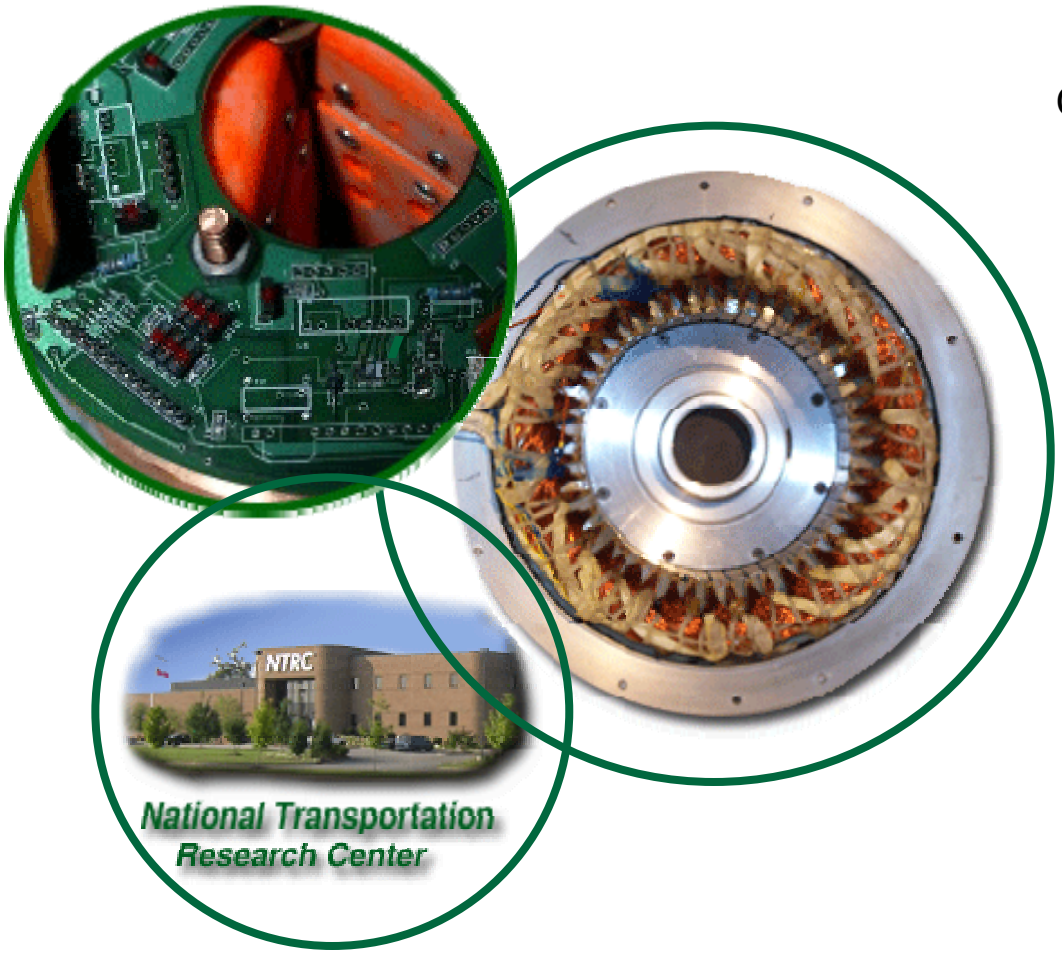
Technology Benchmarking



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Agreement: 13301

Project Duration: FY01 to FY10
FY08 Funding: $582K

DOE Vehicle Technologies Program
Overview of DOE VTP APEEM R&D

North Marriott Hotel and Conference Center
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Managed by UT-Battelle
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This presentation does not contain any proprietary or confidential information

Purpose of Work

- **In FY08, ORNL will benchmark the traction drive for the Lexus LS 600h**

- **Lexus interesting from component perspective, not from vehicle perspective**

Responses to Reviewers' Comments

- **Comment: "It is foundational to document the SOA in helping us not reinvent the wheel and establish reference points"**
- **Comment: "Would like to see more analysis of control schemes by Honda and Toyota"**
  - *Vehicle-level benchmarking includes analysis and documentation of control strategies. This work is done by ANL under the vehicle systems activity. A database has been established that contains all benchmarking information from ANL and ORNL.*
- **Comment: "Want to see directional trends"**
  - *The recently completed report documenting benchmarking of the Toyota Camry that contains a table that summarizes directional trends.*

Barriers

VTP Activities Related Challenges

- Support VTP APEEM R&D Planning by providing status of select on-the-road technologies through assessment of packaging, fabrication, and performance during comprehensive testing
  - Confirm validity of program technology targets
  - Render insight for program direction
  - Ensure we don't "reinvent the wheel"
- Support vehicle modeling efforts by providing detailed subsystem performance information over the entire operational range

Approach

- **Evaluate 2008 Lexus LS 600h subsystems**
  - Teardown
    - Conduct functionality assessment and volumetric/mass analysis of power control unit (PCU) and transaxle
      - Magnets, capacitors, motor/gen, inverters, converter, gears, cooling system, etc.
    - Assess double-sided cooling technology of intelligent power module (IPM)
    - Determine additional intricacy associated with IPM fabrication
    - Evaluate Ravigneaux gear system of the electronic continuously variable transmission (ECVT)
      - Similar clutching/braking mechanism as in conventional AT
  - **Experimental evaluation**
    - Perform hysteresis tests upon magnets
      - Strength and vulnerability versus temperature
    - Obtain capacitor properties such as ESR, DF, and capacitance as a function of temperature and frequency
    - Conduct back-emf, locked-rotor, and spinning loss tests
    - Determine efficiency and performance of PCU and drive motor
    - Study impact of various conditions (e.g. coolant temperature) upon continuous operation

Technical Accomplishments FY07

- Evaluated subsystems of Prius, Accord, and Camry for design, packaging, efficiency, and performance

Comparison of Accord, Prius, and Camry specific power/power density			
Component & Parameter	**Accord (12 kW)**	**Prius (50 kW)**	**Camry (70 kW)**
Motor			
Peak power density, kW/L	1.15	3.3	~5.9
Peak specific power, kW/kg	0.53	1.11	~1.7
Inverter (excluding generator inverter and buck/boost converter)			
Peak power density, kW/L	2.89	5.7	~11.7
Peak specific power, kW/kg	2.37	5.7	~9.3

Toyota systems use 70°C coolant; program targets based on 105°C coolant

Technical Accomplishments FY07 (cont'd)

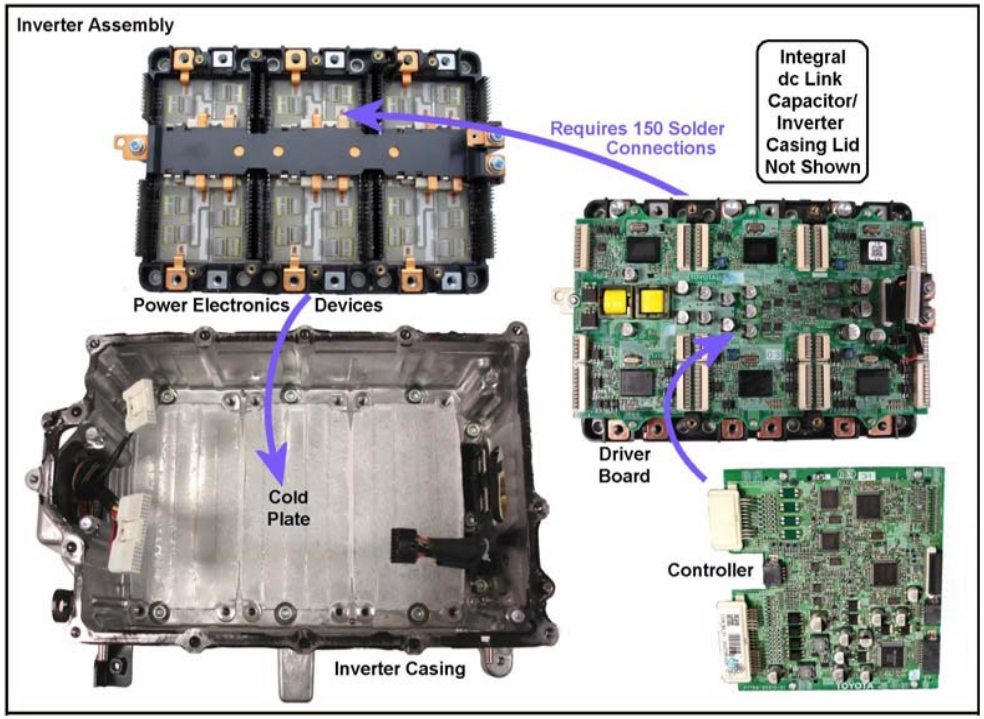
- **Synergy drive system**
  - Power split capabilities – motor, gen, regen, etc.
  - Motor, generator, and planetary, drive, differential gears housed in transaxle
  - Continuously variable transmission (CVT) – simple and efficient design
  - PCU and transaxle are compact assemblies
- **Motor technology***
  - Toyota/Lexus currently have highest capabilities of foreign technologies
  - Increased speed Prius – 6,000 rpm; Camry – 14,000 rpm
  - Peak power: Prius – 50 kW; Camry – 70 kW
  - Continuous Power: Prius – 20 kW; Camry – 33.5 kW
    - Function of speed, coolant temperature, and stator temperature limit
  - Torque: Prius – 400 Nm; Camry – 670 Nm
    - Higher torque per current after speed reduction gear
- **Power control unit***
  - Boost converter: Prius – 20 kW; Camry – 33.5 kW
  - DC link voltage: Prius – 500 V; Camry – 650 V
    - Accommodates higher speed and power capability
  - IGBT structure: Prius – planar gate; Camry – trench gate
  - IPM cooling: Prius/Camry single sided; Lexus LS 600h – double sided

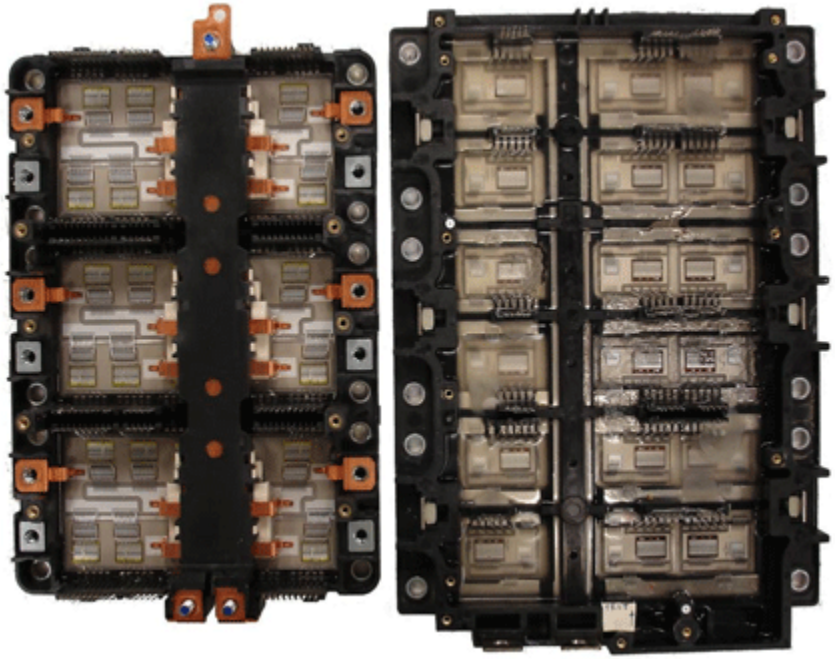
* Verified through benchmark testing

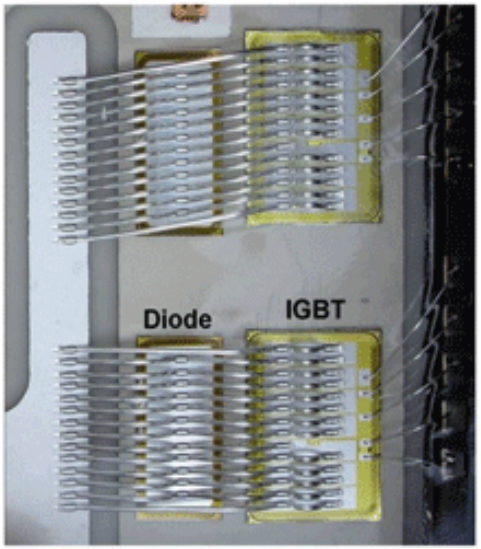
Technical Accomplishments FY07 (cont'd)

- **Example of PCU teardown**
  - Comparison of size and power capability
  - Comparison of power electronics design and layout

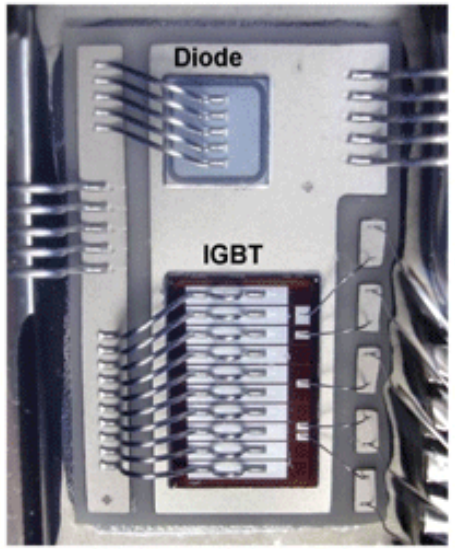
- **Lexus LS 600h IPM expected to be much more advanced**
  - Double sided power module and cooling infrastructure







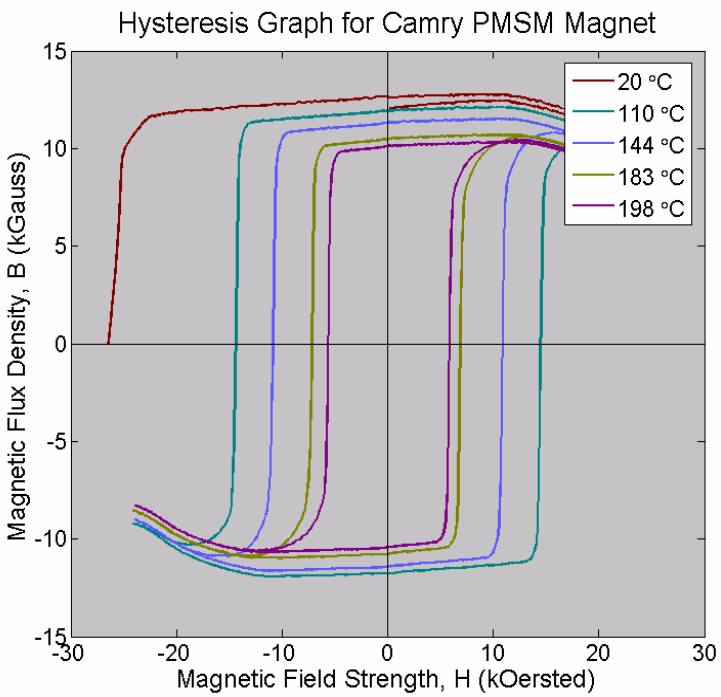
Camry Motor Inverter: 18 IGBTs and Diodes

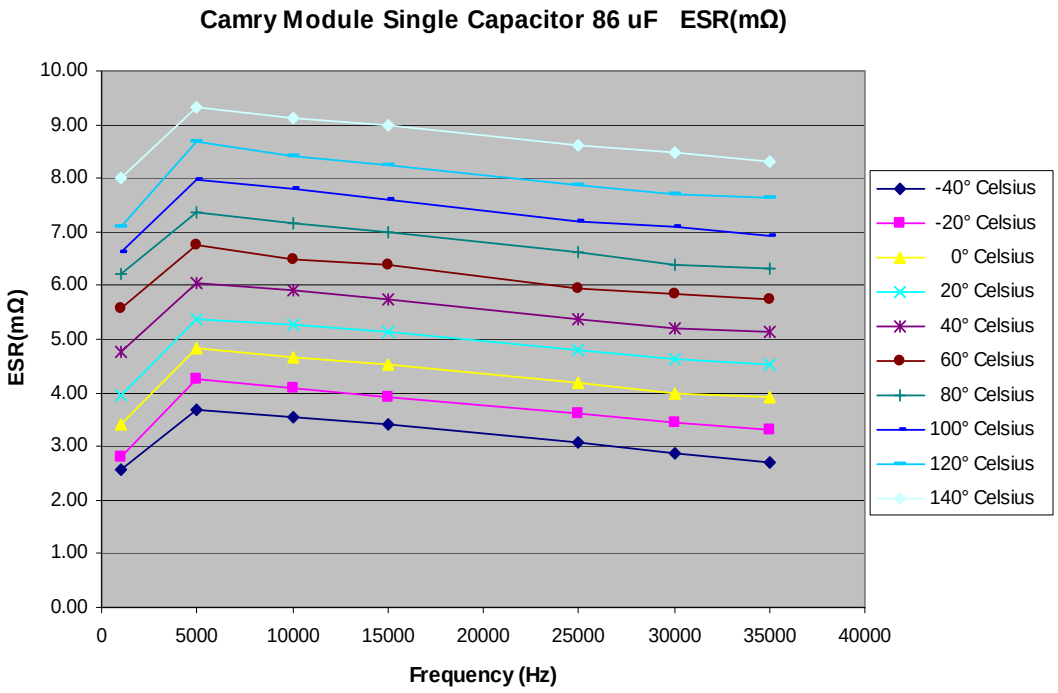


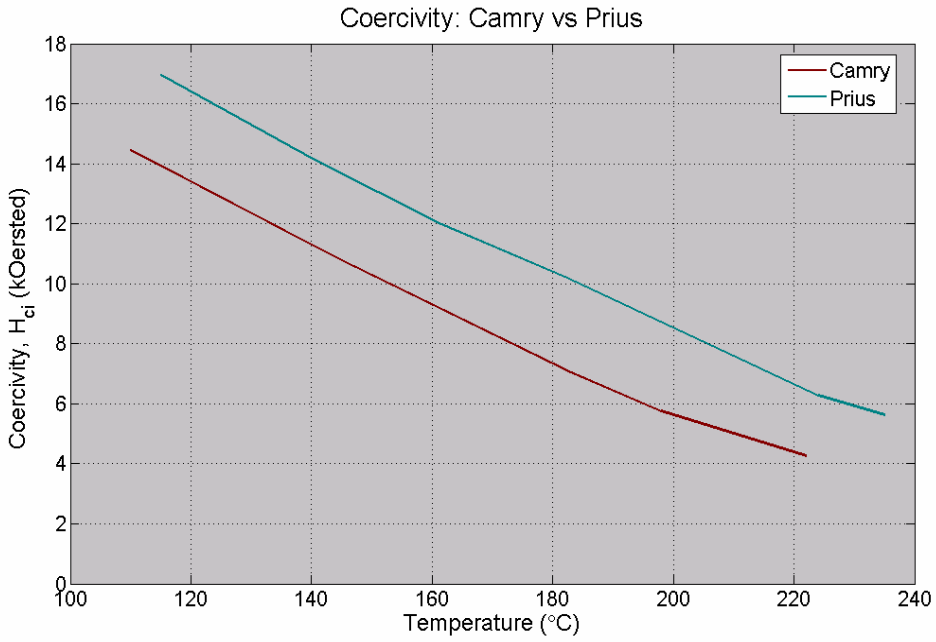
Prius Motor Inverter: 12 IGBTs and Diodes

Technical Accomplishments FY07 (cont'd)

- **Example of component analysis**
  - **Hysteresis tests**
    - Comparison of magnet coercivity and remanence versus temperature
      - Determine if magnets are cheaper
      - Camry more susceptible to demagnetization
      - 70% of Prius coercivity
  - **Capacitor tests**
    - ESR, DF, capacitor tests performed at various frequencies and temperatures

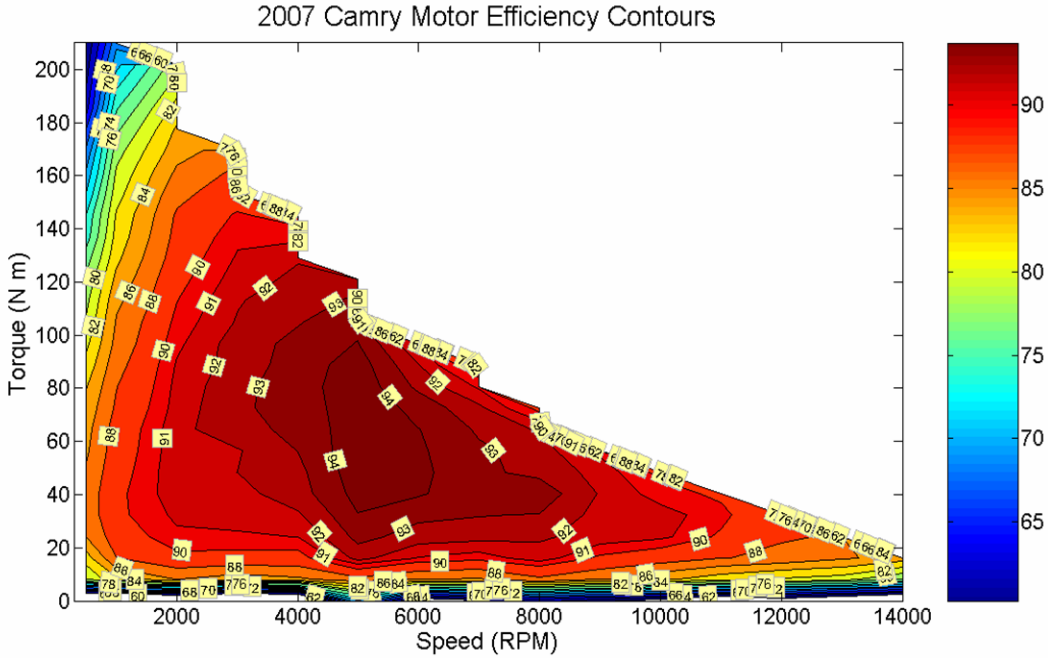


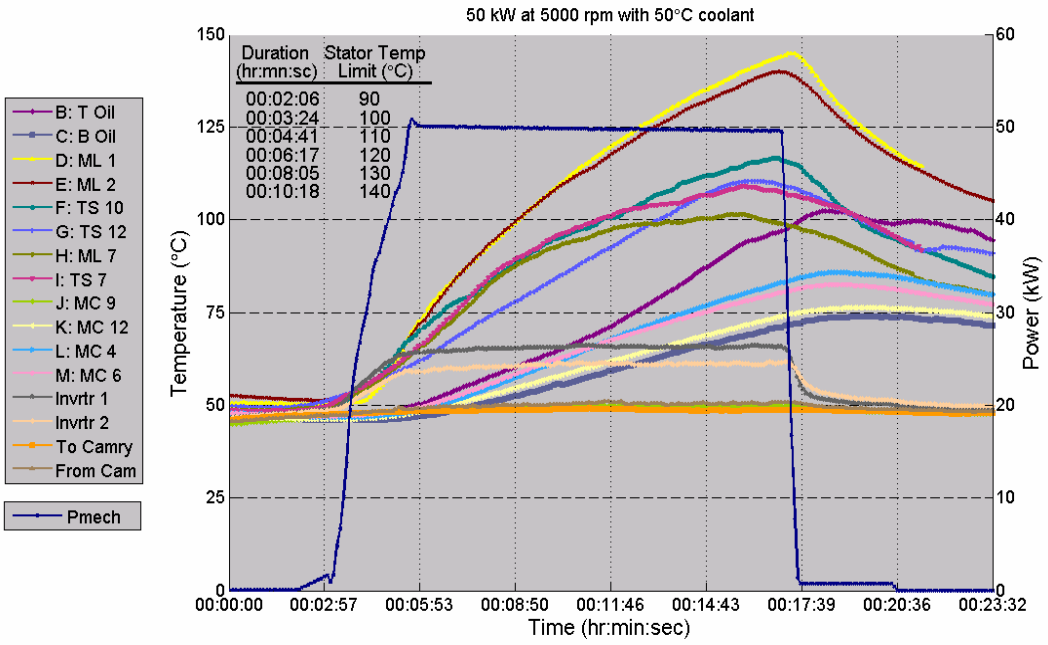


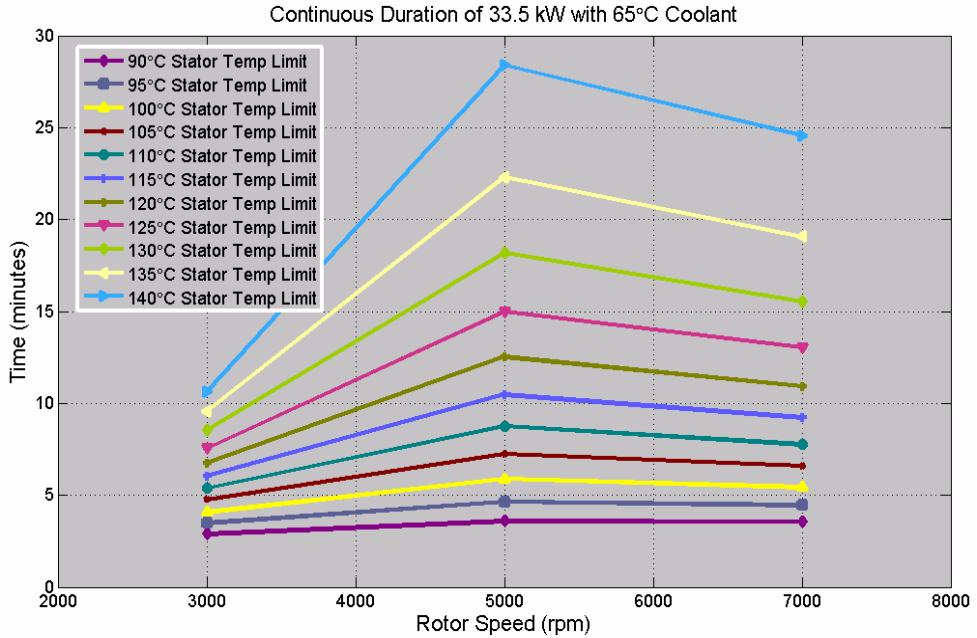


Technical Accomplishments FY07 (cont'd)

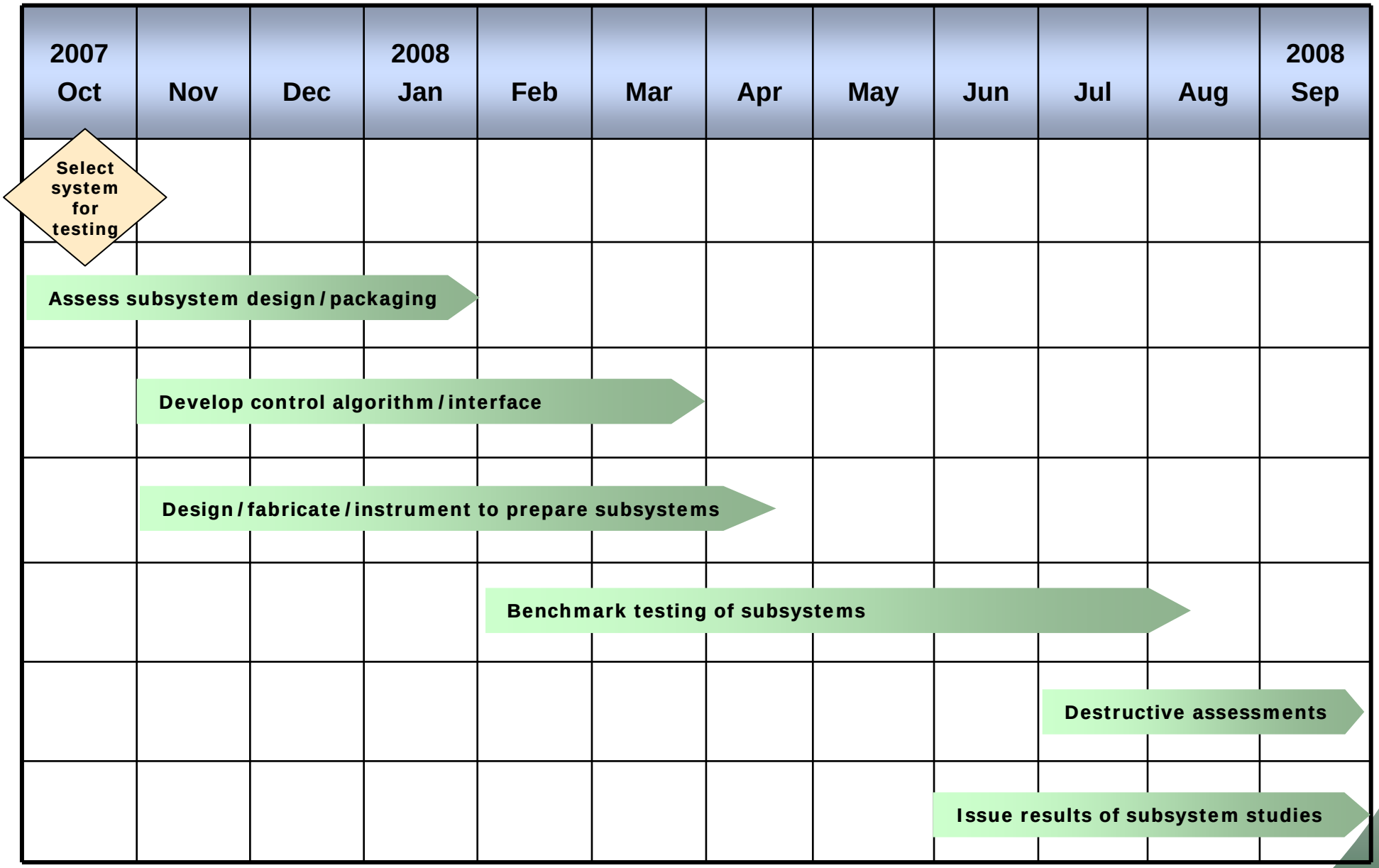
- Efficiency and continuous test results
  - Steady state efficiency map
  - Continuous duration
    - Dependent upon speed, coolant temperature, and stator temperature limitations
    - Camry much higher than Prius







Timeline for FY08



Technical Accomplishments FY08

- Completed Camry benchmarking report
- Selected Lexus LS 600h
  - Includes novel power semiconductor cooling technique and IGBT design – double sided cooling
  - Improved ECVT design with increased power rating
- Purchased PCU and ECVT
- Partially disassembled PCU and ECVT and initiated design assessment

Technical Accomplishments FY08 (cont'd)

- Designed appropriate hardware needed to adapt ECVT to ORNL dynamometer test cell
  - Spline shaft for direct coupling to motor inside ECVT
    - No gear reductions
    - Currently being fabricated
  - Structure to provide proper support and shaft alignment
    - Currently being fabricated
  - Planned modification of oil apparatus for cooling and lubrication while maintaining functionality equivalent to OEM components
    - Equivalency to be verified through testing

Technology Transfer

- NA

Activities for Next Fiscal Year

- **FY09 benchmarking efforts will focus on technologies of interest (coordinate PEEM with vehicle level interest)**

Summary

- Benchmarking plays vital role in PEEM planning and target assessment
- Also provides critical information to vehicle systems modeling effort
- Established SOA for Toyota Prius and Camry and Honda systems
- Will complete assessment of Lexus system in FY08
- FY09 system TBD

Publications, Presentations, Patents

- ORNL/TM-2007/190, *Evaluation of the 2007 Toyota Camry Hybrid Synergy Drive System*, T. A. Burress, R. H. Staunton, and C. L. Coomer, November 2007.
- ORNL/TM-2006/535, *Evaluation of 2005 Honda Accord Hybrid Electric Drive System* , by R. H. Staunton, T. A. Burress, and L. D. Marlino, published September 11, 2006
- ORNL/TM-2006/423, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System*, by R. Staunton, C. Ayers, J. Chiasson, T. Burress, & L. Marlino, published May 16, 2006.
- ORNL/TM-2005/33, *Report on Toyota Prius Motor Thermal Management,* by J. S. Hsu, et. al., published February 14, 2005.
- ORNL/TM-2004/247, *Evaluation of 2004 Toyota Prius Hybrid Electric Drive System Interim Report,* by C. W. Ayers, et. al., published November 23, 2004.
- ORNL/TM-2004/185, *Report on Toyota/Prius Motor Torque-Capability, Torque-Property, No-Load Back-EMF, and Mechanical Losses*, by J. S. Hsu, et. al., published June 30, 2005 ORNL/TM-2004/137, *Report on Toyota/Prius Motor Design and Manufacturing Assessment,* by J. S. Hsu, C. W. Ayers, and C. L. Coomer, published July 2004.

Questions