# 2013 DOE Vehicle Technologies Program Review

## Next Generation Inverter

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General Motors
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Project ID # **APE040**



General Motors Company

DESIGN BUILD SELL
THE WORLD'S BEST VEHICLES

# Overview

## Timeline

- Start - October 2011
- Finish – January 2016
- 2.0% Complete

## Barriers

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

## Budget

- Total project funding
  - DOE - $6.0M
  - GM - $10.6M
- Funding received
  - FY12 - $0.8M
  - FY13 - $1.1M

## Partners

- Lead – General Motors
- Tier 1, 2, & 3 Suppliers - Hitachi, Delphi, Infineon, HRL, Panasonic, AVX, Kemet, and VePoint
- 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

- Program, develop the technologies and the engineering product design for a low cost highly efficient next generation power inverter capable of 55kW peak/30kW continuous power.
- Current (3/12 through 3/13), investigate, experiment, and evaluate potential technology for automotive application, begin concept and breadboard

## Addresses Targets

- The Inverter is to improve the cost of the power electronics to $3.30/kW produced in quantities of 100,000 units, and the power density to 13.4kW/l, and a specific power of 14.1kW/kg, with an efficiency >94% (10%-100% speed at 20% rated torque) to meet the DOE 2020 goals

## 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 trades.

# Milestone

| 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 | |
| June 2014 | Critical Design Review | |

# Approach

- Engage with Tier 1, 2, and 3 suppliers along with National Labs to co-develop technology that reduces cost and increase efficiency, without increasing volume or mass
- Ensure modularity and scalability of inverter to meet all vehicle applications
  - Packaging will fit in all vehicle applications
  - Consistent electrical parameters and mechanical structure
  - Has to adhere to global manufacturing processes
  - Has to provide adequate cooling for the capacitor
  - Has to have low inductance
- Demonstrate technology to verify feasibility and cost

# Strategy

- Inverter requirements need to be refined to better describe real vehicle use
  - Inputs necessary for actuate results are as follows: vehicle, powertrain, and electric traction system
- Select technologies that are aligned with vehicle application to make common inverters
  - Power module, gate drive, capacitor, and control card
- Cost reduction versus performance trade-offs
- Ensure compatibility with future switches

# Accomplishments - Cost

- Assessment of three inverter types with complete cost models
  - Transfer molded
  - Encapsulated
  - Conventional
- Identified cost elements
  - Recurring – material, labor, overheads, etc.
  - Non-Recurring – engineering, equipment, etc.
  - Other – logistics, packaging, misc.
- Developed understanding of cost reduction attributed to technology improvements and commonality of design

# Accomplishments – Specifications/Requirements

- Complete matrix of electric drive applications with requirements has been completed
  - Integrated and remote mounted applications
  - Improved requirements in critical areas such as thermal conditions over life and DC bus ripple
- Finalize specification for Next Gen Inverter
- Trade study of validation test requirements based on modular/scalable inverter and resulting simplification

# Validation Impact Assessment- Current Approach

## Inverter Assembly Level

**Test Program Summary**
Req' d Test Samples - XX
XX Months

- Functional / Parametric Tri-Temp, Tri-Voltage
- Power Temperature Cycling
- Thermal Shock
- High Temperature Durability
- High and Low Temperature Storage
- Mechanical Shock
- Vibration w/Temp Cycling
- Humid Heat Cyclic
- Humid Heat Constant
- Connector Abuse
- Acoustic Noise
- Transportation-Shipping Tests
- RFMP ("Rapid Failure Mode Precipitation")
- LV Electrical Validation Tests
- HVDC/HVAC Electrical Validation Tests
- IP6KX- Dust
- IPX9K - Water spray or immersion
- Salt Spray- Corrosion
- EMC Tests

**Tier 2 Critical Subassembly Validations**

## LV/HV Connector Systems

**Test Program Summary**
Req' d Test Samples – XXConnector Pairs
XX Months

- Parametric Tests
- Terminal Electrical Tests
- Terminal Mechanical Tests
- Thermal Aging
- Mech. Shock
- Vibe w/Thermal Cycling
- Thermal Shock
- Temp/Humidity Cycling
- Heavy Duty Test
- Connector System Electrical Tests
- Seal Test
- Submersion
- Water Intrusion
- Corrosion
- Mech. Assist Connector
- Fluid Resistance
- Pressure/Vacuum Leak
- High Pressure Spray
- Flammability
- Temperature Rise

## Bulk Capacitor

**Test Program Summary**
Req' d Test Samples – XXCapacitor Assys
XX Months

- Electrical Characterization
- Thermal Shock
- Mechanical Shock
- Vibration
- Operating Life
- High Temperature Storage
- Biased Humidity
- Physical Dimensions
- Resistance to Solvents
- Flammability
- Hi Pot Test
- Temperature Rise

## Power Module

**Test Program Summary**
Req' d Test Samples – XX hexpack modules or 210 half-bridge modules
XX months

- Parameter Tests
- Thermal Shock
- Temperature Cycling
- Mechanical Shock
- Vibration, variable frequency (Sine Sweep)
- Terminal and Tightening Strength
- Power Cycling (Fast Cycle)
- Power Cycling (Slow Cycle), aka IOL
- High Temperature Reverse Bias, $V_{CE}$ (HTRB)
- High Temperature Gate Bias, $V_{GE}$ (HTGB)
- Low Temperature Storage
- High Humidity High Temperature Reverse Bias ($H^3TRB$)
- Stall- Low Speed Launch Durability
- Short Circuit Test Demonstration

# Modular/Scalable Approach- Level 1,2 or 3

## Initial Validation

**Inverter Assembly Level**

**Focused on performance demo, power bus interconnections, enclosure seals and application dependencies. Reduced samples.**

Test Program Summary
Req' d Test Samples - XX
XX Months

- Functional / Parametric Tri-Temp, Tri-Voltage
- Mechanical Shock
- Vibration w/Temp Cycling
- Humid Heat Cyclic
- Connector Abuse
- Acoustic Noise
- Transportation-Shipping Tests
- RFMP ("Rapid Failure Mode Precipitation")
- IP6KX- Dust
- IPX9K - Water spray or immersion
- Salt Spray- Corrosion
- EMC Tests

**LV/HV Connector Systems**

**One time Qualification testing of ~XX Connector pairs, then re-use from Validated Connector Systems BOM**

**Integrated Power Module- Level 1, 2 or 3**

**Primary focus of validation resources, samples and reliability demo.**

Test Program Summary
Req'd Test Samples – XX Integrated Power Modules
XX months

- Functional / Parametric Tri-Temp, Tri-Voltage
- Module Parametric
- LV Electrical Transient
- HVDC/HVAC Electrical Transient
- Thermal Shock
- Power Temperature Cycling
- High Temperature Durability
- Low Temperature Storage
- Vibration w/Temp Cycling
- Mechanical Shock
- Terminal and Tightening Strength
- Power Cycling (Fast Cycle)
- Power Cycling (Slow Cycle), aka IOL
- High Temperature Reverse Bias, $V_{CE}$ (HTRB)
- High Temperature Gate Bias, $V_{GE}$ (HTGB)
- High Humidity High Temperature Reverse Bias ($H^3$TRB)
- Stall- Low Speed Launch Durability
- Short Circuit Test Demonstration

**Capacitor Bobbin Assy**

**Critical components qualified for Integrated Power Module.**

**Other possible critical components:**

- **Current Sensor**
- **Gate Drive Smart IC**
- **…**

Test Program Summary
Req' d Test Samples – XX Bobbins
XX

- Electrical Characterization
- Thermal Shock
- Mechanical Shock
- Vibration
- Operating Life
- High Temperature Storage
- Biased Humidity
- Physical Dimensions
- Resistance to Solvents
- Flammability
- Hi Pot Test
- Temperature Rise

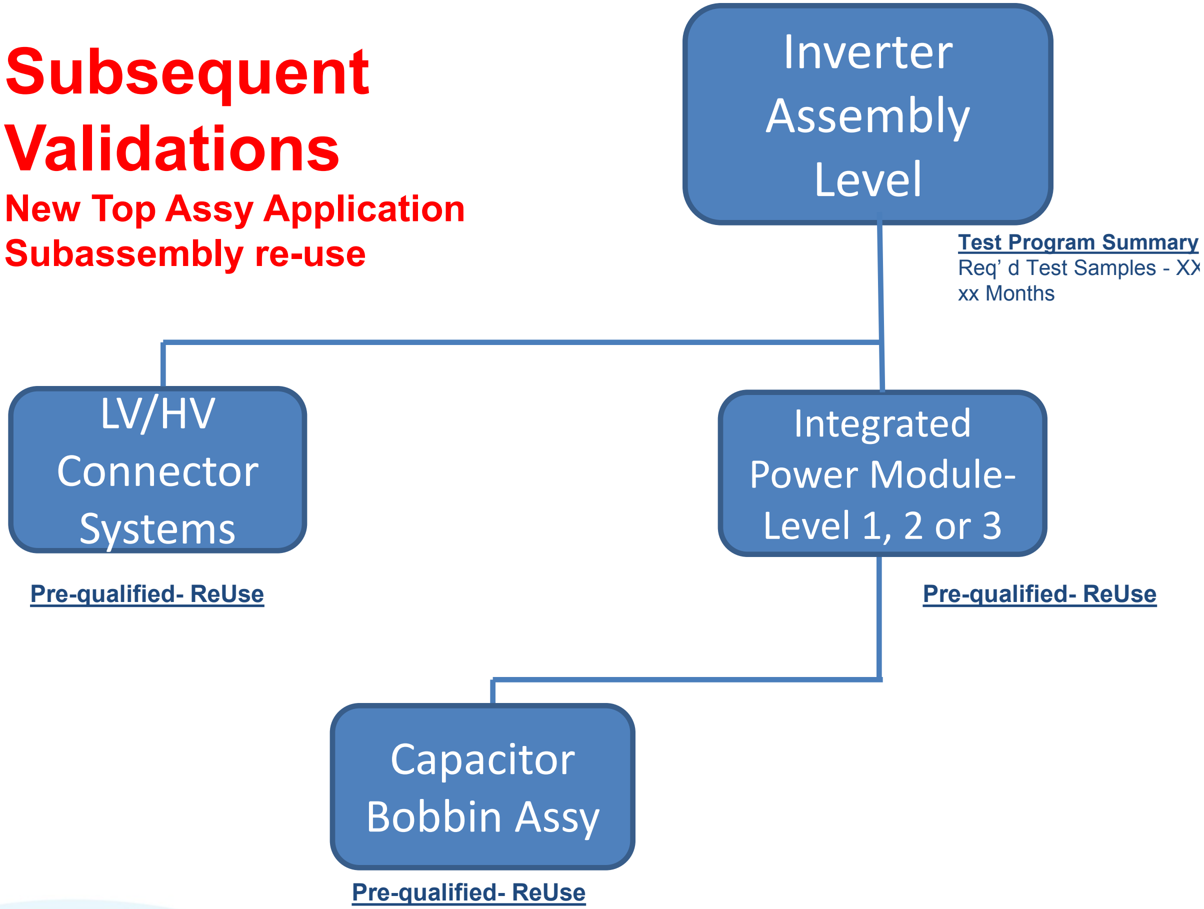
**Key Points:**

1. **Integrated Power Module core component validation designed around all electric drive applications and packaging locations envisioned.**
2. **"On the shelf" then for use in other packaging configurations.**
3. **Top Assembly level effort reduced.**
4. **Reliability demo pushed down to Integrated Module level**

# Modular/Scalable Approach- Level 1,2 or 3

## Subsequent Validations

**New Top Assy Application**
**Subassembly re-use**




Functional / Parametric Tri-Temp, Tri-Voltage
Mechanical Shock
Vibration w/Temp Cycling
Humid Heat Cyclic
Connector Abuse
Acoustic Noise
Transportation-Shipping Tests
RFMP ("Rapid Failure Mode Precipitation")
IP6KX- Dust

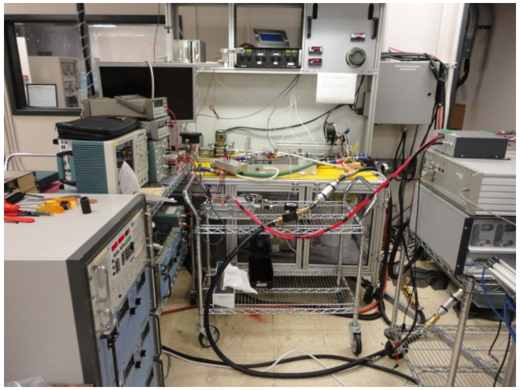
IPX9K - Water spray or immersion
Salt Spray- Corrosion
EMC Tests

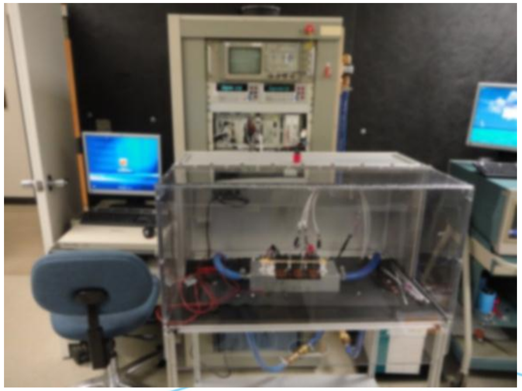
# Validation Reduction Over Current

| | Current Approach | | Modular /Scalable | | Modular/Scalable Re-Use | |
|---|---|---|---|---|---|---|
| | Qty. | Duration | Qty. | Duration | Qty. | Duration |
| Inverter Assembly | | | 58% | 56% | 58% | 56% |
| Power Module | | | | | 100% | 100% |
| Bulk Capacitor | | | | | 100% | 100% |
| LV or HV Connector Systems | | | | | 100% | 100% |

# Accomplishments – Technology Evaluation

- Power Module
  - Thermal cycling testing
    - Transfer Molded – version 1 test complete, 2nd version now in test
    - Encapsulated – in test
  - Power cycling testing
    - Transfer Molded – version 1 test complete, 2nd version now in test
    - Encapsulated – in test





## Baseline Electrical, Isolation and $R_{th(j-w)}$ Measurements (13 Modules)

**3 Modules**

1. **Power Cycling** – 50°C to 150°C ΔT on IGBT, 9,000 cycles
2. Interim Measurements
3. **Power Cycling** – 50°C to 150°C ΔT on IGBT, 9,000 cycles (18,000 cumulative)
4. Interim Measurements
5. **Power Cycling to Failure** – 50°C to 150°C ΔT on IGBT, 50,000 cumulative cycles max

**3 Modules**

1. **Intermittent Operation Life** – 55°C to 125°C on Base plate ΔT, 4500 cycles
2. Interim Measurements
3. **Intermittent Operation Life** – 55°C to 125°C on Base plate ΔT, 4500 cycles (9,000 cumulative)
4. Interim Measurements
5. **Intermittent Operation Life to Failure** – 55°C to 125°C on Base plate ΔT, 18,000 cumulative cycles max

**3 Modules**

1. **Rapid Thermal Cycling** – -30°C to 105°C Coolant Transitions, 333 cycles
2. Interim Measurements
3. **High Temperature Gate Bias ?** – 125°C Air, VGE=20V, 333 Hours
4. Interim Measurements
5. **Multi-Axial Random Vibration** – 6 grms, 30 min
6. Interim Measurements

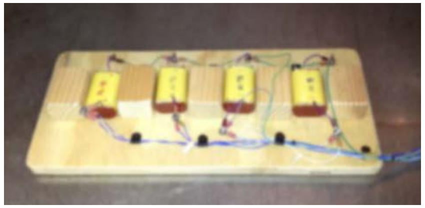
*Repeat Sequence to Failure, 3 times through sequence maximum*

**1 Module**

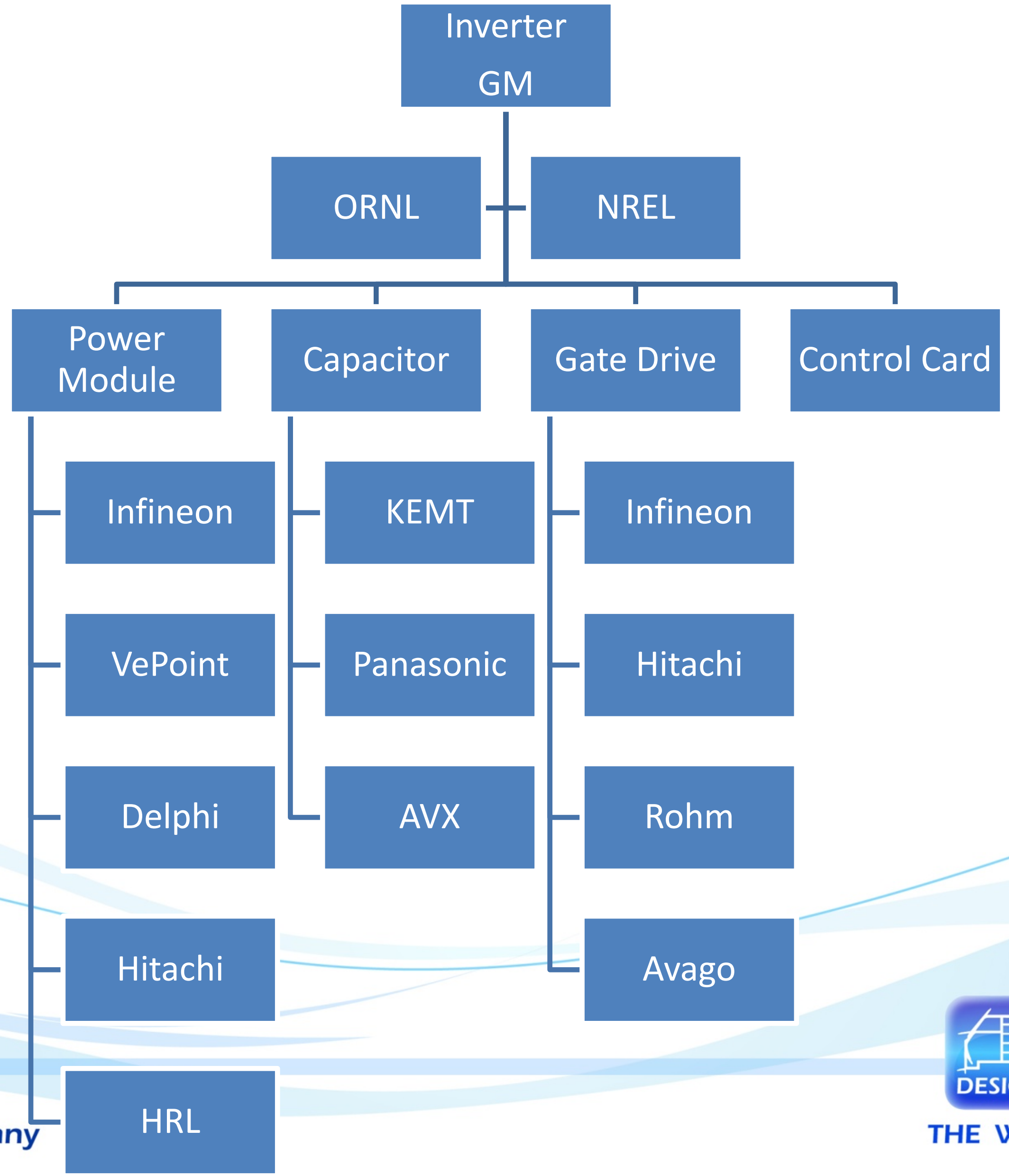
1. **Power Cycling to Failure (Design Margin Testing)** – 50°C to 175°C ΔT on IGBT, Interim Checks every 4500 cycles, 18,000 cumulative cycles max
2. Final Measurements, Failure Analysis

# Accomplishments – Technology Evaluation (con't)

- Capacitor - in test
- Gate drive – three different chip sets being evaluated
- Control card built and under test



# Collaborations and Coordination



# Future Work

FY13

- Continue Technology Assessment and Improve Production Cost Assessment
- Start Design Concept
- Build early unit for evaluation

FY14

- Concept Design Review – DOE "Go/No Go"
- Critical Design Review

# Summary

- CTS (Component Technical Specification) completed
- Power module testing
  - Version 1 transfer molded complete
  - Version 2 transfer molded, and encapsulated in test
- Capacitor in testing
- Three gate drive chip sets under evaluation
- Control card built and under test

# Questions

?

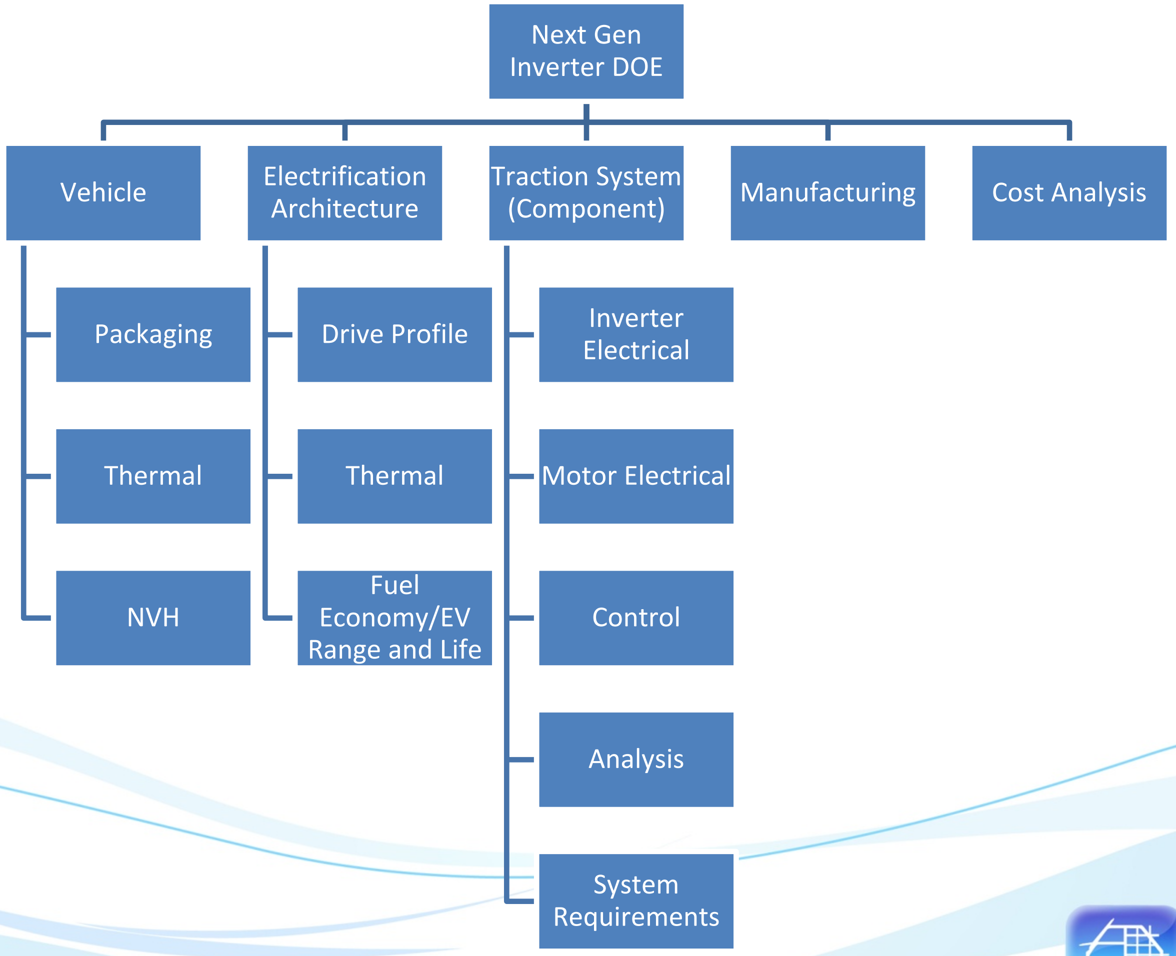
Next Generation Inverter

# Backup

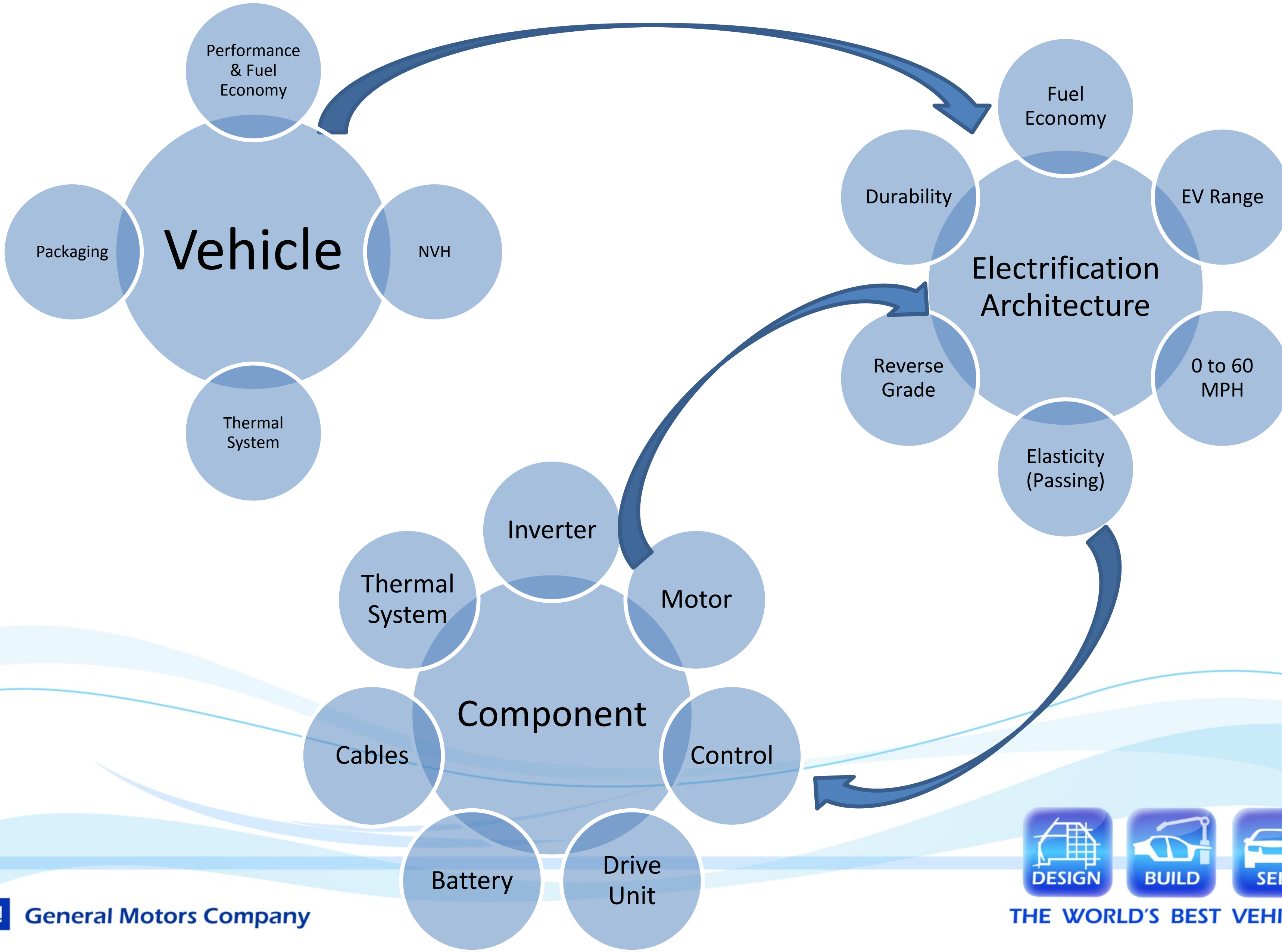
# Cost Reduction Targets by System and Component Category

| | Current 55kW DOE | Moderate Risk | Medium Risk | High Risk | Reduction Path |
|---|---|---|---|---|---|
| *System/Packaging* | $143 | ($70) | ($20) | ($34) | Simplify interconnections and interfaces, elimination of discrete current sense. Determine inverter layouts optimized for cost (efficient layout and scalability/modularity) and efficiency. |
| *Power Module* | $117 | ($62) | | | Develop scalable module, interconnects, jointing, on-chip current and temp sense, reduce package inductance, replace high cost materials, and. Integration of heat sink and chassis. Cost effective GaN, SiC, or other advanced switches allowing for significant increase in power density. |
| *Capacitor* | $100 | ($40) | | ($20) | Advanced film technology, thinner films- increase temperature, 140 to 150C, and increase dielectric constant, 2.3 to 3.0, improving density. Additionally reduce capacitance requirement through better system management. |
| *Gate Drive* | $27 | ($4) | | | Integrate chips to decrease PWB area and part count. Improve gate drive IC to support on-die current and temp sense. Ensure driver compatibility with SiC and GaN. |
| *Control Card* | $48 | ($15) | | | Integrate two processors into dual core chip, integrate torque security chips. |
| *Total Cost Savings* | | ($191) | ($20) | ($54) | |
| *Total Inverter Cost* | $435 | $244 | $224 | ***$170*** | DOE Target is $182 |

# Areas of Discipline/Responsible Engineers



# Data Flow/Elements for Proper System Requirements



# Analysis/Interactions Required for Proper Component Requirements