Liter	5 Liter	77%
Weight	7.6kg	6kg	79%
Coolant Pressure Drop	2.3 PSI	0.73PSI (5kPa)	32%

4.3 Technical Achievements Highlights in FY2006

In FY2006, we continued working on the Alpha prototype testing work, completed the Beta design and part purchasing, and developed the manufacturing process to produce the final prototype.

4.3.1 Continued electrical evaluation test on Alpha prototype

Figure 17 shows the test implementation for the Alpha prototype. At the end of FY2005, we had finished the efficiency test at Vi = 200V, 300V, 350V and up to 5kW, and achieved 92% efficiency target. The remaining issue was when input voltage reached towards 400V, the efficiency dropped substantially and excessive switching noise appeared in the synchronized rectifier switches. This problem prevented the dc-dc converter from delivering full power at 400V.

Trouble-shooting effort had been made in the earlier FY2006 to solve the switching noise problem. It turned out to be a higher Qrr loss occurred at hot coolant test condition. When coolant was raised to 90°C, the ambient temperature surrounding the die and gate drive circuit arose. It caused a small change in signal delay. However, the delay was big enough to cause a higher reverse recovery current in rectifier turn on/off transitions, leading excessive Qrr loss on the rectifiers. An improvement was made in the gate drive circuit to compensate the small delay due the high temperature operation. The dc-dc passed the full input voltage (Vi = 400V) and full power (Po = 5kW) operation at 90°C coolant test. The overall efficiency kept 92% above, as shown in the final test result in Figure 3.

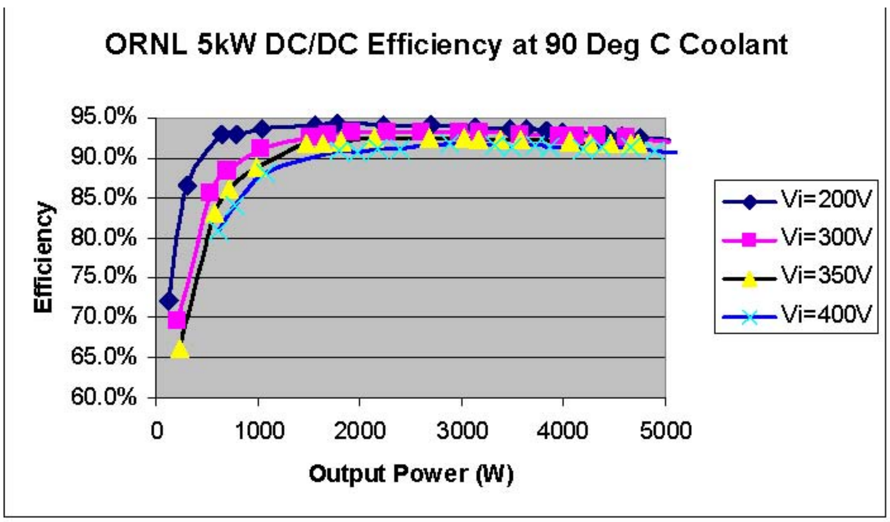
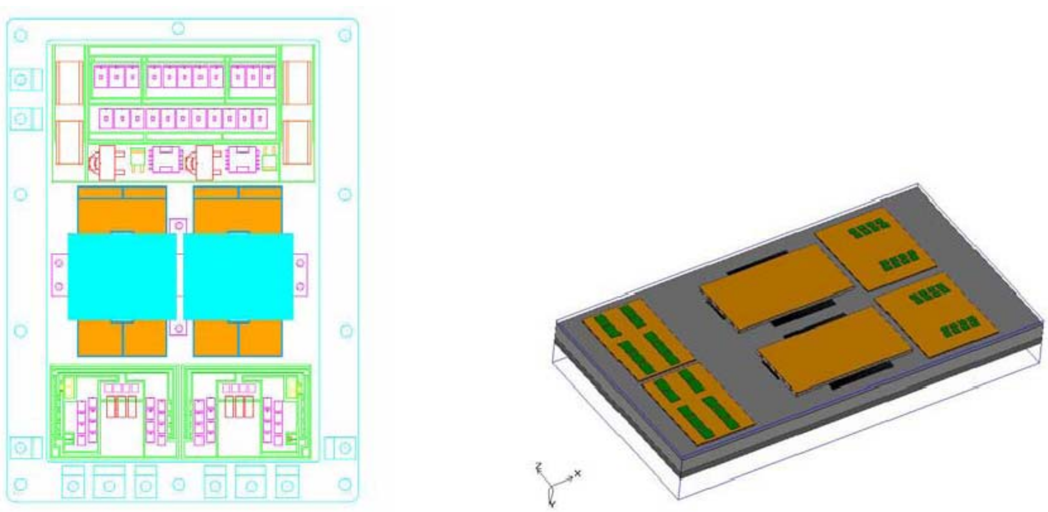


Figure 17. Efficiency test results at Vi = 200V, 300V, 350V, and 400V.

4.3.2 Cost reduction – Beta design

The cost of the customized power module is a major portion of the dc-dc converter. It was more than 50% of the overall dc-dc converter. In the beta design, a new lead frame design concept was adopted to eliminate signal pin inserts. As a result, the power module baseplate width was reduced by 33mm. Figure 18 depicts the Alpha and Beta power module design. The reduction of the power module width saves the power module cost by 7%. Improved leadframe design also save the tooling cost the Beta prototype development. The high volume cost estimation based on the Beta design is $458 at high volume, it reached 82% of the DOE goal.



(a) Alpha (203 X 315 mm). **(b) Beta (170 X 315 mm).**

Figure 18. Alpha and Beta power module layout.

4.3.3 Volume and weight reduction

The 33mm saving in power module width dimension also contributes the volume and weight reduction in the final packaging. To pass the environmental requirement and test, an aluminum cast housing has been designed for Beta prototype. The total volume is reduced to 5.1 liter from the 6.5 liter in Alpha prototype. Figure 19 shows the final Beta dc-dc converter packaging without cover.

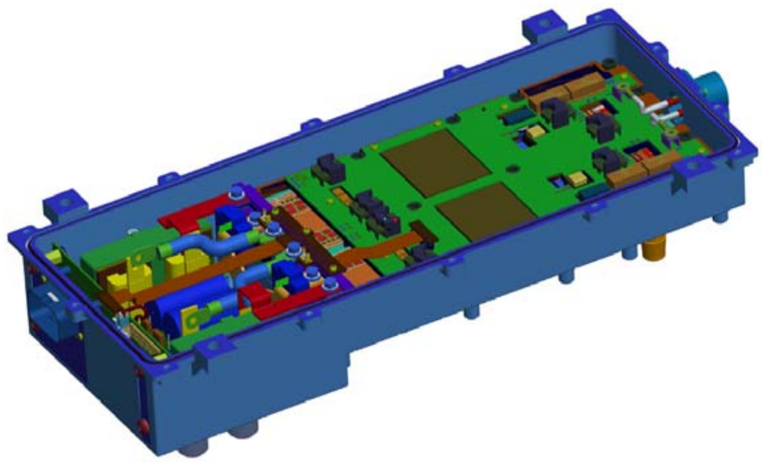


Figure 19. The Besta version of dc-dc converter (5.1 Liter).

The adoption of power module design greatly simplified the interconnection of the dc-dc converter. The part count is reduced to total 42 parts, including two wire harnesses and 11 types of fasteners. The Table 4 lists the bill of material of the Beta design and the weight estimation. The total weight is 7.4kg. Although the aluminum housing is included, the total weight is 0.2 kg less than the Alpha prototype.

Table 4. The BOM and weight of Beta design

	Part Description/Remarks	Ballard Part No.	Drawing No.	Qty /Per Mo	Weight�(kG)
1	Fasteners, M4X8, (Inductor Bracket to Housing)	5109167		10	0.001
2	Fasteners, M3X10, (HV connector to Housing)	5109391		4	0.002
3	Fasteners, M5X12 , (Cover to Housing)	5109393		17	0.002
4	Sealing Washer, Fastener to Housing	5109394		8	
5	Inductor, 4.5uH, 125A, 100Vpk, 100KHz Ripple	5109397		4	0.295
6	Pad, Silicon Gel Gasket, Inductor Bracket, ORNL	5109605	DRW5106205	2	
7	Fasteners, M5x8, (Control BRD to Stand-off)	5110338		4	0.001
8	Fastener, Hi-Low, Gate DRV to Plastic Bracket,	5110602		13	0.001
9	Fasteners, M4X12, (LV Positive Busbar to PCB Capacitor ASY)	100330-PAA		4	0.002
10	Connector, 2Pin, 1 Row	101666-PAA		1	
11	Fastener, Hi-Low, Control Board to Housing	102264-PAA		4	0.005
12	Capacitor, Ceramic, 200V, 0.01uF, 10%, Radial	5106357-s		2	
13	Fasteners, M5X14, (LV Connections to Power Module)	5108401-s		6	0.003
14	Fasteners, M5X10, (Inductor Cables to Inductor)	5108404-s		2	0.002
15	Capacitor, Ceramic, 200V, 0.15uF, 10%, Radial	5106359-s		1	
16	Gasket, HV Connector to Housing	5109392		1	0.005
17	Fasteners, M6X16, (AC Connector, Negative)	5109511-s		2	0.005
18	Brass Hose Fitting, Barb X Male Pipe for 3/4" Hose Id, 3/4" Pipe	5110760		2	0
19	HEX Nut, M5, (Inductor Cable to Inductor)	5110481-S		6	0.005
20	LV Positive Busbar Cable, Inductor(3&4) to Power Module, ORNL	5109603	DRW5106203	2	0.01
21	Connector, High Voltage, ITT Cannon ORNL	5111030		1	0.07
22	O-ring, Inside coolant channal, ORNL	5110400	DRW5106911	1	0.005
23	O-ring, Outside, Cooling Channel, ORNL	5110407	DRW5106911	1	0.005
24	O-Ring, Electronic Housing, ORNL	5110528	DRW5106911	1	0.005
25	O-Ring Seal, Divider Coolant, ORNL	5110550	DRW5106913	1	0.005
26	Harness, 2-Pin, Control BRD to Capacitor BRD	5109387	DRW5105907	1	0.005
27	Current Sensor	5109144		2	0.023
28	Electronic Box Cover -Oakridge	5109098	DRW5105707	1	0.76
29	Capacitor, Electrolytic, 8200uF, 25V, 150Deg C	5109637		2	
30	Busbar Assembly, LV Positive	5109105	DRW5105712	1	0.09
31	LV Positive Busbar, Inductor(1) to Power Module, ORNL	5109600	DRW5106199	1	0.025
32	LV Positive Busbar, Inductor(2) to Power Module, ORNL	5109601	DRW5106200	1	0.025
33	Busbar Assembly, LV Negative	5109102	DRW5105709	1	0.023
34	HSG - ELEC BOX	5109101	DRW5105708	1	2.295
35	AC Connector, LV Positive	5109808-s		2	0.145
36	Inductor Bracket, ORNL	5109104	DRW5105711	2	0.01
37	Stand-off, Female-Female, 15mm Body, M5 thread	5109604	DRW5106204	4	0.005
38	Fastener, M5X30, (Power Module to Housing)	5108406-s		15	0.006
39	Flex Circuit, Gate Drive Board to Control Board, ORNL	5109141	DRW5105742	1	0.05
40	PCB Bare Board, LV Capacitors, ORNL	5109650		1	0.1
41	Power Module			1	1.535
42	PCB Assembly, Control Board, ORNL	5109173	DRW5105735	1	0.55

Weight (kg)	**7.378**
DOE Target (kg)	**6**
% of Target	**81%**

Figure 20 illustrates the bottom view of the Beta packaging. It shows the interfaces between the dc-dc converter and the end-user. The HV connector connects the high voltage input (200V–400V) into the dc-dc converter, the LV studs is the 12V output to deliver the low voltage power to 12V battery and load in a vehicle. The coolant in/outlet ports bring in a circulating coolant into the unit to remove the heat generated in the dc-dc converter. The signal connector is the control path between the dc-dc converter and vehicle controller. It includes the voltage command and enable signal through a CAN interface.

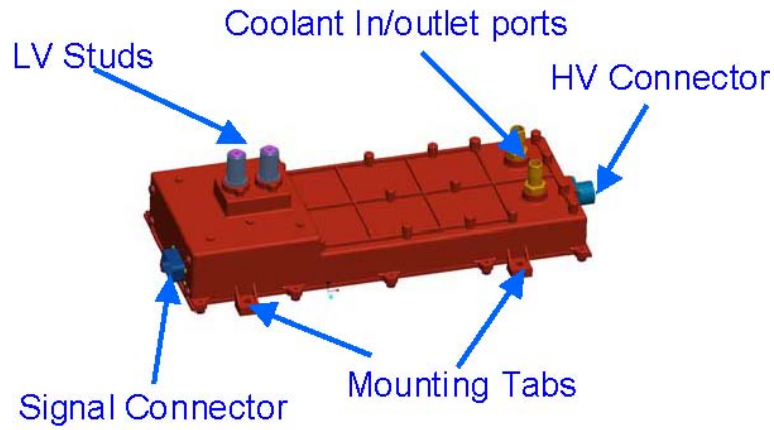


Figure 20. Beta DC-DC converter interfaces.

4.3.4 Thermal design improvement

Two major design improvements have been made in the Beta design: the leadframe material and baseplate material.

In order to meet 105°C coolant operation requirements, AMODEL A-4133 L had been selected to make the high temperature plastice leadframe. It has the property of high heat resistance, high strength and stiffness over a broad temperature range, low moisture absorption, excellent chemical resistance, and excellent electrical properties. It has been advantageously used for many automotive electrical and electronics applications. Its heat deflection temperature is as high as 300°C. The inject mold was required to manufacture the plastic leadframe. It added a substantial tooling cost for the Beta prototype development.

In order to design for 15 years reliability requirement, a Aluminum Silicon Carbide (AlSiC) had been selected for power module baseplate material. The AlSic composite materials are designed to have a high thermal conductivity and a controlled thermal expansion (CTE) behavior that provides better CTE matching between substrate and baseplate. A baseplate and substrate assembly was build to perform the thermal cycle test. It passed thermal shock test (40ºC to +125ºC) 100 times without delamination.

4.3.5 Coolant channel final design

The 105°C coolant operation requirement brings a quite bit challenge to the thermal design. The junction temperature is targeted at 125°C to allow MOSFET switches operate at a higher efficiency. There is only 20°C of temperature rise budgeted from die to coolant. In Alpha design, a pin-fin pattern was designed in coolant channel to achieve lower thermal impedance, as shown in Figure 21.

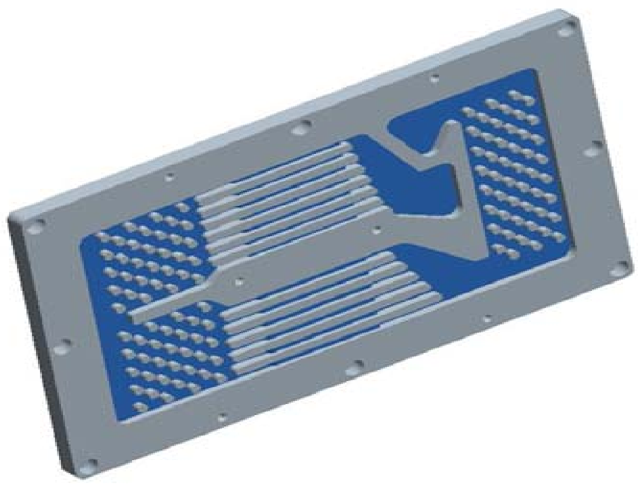


Figure 21. Alpha baseplate pin-fin design with pin-fin.

The pin-fin structure increases the surface area of the baseplate and also increases the velocity of fluid in the coolant channel. As a result, the thermal resistance can be very low. However, the test result in Alpha baseplate design revealed that pressure drop with pin-fin design is as high as 2.3psi at 7 liters/min, which is three times higher than the DOE goal (0.73psi). In Beta design, a decision was made to eliminate all pin-fins to meet the pressure drop target. The baseplate was redesigned as shown in Figure 22. A sample plate was made to test the pressure drop. The test result verified that the pressure drop in the baseplate coolant channel drops to 0.25psi at 25C at 7liter/min coolant flow rate. It meets very well with the DOE target of 0.73psi.

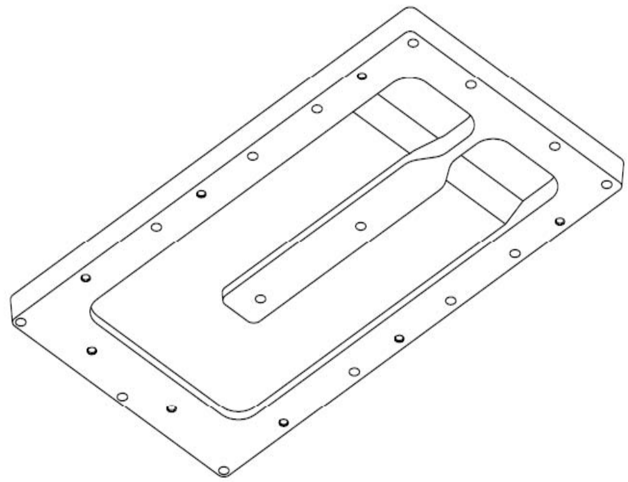


Figure 22. Beta baseplate design without pin-fin.

The location of inlet and outlet ports was also adjusted accordingly to minimize the turbulence of the coolant inside the channel. A 15mm chamfer was added in the in inlet/outlet chamber. The simulation result of the fluid field is shown in Figure 23.

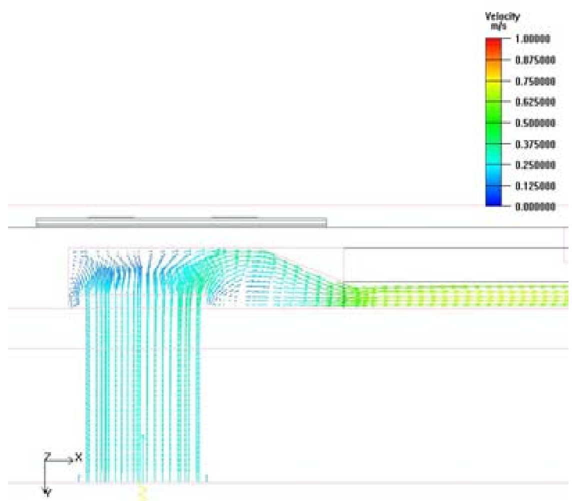


Figure 23. Coolant channel fluid simulation.

Thermal simulation was also performed by ICE pack to verify the junction temperature is within 125°C limit. The result looks very promising. The Max Junction Temp is 122.4°C at worst case as shown in Figure 24.

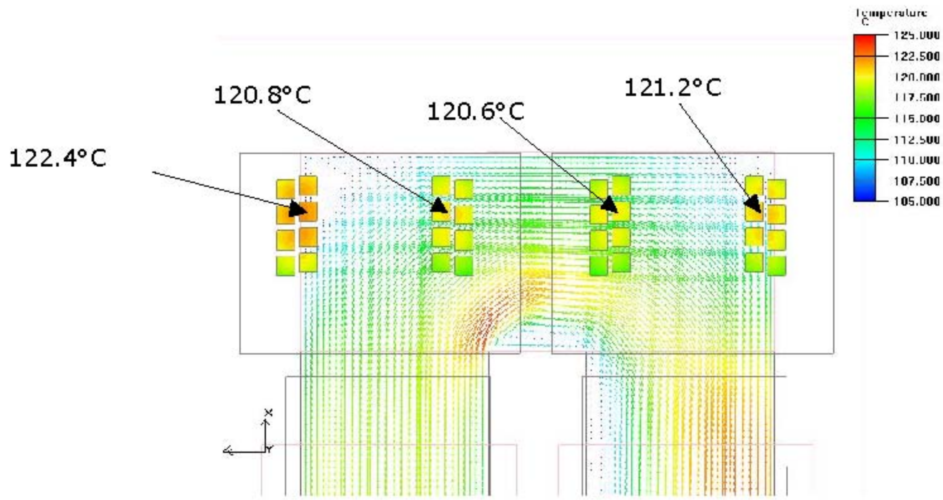


Figure 24. The thermal simulation results.

4.3.6 Solving practical issue

Given the coolant temperature range of –40ºC to +105 ºC, a coolant pressure peak was detected as high as 60 psi. It broke the O-ring seal of the baseplate and caused leak of coolant. Figure 25 illustrates baseplate coolant leak test setup. Figure 26 demonstrates the initial seal design leaked at -18ºC. After a few iteration, the seal design was improved and passed the leakage test during whole range of –40ºC to +105 ºC.

Figure 25. Baseplate leak test setup.

Figure 26. Baseplate leaks with initial seal design.

4.3.7 Conclusion for FY2006

In the FY2006, we have finished testing of Alpha prototype. Based on the Alpha test result, we have made dramatic improvement through the second round design – Beta design. The up-to-date status summary from the Beta design is listed in Table 3.

Table 5. Up-to-date status summary from the Beta design during FY2006

	DOE Goal	Beta Design Results (7/25/06)	Beta Design % Target
Output Power	5kW	5.1kW	102%
Efficiency	92%	93%	101%
Cost Estimation	$375 total, ($75/kW)	$458	82%
Coolant Temperature	105 Deg C	105 Deg C	100%
Volume	5 Liter	5.1 Liter	98%
Weight	6kg	7.4kg	81%
Coolant Pressure Drop	0.73PSI (5kPa)	0.25 PSI	292%

4.4 Technical Achievements Highlights in FY2007

We have had very promising test results in the Alpha prototypes. The focus of the FY2007 is on the manufacturing Beta prototype the final test.

4.4.1 Manufacturing process development – power module process

The power module process includes solder paste printing, die attachment, reflow wire bonding, intermediate testing, end of line testing, as shown in Figure 27. Figure 28 shows the wire bond operation on the power module baseplate. There are enormous iterations to work out a appropriate temperature profile for the reflow and wire bond program for the bonding machine.

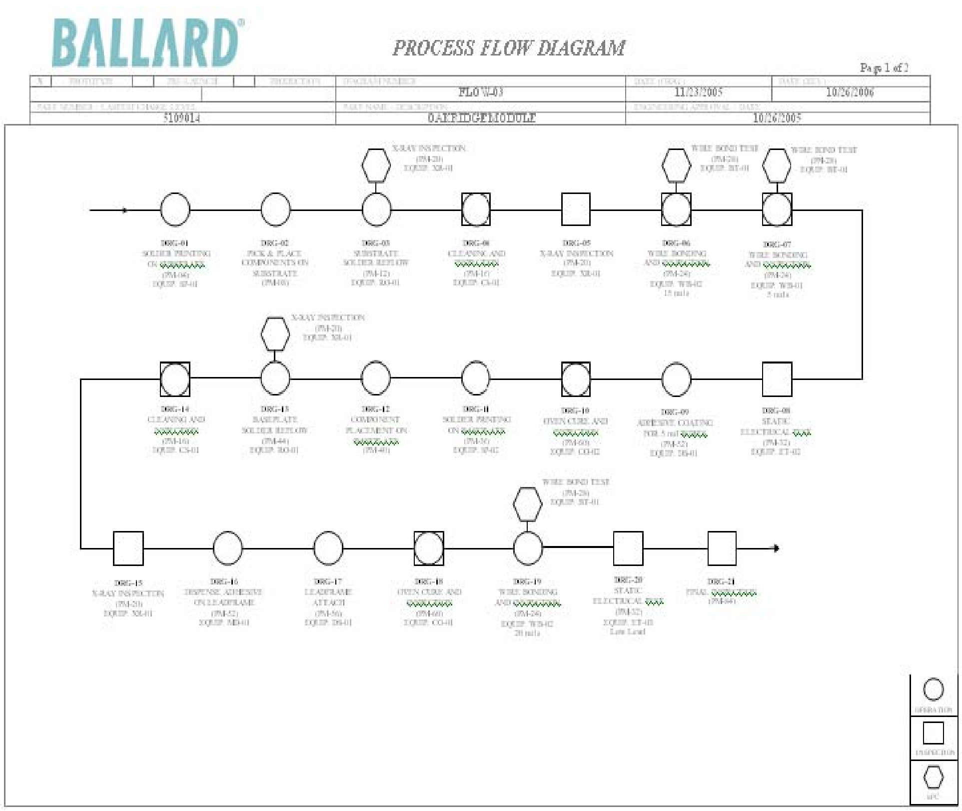


Figure 27. DC-DC power module process flow diagram.

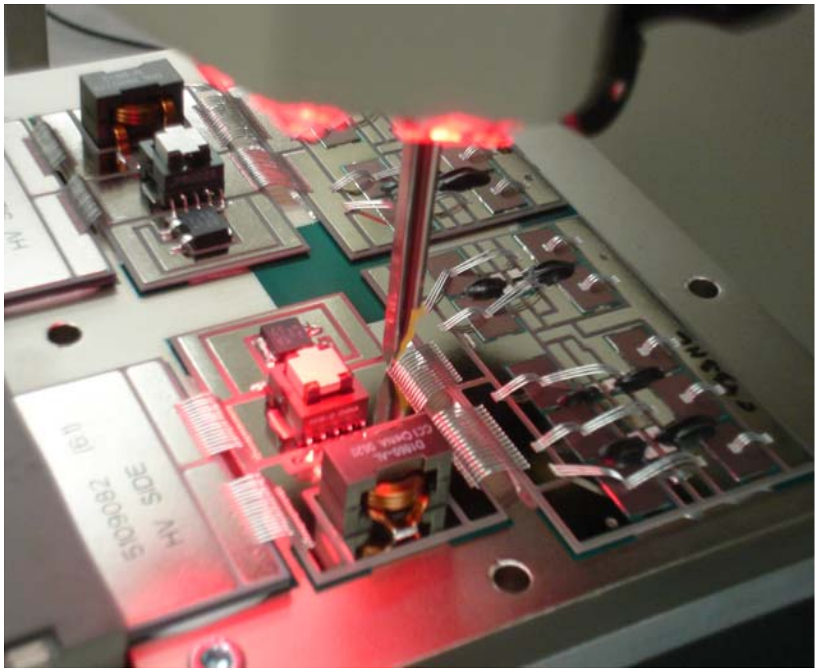


Figure 28. Wire bonding operation.

4.4.2 Manufacturing process development – pilot plant process

Manufacturing process is operation sequence that assembles parts in the BOM into a finished dc-dc converter. Figure 29 shows a screen shot of one assembly step. The parts to be assembled are listed. The torque values are specified. After completion, the actual torque value is recorded. Figure 30 shows the flow of consecutive three steps.

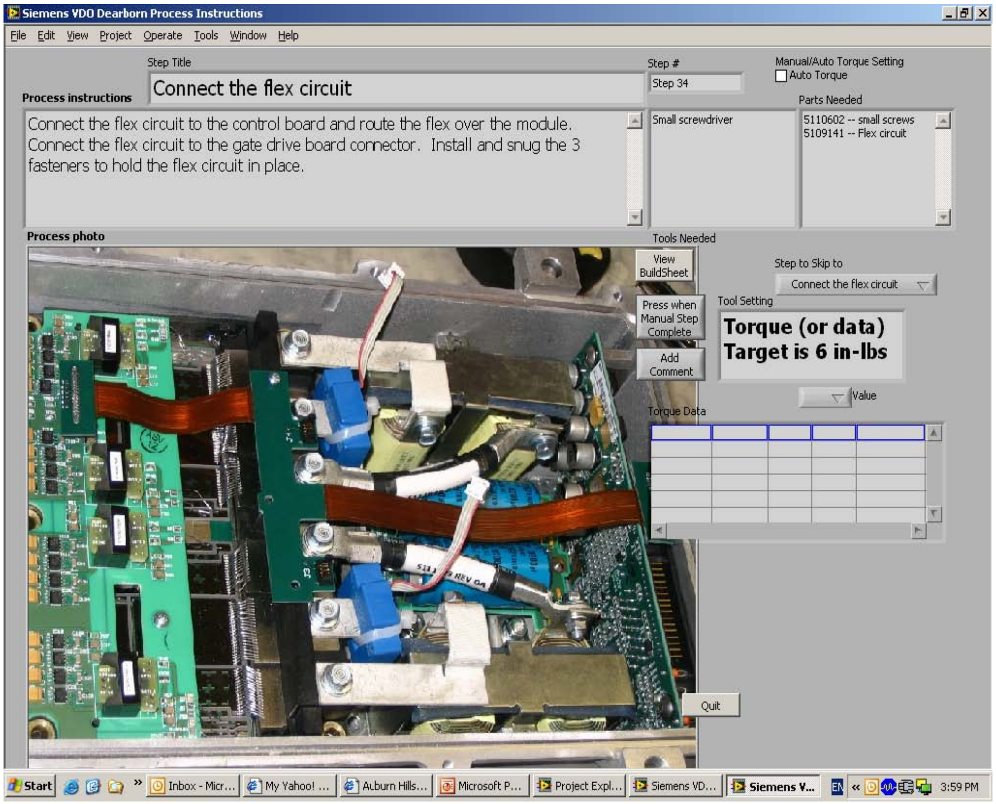


Figure 29. An example of assembly step.

Figure 30. Assembly process flow diagram.

4.4.3 Beta prototype fabrication

Twenty set of power module components and 20 sets of dc-dc converter parts have been planned. Nine power modules has been fabricated and five finished dc-dc converters have assembled for the final testing. Figure 31 shows the finished power modules in the clean room.

Figure 31. Finished ORNL Beta power modules.

4.4.4 Beta dc-dc converter prototype final testing

Four units of the Beta dc-dc converters have been tested at the Ballard facility to verify the final design. The test results among units are consistent. Figure 32 show the efficiency test setup. It includes the chiller that can provides up to 105ºC coolant, high voltage power supply with 200V–400V adjust range, 5kW low voltage electronic loads and meters.

Figure 32. Engineering test setup for up to 105ºC operation.

Figures 33–36 shows the test efficiency mapping. The test conditions are:

- Four input voltages: 200V, 300V, 350V, 400V;
- Two output voltages: 13.3V, 15V;
- Two coolant temperatures: 25ºC, 105ºC; and
- Load varies from 0–5kW.

From the test results, we can see the peak efficiency reaches 94%. The most efficiency curves are 92% or better. At 105ºC coolant, the efficiency drops about 1% comparing with 25ºC coolant. Efficiency at 15V output is about 1% higher than a lower output like 13.3V, because the load current is lower at higher voltage. It favors in a reduction of conduction loss.

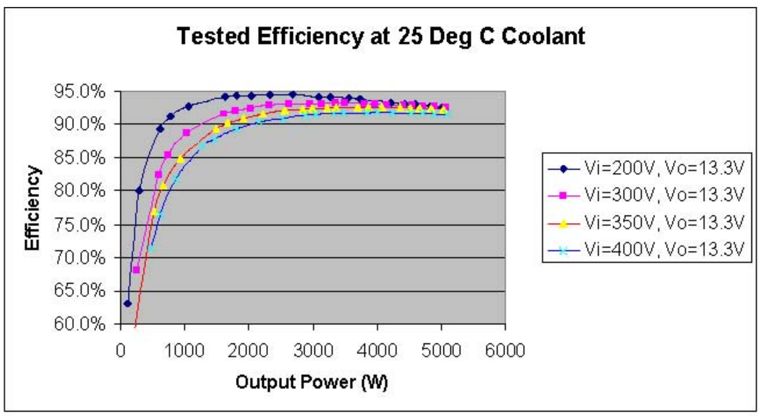


Figure 33. Efficiency test results at Vo = 13.3V, coolant temperature =

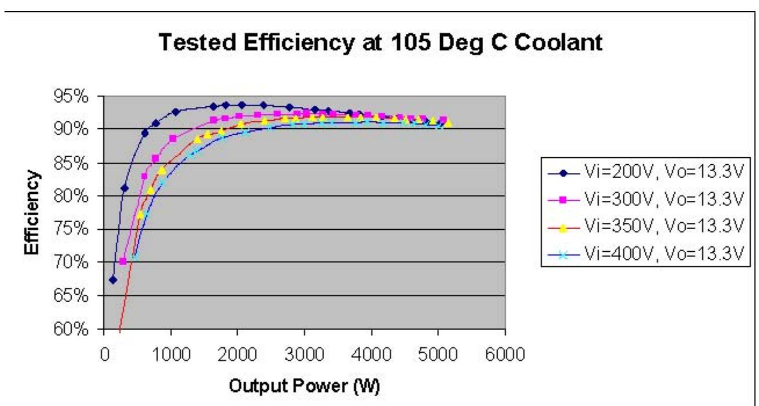


Figure 34. Efficiency test results at Vo = 13.3V, coolant temperature = 150°C.

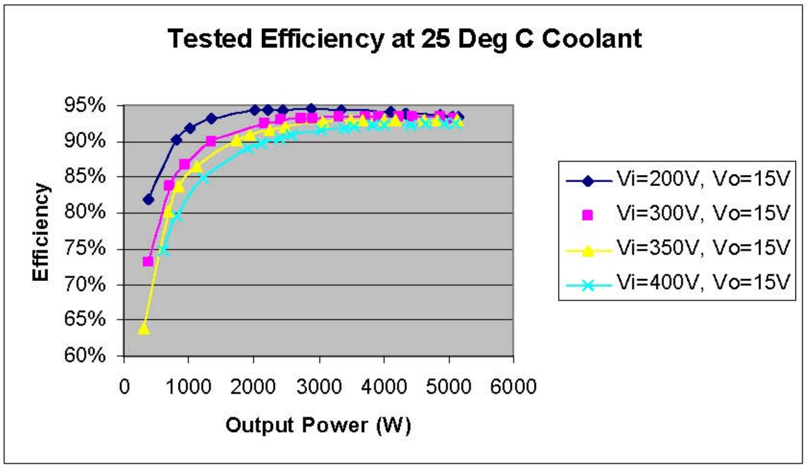


Figure 35. Efficiency test results at Vo = 15V, coolant temperature = 25°C.

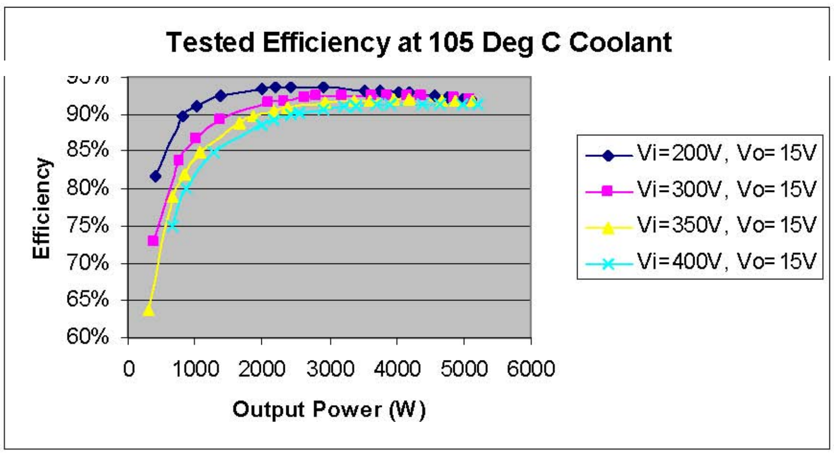


Figure 36. Efficiency test results at Vo = 15V, coolant temperature =

Figure 37 shows an infra red photo taken when the dc-dc converter operate at 5kW continuously at 105ºC. From the photo we can see that some areas in the floor reach 125ºC as it was designed.

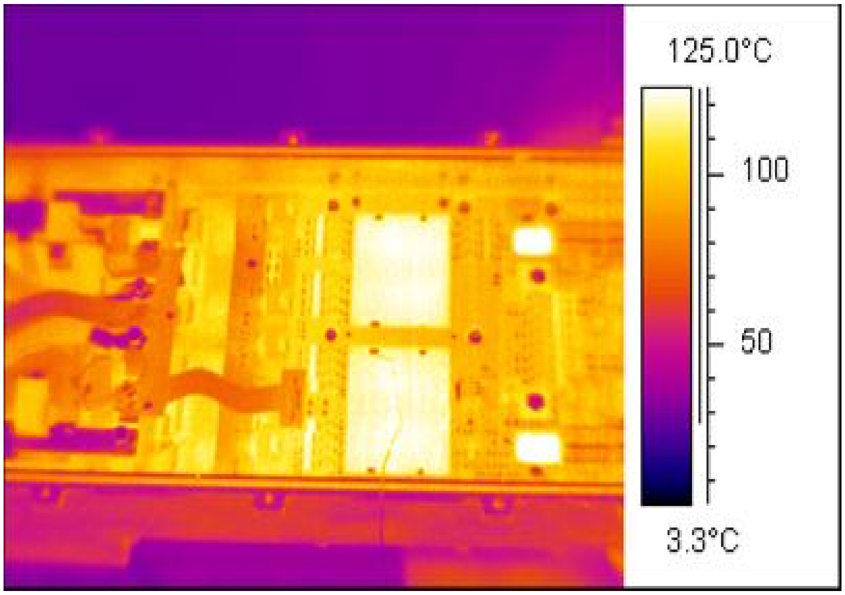


Figure 37. A infra red photo for dc-dc converter test condition: Vi = 300V, Po = 5kW, coolant temperature = 105°C.

5 FINAL PROGRAM REVIEW AND WITNESS TEST

5.1 Beta Prototype Size and Dimensions

Figure 38 shows the volume data from the CAD model. It reaches a total volume of 5.1 Liter, which is slightly over DOE target of 5 Liter. Figure 39 depicts the dimension of the Beat prototype. It shows four mounting tabs that can be used to mount the unit into vehicle for on-road testing.

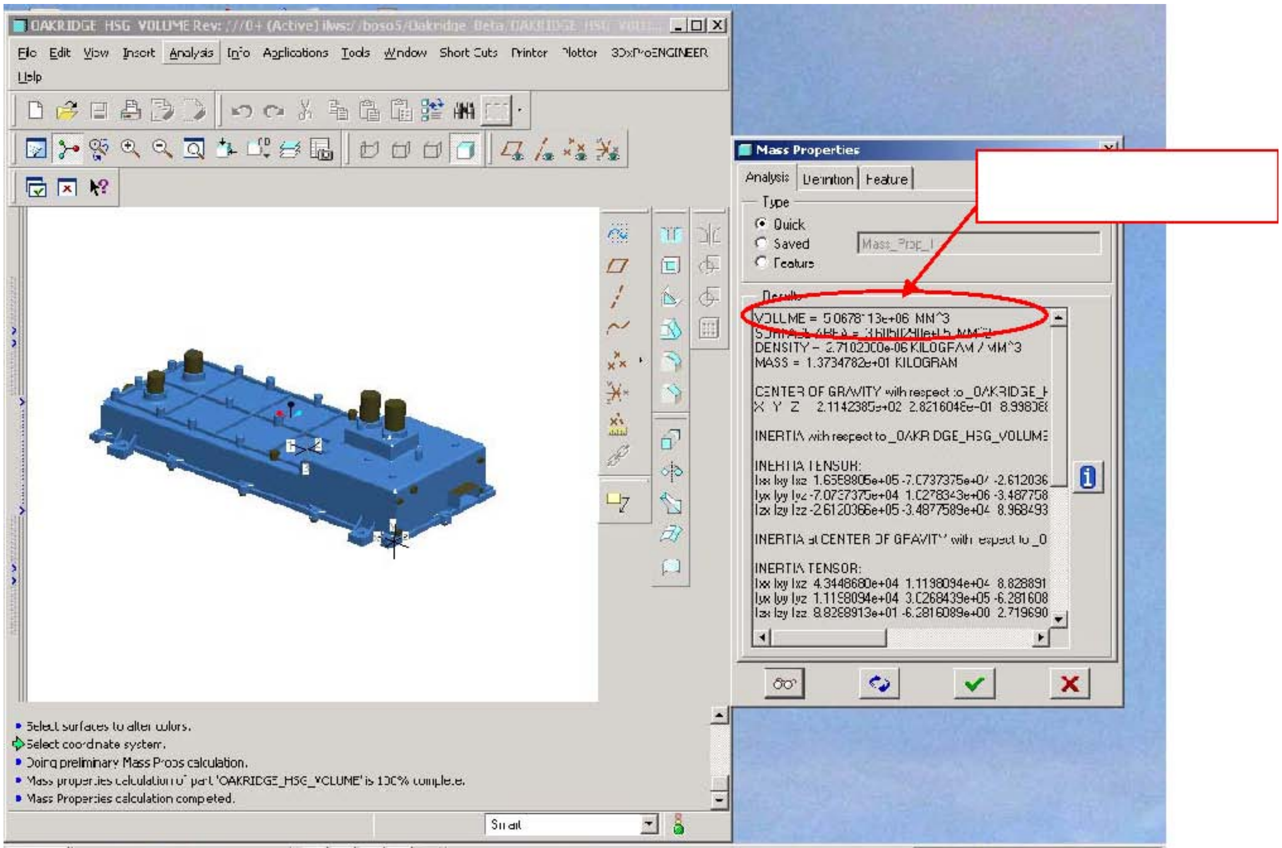


Figure 38. The volume data from CAD model.

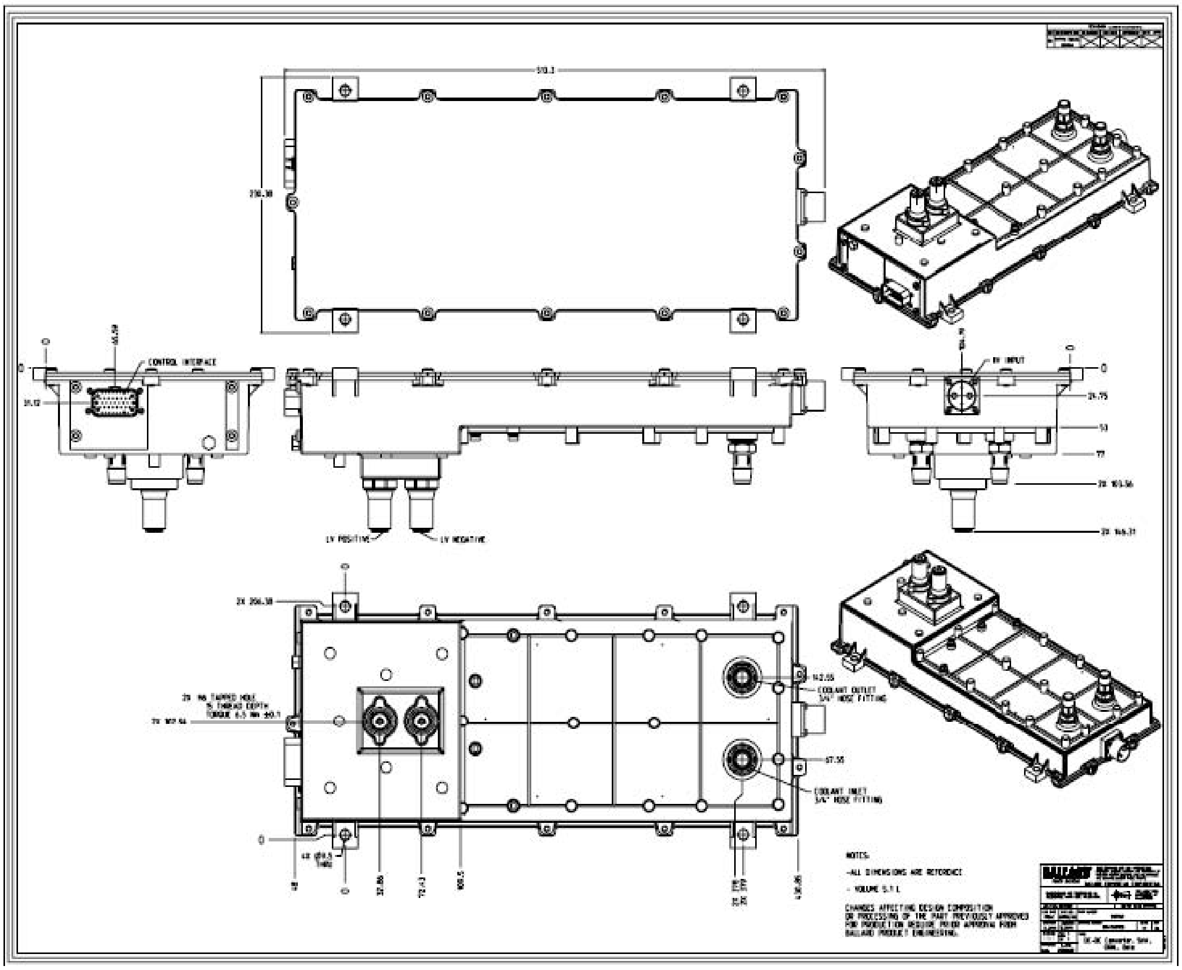


Figure 39. The Beta dc-dc mechnical dimensions.

5.2 Beta Prototype Weight

Table 6 shows BOM lists of the Beta dc-dc converter assembly. The measured weights for individual parts are sown in the table. The total weight ends up with 8.33kg. It is higher than the DOE target. The plan to reduce the weight will be discussed later.

Table 6. Beta dc-dc converter BOM and weight results

	Level	Ballard P/N	Description	Quantity	Weight/pc (Lb)	Weight	Weight (Kg)
1	1	5110394	PWR MOD ASY	1	6.17	6.17	2.80
2	1	5109101	HSG - ELEC BOX	1	4.57	4.57	2.07
3	1	5109397	IND- 4.5UH 125A 100APK 100KHZ	4	0.664	2.656	1.21
4	1	5109098	CVR - ELCT BX	1	1.674	1.674	0.76
5	1	5109808	CONN-AC FEEDTHRU	2	0.32	0.64	0.29
6	1	5110760	FTG COOL ORNL	2	0.182	0.364	0.17
7	1	5109173	BRD ASY- BTA CNTRL - ORNL	1	0.3	0.3	0.14
8	1	5109651	BRD ASY-BT LV CAP - ORNL	1	0.226	0.226	0.10
9	1	5109105	BUSBAR- POS	1	0.192	0.192	0.09
10	1	5110528	O/RG ELETR HSG ORNL	1	0.18	0.18	0.08
11	1	5111889	CBL BSBR - LV POS -ORNL	2	0.084	0.168	0.08
12	1	5109104	BRKT-IND	2	0.078	0.156	0.07
13	1	5109102	BUSBAR - NEG	1	0.152	0.152	0.07
14	1	5108406	SC- PAN/HD TORX M5X0.7X30	15	0.01	0.15	0.07
15	1	5109393	SCR- M5 X 12 BUTT HD SCKT CAP	17	0.006	0.102	0.05
16	1	5109144	CURR SNS - HAFS 400-S/SP1	2	0.046	0.092	0.04
17	1	5109142	CONN - HV ASY	1	0.062	0.062	0.03
18	1	5108401	SC-HEX/HD M5X0.8X14 CAP FL/SPG	8	0.01	0.08	0.04
19	1	5109601	BUSBAR - LV POS	1	0.048	0.048	0.02
20	1	5109600	BUSBAR - LV POS	1	0.046	0.046	0.02
21	1	100330-PAA	BLT-M4 X 0.7 X 12 CAP HD	9	0.004	0.036	0.02
22	1	103371-PAA	BLT-M5 X 18 HEX SCKT CAP	4	0.008	0.032	0.01
23	1	5109511	SCR- FLNG HEX HD M6 X 16-10.9	2	0.014	0.028	0.01
24	1	5109654	BRD-ASY BETA SGNL CONN FLX - O	1	0.026	0.026	0.01
25	1	5110481	HEX FLNG NUT-M5X0.8 ZN PLT ST	6	0.004	0.024	0.01
26	1	5109167	SCR - M4 X 8 HX SCK	10	0.002	0.02	0.01
27	1	100362-PAA	PLG-DRYSEAL TPR THD 1/8 X 27	1	0.02	0.02	0.01
28	1	5109604	STD OFF-CNTRL BRD TO HSG	4	0.004	0.016	0.01
29	1	5110338	SCR - M5 X 8 SCKT HD CAP	4	0.004	0.016	0.01
30	1	5108404	SC- PAN/HD M5X0.8X10	2	0.006	0.012	0.01
31	1	5109394	WSHR - SE FOR M5 SCR	12	0.001	0.012	0.01
32	1	5110407	O/RG - COOL CH	1	0.01	0.01	0.00
33	1	5110400	O/RG - COOL CH	1	0.01	0.01	0.00
34	1	5109605	GSKT-SIL GEL PAD IND BRKT	1	0.01	0.01	0.00
35	1	5109391	SCR- M3X10 BUTT HD SCKT CAP	4	0.002	0.008	0.00
36	1	5111892	STND-OFF, SS M4 - ORNL	1	0.008	0.008	0.00
37	1	5110550	O/RG SEAL DIV COOLANT ORNL	1	0.004	0.004	0.00
38	1	5112662	HRNS- 2 PIN CONTR BRD TO CAP B	1	0.004	0.004	0.00
39	1	102264-PAA	BLT-#4 X 24 PAN HD	4	0.001	0.004	0.00
40	1	5109392	GSKT- HV CONN TO HSG	1	0.002	0.002	0.00
41	1	103614-PAA	WIR-CA TIE NYLON 5.5 X0.13IN	2	0.001	0.002	0.00
42	1	5111709	ORNG, EPDN - ORNL	2	0.001	0.002	0.00
43	1	5110602	SCR- 4-24X1/4- HI-LOW ZN PLT S	13	0.002	0.026	0.01
				Total Weight (Lb) =		**18.36**	
				Total Weight (Kg) =			**8.33**

5.3 Final Program Review and Witness Test

The final program review was held on March 22, 2007 at Siemens VDO (Prior Ballard), 15001 Commerce Dr. North, Dearborn, Michigan. Ten people from USCAR EETT team joined the final review. A facility tour was also conducted to show the Clean room, pilot plant assembly line, test labs, and dynomometers. The review team is listed below:

- Rafi Al-Attar, DCX
- Greg Smith, GM
- Franco Leonardi, Ford
- Mark Mehall, Ford
- Edward Jih, Ford
- Molly Close, DCX
- Niklas Pettersson, DCX
- Laura Marlino, ORNL
- Ray Fessler, Biztek Consulting (DOE support)
- Natalie Olds, USCAR

5.3.1 Final test result summary and DOE goal achieved

Table 7 summaries the results that we have achieved for this program. We have achieved five of seven goals. The weight target can also be achieved in the high volume production design. The cost can also be improved. The opportunities to improve these two parameters will be discussed in the later section. The coolant pressure exceeds the goal by 192% due to the effort on the thermal and coolant channel design.

Table 7. Final test results and DOE goal achieved

	Parameters	DOE Goal	Beta Final Test Result (3/15/2007)	% Goal Achieved
1	Output Power	5kW	5.1kW	102%
2	Efficiency	92%	93%	101%
3	Cost Estimation	$375 total, ($75/kW)	$458	82%
3	Coolant Temperature	105 ºC	105 ºC	100%
5	Volume	5 Liter	5.1 Liter	98%
6	Weight	6kg	8.33kg	72%
7	Coolant Pressure Drop	0.73 PSI (5kPa)	0.25 PSI	292%

5.3.2 Witness test

A witness test was performed on March 23, 2007 with ORNL management team and Ballard engineers. The attendee's lists are:

- Laura Marlino, ORNL
- Gui-Jia Su, ORNL
- Lizhi Zhu, Ballard
- Dawud Zama, Ballard
- Richard Debbin, Ballard
- Miaosen Shen, Ballard

The lab setup for the witness test is shown in Figure 40. The Beta prototype with S/N 10004 was tested. The coolant was set at 105ºC prior the test because it takes a while to ramp the temperature up. The following tests were performed during witness test.

- dc-dc functional checking at all voltage and load conditions;
- dc-dc efficiency mapping at 200V, 300V, 400V at from 600W to 5000W at 105ºC; and
- Load dump test.

The overall test went smoothly. DC-DC converter was demonstrated to be able to operate at 5kW continuously at 105ºC without any issue. The total test lasted about 2 hours. The load dump waveform is shown in Figure 41. During load dump, the dc-dc is very stable and only takes 15ms to settle down the transient. The peak voltage reaches 15.1V and voltage overshoot is only 1.7V.

Figure 40. Witness test lab setup.

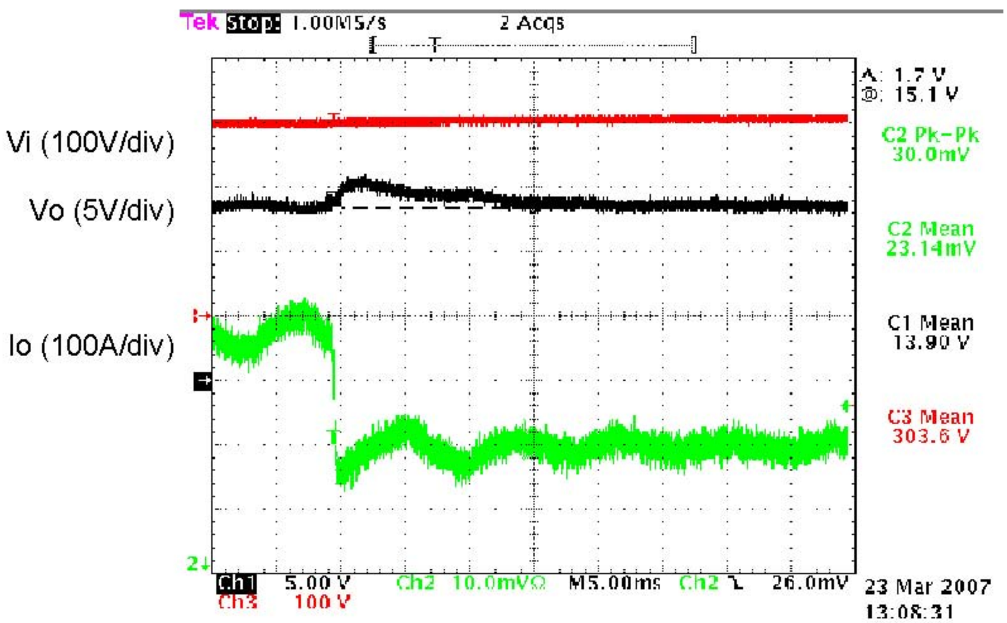


Figure 41. Load dump test Vi = 300V, V0 = 13.3V, Po = 5kW load dump.

A small issue that we encountered during the witness test was that we found the dc-dc measured efficiency was a little bit lower that we had tested before. We spent another week to trouble shoot the issue after the witness test. It ended up that the location where the multimeter was put during the witness test had some noises which caused the multimeter had a lower-shifted reading. Unfortunately this noise was generated by the dc-dc converter. We spent another week to find a permanent solution by adding an EMC grounding wire to eliminate the common mode noise, as shown in Figure 42. The interference was greatly reduced. As a result, the multimeter reading is not sensitive to the location anymore and all the efficiency number goes back to the same result as it is shown in Figures 33–36.

On April 17, 2007, we conducted the second witness test and demonstrated the efficiency mapping to ORNL program manager Laura Marlino, when she was in town for SAE conference at Detroit. The efficiency test result proved to be consistent with our earlier engineering test result shown in Figures 33–36.

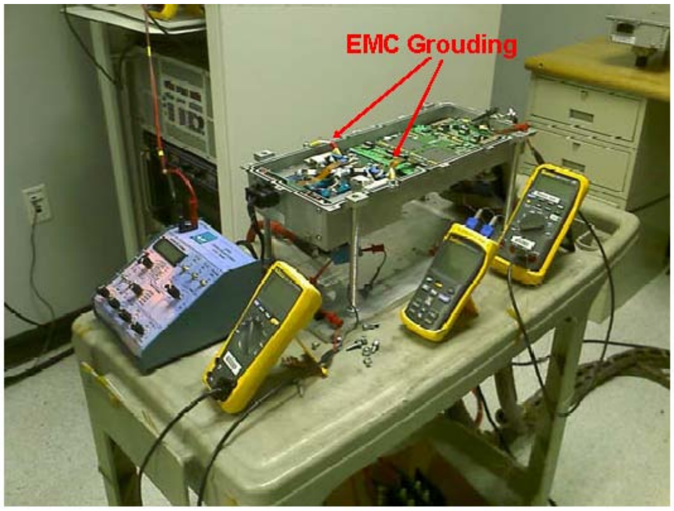


Figure 42. Grounding wires added to lower the EMC.

6 EXECUTIVE SUMMARY AND FUTURE DIRECTIONS

6.1 Summary

The goal of this project is to develop and fabricate a 5kW dc-dc converter with a baseline 14V output capability for fuel cell and hybrid vehicles. We have conducted three round of prototype design to prove the technical concepts: 1) a segmented dc-dc power module (2.5kW) to investigate the feasibility of power module design and integrated planner transformer, 2) a full 5kW dc-dc Alpha power module was developed with the proposed dc-dc converter topology to prove to full function of the dc-dc converter with full power and voltage range. 3) a beta version of the dc-dc converter was designed to meet high temperature and reliability requirement, and verify volume and weight target. Also we have built five Beta version final dc-dc converters prototypes and achieved/exceeded the following goals over three year development as shown in Table 7 above-mentioned.

- Higher power (5kW)
- Higher efficiency (92%)
- High coolant temperature capability (105 °C)
- High reliability (15 Years/150,000miles)
- Smaller volume (5L)
- Low pressure drop (5kPa)

We have seen there are some gaps existed on the following two goals based on the result that we obtained on our Beta version design.

- Lower weight (6kg)
- Lower cost ($75/kW)

However, we believe the weight goal can be achieved in the next round of high volume design. We also have explored the opportunities to reduce cost in volume production. In the following section we will discuss this topic in details.

6.2 Future Directions

6.2.1 Weight reduction

The DOE weight target is 6kg. Our Beta design result currently is 8.33 kg, over the target by 2.33kg. However, if you looked at the BOM, you would find the first five parts occupied 85.6% of the total weight. The Pareto analysis for the first five part is shown in Figure 43 as below.

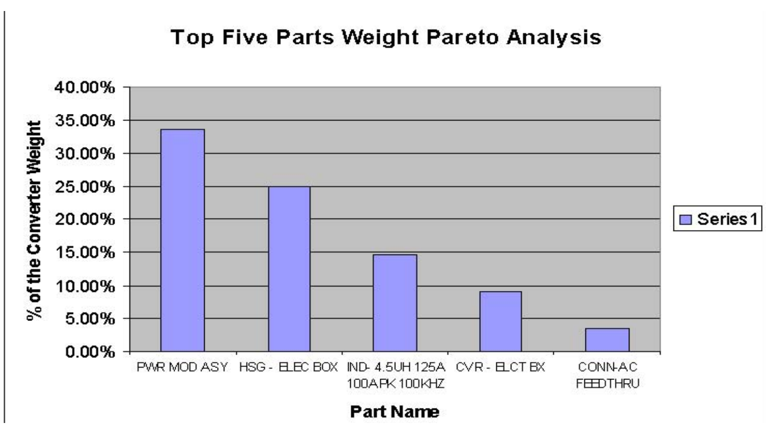


Figure 43. Weight Pareto analysis.

Those five parts are listed in the following table.

Table 8. First five parts and weight reduction plan

	Level	Ballard P/N	Description	Quantity	Weight/pc (Lb)	Weight	Weight (Kg)	% Reduction	Weigh Saved
1	1	5110394	PWR MOD ASY	1	6.17	6.17	2.80	0.45	1.26
2	1	5109101	HSG - ELEC BOX	1	4.57	4.57	2.07	0.35	0.73
3	1	5109397	IND- 4.5UH 125A 100APK 100KHZ	4	0.664	2.656	1.21	0	0.00
4	1	5109098	CVR - ELCT BX	1	1.674	1.674	0.76	0.3	0.23
5	1	5109808	CONN-AC FEEDTHRU	2	0.32	0.64	0.29	0.6	0.17
						Sub total (kg)	**7.13**		**2.39**
						DC/DC Total (kg)	**8.33**		
						%	**85.6%**		

There are three opportunities to meet the weight target. Here is the weight reduction plan:

1. Power module currently occupies 2.8kg. Moving coolant channel to housing will reduce the thickness of the baseplate, resulting in 45% of weight reduction.
2. Housing and cover currently occupies 2.83kg. This part was done with the sand casting. In high volume production, it will be die casting, which allows wall thickness to be reduced from 4mm to 2mm-2.5mm, resulting in 35% of weight reduction. The cover is over designed for the beta design can be reduced 30% in the high volume production.
3. The LV output studs occupy 0.29kg. This is an existing motor feed-thru part that we used in the other E- drive product. The length is more than what we need for the dc-dc converter. The reason that we chose this part was to save the project timing and cost. With a custom design for high volume production, the weight can be reduced 60% by setting the right length.

With these three weight reduction plan, we can reduce the weight by 2.39kg, which makes the total dc-dc converter weight down to DOE goal of 6kg. The Table 8 above shows details for the weight saving for each part.

6.2.2 Cost reduction

DOE cost target is $375 for the 5kW dc-dc Converter. Our Beta design result shows a result of $458, which reaches 82% of the DOE target. The usage of two expensive materials in this design can be revisited to reduce the cost in the high volume production. They are: 1)AlSic power module base plate, 2) Silicon Nitride planar transformer windings The opportunities for cost reduction are:

1. Improve the material utilization factor,
2. Work with suppler to identify major cost driver, and
3. Improve the yield.

7 Publications

1) Presentation on USCAR meeting, Southfield, MI, March 30, 2006.
2) Presentation on 2006 DOE FreedomCAR APEEM Annual Review, Pollard Technology Conference Center, Oak Ridge, Tennessee, August 16, 2006.
3) Presentation on Industrial Power Converter Products and Services Session in IEEE IAS 2006, Tampa, FL, October 12, 2006.
4) "An Interleaved High Power dc-dc Converter," US Patent Application No. 20050270806.
5) "Integration of Planar Magnetics Transformer and Power Switching Devices in a Liquid-cooled High Power dc-dc Converter," Patent Application No. 20050270745.

APPENDIX: ORNL Test Verification

To verify the efficiency maps, previously measured by Ballard, tests were done on March 23, 2007 witnessed by ORNL representatives. Laura Marlino and Gui Jia Su were in attendance. Ballard was represented by Lizhi Zhu (PI), Miaoshen Shen (Power Electronics Engineer), Richard DeBin (Test Engineer), and David Zama (Mechanical Packaging Engineer).

All measurement equipment utilized during the testing was verified to be within their calibration dates. No computerized data acquisition system or power meters were used during the testing. All measurements were taken with DVMs and oscilloscopes. Data was then entered into a spreadsheet manually and efficiency calculations derived from the entries.

The unit was tested in the open air in the laboratory at approximately 25°C. The top of the unit was removed to allow probes to be inserted at the test points. The coolant was heated to 105°C and allowed to circulate through the unit. A thermocouple was used to measure the housing temperature and was placed on the underside of the unit near the coolant inlet. The unit was elevated in the air on standoffs for the tests. The testing included capturing efficiency data at different power and voltage levels, measuring the unit's line and load regulation and its dynamic response.

Due to time constraints verification points were chosen at approximately 10% of rated load, maximum efficiency load, rated load, and only one or two points in between. Figures A.1(a)–(c) compare measured efficiency points on March 23rd with those previously taken by Ballard, where the output voltage reference, Voref, was set at 13.3V while the input voltage, Vi was adjusted precisely at 200V, 300V, and 400V, respectively. Tests were repeated with the output voltage commanded to be 15V and the results are shown in Figures A.2(a)–(c).

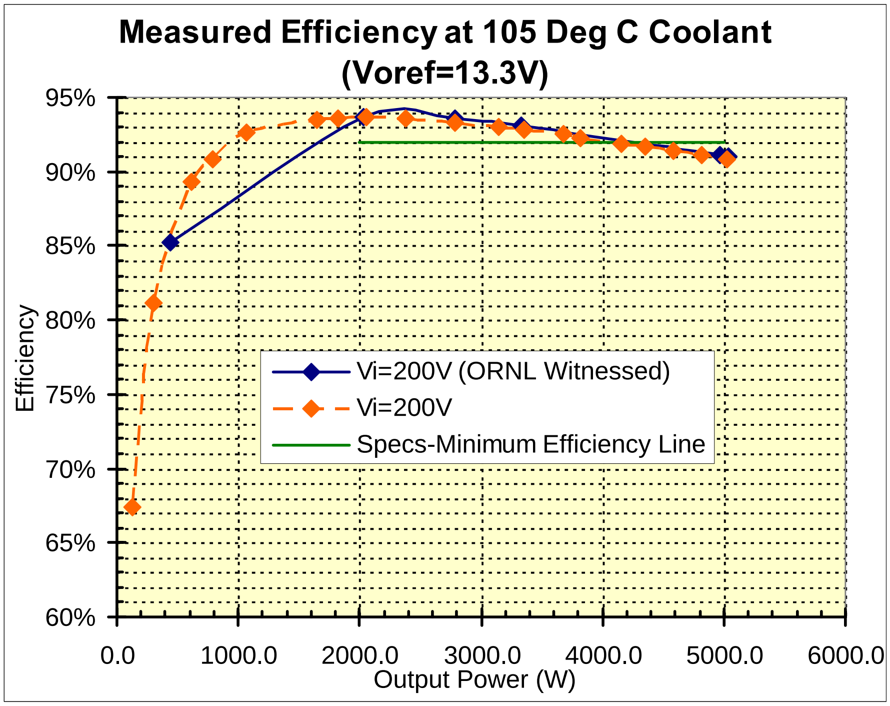


Figure A.1(a). Input voltage at 200V.

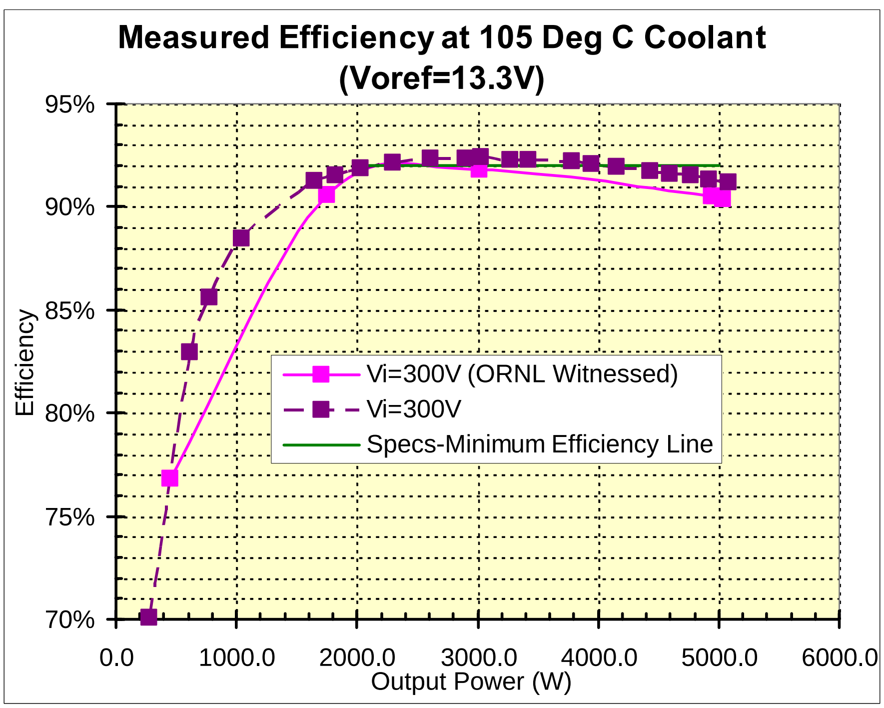


Figure A.1(b). Input voltage at 300V.

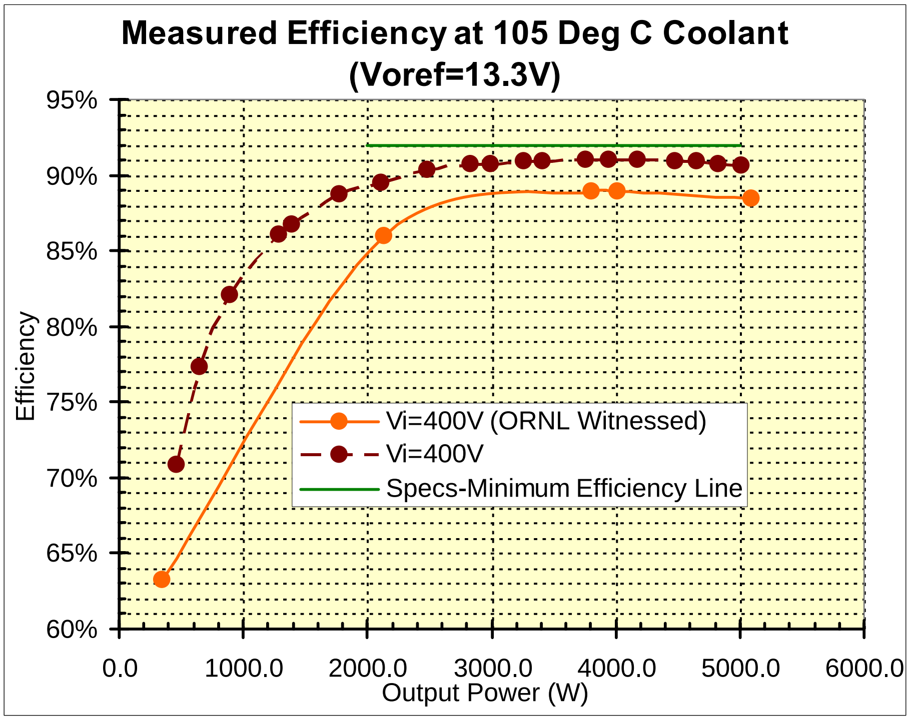


Figure A.1(c). Input voltage at 400V.

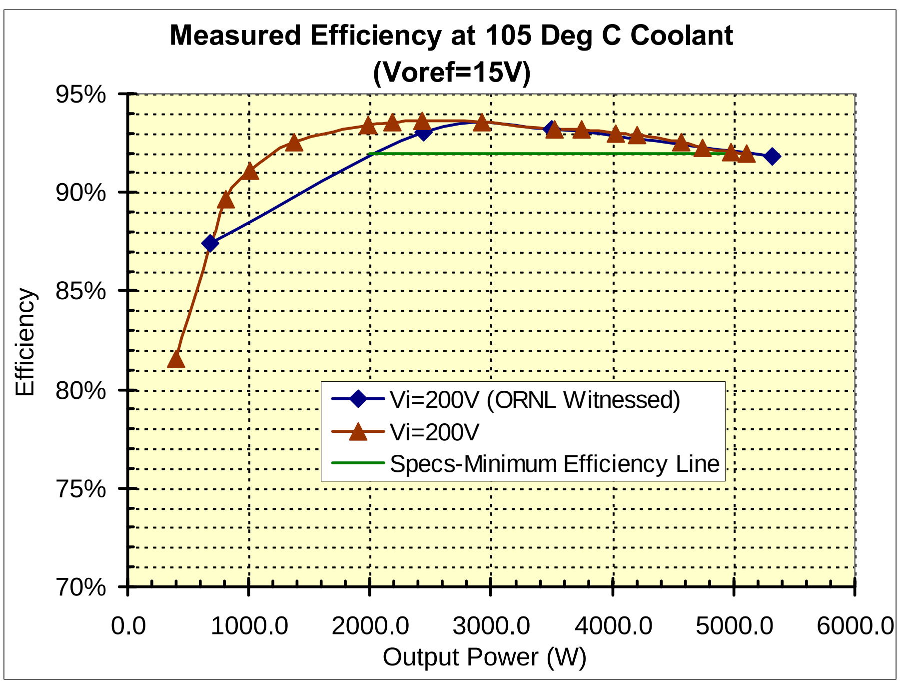


Figure A.2(a). Input voltage at 200V.

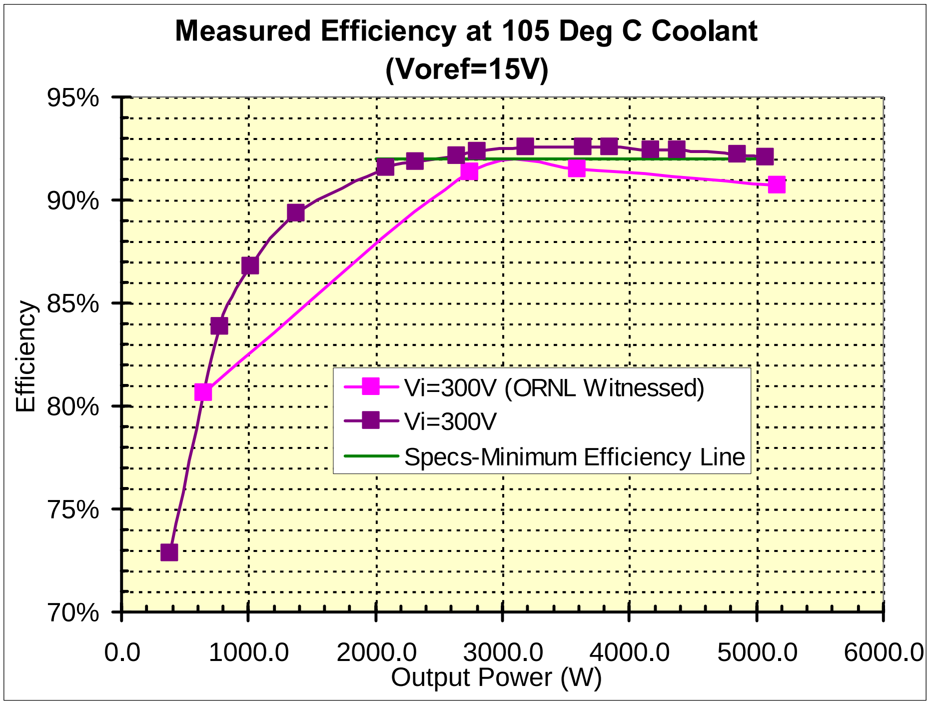


Figure A.2(b). Input voltage at 300V.

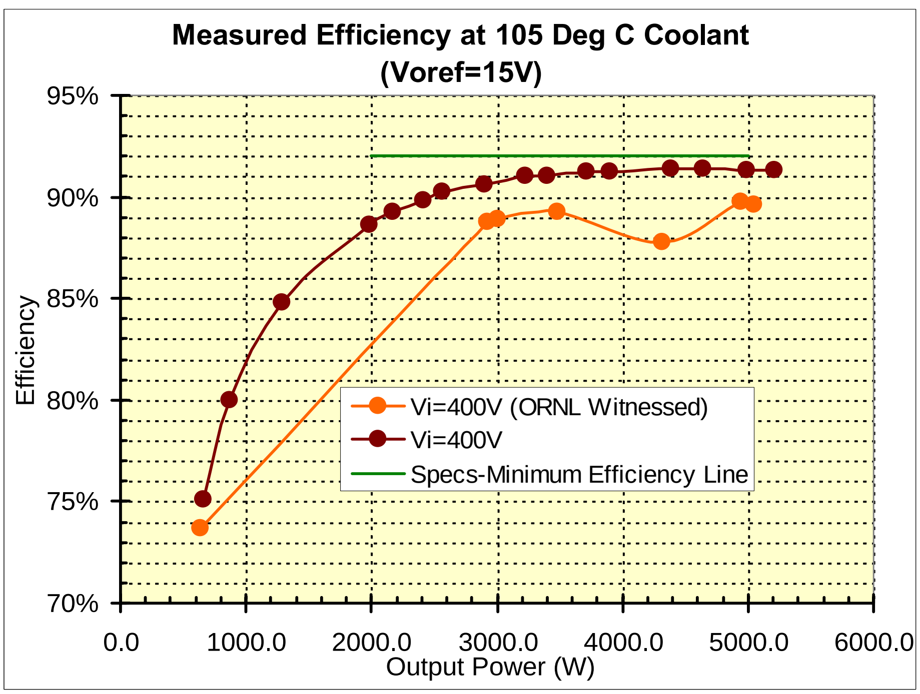


Figure A.2(c). Input voltage at 400V.

The tests indicate the efficiency numbers are similar to those measured by Ballard at Vi = 200V, but drop as Vi increases in both cases of Voref. The data taken on March 23rd was taken on the identical unit that Ballard had previously tested and it was hypothesized that the controller might be the cause of the different results.

In order to compare the test data with the efficiency specification, which states that it should be higher than 92% for loads greater than 40%, the minimum efficiency line is drawn in Figures A.1 and A.2. The best case was obtained in Figure A.2(a), where the efficiency exceeds the specification over a wider load range. Figures A.1(a) and A.2(b) partially meet the specification while the others do not cross the line at all.

Load and Line Regulation

Figures A.3(a) and A.3(b) plots load regulation at different input voltages, along with the boundaries in the specifications, where the output voltage reference was set at 13.3 V in (a) and 15V in (b). It is clear that only the regulation at Vi = 200 V and Voref = 13.3 V is within the boundaries, while in the other cases, the specification is either not met or only partially met.

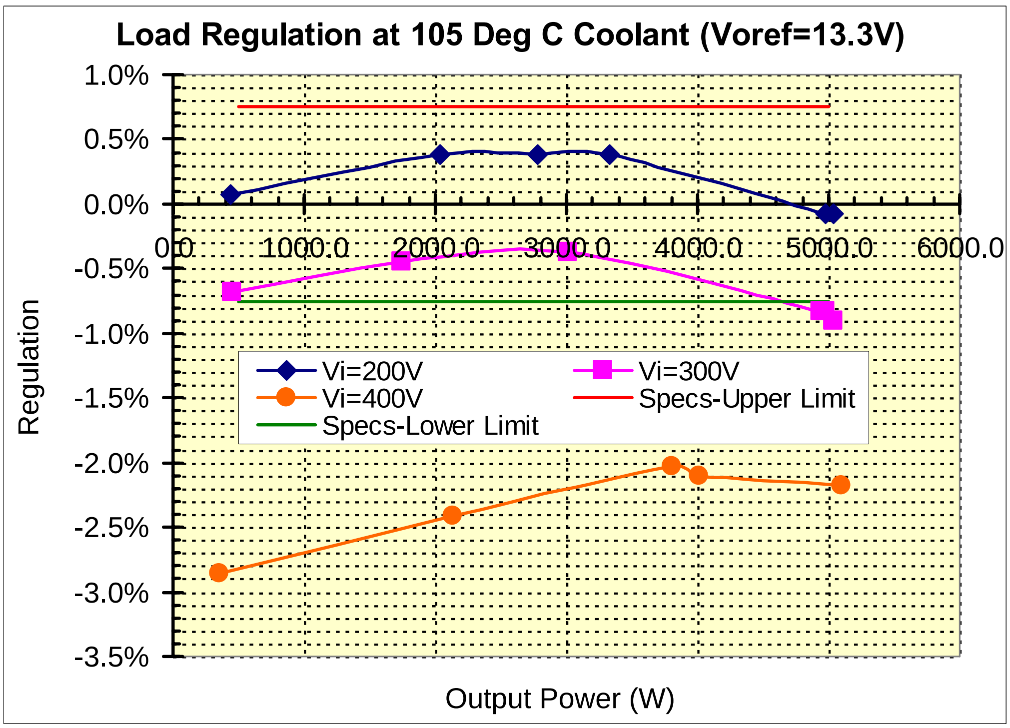


Figure A.3(a). Load regulation with Voref = 13.3V.

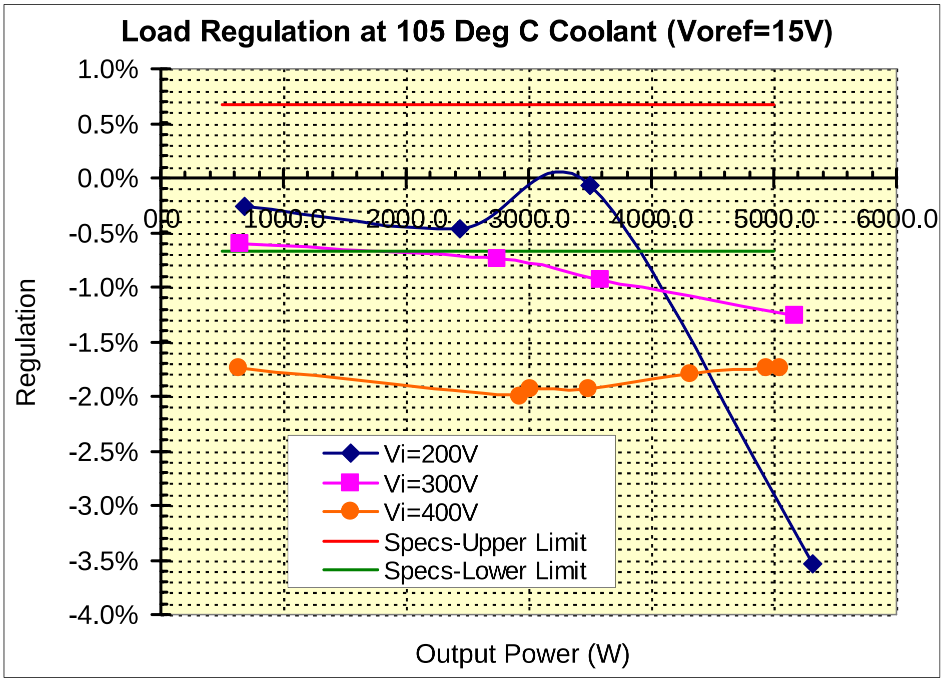


Figure A.3(b). Load regulation with Voref = 15V.

Figures A.4(a) and A.4(b) plots line regulation along with the boundaries in the specifications, where the output voltage reference was set at 13.3 V in (a) and 15 V in (b). The charts show that the test unit only partially met the specifications.

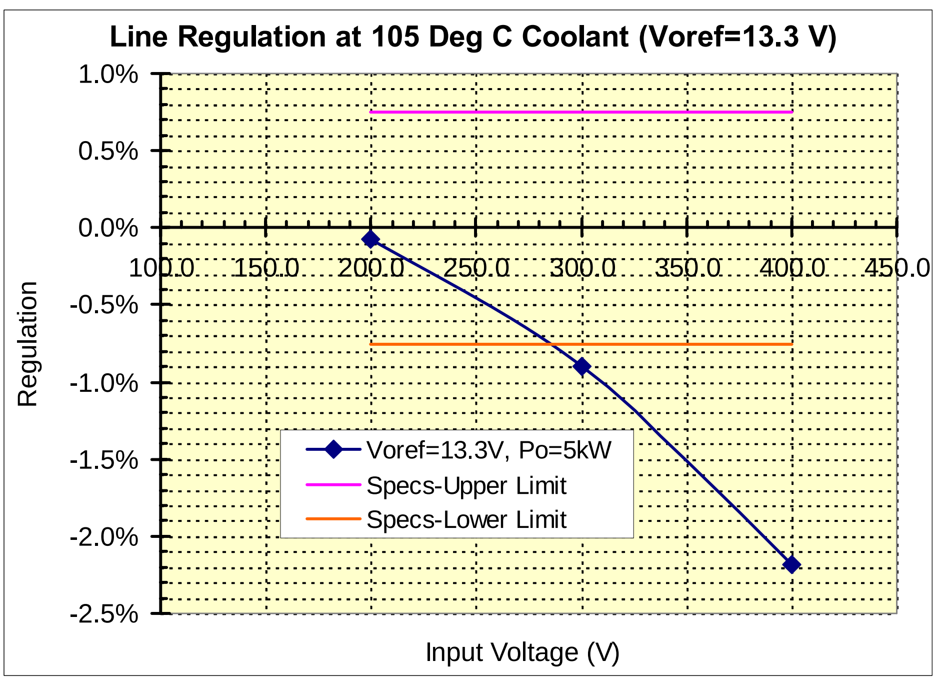


Figure A.4(a). Line regulation test results at Voref = 13.3 V.

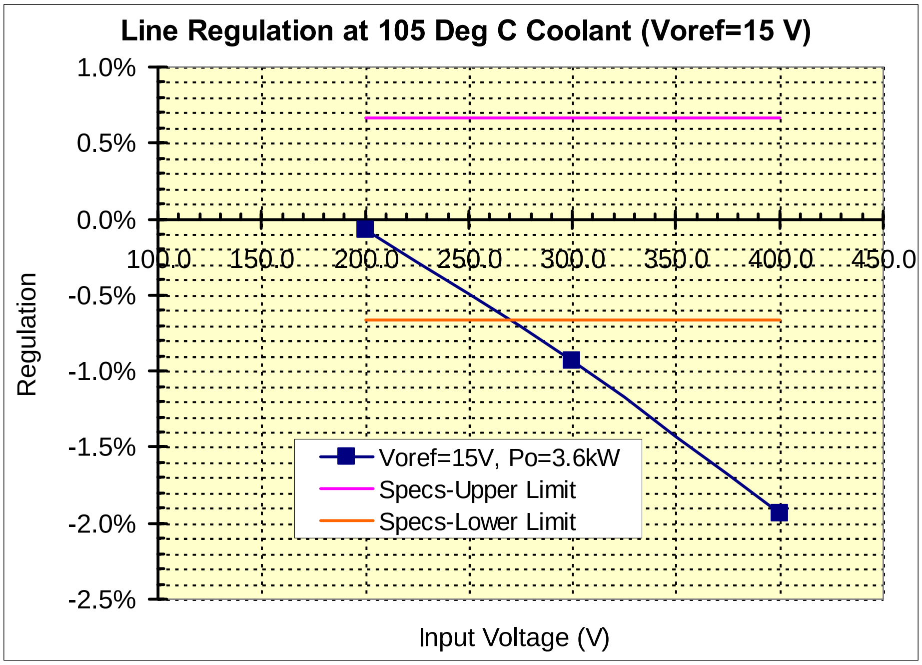
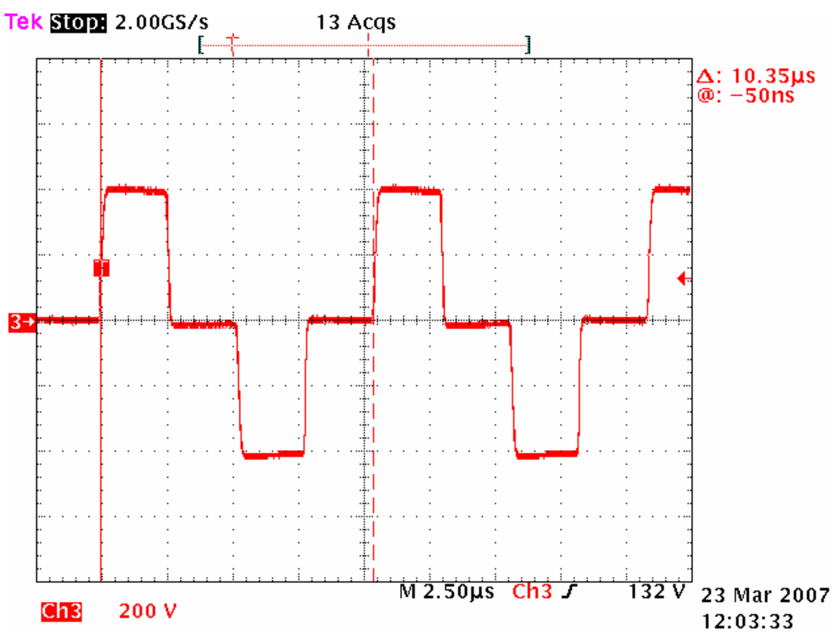


Figure A.4(b). Line regulation test results at Voref = 15 V.

Figure A.5 is a snapshot of the transformer's primary voltage while undergoing conditions with an input voltage of 400V, Voref = 15 V and a power output of the unit at its maximum rating of 5 kW.



TEK00003.tif

Figure A.5. Transformer primary terminal voltage at Vi = 400 V, Voref = 15 V, Po = 5.0 kW.

Figure A.6 shows the dynamic response of the output voltage to a step increase of load power from 2.5 kW to 4.7 kW with Vi = 300 V, and Voref = 13.3 V. Due to the nature of the electronic load devices, the load current ramped quite slowly. It took about 250 ms to reach a stead state level. Because of this time involved no noticeable variations were observed in the output voltage.

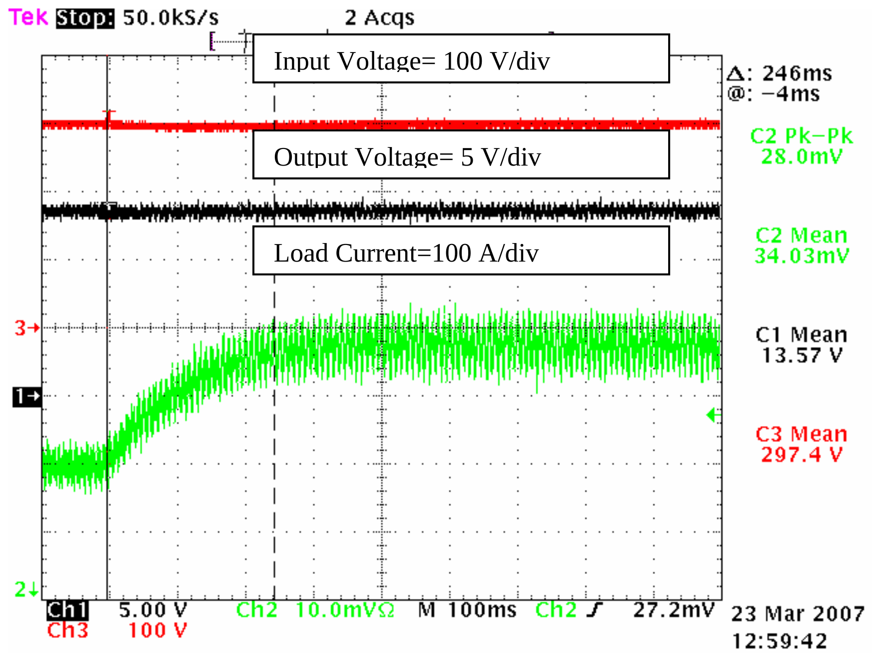


Figure A.6. Dynamic response to a slow increase of load power from 2.5 kW to 4.7 kW with Vi = 300 V, Voref = 13.3 V.

The red trace in Figures A.6, A.7, and A.8 is the input voltage (300V in all three cases). The black trace is the output reference voltage, and the green trace is the load current.

Figure A.7 shows the dynamic response of the output voltage to a step decrease of load power from 4.7 kW to 2.5 kW with Vi = 300 V, and Voref = 13.3 V. An overshoot of 12.8% was observed in the output voltage with a settling time of 15 ms. The settling time is well within the specification of 300 ms, although the specification was made for a full load change and the test was performed under a change of less than 50% of full load.

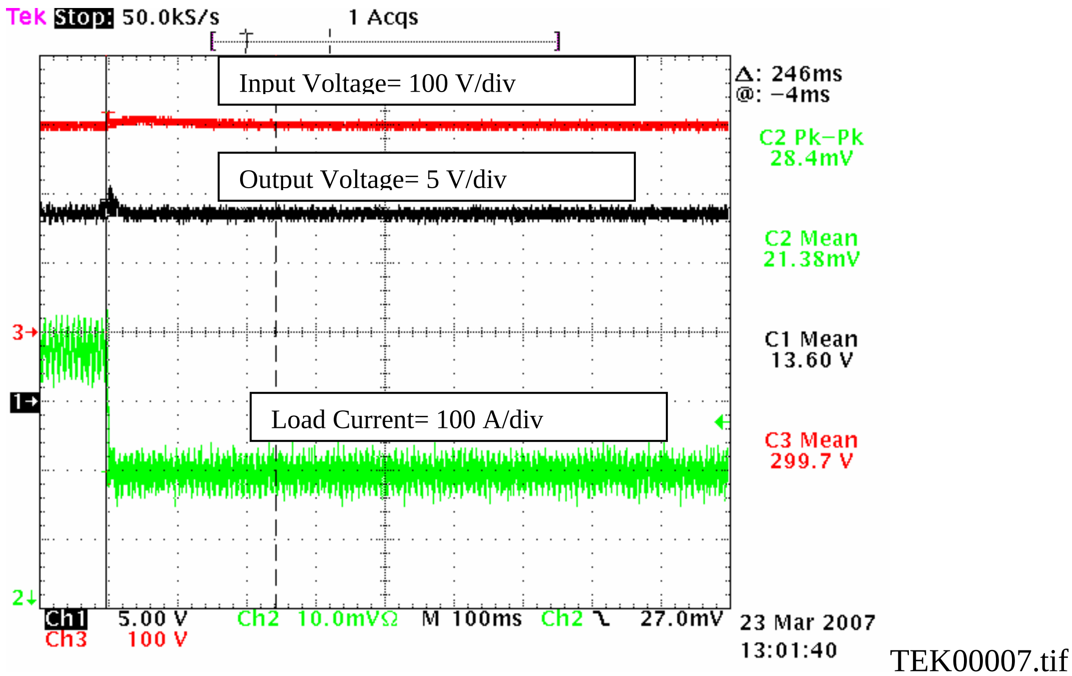


Figure A.7. Dynamic response to a step decrease of load power from 4.7 kW to 2.5 kW with Vi = 300 V, Voref = 13.3 V.

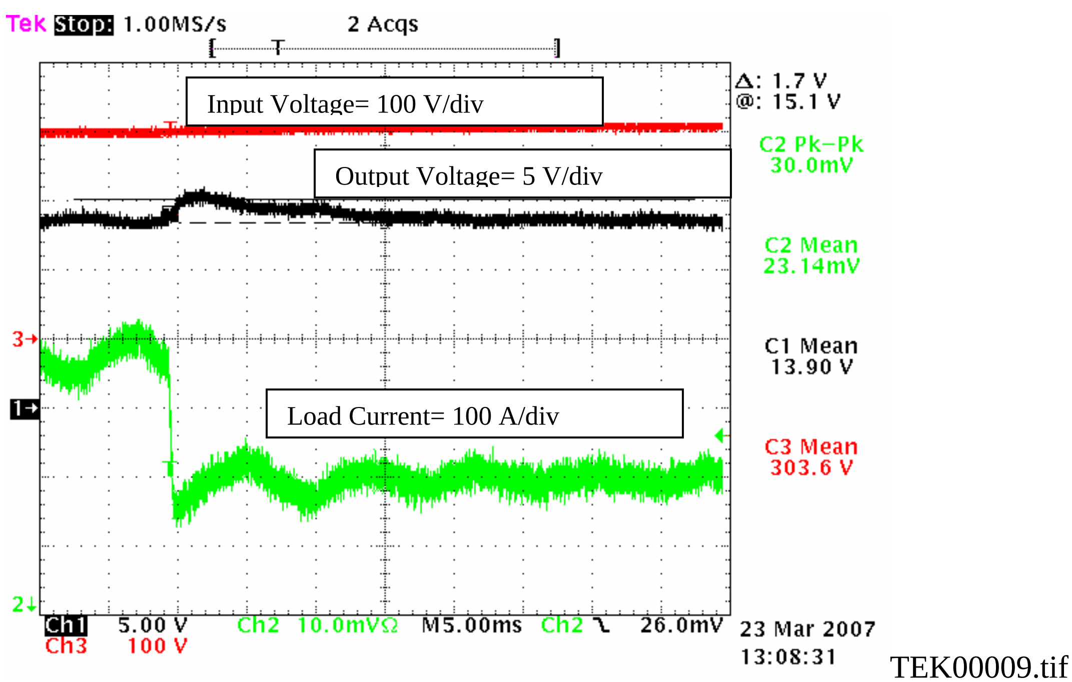


Figure A.8. Same as Fig.7 but with a faster time scale.

Table A.1. Recorded test results (March 23, 2007)
(Voltages and currents measured with Fluke multimeters)

ORNL Witness test			DUT SN: 10004					
Laura, GuiJia, Miaoshen, Richard, Lizhi, David								
Test Durantion: 10:30AM to 12:20PM @105 Deg C								
March 23, 2007,							chiller	housing
P/N:5109169; S/N:10004								
Vi	Vo	Ii	Io	Pi	Po	eff	Tc	Th
[V]	[V]	[A]	[A]	[W]	[W]	[%]	[°C]	[°C]
200.0	13.31	2.60	33.30	520.0	443.2	85.24%	101.0	97.0
200.0	13.35	10.86	152.40	2172.0	2034.5	93.67%	101.3	99.8
200.0	13.35	14.87	208.40	2974.0	2782.1	93.55%	102.4	101.3
200.0	13.35	17.89	249.60	3578.0	3332.2	93.13%	103.3	102.4
200.0	13.29	27.29	374.10	5458.0	4971.8	91.09%	104.2	104.9
200.0	13.29	27.69	379.30	5538.0	5040.9	91.02%	105.4	105.3
300.0	13.21	1.96	34.20	588.0	451.8	76.83%	105.0	105.0
300.0	13.24	6.43	132.00	1929.0	1747.7	90.60%	104.9	108.2
300.0	13.25	10.95	227.60	3285.0	3015.7	91.80%	104.7	110.4
300.0	13.19	18.20	374.60	5460.0	4941.0	90.49%	105.1	111.7
300.0	13.19	18.30	376.80	5490.0	4970.0	90.53%	105.2	112.2
300.0	13.18	18.57	381.90	5571.0	5033.4	90.35%	105.3	112.0
400.0	12.92	1.38	27.00	552.0	348.8	63.20%	105.0	109.5
400.0	12.98	6.21	164.50	2484.0	2135.2	85.96%	105.9	115.3
400.0	13.03	10.70	292.00	4280.0	3804.8	88.90%	105.0	118.0
400.0	13.02	11.28	308.10	4512.0	4011.5	88.91%	105.1	118.8
400.0	13.01	14.41	391.70	5764.0	5096.0	88.41%	105.2	120.0
400.0	13.31	14.02	374.50	5608.0	4984.6	88.88%	105.0	119.0
400.0	13.31	11.51	309.00	4604.0	4112.8	89.33%	105.0	117.9
400.0	13.31	8.94	239.40	3576.0	3186.4	89.11%	104.9	117.0
400.0	13.31	10.05	269.27	4020.0	3584.0	89.15%	104.8	117.3
200.0	14.96	3.92	45.80	784.0	685.2	87.39%	104.8	112.4
200.0	14.93	13.10	163.30	2620.0	2438.1	93.06%	104.9	115.0
200.0	14.99	18.81	233.80	3762.0	3504.7	93.16%	105.8	106.0
200.0	14.47	28.94	367.20	5788.0	5313.4	91.80%	105.2	106.3
300.0	14.81	18.99	348.90	5697.0	5167.2	90.70%	105.3	112.4
300.0	14.86	13.08	241.60	3924.0	3590.2	91.49%	105.3	112.4
300.0	14.89	10.02	184.50	3006.0	2747.2	91.39%	105.1	111.0
300.0	14.91	2.68	43.50	804.0	648.6	80.67%	104.9	107.4

Table A.1. Recorded test results (March 23, 2007) (cont'd)
(Voltages and currents measured with Fluke multimeters)

ORNL Witness test			DUT SN: 10004					
Laura, GuiJia, Miaoshen, Richard, Lizhi, David								
Test Durantion: 10:30AM to 12:20PM @105 Deg C								
March 23, 2007,							chiller	housing
P/N:5109169; S/N:10004								
Vi	Vo	Ii	Io	Pi	Po	eff	Tc	Th
[V]	[V]	[A]	[A]	[W]	[W]	[%]	[°C]	[°C]
400.0	14.74	2.17	43.40	868.0	639.7	73.70%	104.8	110.0
400.0	14.70	8.25	199.20	3300.0	2928.2	88.73%	105.2	106.9
400.0	14.71	8.46	204.60	3384.0	3009.7	88.94%	104.9	116.7
400.0	14.71	9.76	236.90	3904.0	3484.8	89.26%	105.1	118.1
400.0	14.73	12.30	293.10	4920.0	4317.4	87.75%	105.0	119.1
400.0	14.74	13.76	335.10	5504.0	4939.4	89.74%	105.1	120.2
400.0	14.74	14.07	342.20	5628.0	5044.0	89.62%	105.1	120.0

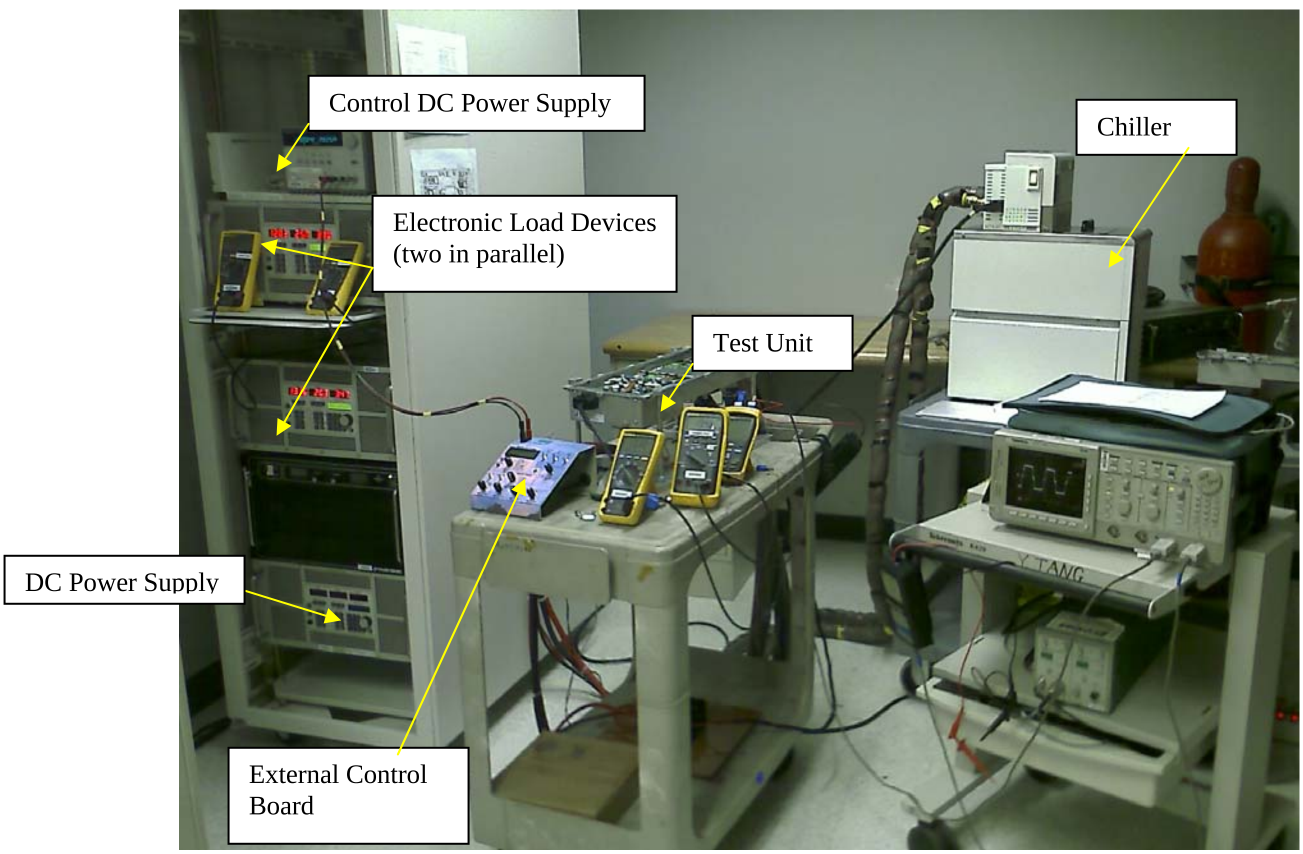


IMAGE_012.jpg

Figure A.9. Photo of test set-up with instrumentation.

IMAGE_013.jpg

Figure A.10. Photo of test set-up with test participants.

IMAGE_017.jpg

Figure A.11. Photo of test set-up showing probe placement.

IMAGE_018.jpg

Figure A.12. Close up photo of test controller developed at Ballard.

Following electrical testing the unit was weighed to confirm the conformance with the contractual targets. A ‘dry’ unit (ie, drained of coolant), part number #10007, was weighed. It weighed 8.28 kg, somewhat higher that the previous Ballard weight assertion of 7.4 kg. The discrepancy was likely due to the low voltage studs, coolant ports and lack of sil gel unaccounted for in the previous Ballard measurement. The earlier weight was arrived at through weights of individual parts that comprised the unit rather than through weighing a completed, sealed unit with production parts.

Volume calculations were taken from the CAD drawing package that the converter was drawn with and was calculated to be 5.1 liters, slightly above the target of 5 liters.

Figure A.13. Unit #10007 weighed during verification testing.

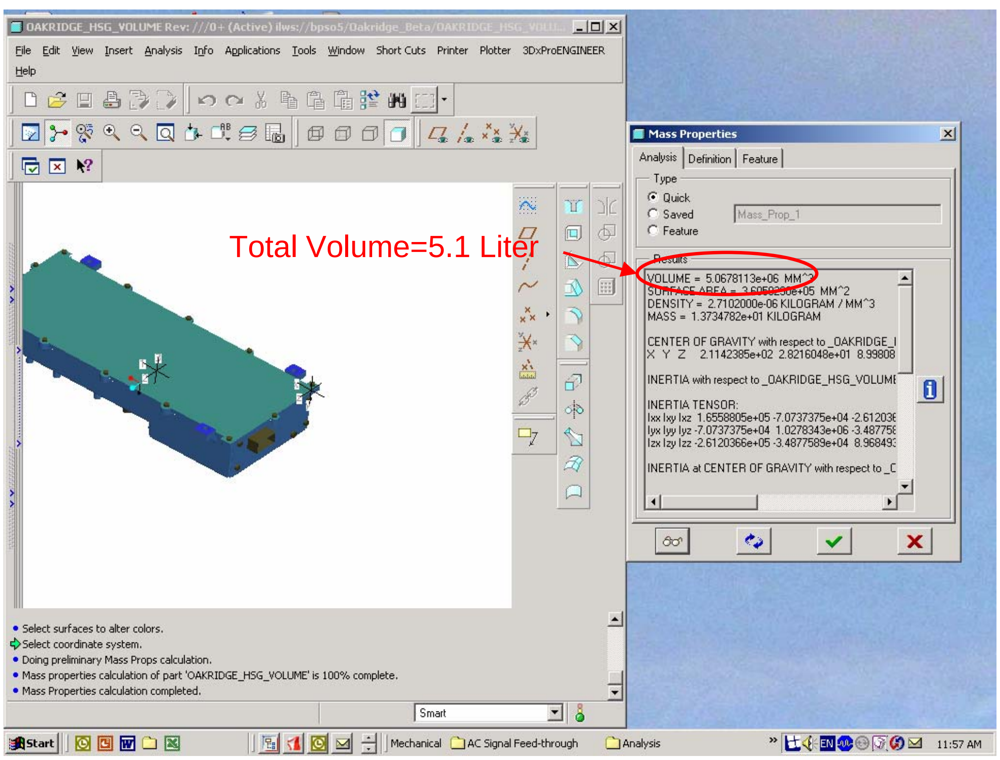


Figure A.14. CAD drawing showing volumetric calculation.

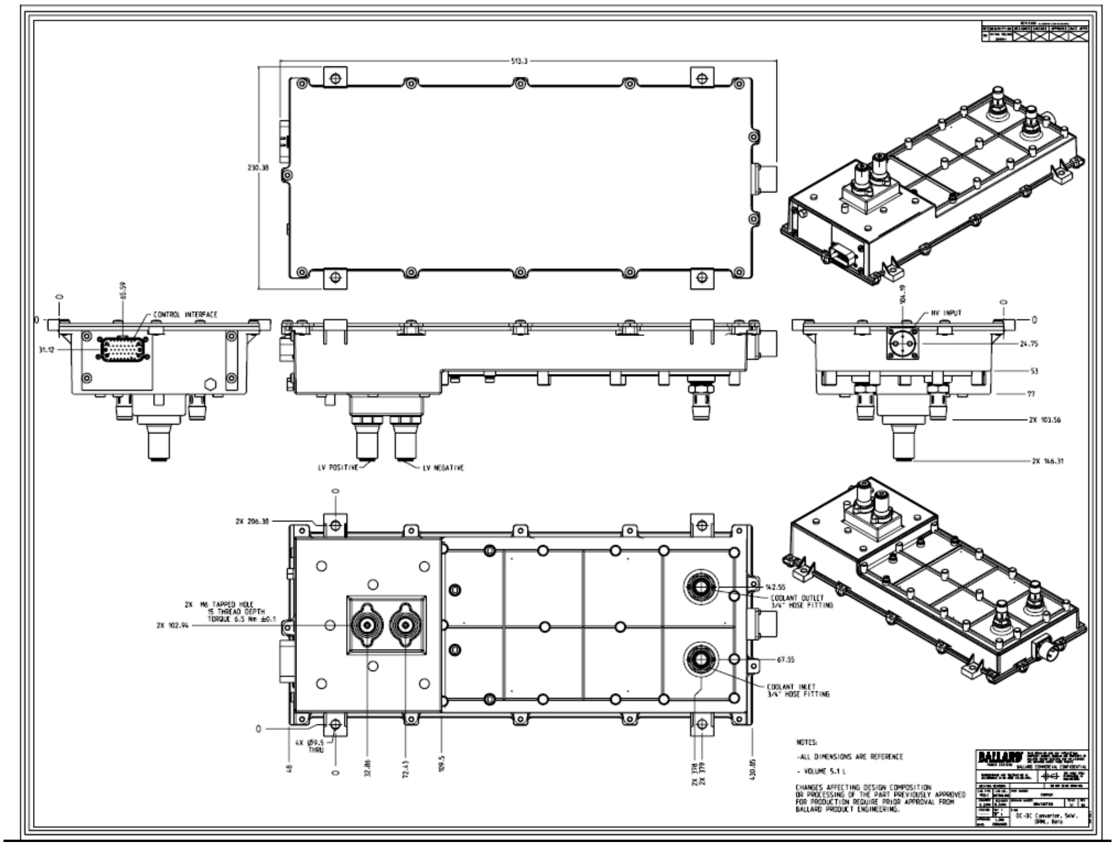


Figure A.15. Mechanical drawing of unit showing dimensions.

List of Test Equipment used in March 23rdTesting:

NesLab RTE-140 Chiller

Multiple Fluke 79 RMS DVMs

Tektronix TDS 754D Oscilloscope

Hewlett Packard Power Supply E3632A (0-15V, 7A)

Power Ten Instruments Power Supply (600V/33A)

(2) Dynaloads RBL 488 11-600-4000

Verification Tests April 17, 2007

Following the verification testing on March 23, 2007 the test setup at Ballard/Siemens was analyzed to determine why the efficiency during testing was below what had previously been measured during in house tests. Some problems with grounding of the unit were uncovered. It was decided to rerun the verification testing with a unit with grounding straps added to the module as seen in Figure A.16 below.

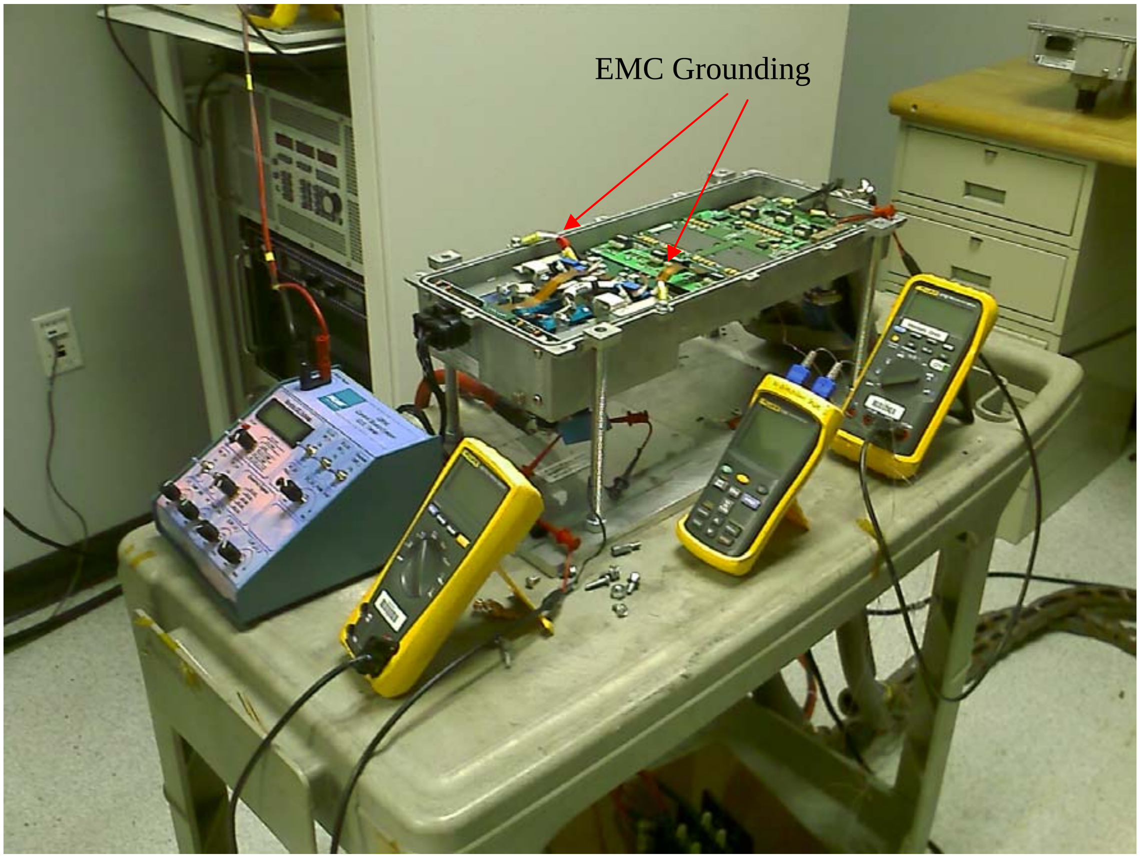


Figure A.16. Test module S/N 10004 with grounding straps.

On April 17, 2007 efficiency tests were repeated at Ballard using the same test equipment as in the original March 23rd test. Figures A.17–A.19 show the results of the retests.

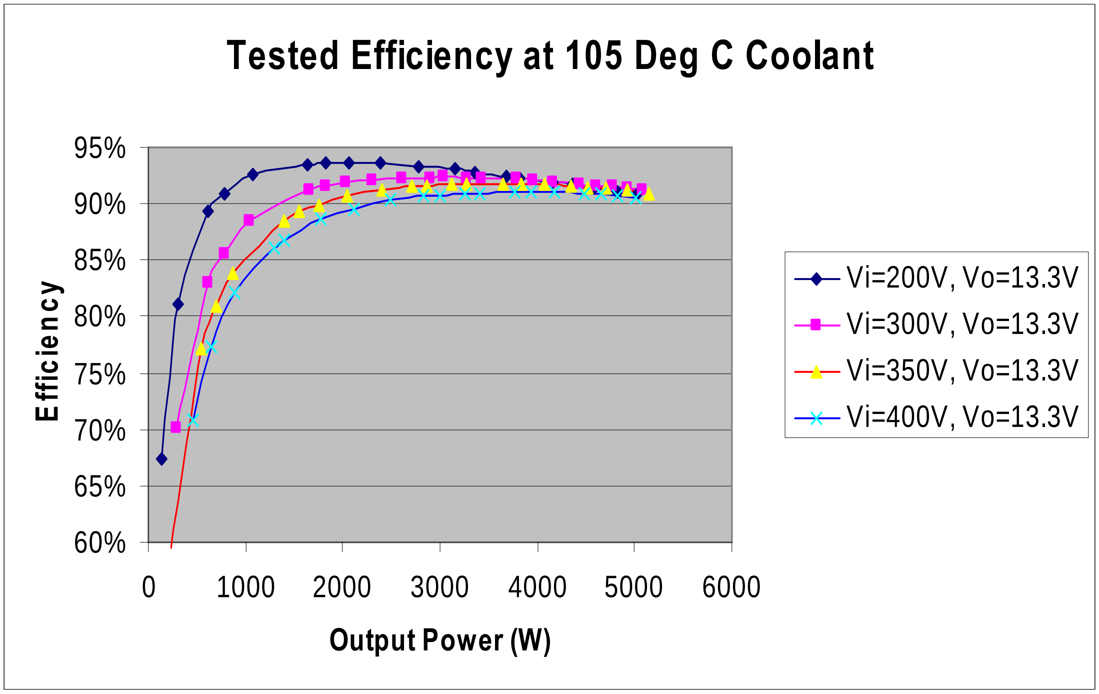


Figure A.17. Efficiency tests at 105ºC coolant, Vo = 13.3 V with varying input voltages.

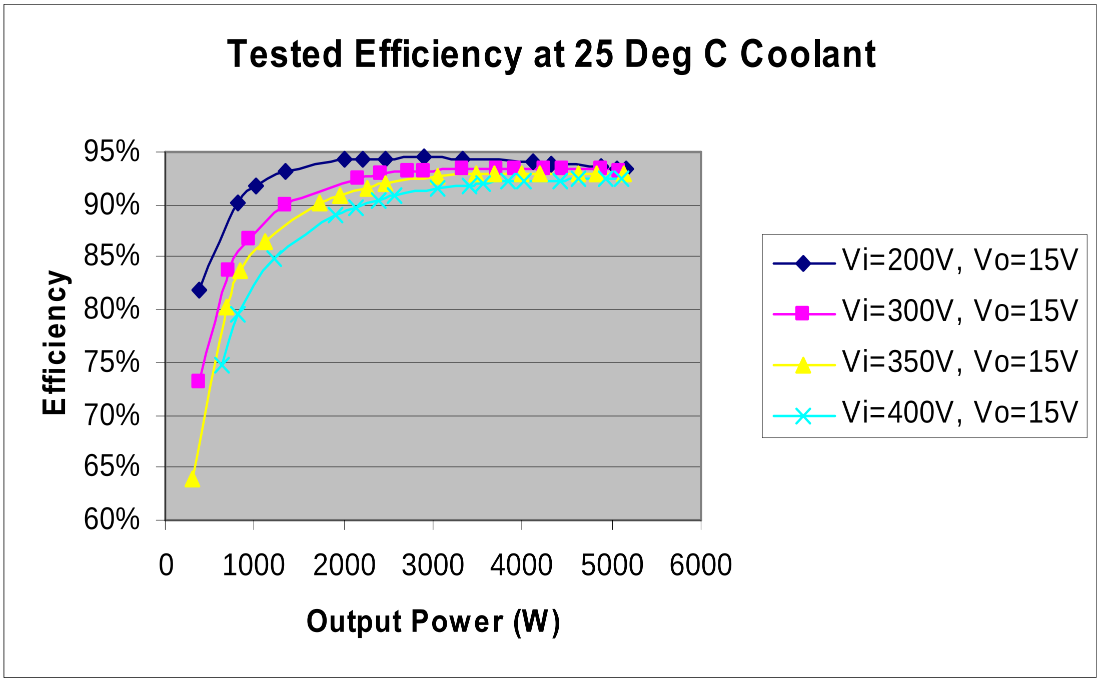


Figure A.18. Efficiency tests at 25ºC coolant, Vo = 15 V with varying input voltages.

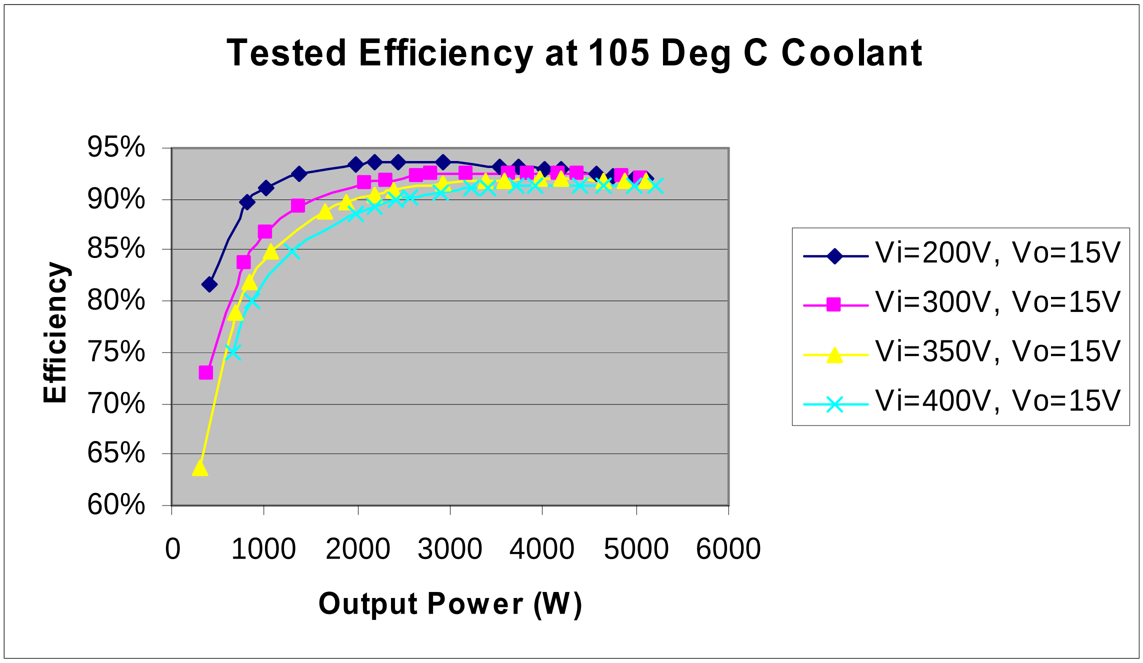


Figure A.19. Efficiency tests at 105°C coolant, Vo = 15 V with varying input voltages.

It was found that the grounding issue had degraded the test results from the previous test effort in March. The new retests proved to be consistent with Ballards earlier in house tests shown in Figures A.33–A.36 of this report. Complete test data is presented in Table 2 below.

Table A.2. Recorded test results (April 17, 2007)
(Voltages and currents measured with Fluke multimeters)

ORNL Witness test **DUT SN: 10004**
Laura, GuiJia, Miaoshen, Richard, Lizhi, David
Test Durantion: 10:30AM to 12:20PM @105 Deg C
March 23, 2007,
P/N:5109169; S/N:10004

DUT SN: 10009
Test Durantion: 9:20AM to 10:00PM @105 Deg C
4/17/2007, Laura, John, Miaosen, Dawud, Lizhi
P/N:5109169; S/N:10009

Vi	Vo	Ii	Io	Pi	Po	eff	chiller Tc	housing Th	Vi	Vo	Ii	Io	Pi	Po	eff	Delta Eff	T1	T2
200.0	13.35	10.86	152.40	2172.0	2034.5	93.67%	101.3	99.8	200.2	13.32	10.79	152.50	2160.2	2031.3	94.03%	0.4%	105.0	105.2
200.0	13.35	14.87	208.40	2974.0	2782.1	93.55%	102.4	101.3	200.0	13.31	14.76	207.80	2952.0	2765.8	93.69%	0.1%	105.6	105.5
200.0	13.35	17.89	249.60	3578.0	3332.2	93.13%	103.3	102.4	199.9	13.31	17.73	248.50	3544.2	3307.5	93.32%	0.2%	105.9	105.7
200.0	13.29	27.29	374.10	5458.0	4971.8	91.09%	104.2	104.9	199.4	13.31	27.23	373.40	5429.7	4970.0	91.53%	0.4%	106.4	106.2
200.0	13.29	27.69	379.30	5538.0	5040.9	91.02%	105.4	105.3	199.4	13.31	27.63	378.50	5509.4	5037.8	91.44%	0.4%	106.4	106.4
													0.0	0.0				
300.0	13.24	6.43	132.00	1929.0	1747.7	90.60%	104.9	108.2	300.7	13.31	6.51	135.50	1957.6	1803.5	92.13%	1.5%	106.1	105.8
300.0	13.25	10.95	227.60	3285.0	3015.7	91.80%	104.7	110.4	300.6	13.31	10.69	223.50	3213.4	2974.8	92.57%	0.8%	108.4	107.9
300.0	13.19	18.20	374.60	5460.0	4941.0	90.49%	105.1	111.7	300.2	13.30	18.01	371.40	5406.6	4939.6	91.36%	0.9%	111.0	110
300.0	13.19	18.30	376.80	5490.0	4970.0	90.53%	105.2	112.2	299.5	13.32	18.35	376.20	5495.8	5011.0	91.18%	0.6%	111.6	110.5
300.0	13.18	18.57	381.90	5571.0	5033.4	90.35%	105.3	112.0	300.2	13.30	18.53	381.50	5562.7	5074.0			111.5	110.4
													0.0	0.0				
400.0	12.98	6.21	164.50	2484.0	2135.2	85.96%	105.9	115.3	400.3	13.31	6.01	163.60	2405.8	2177.5	90.51%	4.6%	107.9	107.6
400.0	13.03	10.70	292.00	4280.0	3804.8	88.90%	105.0	118.0	400.1	13.30	10.58	290.10	4233.1	3858.3	91.15%	2.3%	112.3	111
400.0	13.02	11.28	308.10	4512.0	4011.5	88.91%	105.1	118.8	400.1	13.30	11.33	310.20	4533.1	4125.7	91.01%	2.1%	113.2	111.9
400.0	13.01	14.41	391.70	5764.0	5096.0	88.41%	105.2	120.0	399.9	13.29	14.32	388.80	5726.6	5167.2	90.23%	1.8%	115.3	113.7
400.0	13.31	14.02	374.50	5608.0	4984.6	88.88%	105.0	119.0										
400.0	13.31	11.51	309.00	4604.0	4112.8	89.33%	105.0	117.9										
400.0	13.31	8.94	239.40	3576.0	3186.4	89.11%	104.9	117.0										
400.0	13.31	10.05	269.27	4020.0	3584.0	89.15%	104.8	117.3										
200.0	14.93	13.10	163.30	2620.0	2438.1	93.06%	104.9	115.0	200.4	15.06	13.44	166.70	2693.4	2510.5	93.21%	0.2%	105.5	105.5
200.0	14.99	18.81	233.80	3762.0	3504.7	93.16%	105.8	106.0	199.8	15.00	19.09	238.40	3814.2	3576.0	93.76%	0.6%	106.8	106.3
200.0	14.47	28.94	367.20	5788.0	5313.4	91.80%	105.2	106.3	199.4	14.58	29.40	370.00	5862.4	5394.6	92.02%	0.2%	105.4	105.3
300.0	14.81	18.99	348.90	5697.0	5167.2	90.70%	105.3	112.4	299.9	14.99	18.48	340.80	5542.2	5108.6	92.18%	1.5%	111.5	110.4
300.0	14.86	13.08	241.60	3924.0	3590.2	91.49%	105.3	112.4	300.1	15.00	12.88	239.30	3865.3	3589.5	92.87%	1.4%	110.3	109
300.0	14.89	10.02	184.50	3006.0	2747.2	91.39%	105.1	111.0	300.3	15.00	9.79	181.70	2939.9	2725.5	92.71%	1.3%	108.7	108.1
400.0	14.71	8.46	204.60	3384.0	3009.7	88.94%	104.9	116.7	400.4	14.99	8.32	202.60	3331.3	3037.0	91.16%	2.2%	111.2	110.5
400.0	14.73	12.30	293.10	4920.0	4317.4	87.75%	105.0	119.1	400.2	14.99	11.64	284.40	4658.3	4263.2	91.52%	3.8%	114.7	113.5
400.0	14.71	9.76	236.90	3904.0	3484.8	89.26%	105.1	118.1	400.3	14.99	10.00	244.30	4003.0	3662.1	91.48%	2.2%	112.8	111.9
400.0	14.74	13.76	335.10	5504.0	4939.4	89.74%	105.1	120.2	400.1	14.98	13.80	336.40	5521.4	5039.3	91.27%		116.5	114.7
400.0	14.70	8.25	199.20	3300.0	2928.2	88.73%	105.2	106.9	400.5	14.99	8.23	200.40	3296.1	3004.0	91.14%		111.4	110.7
400.0	14.74	14.07	342.20	5628.0	5044.0	89.62%	105.1	120.0	400.2	14.98	14.04	342.20	5618.8	5126.2	91.23%	1.6%	116.4	114.4
300.0	13.31	8.90	184.20	2670.0	2451.7	91.82%	105.0	121.0										
299.7	13.25	17.23	354.00	5163.8	4690.5	90.83%	105.2	126.2	Load Stepı	12:58:26	13:00							
300.0	13.31	8.91	184.40	2673.0	2454.4	91.82%	105.0	122.0	Load Dum|	13:06:38	13:08:30							

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