

# Benchmarking of Competitive Technologies

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Technologies Program Annual Merit Review and Peer Evaluation Meeting  
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# Overview

## Timeline

- Start: FY04
- Finish: Ongoing

## Budget

- Total project funding
  - DOE: 100%
- Funding received in FY10: \$412K
- Funding received in FY11: \$465K

## Barriers

- Obtaining parts for newly released vehicles
- Integrating ORNL developed controller with OEM components
- Adapting non-standard motor assembly to test cell

## Partners

- Argonne National Laboratory
- Electric Transportation Applications
- Idaho National Laboratory
- National Renewable Energy Laboratory
- ORNL Team Members
  - Steve Campbell, Chester Coomer
  - Andy Wereszczak, Materials Science and Technology Division

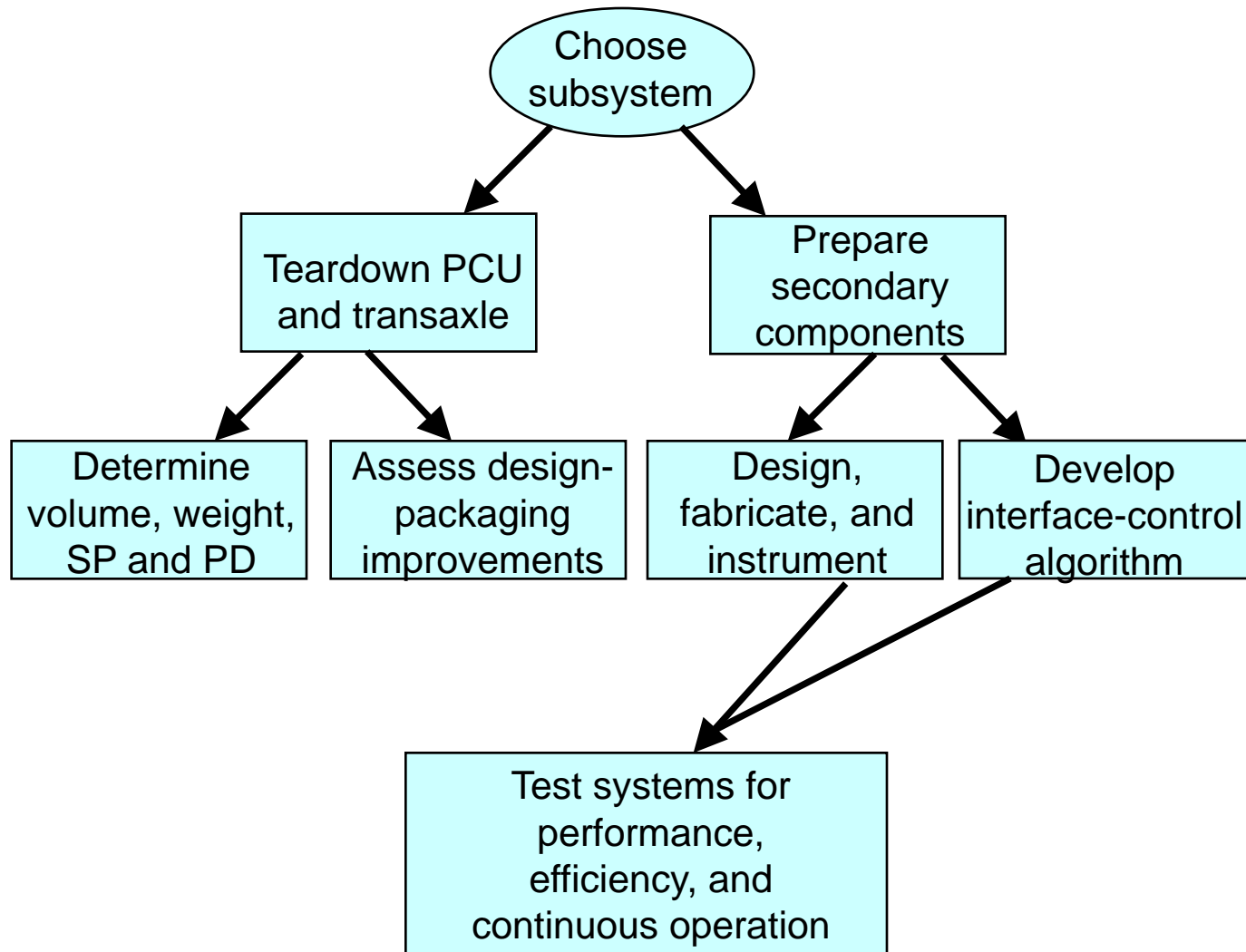
# Objectives

- **Benchmark on-the-road HEV or PEV vehicle technologies**
  - Assess design, packaging, and fabrication characteristics from intensive disassembly of subsystems
    - Determine techniques used to improve specific power and/or power density
    - Reveal compositions and characteristics of key components
      - Trade-offs (magnet strength vs coercivity)
      - General cost analysis
  - Examine performance and operational characteristics during comprehensive test-cell evaluations
    - Establish realistic power rating (18 seconds)
    - Provide detailed information regarding time-dependent and condition-dependent operation
  - Develop conclusions from evaluations and assessments
    - Compare results with other HEV technologies
    - Identify new areas of interest
    - Evaluate advantages and disadvantages of design changes
      - Example: Complexity of LS 600h double sided cooling system
- **FY11 objectives**
  - Complete 2011 Hyundai Sonata hybrid benchmarking studies

# Milestones

Month/Year	Milestone or Go/No-Go Decision
<b>September 2010</b>	<b>Milestone: Completed 2010 Prius testing</b>
<b>September 2010</b>	<b>Go/No-Go decision: Determined which on-the-road HEV or PEV system is available and desirable to benchmark</b>
<b>September 2011</b>	<b>Milestone: Complete 2011 Hyundai Sonata testing</b>
<b>September 2011</b>	<b>Go/No-Go decision: Determine if on-the-road HEV or PEV system is available and desirable to benchmark</b>

# Approach



# Overall Technical Accomplishments

- **Detailed comparisons of progressing technologies**

- 2004 Prius, 2006 Accord, 2007 Camry, 2008 LS 600h, and 2010 Prius
- Focus seemed to be placed on mass in the 2010 Prius packaging
- 2010 Prius motor versus Camry motor
  - Volume comparable - power density roughly proportional to power rating
  - Prius motor mass is lower and specific power is comparable despite lower power rating
- 2010 Prius PE devices versus Camry PE devices
  - Prius volume greater – power density is considerably lower
  - Prius mass lower – specific power is greater

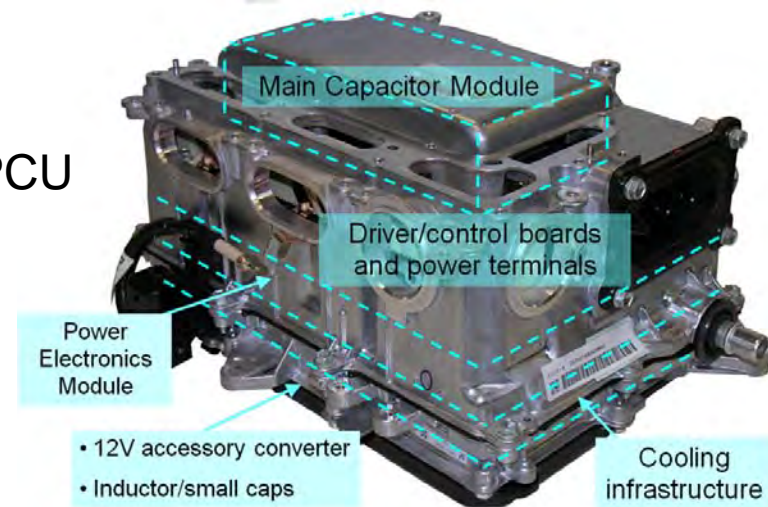
Parameter	2010 Prius (60 kW)	Lexus (110 kW)	Camry (70 kW)	2004 Prius (50 kW)
Motor				
Peak power density, kW/L	4.8	6.6	5.9	3.3
Peak specific power, kW/kg	1.6	2.5	1.7	1.11
Inverter (including converter and excluding generator inverter)				
Peak power density, kW/L	5.9	10.6	7.4	3.6
Peak specific power, kW/kg	6.9	7.7	5	3.7

# Technical Accomplishments (1)

- **2010 Prius teardowns completed**

- Transaxle and PCU has many similarities to Camry design
- PE module bonded directly to heat exchanger, as opposed to previous heat sink approach
- Generator has segmented and potted windings
- 650 Vdc versus 500 Vdc for 2<sup>nd</sup> generation Prius
- Collaborated with PE packaging project
  - Zhenxian Liang, Andy Wereszczak, Laura Marlino

PCU



Direct-mounted  
PEM



Transaxle/ECVT



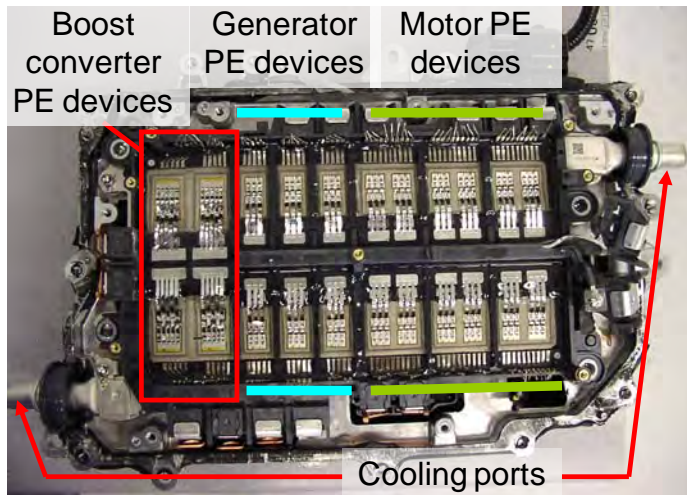
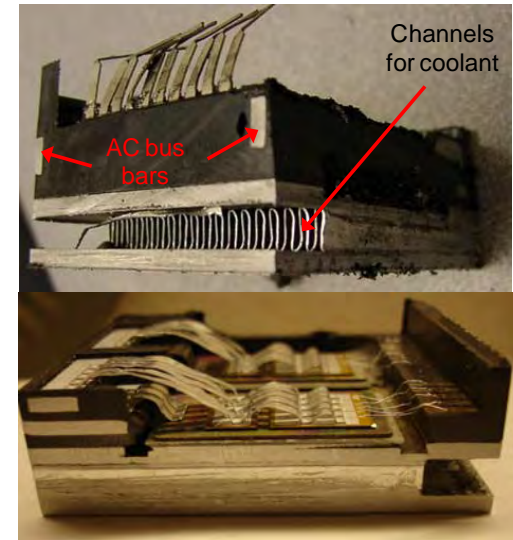
Generator





# Technical Accomplishments (2)

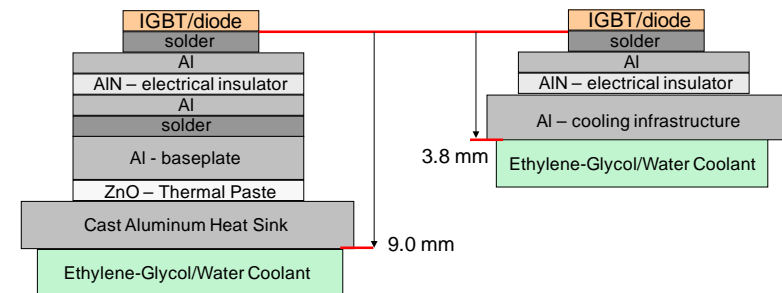
- **2010 Prius PCU has lower mass, but greater volume than Camry and LS 600h**
  - 2007 Camry: 11.7 L and 17.4 kg
  - 2008 LS 600h: 13.7 L and 17.9 kg
  - 2010 Prius: 16.2 L and 13.0 kg
  - 12 V accessory converter included in Prius PCU
- **Thermal conduction path has 58% reduction in comparison to 2004 Prius**
  - Solder layer and thermal paste layer eliminated



2010 Prius PEM



Cross-sections of 2010 Prius PEM

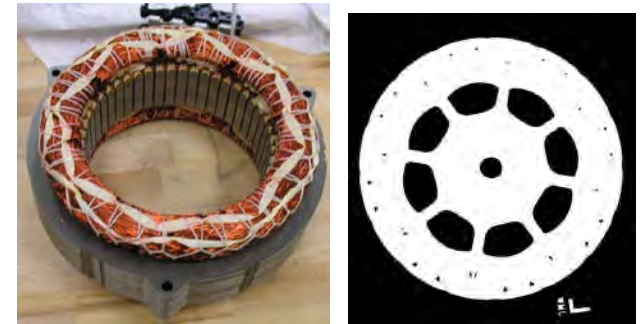


Thermal conduction paths



# Technical Accomplishments (3)

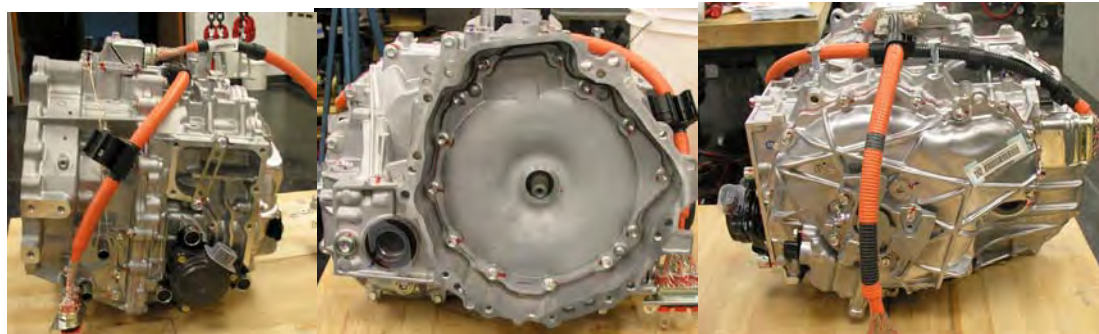
- **Motor stack length is 60% of original Prius, but 84% of Camry**
  - Masses reflect similar comparisons
  - Rotor mass 75% of Camry
- **Neutral brought out to terminal**
- **Significant reduction of motor power-lead size**
- **Rotor laminations have large holes**
  - Reduces mass and perhaps directs flux, thereby decreasing core losses
  - Rotor shaft O.D. is small
  - Same 'V' PM arrangement



2010 Prius Motor Stator and Rotor



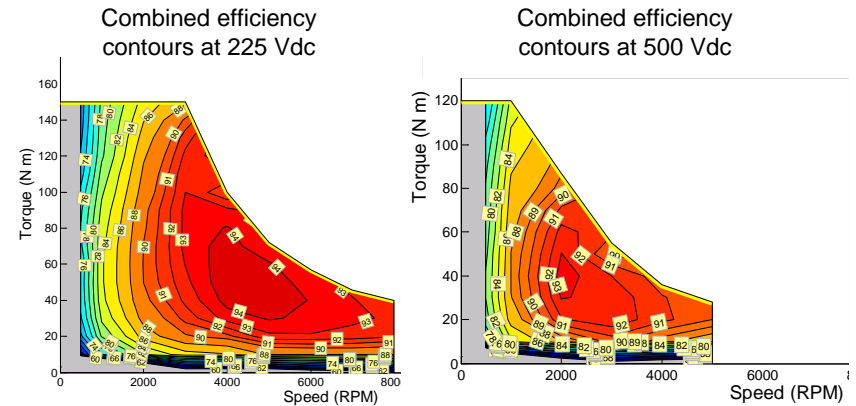
Comparison of Motor Leads



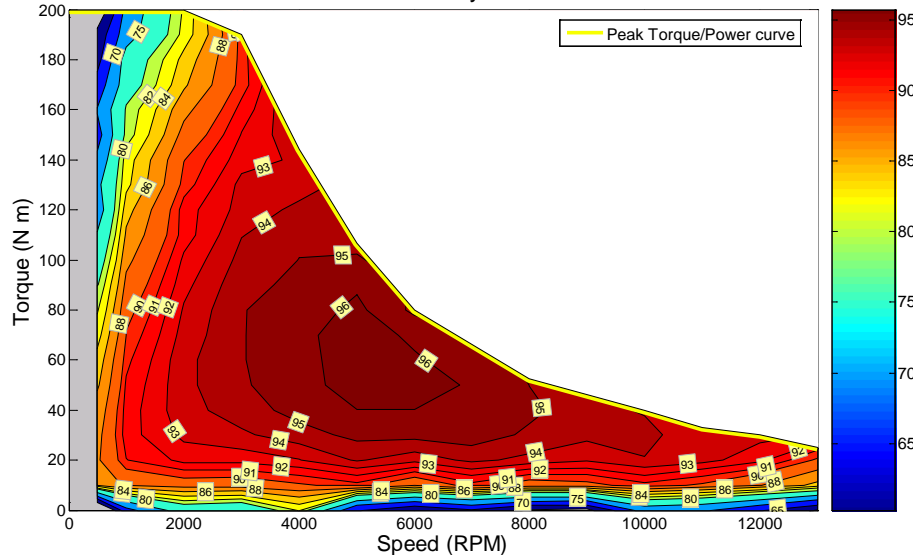
2010 Prius Transaxle

# Technical Accomplishments (4)

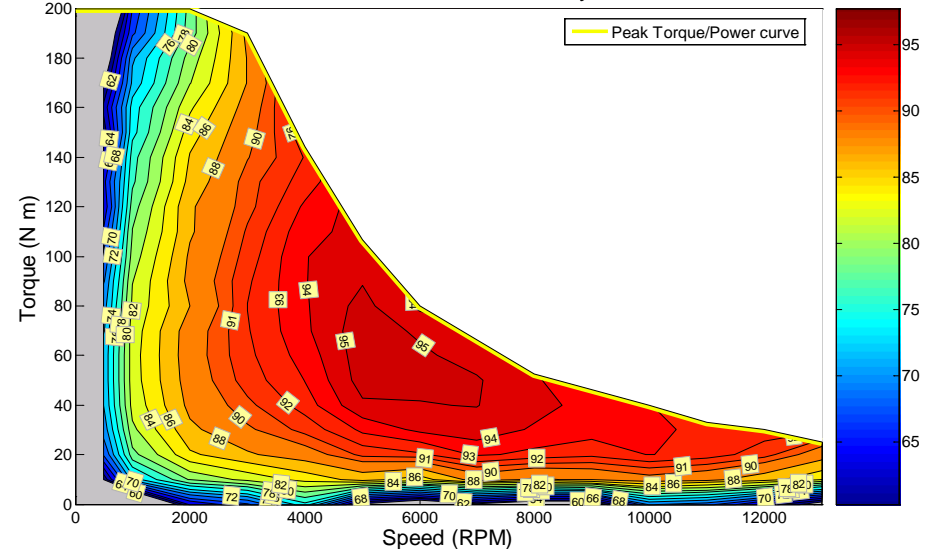
- **Efficiency mapping conducted at 225 Vdc, 500 Vdc, and 650 Vdc**
  - When feasible, operation at lower voltages improves inverter efficiency, as expected
  - Some operation points require increased DC voltage for optimal operation
- **Efficiencies are greater than 90% for a great portion of the operation range**
  - Peak motor efficiency: 96%
- **System is capable of producing 60 kW for 18 seconds**



2010 Prius Motor Efficiency Contours - 650 Vdc



2010 Prius Combined Inverter-Motor Efficiency Contours - 650 Vdc



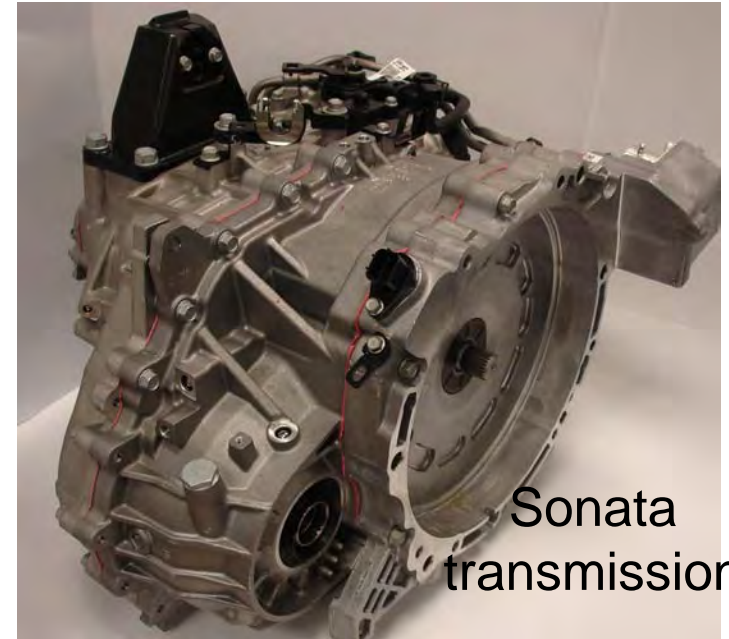
# Technical Accomplishments (5)

- **2011 Hyundai Sonata “Hybrid Blue Drive” teardowns initiated**
- **Sonata hybrid system overview:**
  - 30 kW, 105 Nm interior PMSM
  - 8.5 kW, 45 Nm interior PMSM
  - PMSM inverters and 12 V converter
  - Electric power steering assist
  - Electric motor drives air conditioning compressor
  - ICE: 2.4 L Theta II Atkinson inline 4
  - 270 V lithium polymer battery by LG Chem
    - Uses manganese spinel chemistry
    - 1.4 kilowatt-hour pack
    - Flat package promotes interconnectivity of cells

# Technical Accomplishments (6)

- **Sonata transaxle/transmission**

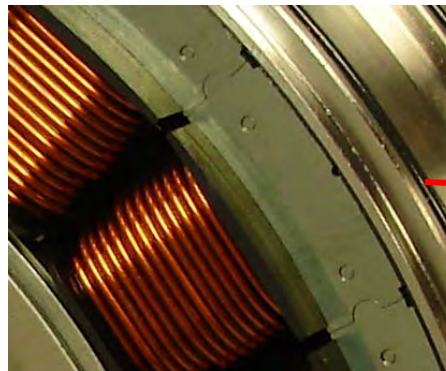
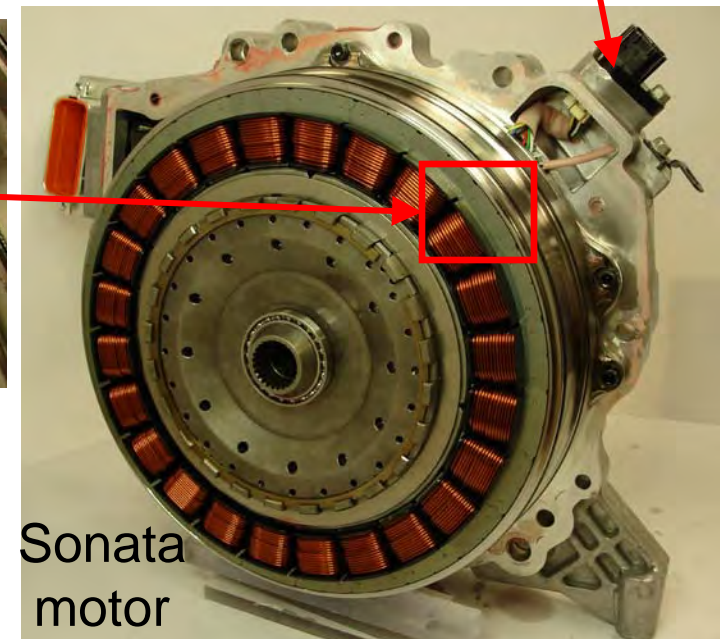
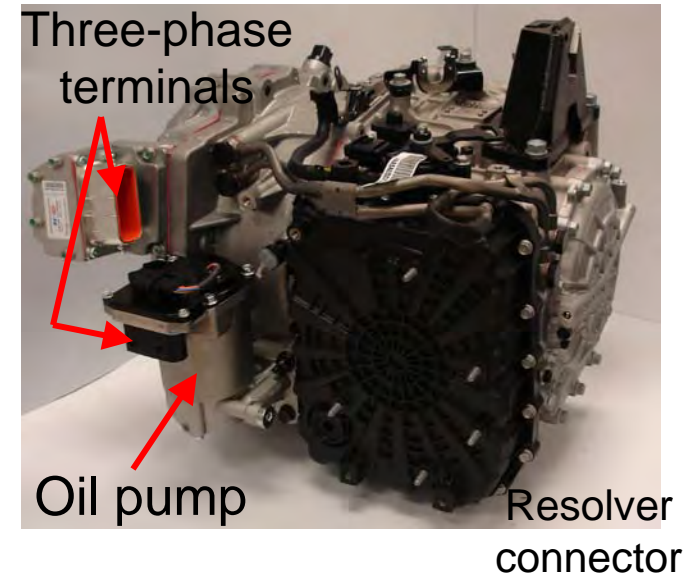
- Conventional six-speed automatic
- Total transaxle mass: 117.2 kg (258.5 Lbs)
  - 2007 Camry Hybrid: 108 kg
- Includes 1 primary electric machine (30 kW)
  - Fixed to transmission input
  - Propels vehicle through 6 gear ratios (versus 1 for Toyota architecture)
  - Purportedly propels vehicle up to 62 mph in electric mode
  - Regenerates during deceleration and braking
- Clutch located between engine and motor and transmission
- Hyundai claims is easily scaled for different vehicle sizes





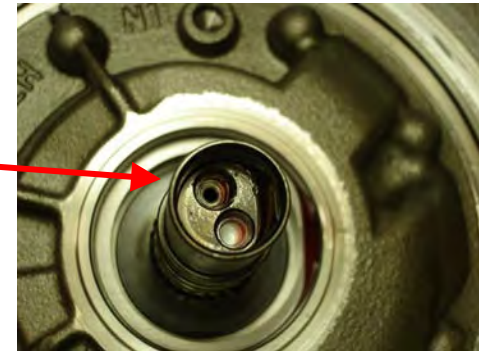
# Technical Accomplishments (7)

- **Motor replaces torque converter**
  - But not simply interchanged
- **Primary motor: 205 Nm and 30 kW ratings**
  - Approximate corner speed: 1400 rpm
  - Motor very similar to Honda hybrids
  - 24 stator teeth and 16 rotor poles
- **Resolver similar to Toyota/Honda**
- **3-phase oil pump**
- **Clutch integrated into motor rotor**



# Technical Accomplishments (8)

- Hydraulic pressure applied to engine clutch via shaft
- Most of stator perimeter cooled by oil path which is formed by two large O-rings
- Conventional transmission cooler used dissipate heat



2 O-rings

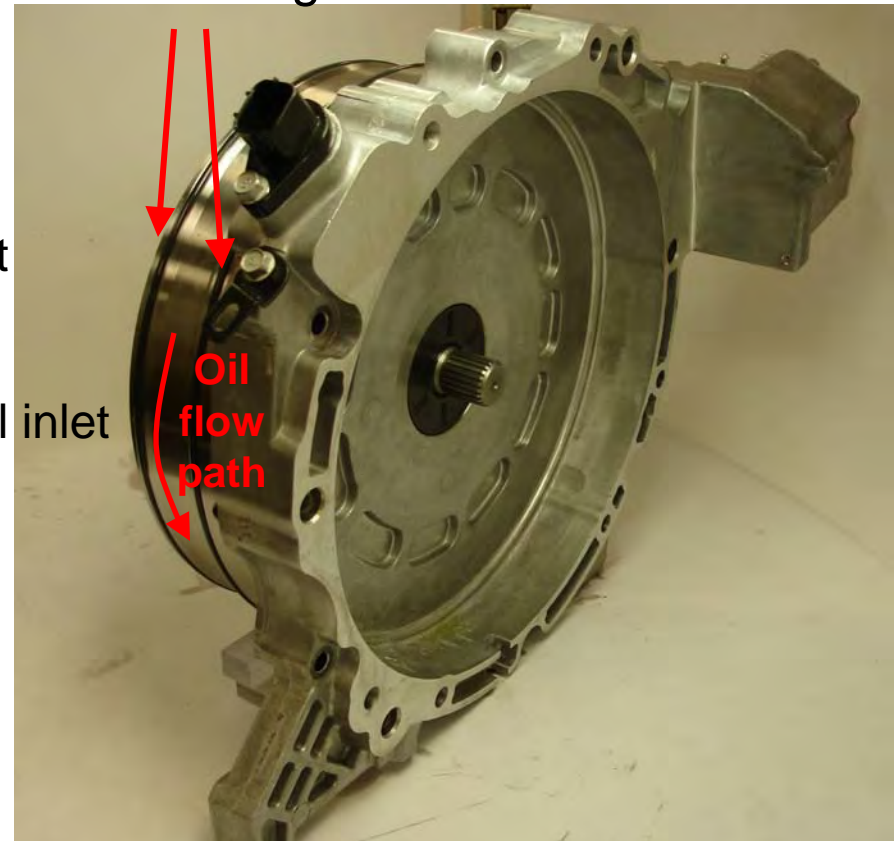
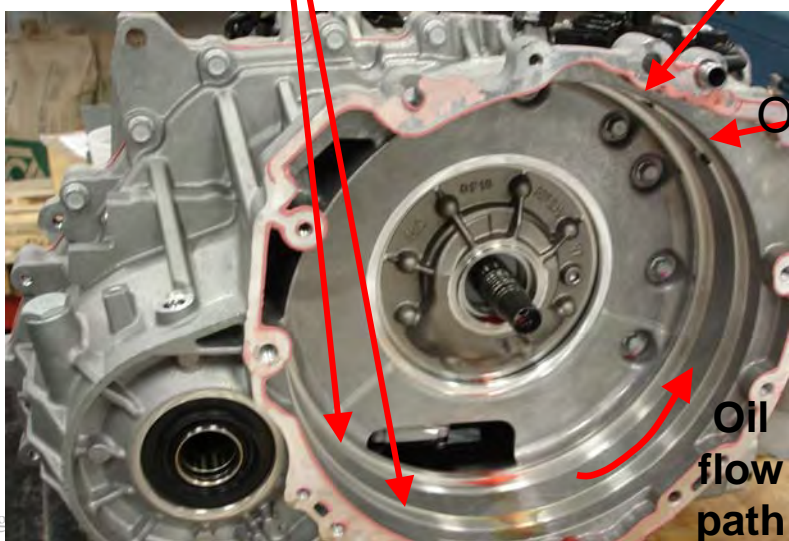
2 seats for O-rings

Oil outlet

Oil inlet

Oil flow path

Oil flow path





# Technical Accomplishments (9)

- **Hybrid Starter Generator (HSG)**
  - 43 Nm, 8.5 kW
  - 3-phase IPM machine
  - Cold start, restart, and generates when low SOC
  - Separate low-temperature coolant loop for HSG and HPCU
  - Drives and driven by engine belt (crankshaft)



# Collaborations

- **Argonne National Laboratory**
  - ANL provides vehicle level data obtained during extensive drive cycle testing which enables the observation of common operation conditions and trends observed on a system-wide basis
  - Converter, inverter, and motor characteristics such as efficiency and performance are supplied to ANL for use in system-wide vehicle modeling
- **Electric Transportation Applications and Idaho National Laboratory**
  - ETA and INL collaborate on a fleet vehicle testing program in which fleet vehicles undergo normal driving and maintenance schedules. The study of components from these vehicles provides information related to the reliability and operation long-term susceptibility of the designs.
- **National Renewable Energy Laboratory**
  - NREL utilizes temperature measurements observed during performance and efficiency tests to assess the characteristics of the thermal management system
  - NREL provides feedback and suggestions in regards to the measurements (such as thermocouple placement) useful to thermal management system assessments
- **Oak Ridge National Laboratory, Materials Science & Technology Division**
  - Provides detailed material analysis of components such as magnets and power electronics packages

# Future Work

- **Benchmarking efforts will focus on technologies of interest to DOE, the Electrical and Electronics Technical Team, and Vehicle Systems Analysis Technical Team**

# Summary

- Various drive systems sub-assemblies fully assessed (Prius, Accord, Camry, LS 600h)
  - Power density and specific power determined
  - Design specifications validated
  - Red highlight indicates 2020 targets reached

Parameter	2010 Prius (60 kW)*	Lexus (110 kW)	Camry (70 kW)	2004 Prius (50 kW)
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Design Feature	2010 Prius*	2008 LS 600h	2007 Camry	2006 Accord	2004 Prius
Motor-related Technology					
Motor peak power rating	60 kW	110 kW	70kW	12.4 kW	50 kW
Motor peak torque rating	207 Newton meters (Nm)	300 Nm	270 Nm	136 Nm	400 Nm
Rotational speed rating	13,500 rpm	10,230 rpm	14,000 rpm	6,000 rpm	6,000 rpm
Power electronics-related Technology					
IPM Cooling	Direct cooled, single side water/glycol loop	Double-sided infrastructure, water/glycol loop	Heat sink with water/glycol loop	Air-cooled heat sink	Same as Camry
Bi-directional DC-DC converter output voltage	200-650 Vdc	~288-650 Vdc	250–650 Vdc	N/A	200–500 Vdc
High-voltage (HV) Ni-MH battery	201.6 V, 6.5 Ah	288 V, 6.5 Ah,	244.8 V, 6.5 Ah,	144V, 6.5 Ah	201.6 V, 6.5 Ah,
	27 kW	36.5 kW	30 kW	13.8 kW	20 kW