2016 DOE VEHICLE TECHNOLOGIES ANNUAL MERIT REVIEW

Next Generation Inverter

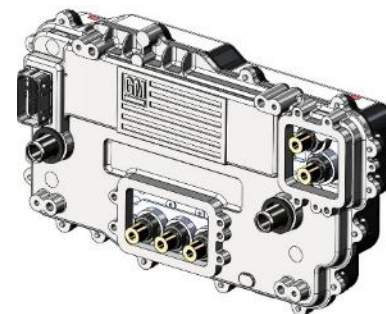
Project ID # EDT040

Author: Zilai Zhao

Presenter: Brian Peaslee

General Motors

June, 2016



GENERAL MOTORS

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OVERVIEW

Timeline

- Start - October 2011
- Finish – January 2016
- 100% Complete

Barriers

- Cost
- Efficiency
- Performance and Lifetime
- Mass and Volume

Funding

	DOE	GM
Budget	**$6.00M**	**$10.60M**
FY11	.04M	.06M
FY12	1.18M	2.09M
FY13	1.94M	3.46M
FY14	1.92M	3.57M
FY15	.73M	1.30M
FY16	.01M	.02M
Total	**$5.82M**	**$10.50M**

Partners

- Lead – General Motors
- Tier 1, 2, & 3 Suppliers - Hitachi, Delphi, Infineon, HRL, Panasonic, AVX, Kemet, and Interplex Industries, etc.
- Collaborations - National Renewable Energy Laboratory, and Oak Ridge National Laboratory

RELEVANCE

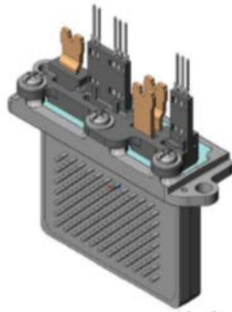
- **Research Focus Area: Inverter**
  - Modularity/Scalability
  - Components – power module, gate drive, capacitor, current sensor and control card
  - Supplier development
- **Objective**
  - Develop the technologies and product design for a low cost highly efficient next generation inverter capable of 55kW peak/30kW continuous power.
- **Addresses Targets**
  - Cost: $3.30/kW produced in quantities of 100,000 units
  - Power Density: 13.4kW/l; Specific power: 14.1kW/kg
  - Efficiency >94% (10%-100% speed at 20% rated torque)
- **Uniqueness and Impacts**
  - Technology Co-development with the Tier 1, 2, and 3 suppliers
  - Detailed knowledge of vehicle application and ability to understand and assess vehicle impacts to make necessary materials and technology trade-offs.

MILESTONES

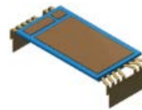
Month /Year	Milestone or Go/No-Go Decision	Status
June 2012	Power Inverters Based on Conventional, Transfer Molded, and Encapsulated Power Module Technology Delivered for Evaluation	Complete
Jan 2013	Initial Technology and Production Cost Assessment Complete with Report	Complete
Jan 2014	Concept Design Review – DOE “Go/No-Go” Decision	Complete
Sept. 2014	Critical Design Review (original scheduled for June 2014)	Complete
Aug. 2015	Demonstration of Inverter Performance	Complete
Sept. 2015	Final cost estimation (originally scheduled for Sept. 2014)	Complete
Dec. 2015	Preliminary reliability study	Complete

MODULE TECHNOLOGY EVALUATION
COLLABORATED WITH ORNL

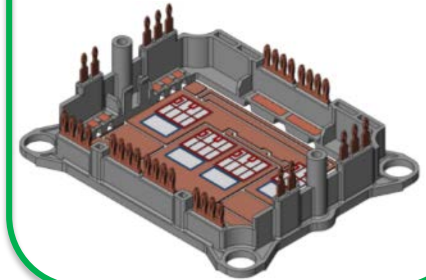
Direct Cooled Transfer Mold

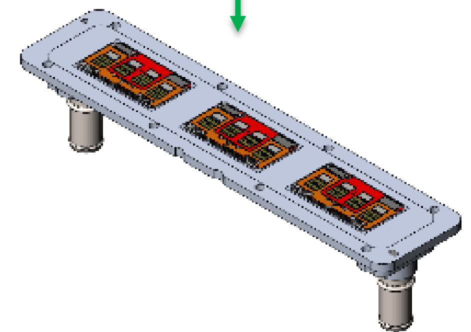


Encapsulated Discrete Device



Gel Module

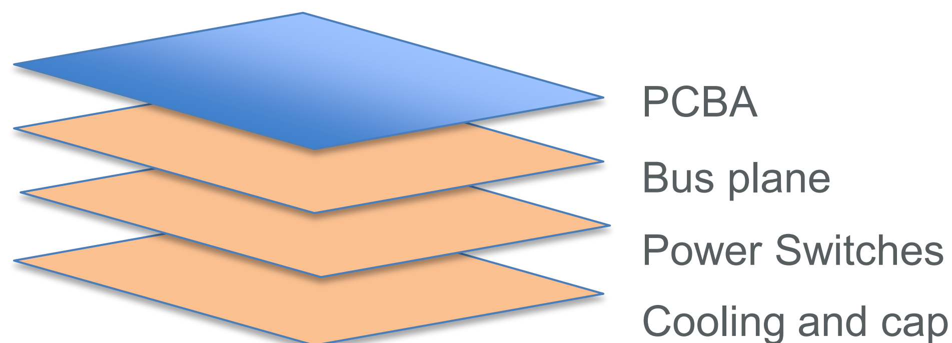




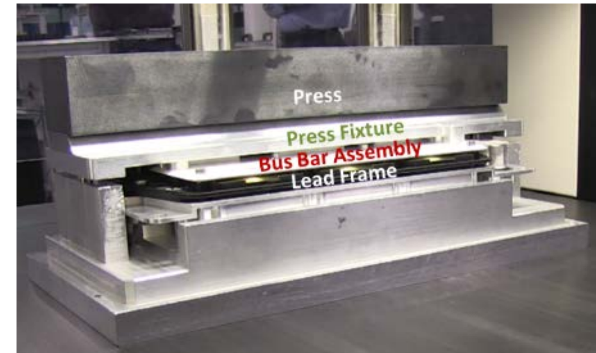
- Relatively mature manufacturing processes, which can be improved to lower cost and increase product performance.
- Highly efficient single-sided can be achieved.
- Can be adapted to work with wide band-gap power devices
- Offers scalability

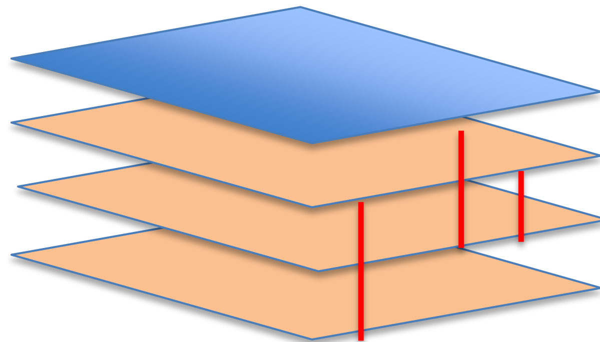
INVERTER DESIGN: INTEGRATED POWER STAGE

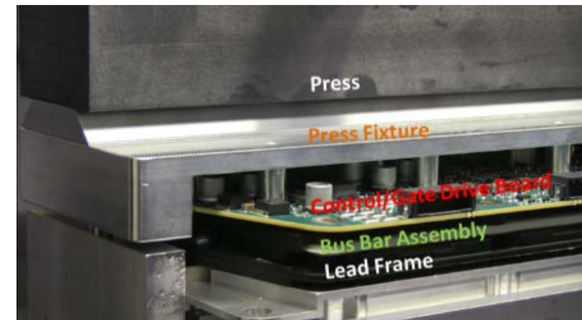
- Integrated power stage: Eliminate boundaries and empty spaces; new partitioning of functionality
- Vertically integrated process: Power stage manufacturing integrated into inverter assembly
- Manufacturability: Unidirectional (bottom to top) assembly process; reduced assembly steps



INVERTER DESIGN: PRESS-FIT PINS
COLLABORATED WITH INTERPLEX INDUSTRIES, INC

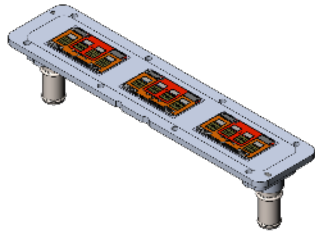


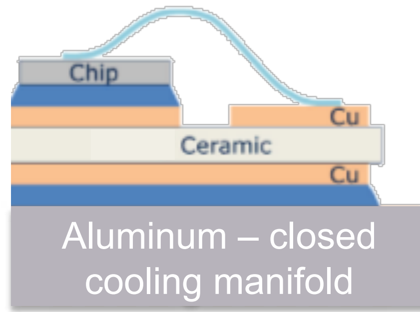




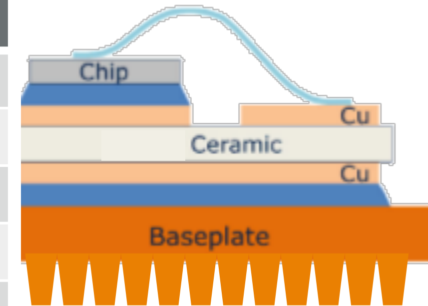
- Reliable joints for connecting two electronics components.
- Make multiple connections with one press operation.
- Process development
    - Fabrication of pins
    - Hole size and tolerance on PCBA
    - Press operation

INVERTER DESIGN: DBC DIRECTLY ATTACHED TO CLOSED COOLING MANIFOLD



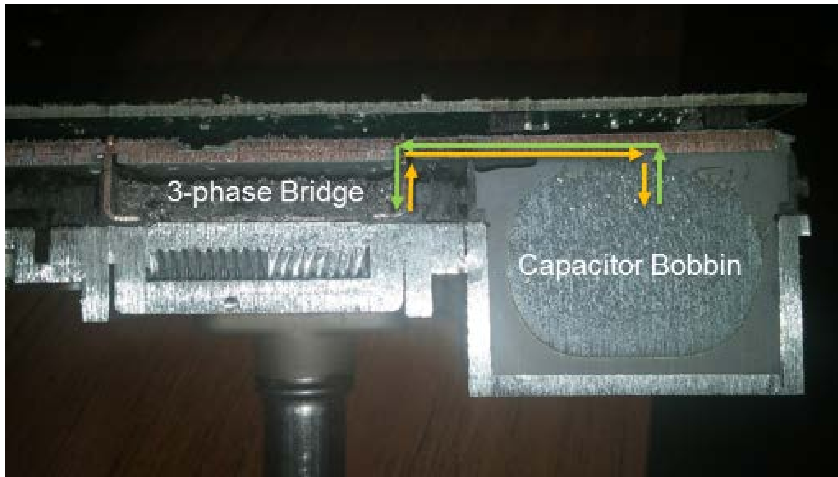


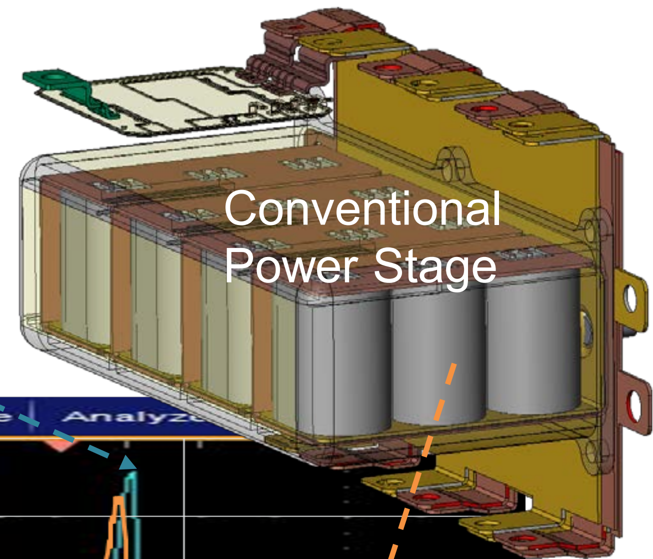
NGI	Current Gen
Die	Die
Solder	Solder
Copper	Copper
Ceramic	Ceramic
Copper	Copper
Solder	Solder
Aluminum	Copper
0.304 k*cm^2/W @ 4 LPM	0.288 k*cm^2/W @ 10 LPM

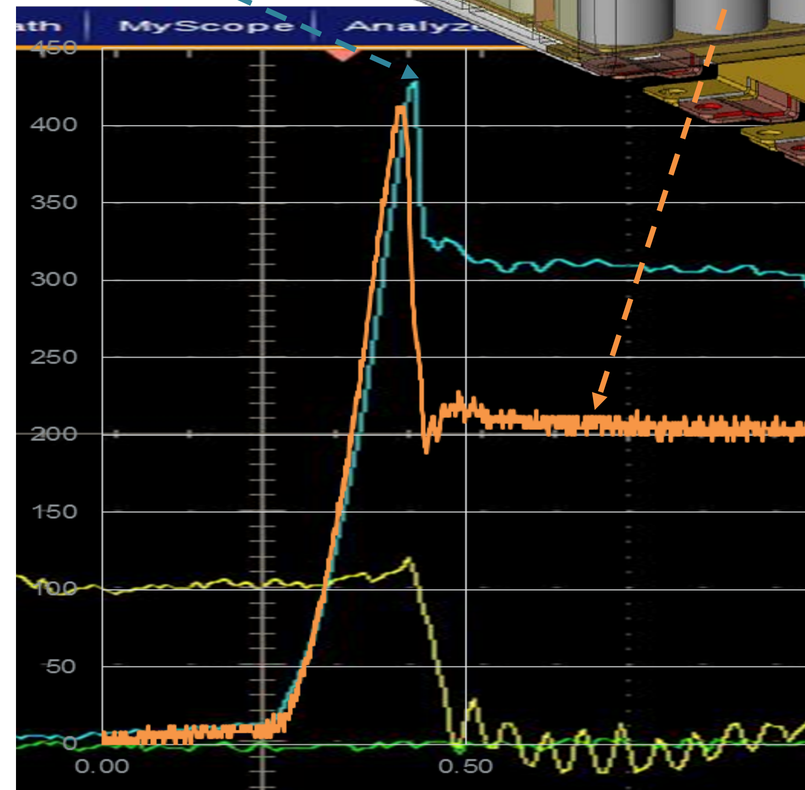


- Switching circuitry built directly on closed cooling manifold
- Thermal performance on par with Cu pin-fin base-plate
- Manufacturability
  - DBC to Al attach is a challenge
  - Vertically integrated process

INVERTER DESIGN: LOW INDUCTANCE DC LOOP (INVERTER LEVEL)



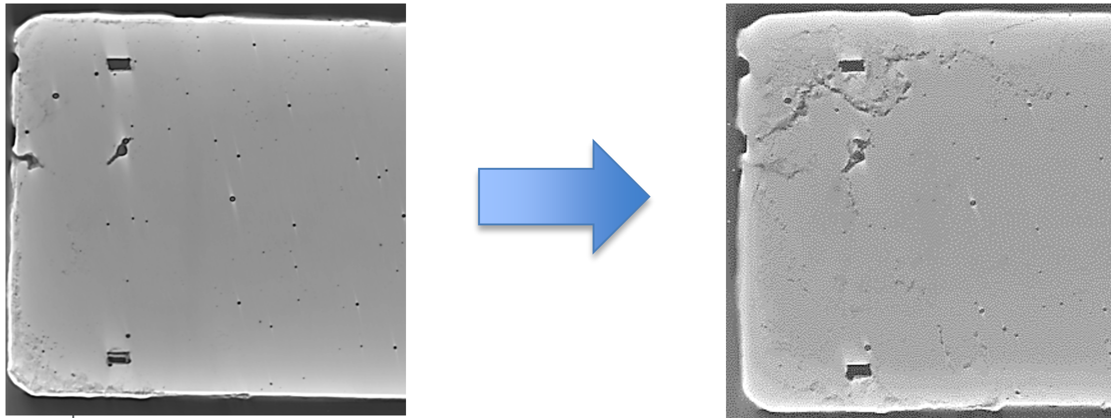




- Low stray inductance in the complete DC loop
- Manufacturability
  - Vertically integrated process
  - Press-fit pins

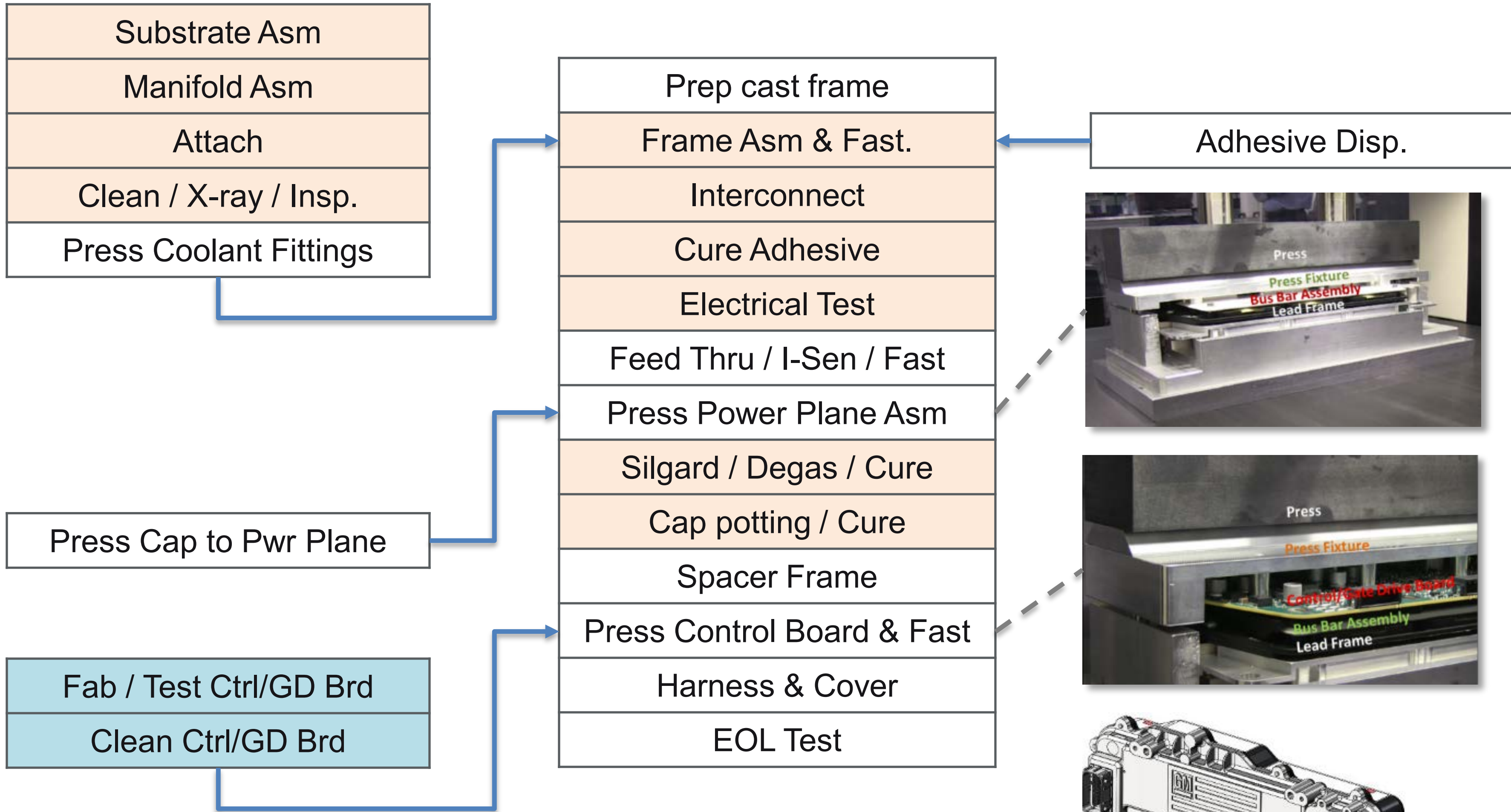
INVERTER BUILD: PROCESS DEVELOPMENT

- Key Processes: die attach, DBC attach, wire bonding, encapsulation of dies and cap bobbins, press-fit pin, final assembly
- Die/DBC attach
  - 20+ configurations evaluated – oven type, solder type, processing parameters
  - Evaluation: Yield, thermal shock (-55°C to 150°C), 3D Xray, Cross-Sectioning
- Encapsulation
  - 5 Configurations evaluated – chemistry, process parameters
  - Evaluation: High temp / high humidity



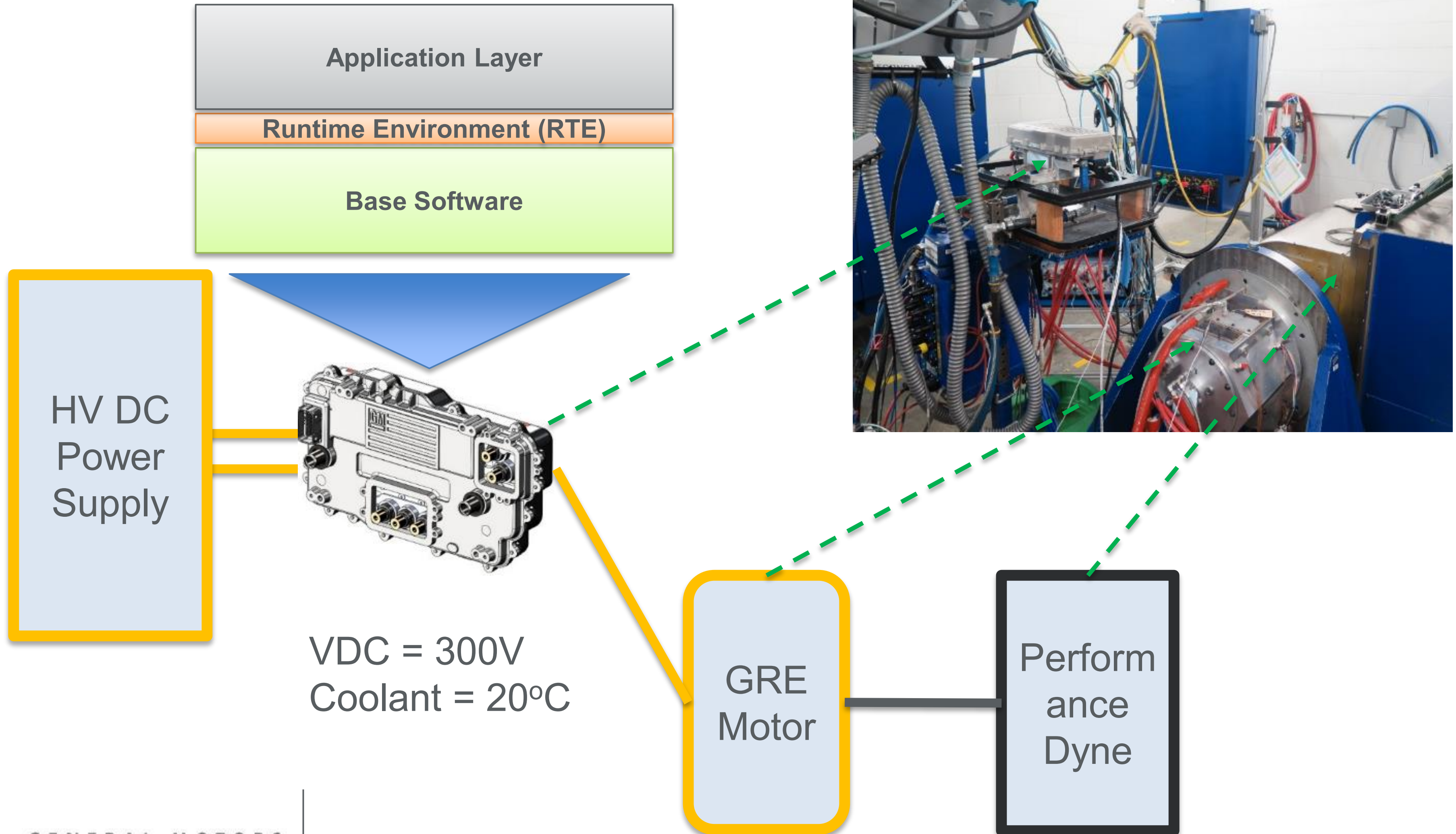
3D X-Ray: DBC attach before and after thermal shock

INVERTER BUILD: PROCESS FLOW

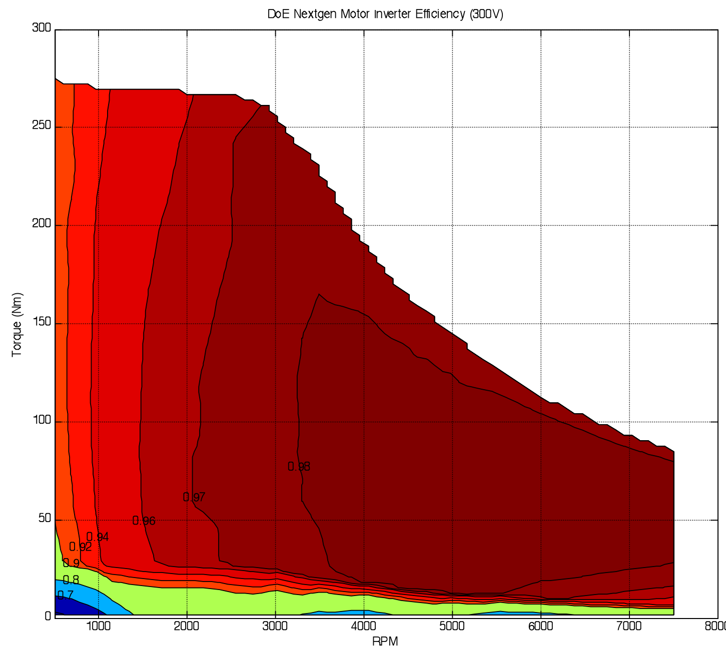


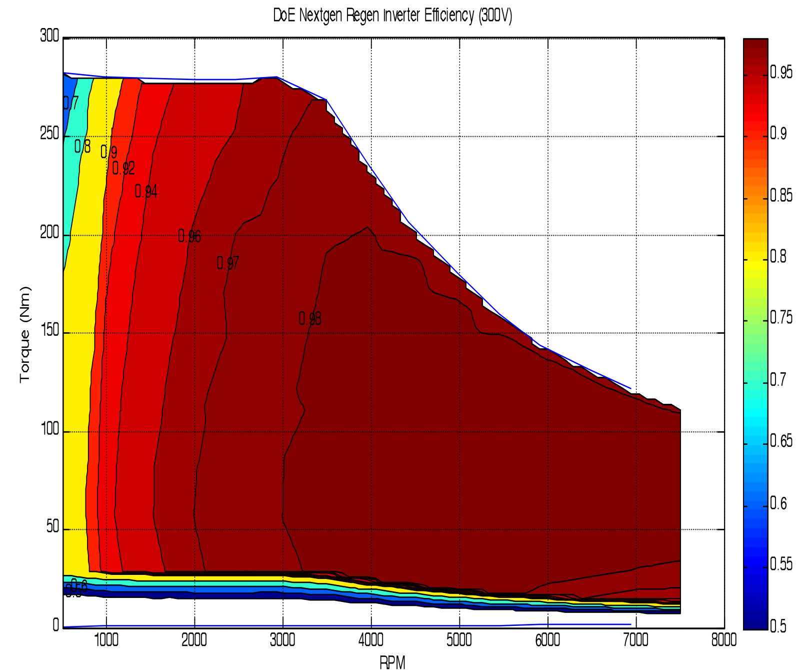
INVERTER ACCEPTANCE TEST

INVERTER PERFORMANCE VERIFICATION
TEST SETUP



INVERTER PERFORMANCE VERIFICATION
EFFICIENCY





- Max Motoring Power: 96 kW
- Max Phase Current: 319 Arms

- Max Regen Power: 87 kW
- Max Phase Current: 320 Arms

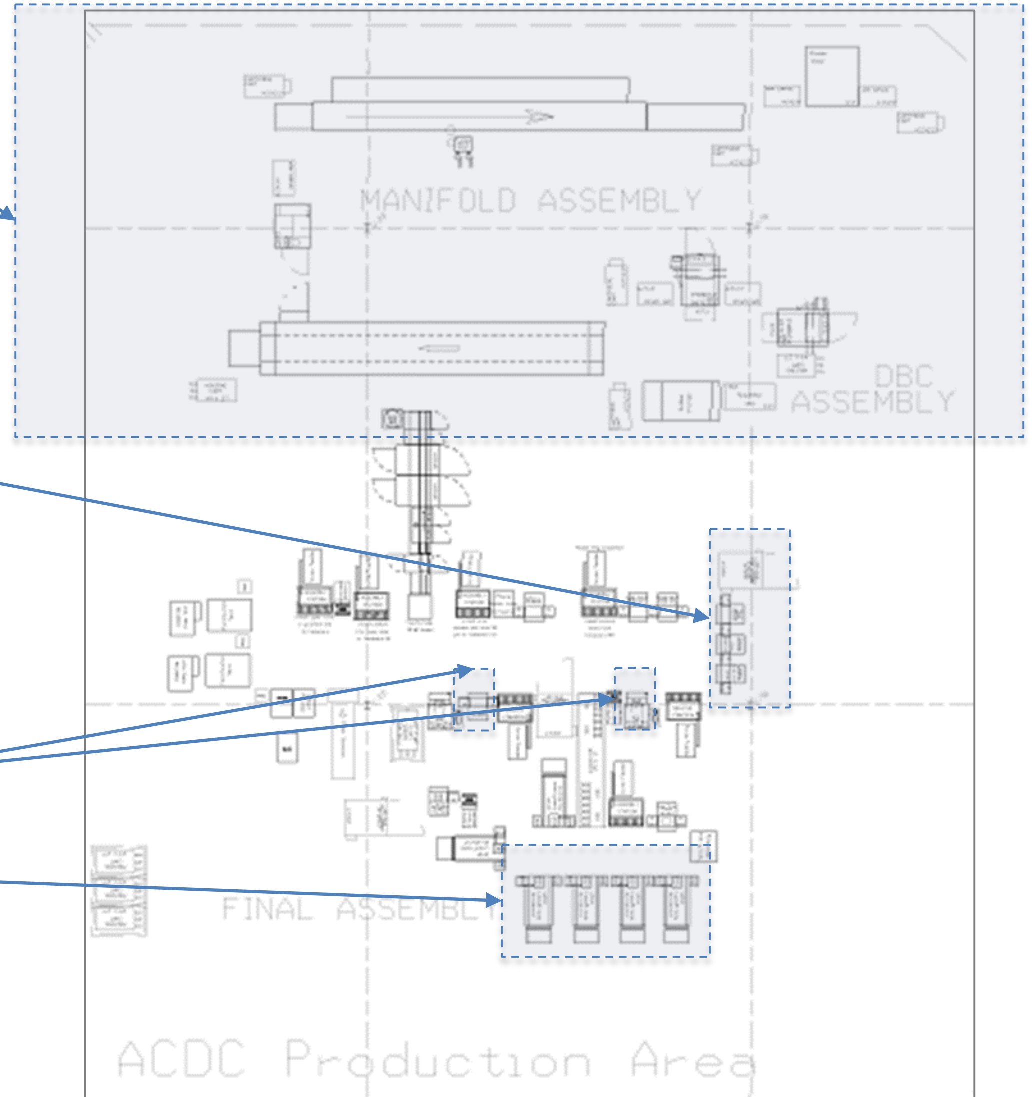
NEXT GEN INVERTER COST STUDY
CRITICAL OPERATIONS

Manifold Assembly
- P&P thin dies
- Die and substrate attach
- Washing

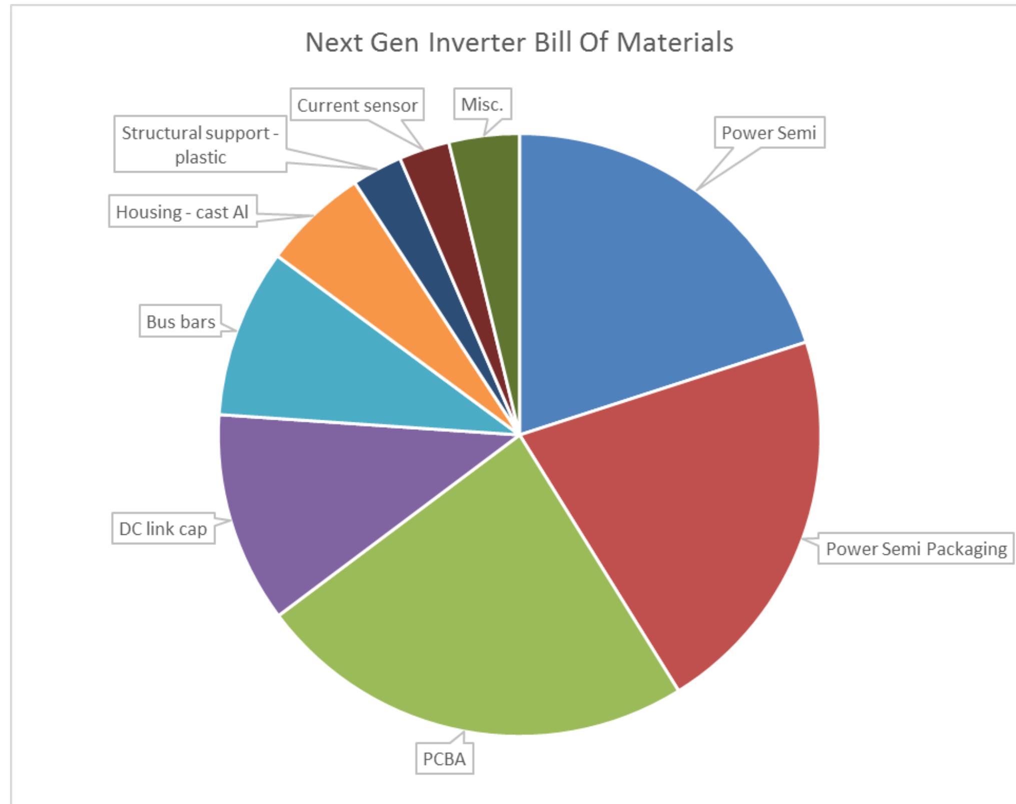
Encapsulation
- Potting dispense (for caps)
- Sylgard dispense (for dies)
- Vacuum
- Cure

Compliant Pin Press

Wire bonding



NEXT GEN INVERTER COST STUDY
BILL OF MATERIALS

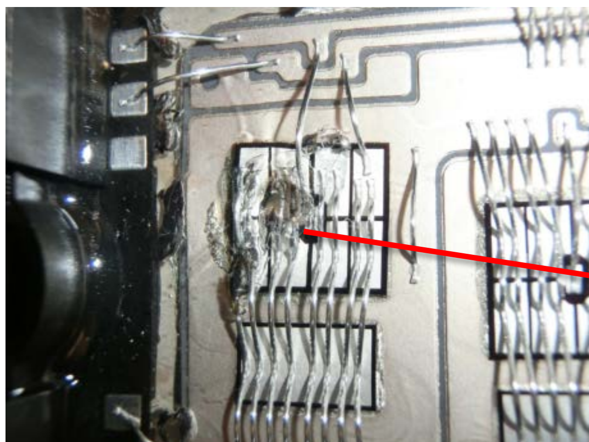


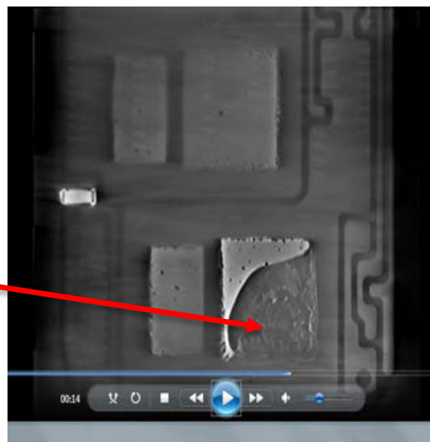
- Achieved significant reduction of “non-power-conversion” materials
- Power semi cost dominant
- Higher volume needed to reduce PCBA cost

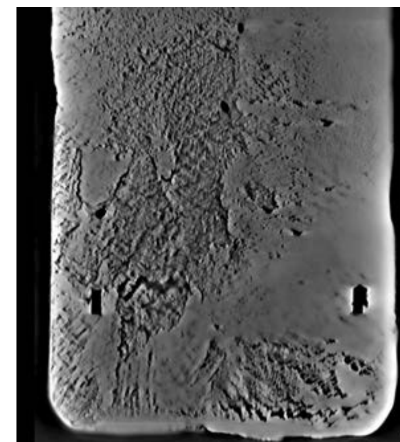
RELIABILITY TEST

- Intermittent Operating Life Test and Power Cycle Test per GM production inverter test requirements
- Test to failure
- Solder layer reliability study, collaborated with NREL.

RELIABILITY TEST FINDINGS AND NEXT STEPS



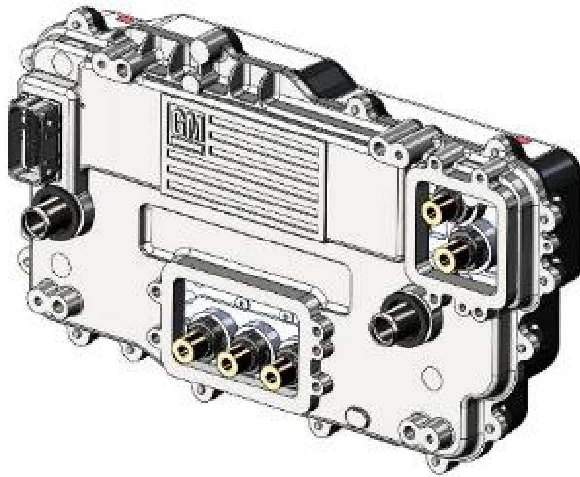




- Root Cause - Rth increased due to degradation in substrate attach => High Tj => die solder reflow and wire bond failure.
- NREL study confirm that substrate attach in this configuration does not have required reliability.
- “Stress relief” added to new configuration – new configuration will be evaluated (outside of this cooperative agreement)

CONCLUSION

- Prototype met DOE 2020 power density target
- Design is projected to meet DOE 2020 cost target at scaled up power level
- Highly integrated design requires vertically integrated manufacturing processes
- Substrate attach process needs further improvement for this design to meeting automotive reliability requirements



THANK YOU FOR YOUR ATTENTION!