Development, Test and Demonstration of a Cost-Effective, Compact, Light-Weight, and Scalable High Temperature Inverter for HEVs, PHEVs, and FCVs

2008 DOE Merit Review

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Oak Ridge National Lab (ORNL)
Dow Corning Corporation (DCC)
General Electric Corporation (GE)

Project Duration: FY 2008 to FY 2010

DOE Vehicle Technologies Program
FY 2008 Annual Merit Review
Hybrid Electric Vehicle Systems
Advanced Power Electronics and Electric Motor Projects

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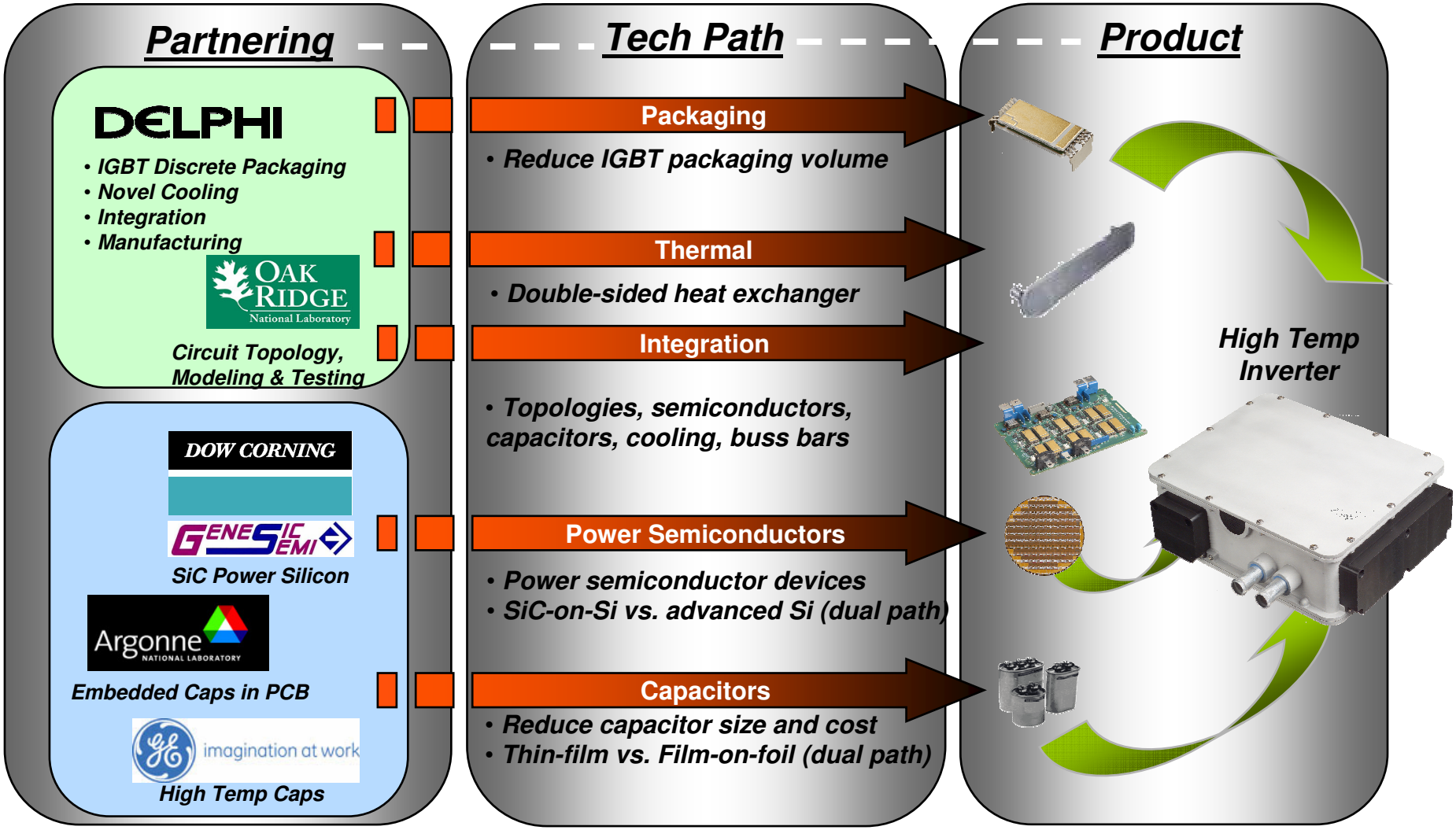
Purpose of Work

- Inverter Cost – must be reduced by 50%
  - Cost of today's available propulsion inverters for HEV, PHEV and FCV contributes to a higher cost/price premium for these vehicles, inhibiting consumer acceptance
- Inverter Volume & Mass – much smaller and lighter
  - Needs to package readily into different OEM platforms
  - Volume & mass driven by bulk capacitors and thermal/mechanical packaging
- Manufacturability – must be improved
  - Today's power silicon modules contain too many parts => too many manufacturing steps => quality, reliability and durability challenges, as well as high cost

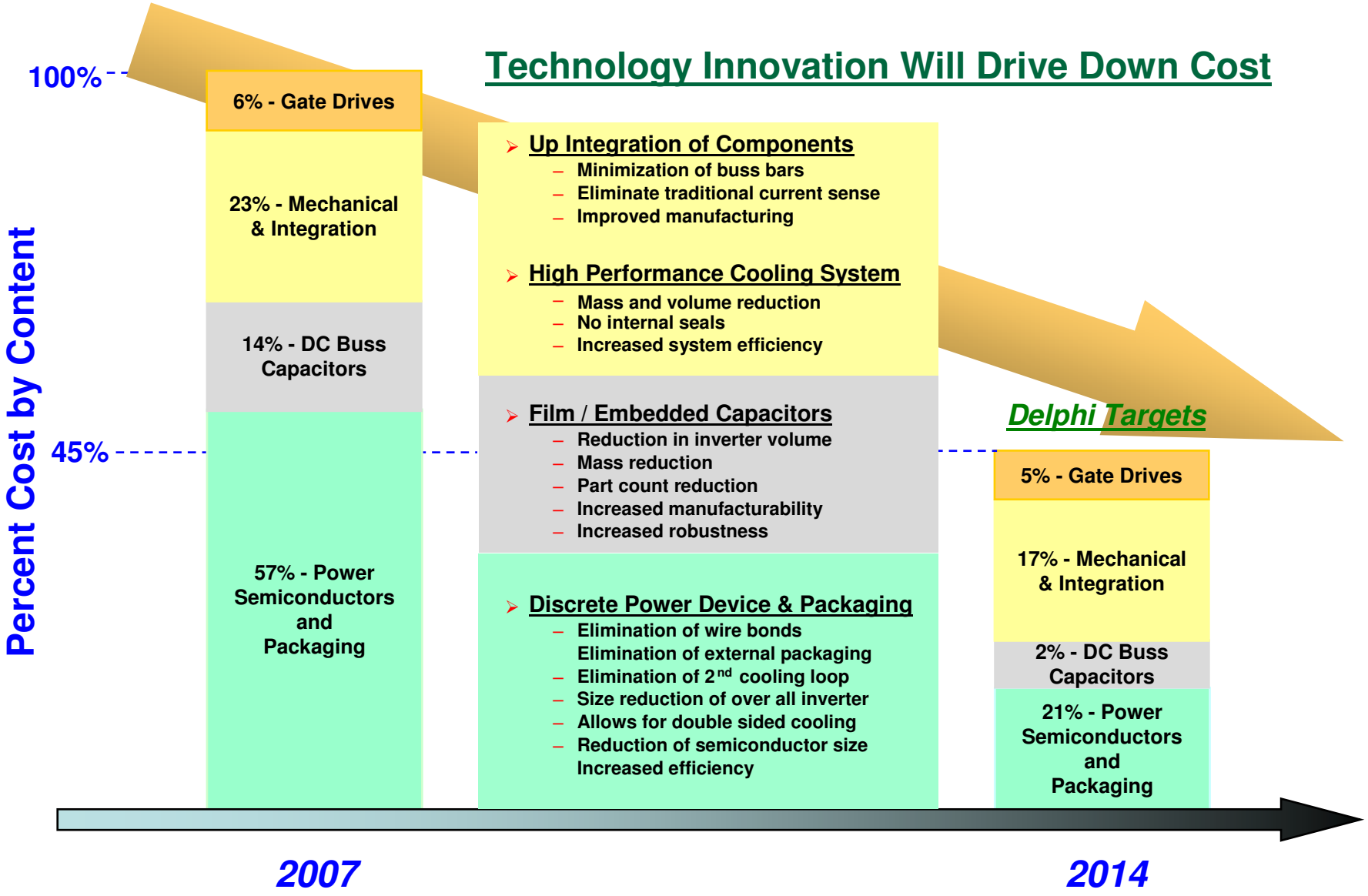
Barriers

- Delphi Challenges
  - Semiconductor Devices and Packaging
    - Design for highest power dissipation while using smallest die size power device
    - Tradeoff SiC/Si advantages vs. system cost
  - System Packaging and Integration
    - Low cost, high performance thermal technologies and solutions
    - High volume design compatible with standard manufacturing processes
- Partner Challenges
  - GE: High Temperature Film Capacitors
    - Film extrusion: quality, uniformity and defect rate
  - Argonne: Film-on-Foil Capacitors
    - PLZT density/uniformity and adhesion to foil (residual stresses, oxide layer)
  - DCC / GeneSiC: SiC-on-Si Power Semiconductor FETs and Diodes
    - Substrate cost and defect formation (quality control and yield)
  - ORNL: Inverter Topologies, Modeling and SiC Device Characterization
    - New models / validation required for high temp devices and system

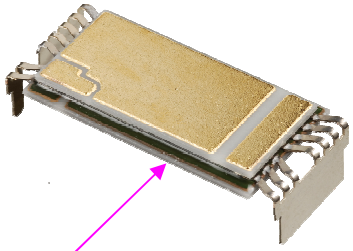
Approach


Partnering
Tech Path
Product
DELPHI
• IGBT Discrete Packaging
• Novel Cooling
• Integration
• Manufacturing
OAK RIDGE National Laboratory
Circuit Topology, Modeling & Testing
DOW CORNING
GENESIC SEMI
SiC Power Silicon
Argonne NATIONAL LABORATORY
Embedded Caps in PCB
imagination at work
High Temp Caps
Packaging
• Reduce IGBT packaging volume
Thermal
• Double-sided heat exchanger
Integration
• Topologies, semiconductors, capacitors, cooling, buss bars
Power Semiconductors
• Power semiconductor devices
• SiC-on-Si vs. advanced Si (dual path)
Capacitors
• Reduce capacitor size and cost
• Thin-film vs. Film-on-foil (dual path)
High Temp Inverter

Approach

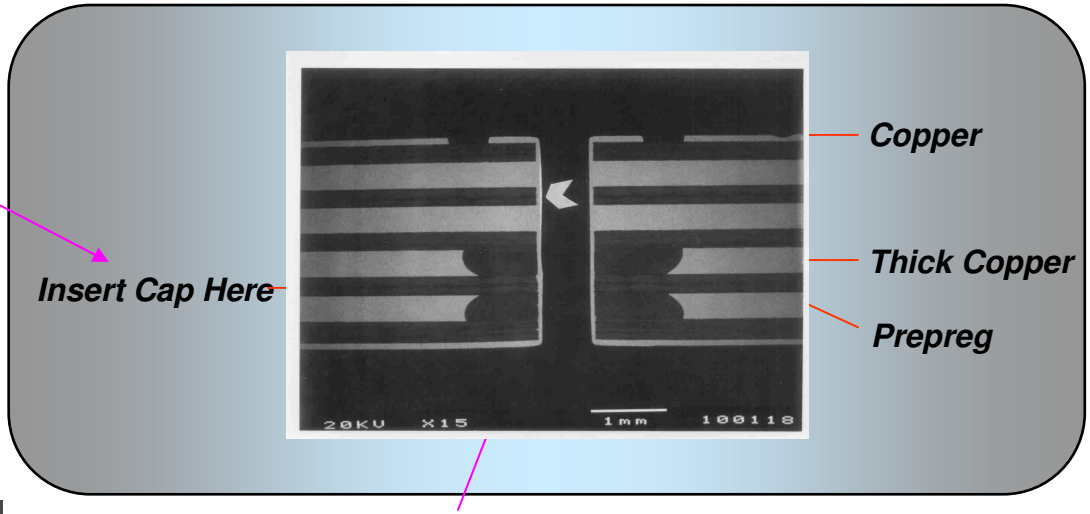

Technology Innovation Will Drive Down Cost
100%
45%
Percent Cost by Content
6% - Gate Drives
23% - Mechanical & Integration
14% - DC Buss Capacitors
57% - Power Semiconductors and Packaging
Up Integration of Components
Minimization of buss bars
Eliminate traditional current sense
Improved manufacturing
High Performance Cooling System
Mass and volume reduction
No internal seals
Increased system efficiency
Film / Embedded Capacitors
Reduction in inverter volume
Mass reduction
Part count reduction
Increased manufacturability
Increased robustness
Discrete Power Device & Packaging
Elimination of wire bonds
Elimination of external packaging
Elimination of 2nd cooling loop
Size reduction of over all inverter
Allows for double sided cooling
Reduction of semiconductor size
Increased efficiency
Delphi Targets
5% - Gate Drives
17% - Mechanical & Integration
2% - DC Buss Capacitors
21% - Power Semiconductors and Packaging
2007
2014

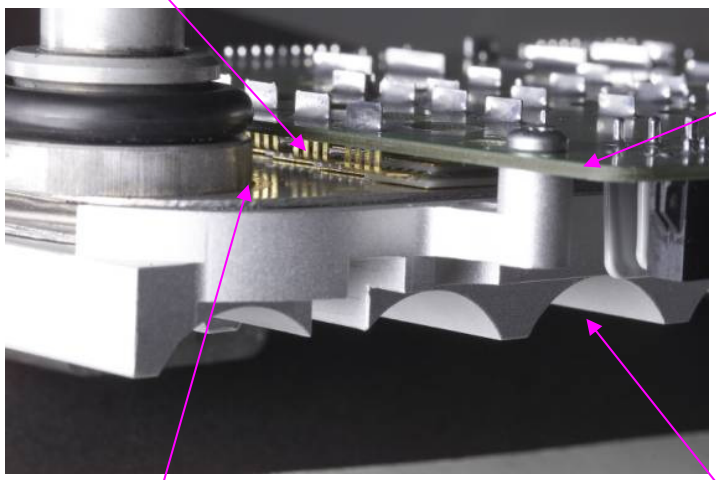
Approach



Embedded Cap

Discrete Power Switch Si or SiC





High Current FR4

High Convection Coefficient Heat Exchanger

Film Cap

Power Stage with Current Sensors on FR4

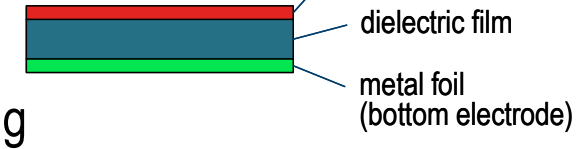
Approach: Power Semiconductors

- Current Power Semiconductors:
  - Higher temperature capability required for next generation inverter system, to eliminate costly and difficult to package separate cooling loop for power devices
  - Lower cost power devices / packaging required to reduce overall inverter system cost
- Delphi is taking a dual path to identify power devices & packaging suitable for inverter applications
- Silicon
  - Devices with solderable frontside and backside connections
  - Thin die & similar die thickness IGBTs and diodes for packaging
  - Higher junction temperature operation
- SiC-on-Silicon
  - A SiC-on-Silicon (SiC/Si) compound semiconductor hybrid device approach is proposed, to combine best of both worlds: SiC (high temp operation) and Si (low cost)
  - Theoretical electrical capability exceeds requirements of future high power inverters
  - SiC/Si solution estimated to be 10X lower materials cost than pure SiC
    - Reduces device size and cooling needs compared to Si devices for high power

Approach: Capacitors

- Current HEV Capacitors:
  - Low temperature capability, poor reliability (electrolytic), low energy density => large & heavy, high cost
  - Advanced high temperature capacitors required for next generation inverter technology
- Delphi is taking a dual path to identify a capacitor design & packaging suitable for inverter applications
- Film Capacitors
  - Identify appropriate dielectric film
  - 140°C continuous use temperature
  - Higher dielectric constant
  - < 10 micron thickness
  - Metallizable for self clearing capability
  - Scaleable to lengths and widths suitable for manufacturing

Film-on-foil capacitor



- Film-On-Foil Capacitors
  - Metal foil coated with thin film PLZT dielectric
    - PLZT/Ni Film-on-Foil and PLZT/Cu Film-on-Foil
  - Stack & embed coated foils directly into printed wire circuit board

Approach: Packaging & Integration

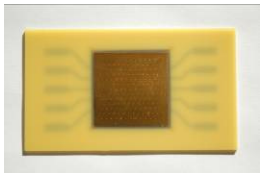
- Power Semiconductor Device Packaging & Integration
  - Design for highest power dissipation while using smallest die size power device
    - Efficiently remove extra heat from both sides of the power device
    - Smallest semiconductor device => smaller semiconductor device package, smaller circuit board, smaller/ lighter overall package size => least cost system
  - Tradeoff SiC/Si advantages vs. system cost
    - Can the benefits of SiC/Si power semiconductors offset the cost?
- Capacitor Packaging & Integration
  - Evaluate high temp film caps with higher dielectric constant for potential to be smaller than film caps available today
  - Determine practicality of embedding DC bulk caps within circuit board, for smallest size, least weight, and compatibility with high volume mfg processes
- System Packaging and Integration
  - Develop low cost, high performance thermal technologies and system solutions
  - Develop a high volume design that is easily manufacturable using standard manufacturing processes

Performance Measures/Technical Accomplishments/ Progress/Results

- This is a new start, all partners on board beginning January 2008
- *Research Phase – Feasibility Study/Proof of Concept*
- Objectives
  - Develop requirements for key technologies to be developed
  - Perform a combination of virtual testing (modeling and simulation) and limited laboratory testing of multiple technology concepts with timing, risks, approach, and outcome for each concept
  - Hold a review of concepts with the DOE for *Go/No-Go* decision for transfer to Phase II development
- Success Criteria
  - Completed requirements documents for key technologies
  - Key technology concepts selected with risks, timing, approach and expected outcome identified
  - Review held with DOE approves progress into Phase II

Performance Measures/Technical Accomplishments/ Progress/Results (cont'd)

- Argonne, ORNL, GE, and Dow Corning have been supplied initial requirements documents for their key technologies
- We have had some prior work with Argonne on processes for embedding capacitors into circuit boards, and measurements of early capacitor samples
  - A dummy capacitor was fabricated for understanding the embedding process
  - A process has been demonstrated that allows film-on-foil capacitors to be fabricated as an independent core in a circuit board
    - Tolerances, chemical exposure to manufacturing process, temperatures and pressures have been documented.



Technology Transfer

- Delphi is a Tier 1 supplier of power electronics and energy storage systems to the automotive industry
- Inverters are a key product for EV, HEV, PHEV, and FCV powertrains
- Meeting the DOE cost, size and weight targets for inverters (along with the performance, reliability, and durability needs of the automotive industry) will expand the market for HEVs, PHEVs, and FCVs
- With success in meeting the auto industry's needs, Delphi plans to commercialize technology from this program

Activities for 2008 Fiscal Year

Task 1 – Define High Temp Inverter Performance Requirements

- A cross-functional engineering team of experts in power electronics/inverter design, systems engineering, mechanical engineering, passive components, and controls engineering will be assembled
- Team will develop preliminary detailed performance requirements for high temp inverter using DOE's inverter specs outlined in FOA
- Team will then develop detailed requirements for high temp caps, power silicon, thermal management and silicon packaging

Activities for 2008 Fiscal Year (cont'd)

Task 2 – Identify High Temp Inverter Technology Concepts

- Team will identify multiple concepts for each key technology with the potential to meet system/component level requirements
  - Including circuit topology, high temp capacitors, improved power silicon and power silicon packaging, innovative thermal management
- Partners will be asked to supply detailed descriptions of each concept to Delphi for Task 3 development
  - Prior designs, layouts, lab data and other technical information related to the technologies will be presented to Delphi
  - Above information will be analyzed, using methods such as Pugh's Analysis, to down-select potential concepts for further development
  - Above information along with concept rationale, risks, timing, and potential outcome will be presented for approval by Delphi for Task 3 development

Activities for 2008 Fiscal Year (cont'd)

Task 3 – Develop, Analyze and Select Concepts for Phase II Development

- Perform a combination of virtual testing *(modeling and simulation),* material analysis and limited laboratory testing for each of the potential enabling technology concepts identified in Task 2
- Hold a review of concepts with DOE for transfer to Phase II development

FY 2009 (Phase IIA)

- Test and evaluate the technologies defined in Phase I (FY08)

FY 2010 (Phase IIB)

- Using the technologies developed in Phase IIA (FY09) in conjunction with our building block inverter technologies, design, build and test an inverter to meet the DOE requirements

Summary

- Meeting the cost, size and weight as well as application requirements for inverters will help the automotive industry expand the market for energy efficient and alternative energy compatible HEVs, PHEVs, and FCVs
  - *This will help to reduce U.S. dependence on foreign oil and reduce greenhouse gas emissions*
- Delphi has assembled a cross-functional engineering team of experts in power electronics/inverter design, systems engineering, mechanical engineering, passive components, and controls engineering
- Our partners Argonne, ORNL, Dow Corning and GE are providing new capacitor technology, new discrete power devices, simulation, modeling and test expertise to help Delphi develop a low cost, compact, light-weight, high-temperature inverter to meet the DOE targets
- Delphi is developing this technology with commercialization in mind

Publications, Presentations, Patents

- This is a new start
- All partners fully on board starting in January 2008