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Presentation Outline

- **Ford Global Sustainability Outlook**
  - Global factors impacting future vehicle technologies
  - Technology roadmaps to transportation sustainability
  - Role of thermoelectrics in vehicle applications

- **Thermoelectric Waste Heat Recovery**
  - Vehicle Electrical System Demand
  - Ford Thermoelectric Generator Progress Update
  - Requirements for a thermoelectric generator

- **Thermoelectric HVAC**
  - TE heat-pump device development
  - TE materials for heating & cooling
  - Comfort-based design criteria

- **Conclusions and Questions**

Global Sustainability Outlook

- Fuel economy trends driven by global factors:
  - US and California (CAFE, AB32)
  - EU CO_2 Regulations and Fuel Taxes
  - Global Oil Prices
- Fuel prices will be put under pressure by increasing demand from emerging markets
- Regulations in emerging markets are lagging developed countries only by a few years

> "We are committed to being a leader in fuel economy in every product segment in which we compete. In keeping with our heritage as a company, we introduce new technology on a large scale."
>
> \- William Clay Ford Jr., June 2010

* http://www.ford.com/microsites/sustainability-report-2009-10/default

Ford Technology Migration Path

2007 → 2011 → 2020 → 2030

NEAR TERM

Begin migration to advanced technology

- Significant number of vehicles with EcoBoost engines
- Electric power steering
- Dual clutch and six-speed transmissions replace four- and five-speeds
- Flexible-fuel vehicles
- Additional hybrid applications
- Increased unibody applications
- Introduction of additional small vehicles
- Battery management systems
- Aerodynamics improvements
- Stop/start systems (micro hybrids)
- CNG/LPG prep engines available in select markets

MID TERM

Full implementation of known technology

- EcoBoost engines available in nearly all vehicles
- Electric power steering – high volume
- Six-speed transmissions – high volume
- Weight reduction of 250–750 lbs.
- Engine displacement reduction facilitated by weight reductions
- Additional aerodynamics improvements
- Increased use of hybrids
- Introduction of battery electric and plug-in hybrid vehicles
- Vehicle capability to fully leverage available renewable fuels
- Diesel use as market demands
- Increased application of stop/start

LONG TERM

Continue leverage of hybrid technologies and deployment of alternative energy sources

- Increased percentage of internal combustion engines using renewable fuels
- Volume expansion of hybrid technologies
- Continued leverage of plug-in hybrid and battery electric vehicles
- Introduction of fuel cell vehicles
- Clean electric/hydrogen fuels
- Continued weight reduction through use of advanced materials

Trends:

- **Improved fuel economy driven by both regulatory and consumer pressure**
- **Technologies that can be implemented on global platforms and vehicles are most desirable**
- **Technologies that improve fuel economy and reduce CO_2 at a reasonable cost to the consumer will be implemented early**

Implications of Ford Sustainability Plans for Thermoelectrics

- Multiple technologies are competing to improve regulated fuel economy and to attract consumers through marketable features. Winners will be determined by their ability to complete on several factors:
  - Cost (total cost, $/mpg saved, etc…)
  - Robustness (200K + durability)
  - Ease of migration across fleet (B-car, Full-size truck, gas, diesel)
  - Ease of integration (migration ability, partnerships with T1)
  - Marketable feature (OEM revenue opportunity and differentiation)
  - Performance (W/kg, W/m^3, W-hr/kg , W-hr/m^3, W/$)

- How is Ford investigating these factors?
  - Developing strong partnerships in the value chain
  - Leveraging government investments into TE technology
  - Providing critical feedback to support business-case analysis

DOE Phase 5 TEG Program

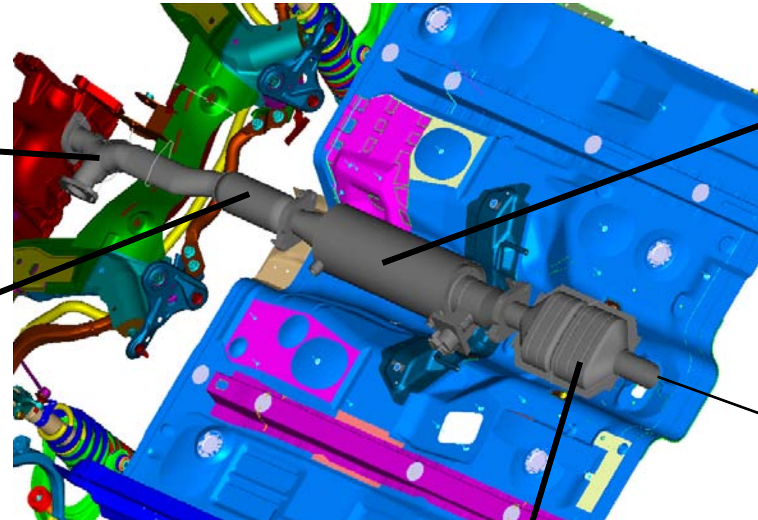
Evaluate TEG on a Ford Fusion with 3.0L V-6 Engine

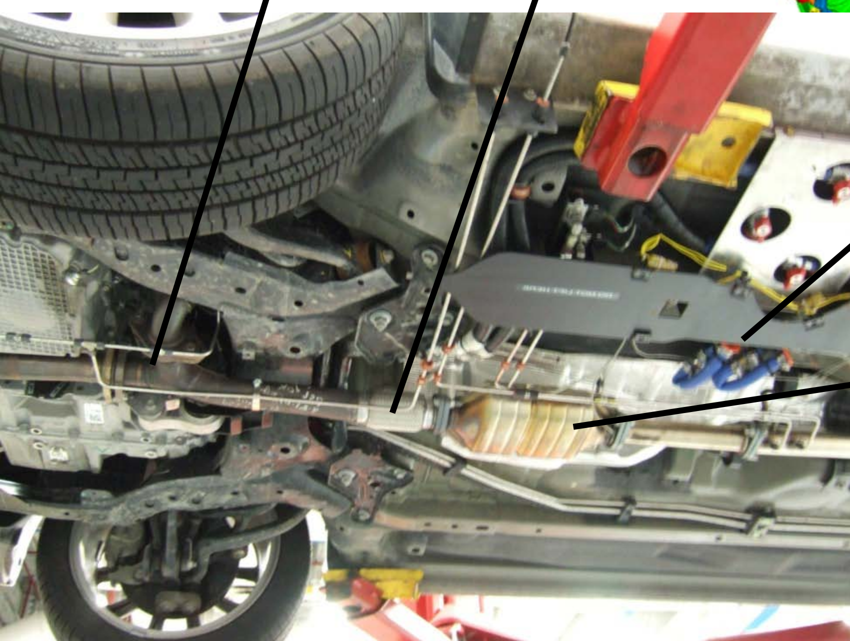
Vehicle-Level Demonstration of TEG Technology

- Design with central bypass
- Separate low-temperature cooling loop
- Half-Heusler + Bi_2Te_3 segmented TE elements
- Major benefit in a vehicle-level demonstration is to understand systems-integration implications

- Anticipated power: ~500 Watts (peak)
- Test cycle: US06 (highway cruise ~100kph)
- April 2011 completion timeframe
- Results reported at the DOE AMR

Packaging for Prototype TEG





Y-Pipe
(from lightoff catalysts)

Flex
Coupling

TEG

To Exhaust

Coolant Lines

Underfloor
Catalyst (not yet moved)

To Exhaust

Automotive Requirements for a TE Generator

Requirements	Examples
• Backpressure limit in TEG HEX	• Idle, design point, max speed-load
• Temperature limit for TE materials	• Max and min conditions
• Durability test requirements	• Shock loading, vehicle test cycles, hot ambient, cold start, trailer-tow, corrosion, etc…
• Performance test requirements	• Design targets for power generation, backpressure, system mass, volume, etc…
• Assembly requirements	• Electrical, mechanical, fluid connections
• Control and sensor requirements	• Internal temperature, valve position, CAN signal requirements, etc…
• Power conditioning	• V-I requirements, series-parallel requirements
• Recycling	• Plan for reclaiming RoHS materials, etc…
• Price and Performance	• $/W target at design point

Alternator Replacement by a TEG

- A TEG must be able to provide necessary power to the vehicle under extremely challenging conditions:
  - Idle
  - City drive cycle (Start-Stop)
  - +50°C to -30°C ambient conditions
  - Full accessory loads, including current spikes
  - Reduce TOTAL fuel consumption, weight, and cost compared to an alternator/battery system

Thermoelectric Waste Heat Recovery: Potential Benefit for Fuel Economy and CO_2

- Electrical System Demand
  - Maximum system demand: 14-V @ 200-A (~3kW)
  - Typical system demand: ~1kW
  - Typical regulatory cycle demand: 0.2 – 0.4 kW

- Potential for Fuel Economy and CO_2 Benefit
  - Regulatory Cycle: 0.2 to 0.4 L/100km (5 to 10g CO_2/km)
  - Consumer Cycle: >1 L/100km (>24g CO_2/km)

- Potential Value of a TEG
  - Regulatory Cycles:
    - US CAFE (based on NHTSA cost analysis): ~$0.50 to $1.00 per watt
    - EU Reg (based on EU CO2 fines): ~$3 to $5 per watt
  - Consumer Cycles:
    - Potential benefit for off-cycle credits, electrical power charge-margin
  - True value is based on competition with other technologies
    - Cost per % fuel economy gain
    - Total fuel economy improvement potential

Ford TE HVAC Project

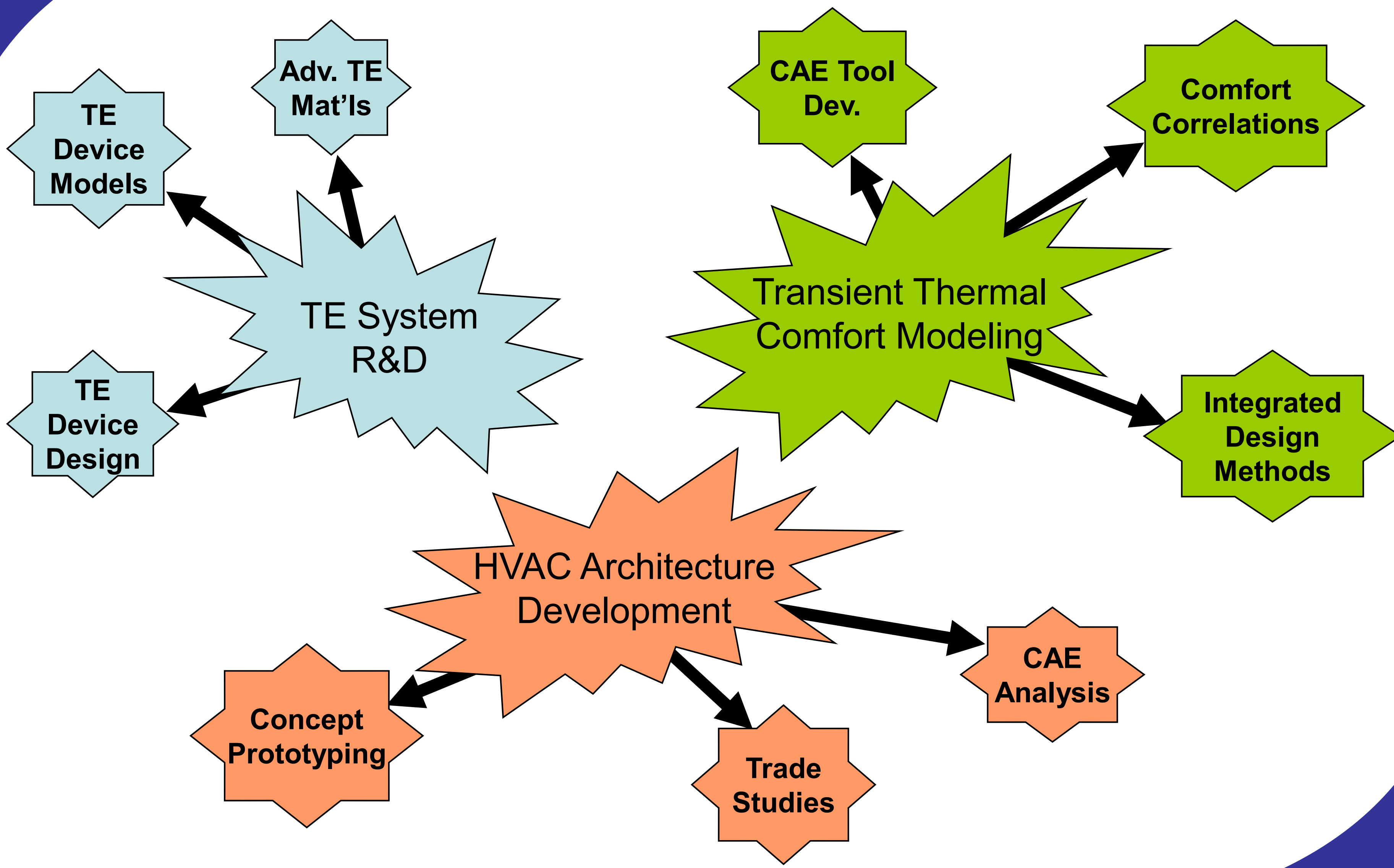
- **3.5-year cooperative agreement with US Dept. of Energy**
  - **Goal:** Identify and demonstrate technical and commercial approaches need to accelerate deployment of a zonal TE HVAC system in automobiles.

- **Objectives:**
  - 33% reduction in A/C compressor power usage
  - TE performance: $COP_{cooling} > 1.3$, $COP_{heating} > 2.3$
  - Reduce total HVAC energy consumption
  - Assess technical and commercial viability for use in automotive applications
  - Integrate, test, and deliver to DOE demo vehicle with a prototype TE HVAC system

- **Phase 1: (Oct. '09 to Nov. '10)**
  - Develop requirements and targets, benchmark baseline vehicle performance
  - Model, design and test at liquid-to-air TE heat-pump addressing commercial and technical metrics
  - Assess and develop CAE and Occupant Thermal Comfort Tools for a zonal, comfort-based system design
  - Research into advanced TE devices and p-type TE materials

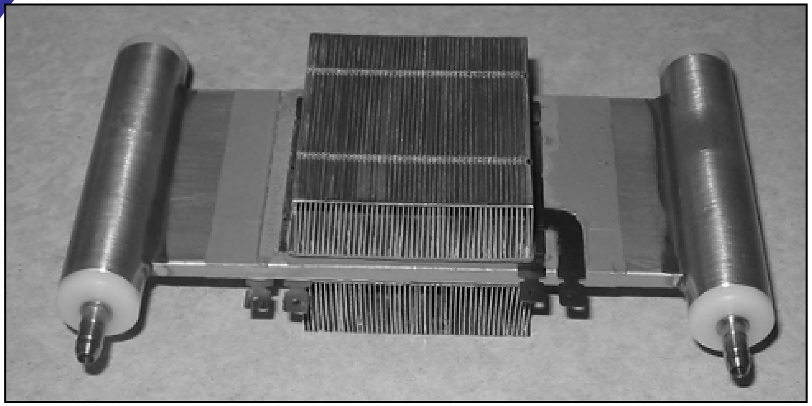
- **Phase 2 (Dec. '10 to Oct. '11)**
  - Develop and investigate a TE HVAC system architecture to meet program objectives
  - Model performance of selected architecture on vehicle efficiency benefit
  - Engineer advanced TE devices for vehicle deployment. Research n-type TE materials.

- **Phase 3 & 4 (Nov. '11 to Apr. '13)**
  - Engineer, build, and test TE HVAC subsystems
  - Install system into vehicle, evaluate performance
  - Deliver vehicle to DOE for further study

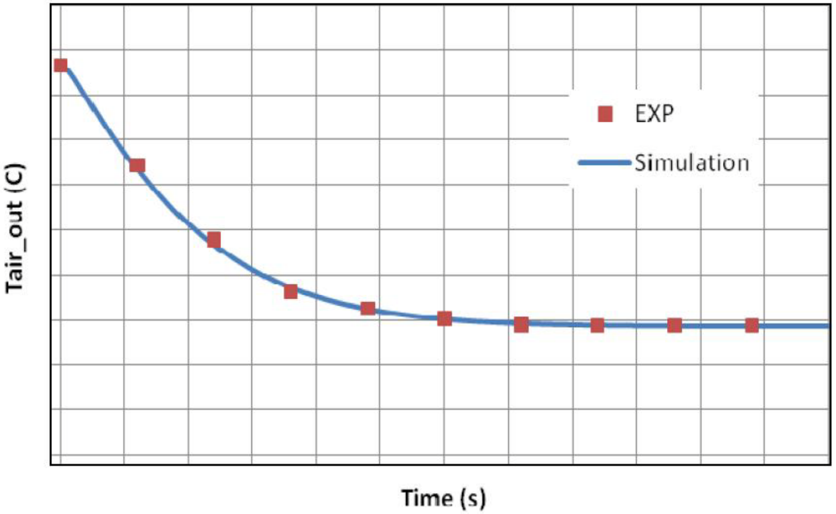


TE System R&D
Adv. TE Mat'ls
TE Device Models
TE Device Design
Transient Thermal Comfort Modeling
CAE Tool Dev.
Comfort Correlations
Integrated Design Methods
HVAC Architecture Development
Concept Prototyping
Trade Studies
CAE Analysis

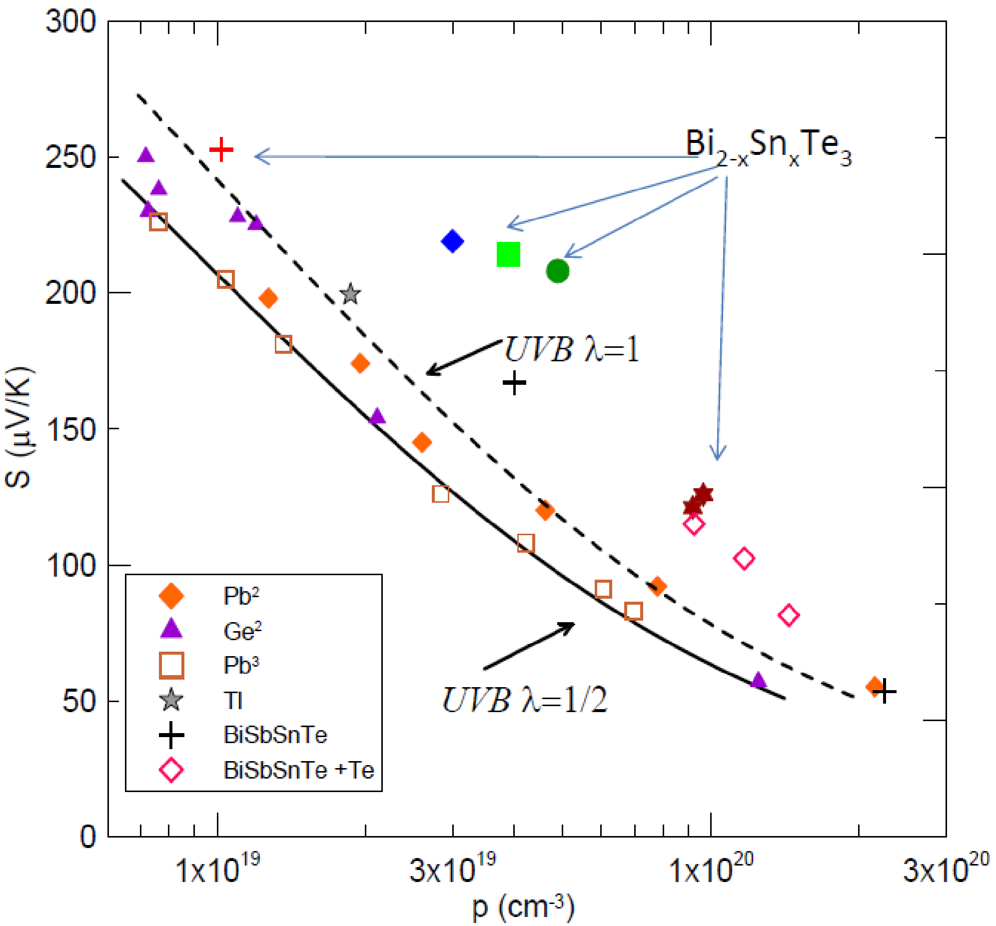
TE Device and Materials Development



BSST 50 Watt Prototype
Liquid-to-Air TE Heat Pump

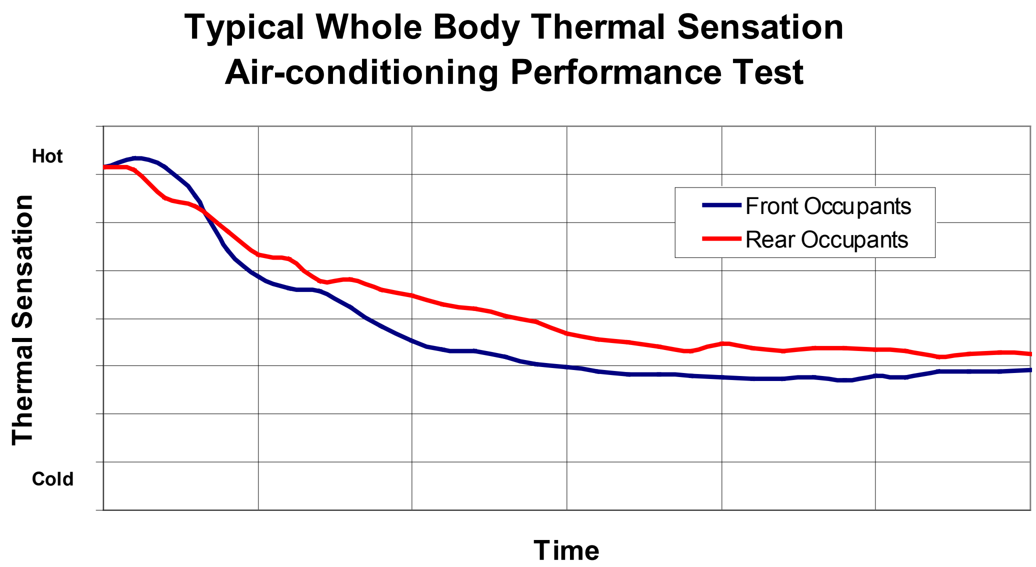


TED-model validation results



*C.M. Jaworski, V.A. Kulbachinskii and J.P. Heremans "Tin forms a Resonant Level in Bi2Te3 that Enhances the Room Temperature Thermoelectric Power", Phys. Rev. B **80** 233201 (2009)*

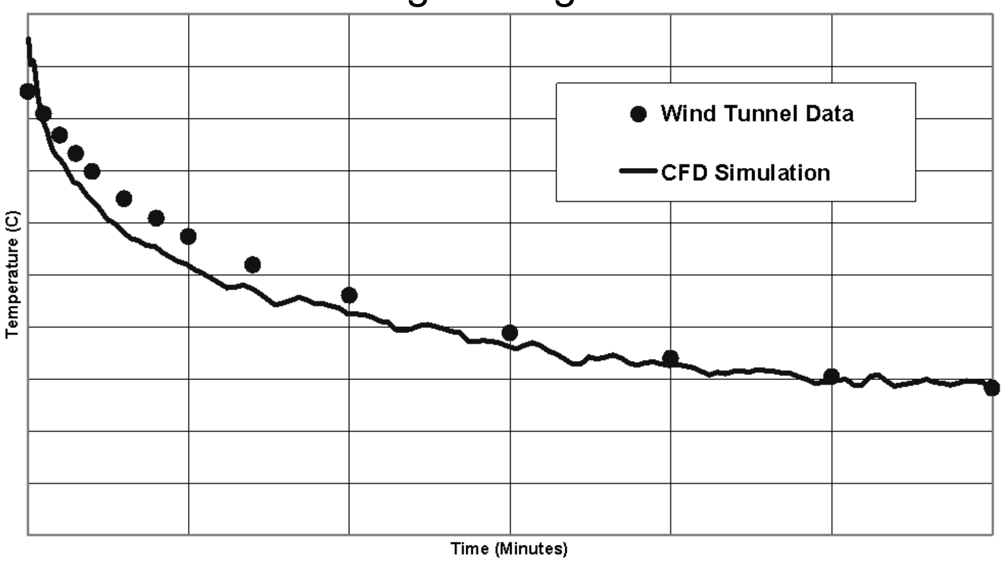
Occupant Thermal Comfort: Test vs Modeling

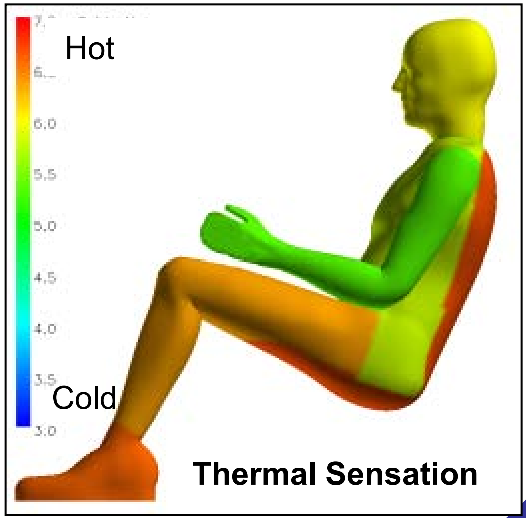


Occupant Thermal Sensation Predictions are a Function of:

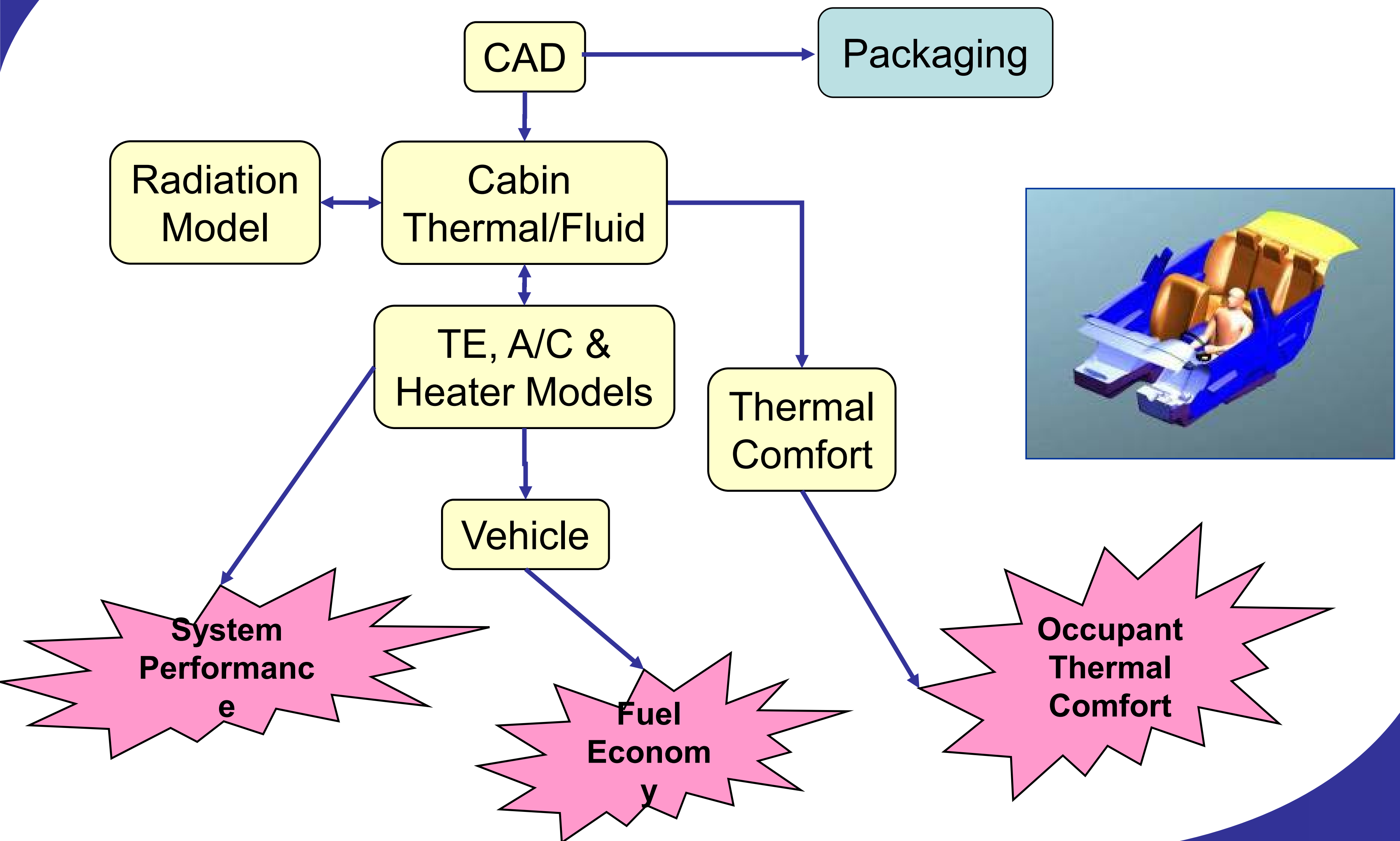
- Temperature
- Air Velocity
- Solar Load
- Surface Radiation
- Humidity
- Clothing

CFD vs testing show good correlation





Development of a TE HVAC Architecture



Next Steps

- TE Waste Heat Recovery Project:
  - Install and test TEG
    - Assess actual vs modeled performance
    - Understand packaging and systems-integration issues
  - Study full-integration requirements, including power conversion, control strategy, and regulatory benefits
  - Develop business case to determine production feasibility
    - This can guide research, engineering, and manufacturing investment decisions
  - Continue to support development of advanced materials and processes to improve efficiency, reduce cost, weight, packaging space

- TE HVAC Project:
  - Continue to develop and assess HVAC architectures that can utilize the unique advantages of TE technology through the use of thermal comfort-based analysis and design
  - Agressively work to improve cost and performance of TE materials and devices
  - Develop systems-level requirements for a TE-based HVAC system hardware

Conclusions

- Application of thermoelectrics into vehicles will remain limited in the near-term, until significant fundamental issues are solved
- Advantages of thermoelectric technology exist in the mid- to long-term horizon
- Significant research and investment is still needed in the areas of cost, performance, thermal management, systems integration, manufacturing, and durability

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