CoolCab Test and Evaluation & CoolCalc HVAC Tool Development

US Department of Energy
Annual Merit Review

Presenter & P.I.:
Jason A. Lustbader
National Renewable Energy Laboratory

Team:
Travis Venson
Matthew Jeffers
John Langewisch
Jon Cosgrove
John P. Rugh

Wednesday May 16, 2012

Project ID # VSS075

Overview

Timeline

Project Start Date: FY06

Project End Date: FY15

Percent Complete: 55%

Budget

Total Project Funding:

DOE Share: $2,700K

Contractor Share*: $810K

Funding Received in FY11: $500K

Funding for FY12: $475K

**Direct funds and in-kind contributions (not included in total)*

Barriers

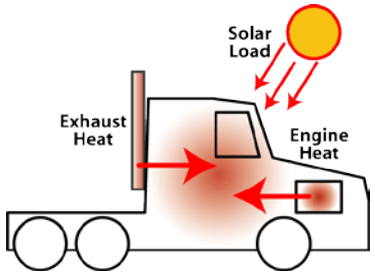
- **Risk Aversion** – *Industry lacks key performance data on HVAC loads and truck cab thermal load reduction technologies*
- **Cost** – *Truck fleets operate on small profit margins and are sensitive to purchase costs for equipment*
- **Computational models, design and simulation methodologies** – *Industry lacks adequate heavy-duty truck thermal load models*

Partners

- Collaborations
  - Daimler Truck (SuperTruck)
  - Kenworth Truck (PACCAR)
  - Volvo Truck
  - Oshkosh
  - 3M
  - Dometic
  - Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems
- Project lead: NREL

Relevance – Project Description

THE CHALLENGE



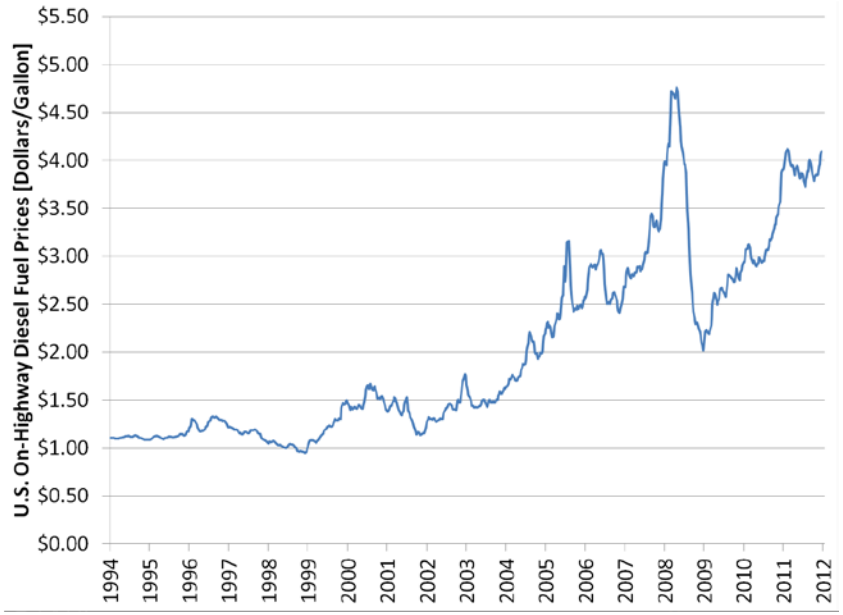
- **838 million gallons of diesel fuel used annually for long-haul truck rest period idling***
  - More than 2 billion gallons with workday idling**
- **Idling is done to:**
  - Heat or cool the cab/sleeper
  - Keep the fuel warm (prevent gelling)
  - Keep the engine warm (startup)
- **Truck fleets operate over a wide range of environmental and use conditions**

* Stodolsky et al., *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks.* 2000. ANL/ESD-43

** Gaines et al., "Estimation of Fuel Use by Idling Commercial Trucks," 85th Annual Meeting of the Transportation Research Board, Washington, D.C., January 22–26, 2006, Paper No. 06-2567.

THE OPPORTUNITY

- Reducing the load will enable idle reduction technologies
- Fleet owners and operators are economically motivated
  - 2- to 3-year payback
  - Direct impact on bottom line



Data Source: EIA Short-Term Energy Outlook http://www.eia.gov/petroleum/gasdiesel/, March 2012

Relevance – S.M.A.R.T Goal

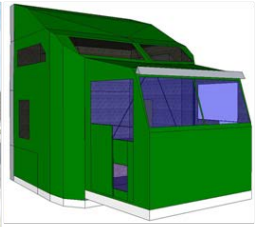
Demonstrate at least a 30% reduction in long-haul truck idle climate control loads with a 3-year or better payback period by 2015.

Relevance – Objectives

- **Overall Objectives**
  - Design efficient thermal management systems that keep the occupants comfortable without the need for engine idling
  - Develop analytical models and test methods to reduce uncertainties and improve performance in idle reduction technologies
  - Apply analytical tools and test methods to research and develop technologies to reduce costs of idle reduction systems
  - Collaborate with industry partners to develop and apply viable solutions to enable market penetration
- **FY12 Objectives**
  - Characterize the performance of thermal load and idle reduction technologies through field testing and evaluation
  - Release, refine, and utilize CoolCalc to help predict HVAC load and idle reduction in sleeper cabs
  - Identify impacts on fuel economy over a wide range of operating conditions

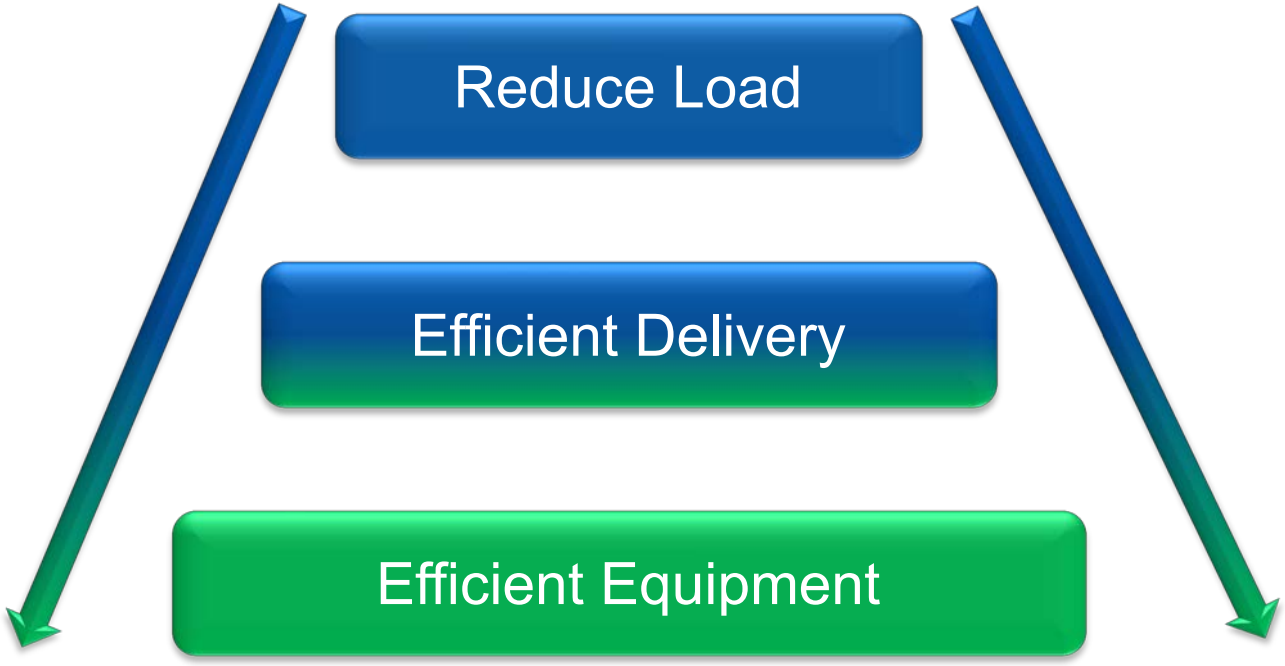
Milestones

Date	Key Milestone
April 2011	• SAE World Congress paper and presentation
July 2011	• Released initial version of CoolCalc & user guide
September 2011	• Completed technology evaluations on trucks • Assessed the impact of thermal- and idle-reduction systems
April 2012	• Developed and validated CoolCalc model of Volvo truck • Applied model to guide summer testing
July 2012	• SAE Commercial Vehicles Engineering Congress (COMVEC) paper
September 2012	• Complete testing of truck and test bucks • Assess the impact of thermal and idle reduction technologies • Estimate impact on fuel use
October 2012	• SAE Thermal Management Systems Symposium • SAE World Congress paper



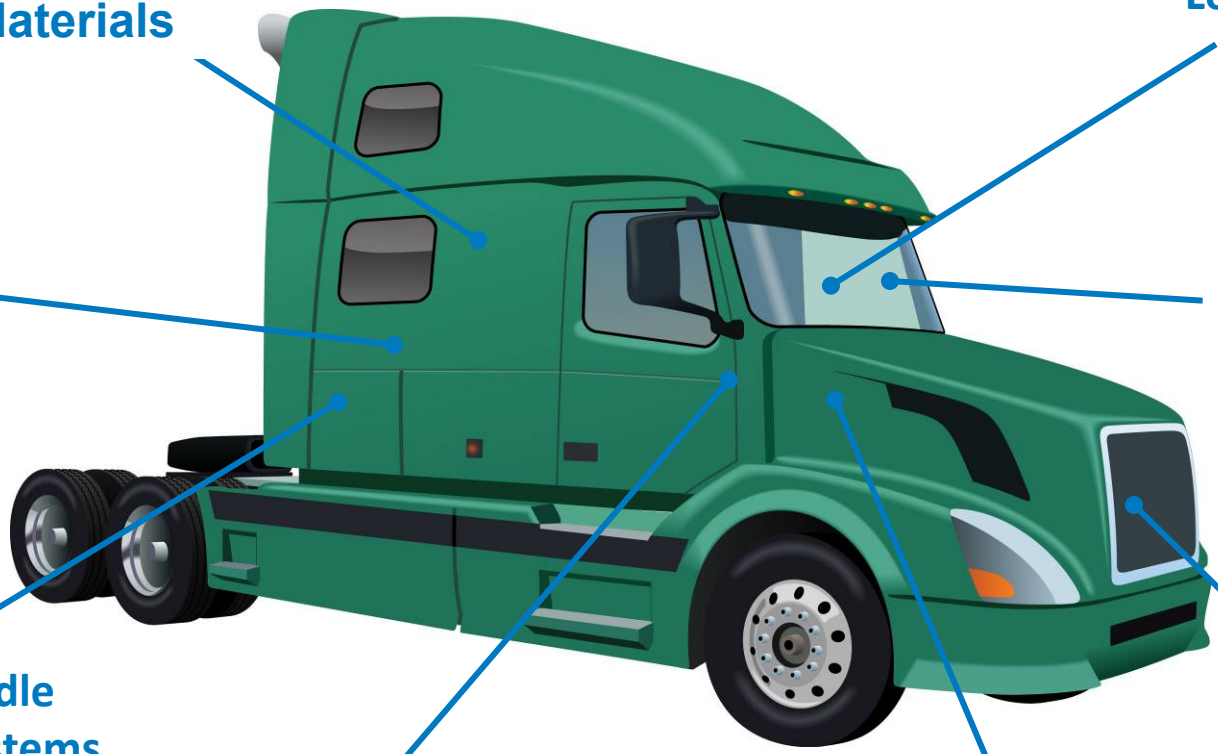
Approach – System Level

System Level Solution



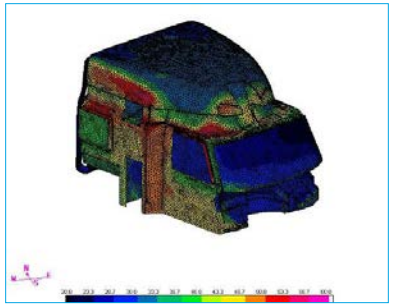
Decreases in load have a larger impact on fuel use due to equipment and delivery losses.

Approach – Advanced Technologies



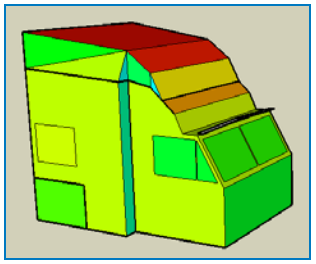
Approach – Suite of Tools

Detailed Analysis

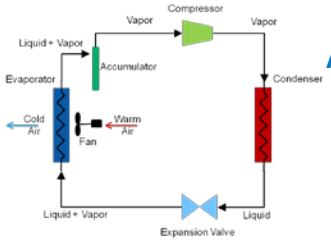


CFD – Fluid Flow

CoolCalc



Load Estimation



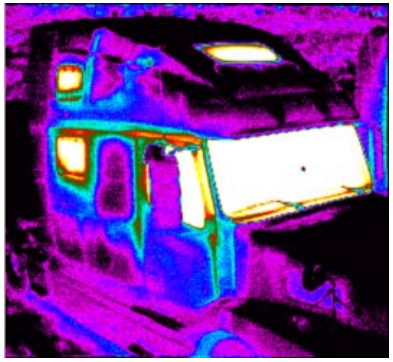
A/C Model – Compressor Power

Fuel Consumption

Vehicle Modeling

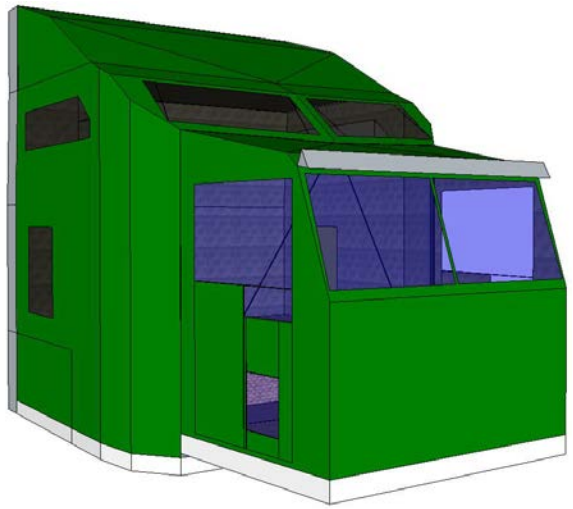
Testing

In-Use Validation



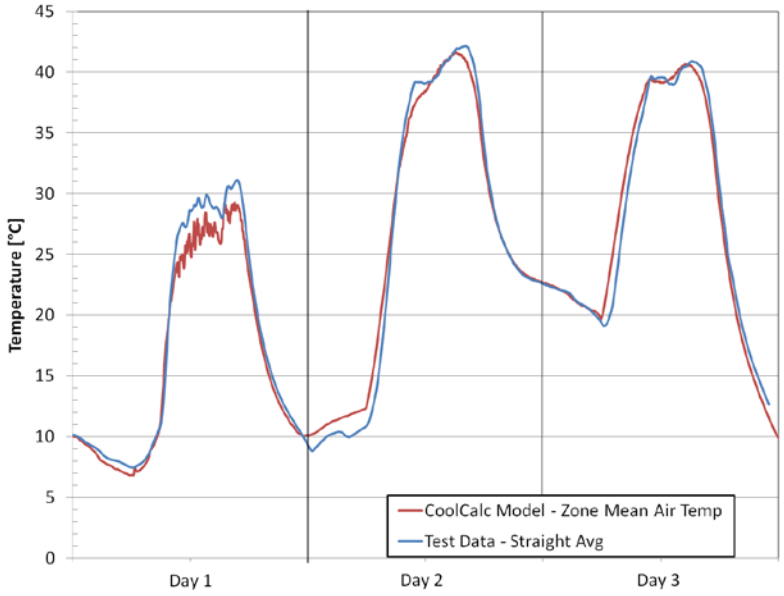
CoolCalc Rapid HVAC Load Estimation

- **Physics-based model**
  - No meshing
  - Flexible geometry
  - Less time intensive
  - Excludes unnecessary detail
  - Easy to use
- **Applications**
  - Trade-off studies
  - Technology impact estimation
  - Preliminary design
  - Focus more detailed CFD studies
- **Key input parameters**
  - Truck cab geometry
  - Material properties
  - Climatic conditions
  - A/C system settings
- **Outputs**
  - Calculate loads
  - Estimate potential load reduction
  - Fuel use impacts



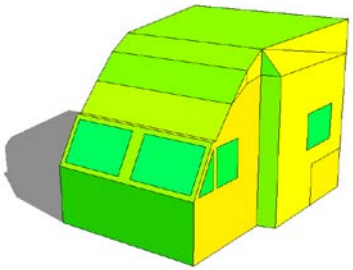
Leverages:
- EnergyPlus
- OpenStudio

Average Sleeper Air Temperature

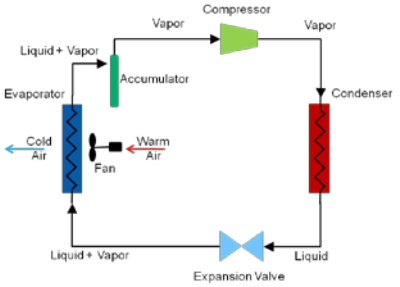


Lustbader et al., "CoolCalc: A Long-Haul Truck Thermal Load Estimation Tool", SAE World Congress, Detroit, MI, April 12-14, 2011, Paper No. 2011-01-0656

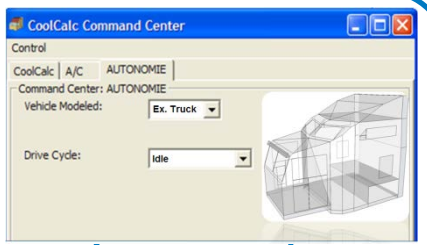
COOLCALC



T_{amb}, Q_{evap}



$P_{comp}(T_{amb}, Q_{evap})$



Autonomie

Fuel Use (T_{amb}, P_{comp})

Fuel Use (T_{amb}, Q_{evap})

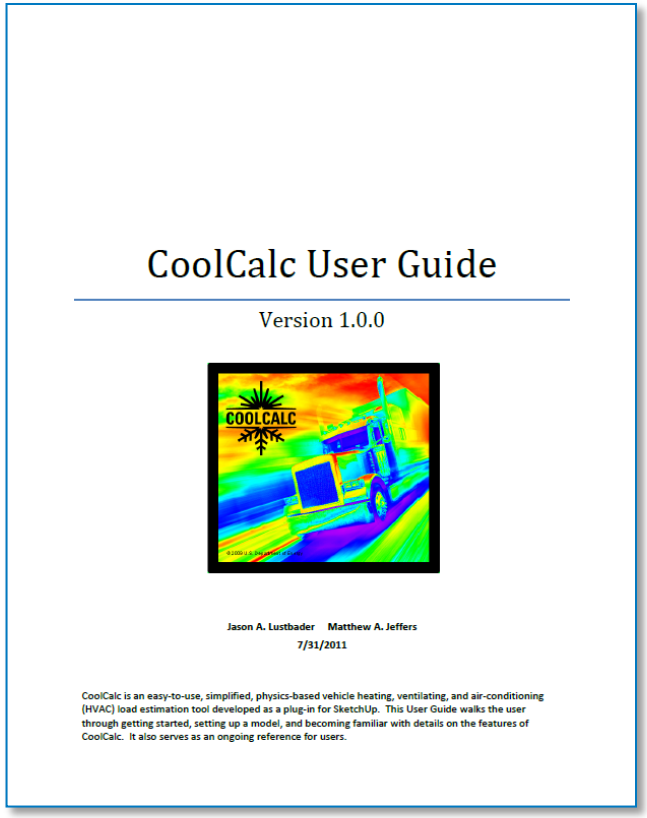
Fuel Use Rate

Approach: CoolCab Project Phases

- **Phase I – Baseline Testing and Model Development**
  - Build and validate CoolCalc models
  - Characterize test truck performance as received
  - Calibrate control truck
- **Phase II – Thermal Load Reduction**
  - CoolCalc and A/C model studies
  - Modify vehicle with thermal management technologies
  - Measure impact on temperature and heat loss
- **Phase III – Idle Reduction**
  - Characterize the impact of thermal load reduction technologies on idle reduction systems
  - Measure A/C and heater load reduction
  - Model fuel use impacts over range of operating conditions

Technical Accomplishment – CoolCalc

- **Initial release of CoolCalc to industry partners**
- **CoolCalc User Guide**
  - Helps users through entire simulation process from installation to processing simulation results
  - Serves as a reference for performing the most important/frequent tasks
  - Trouble-shooting common errors
- **Improved robustness and usability**


CoolCalc User Guide

Version 1.0.0

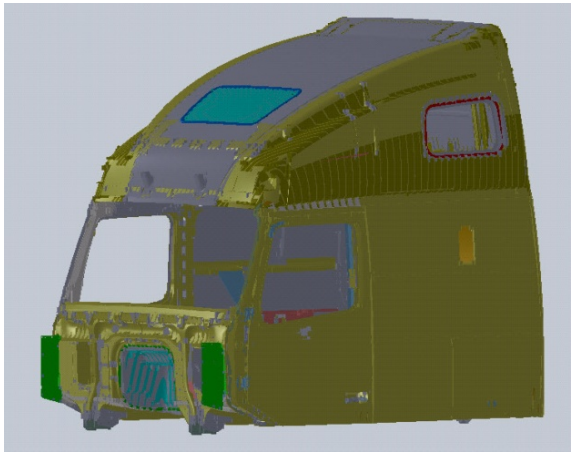
Jason A. Lustbader Matthew A. Jeffers

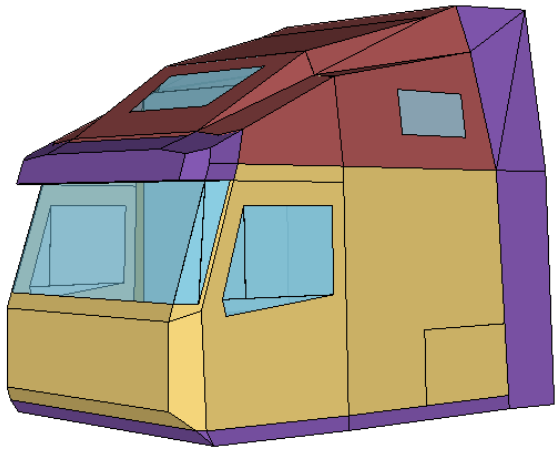
7/31/2011

CoolCalc is an easy-to-use, simplified, physics-based vehicle heating, ventilating, and air-conditioning (HVAC) load estimation tool developed as a plug-in for SketchUp. This User Guide walks the user through getting started, setting up a model, and becoming familiar with details on the features of CoolCalc. It also serves as an ongoing reference for users.

Technical Accomplishment – Volvo CoolCalc Model

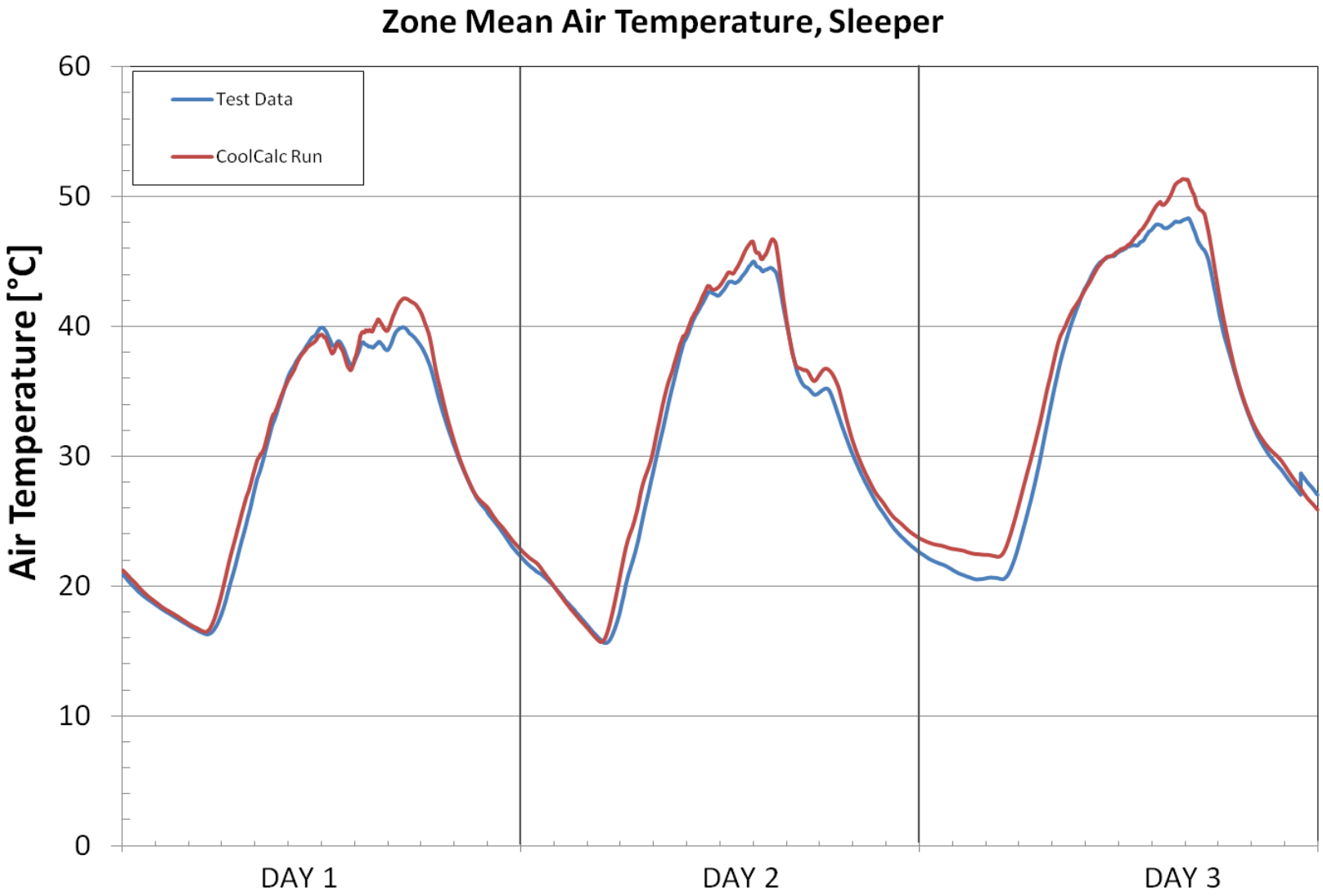
Developed CoolCalc model of Volvo truck





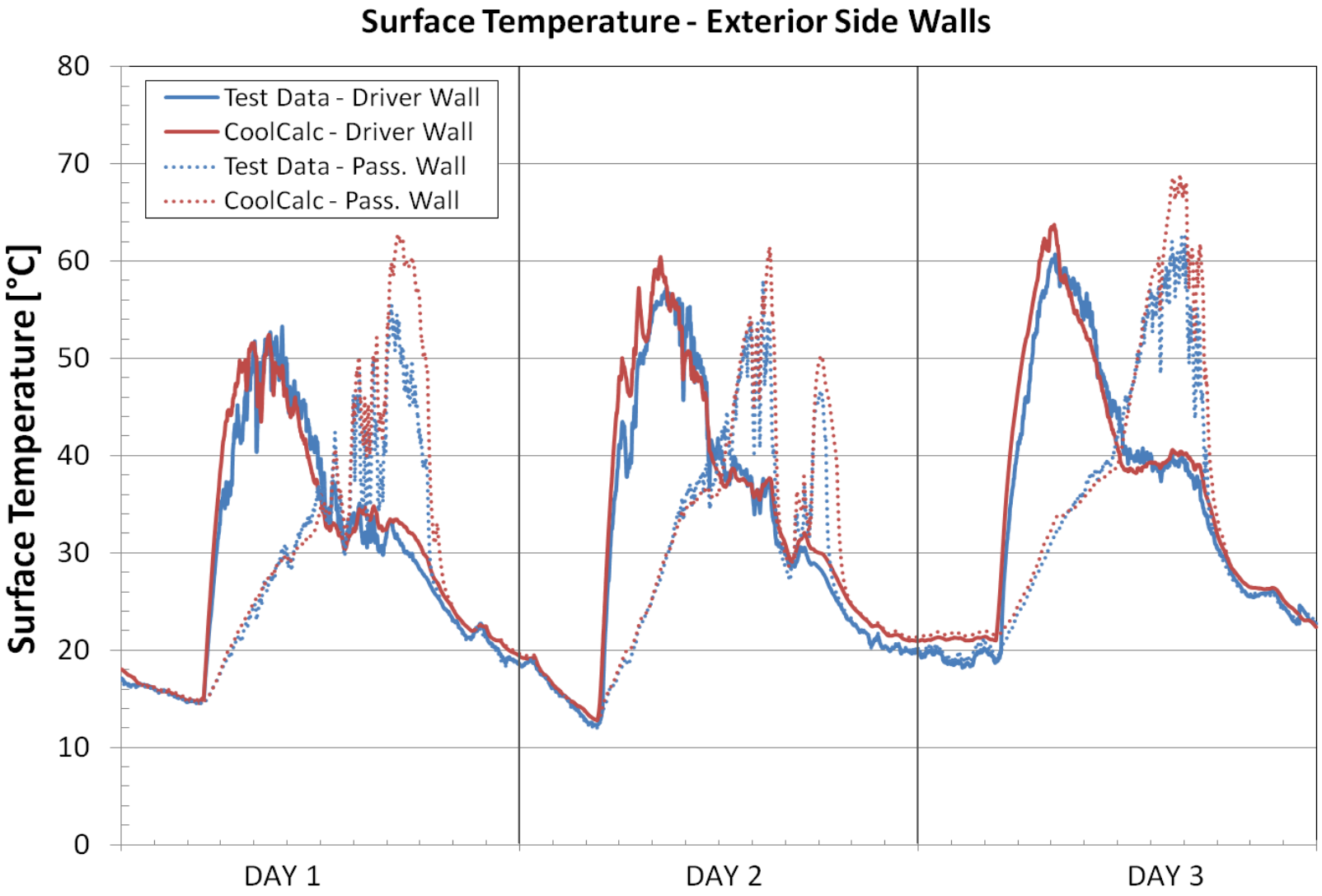
Technical Accomplishment –Preliminary Validation

Preliminary model results demonstrate good correlation to test data



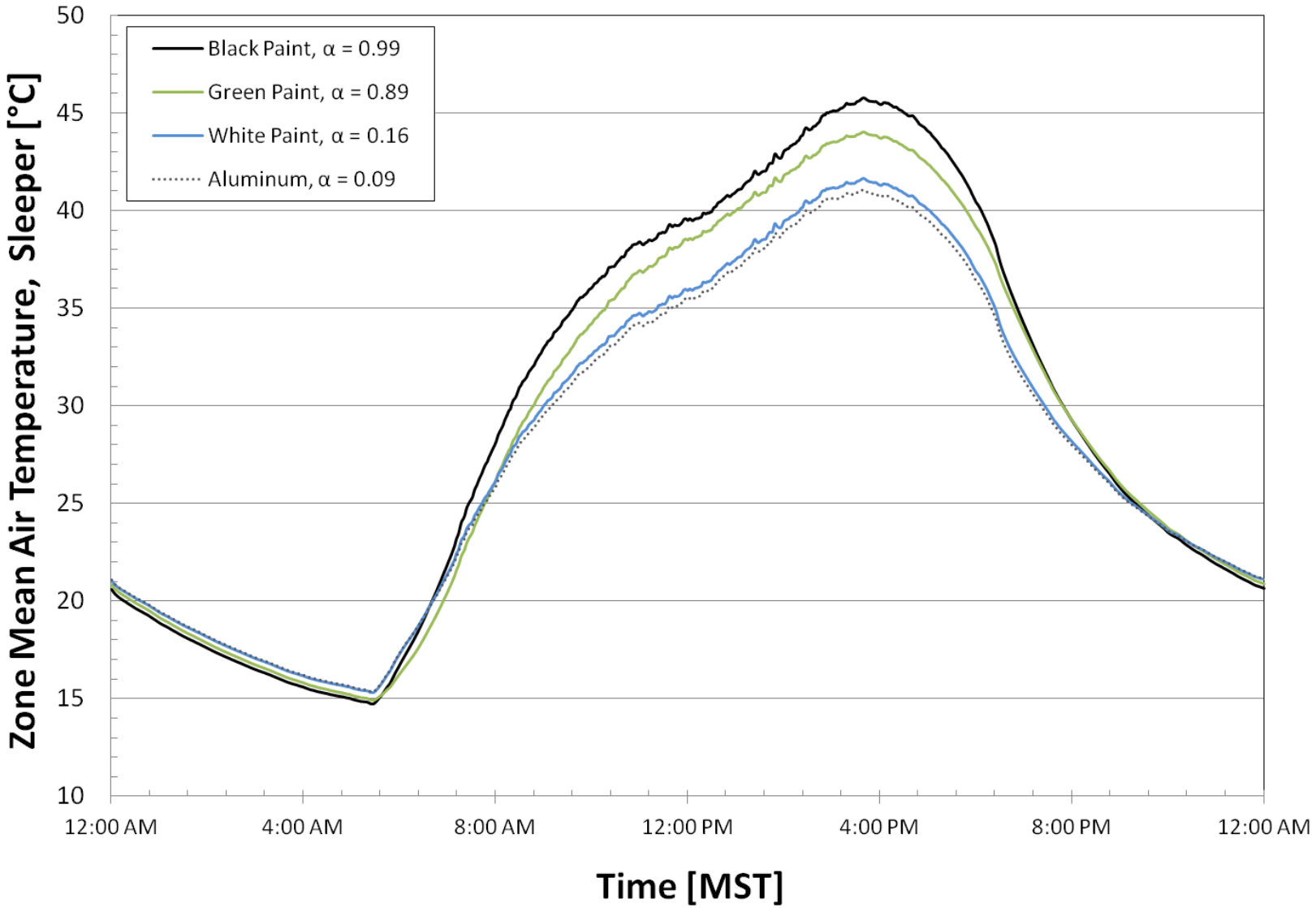
Technical Accomplishment –Preliminary Validation

Impacts of weather, solar angle, and vehicle orientation are captured in the model



Technical Accomplishment – CoolCalc Application

Generic cab model shows reduction in sleeper air temperature during thermal soak



Technical Accomplishment – CoolCalc Application

Generic cab model shows 25% maximum possible air temperature reduction from paint

Radiant Barrier Results

Baseline Configuration	Modified Configuration	β - Average Air Temp Reduction, Cab	β - Average Air Temp Reduction, Sleeper
Black Paint	Aluminum Radiant Barrier	24%	27%
Green Paint	Aluminum Radiant Barrier	17%	20%
White Paint	Aluminum Radiant Barrier	3%	5%

Paint Results

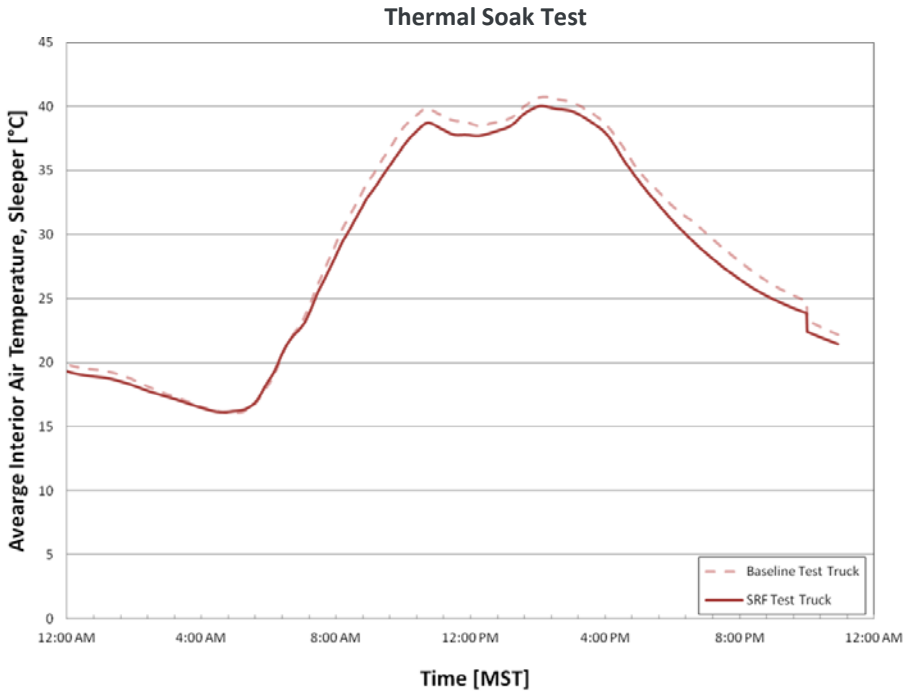
Baseline Configuration	Modified Configuration	β - Average Air Temp Reduction, Cab	β - Average Air Temp Reduction, Sleeper
Black Paint	White Paint	22%	25%
Green Paint	White Paint	15%	16%

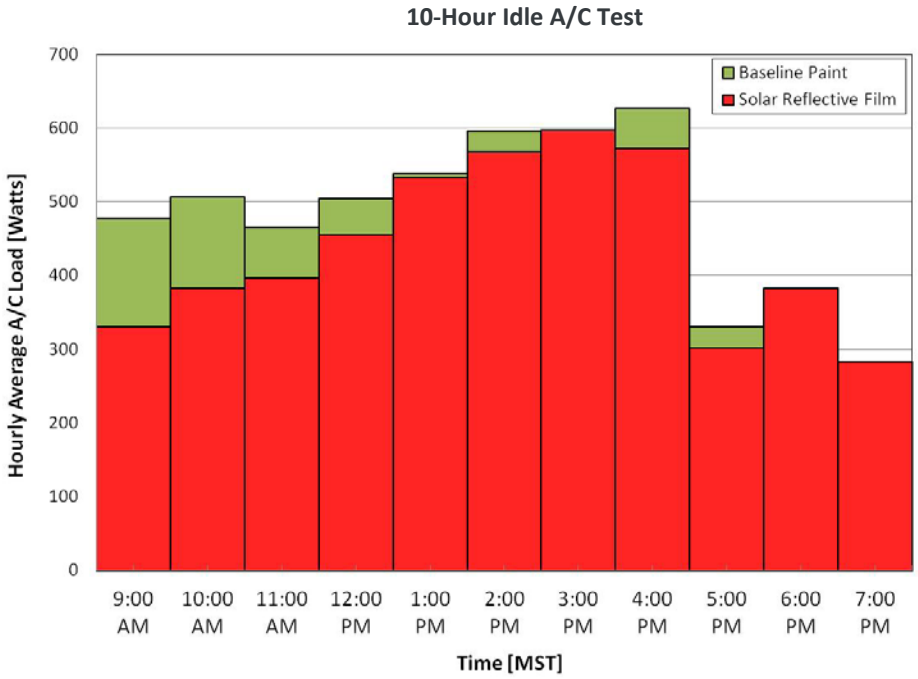
$$\beta = \frac{\overline{T}_{\text{baseline}} - \overline{T}_{\text{modified}}}{\overline{T}_{\text{baseline}} - \overline{T}_{\text{ambient}}} \times 100\%$$

Technical Accomplishment – Impact of Solar Reflective Film

Identified 8% reduction in A/C load through application of a solar reflective film

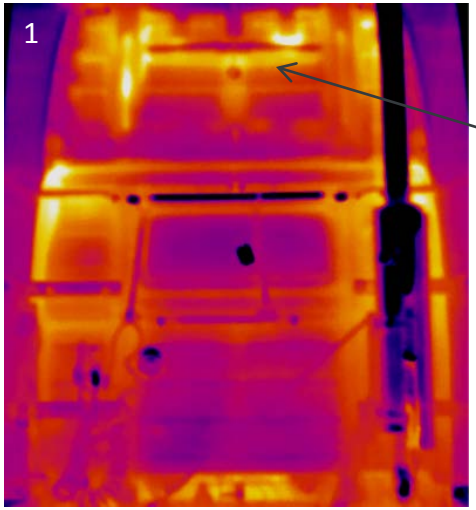
- 3M Solar Reflective Film
  - Applied to cab/sleeper exterior
  - 1-2°C reduction in temperatures
  - 8% reduction in A/C load
  - More effective on darker trucks



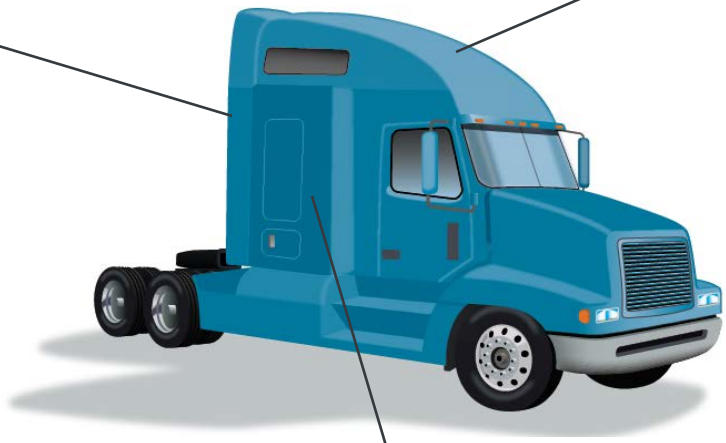


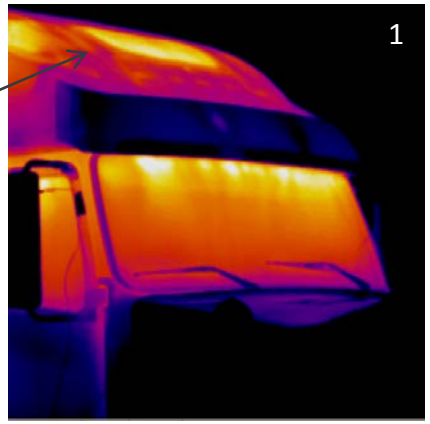
Technical Accomplishment – Infrared Imaging

Identified opportunities to reduce heat loss/gain in walls, roof cap, structural members, and glass

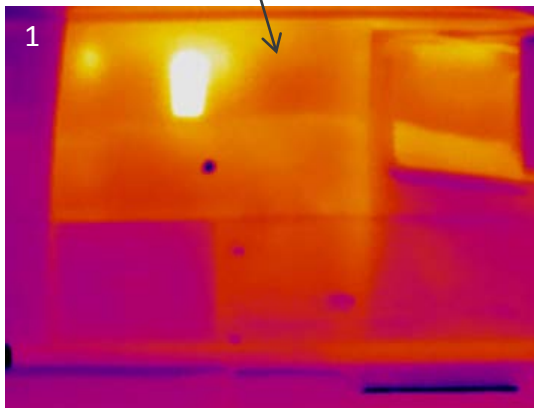


Rear View - structural members





Isometric view – roof cap and glass

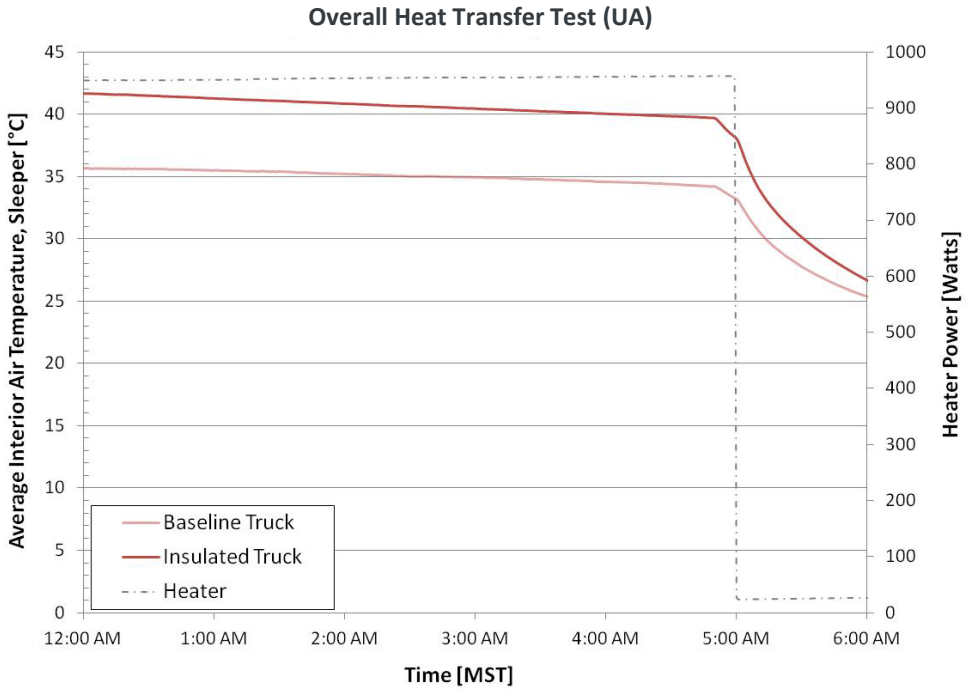


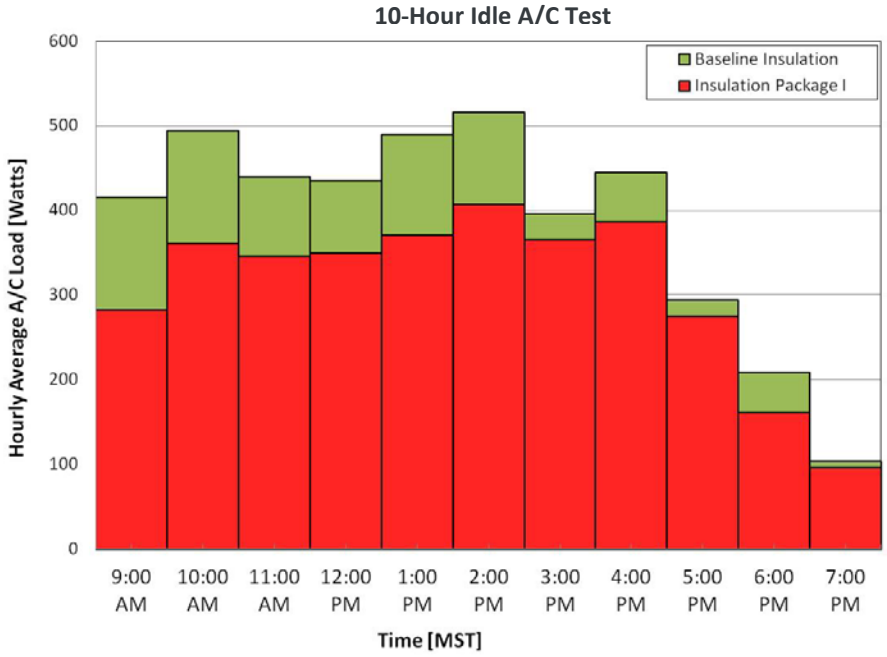
Side View – sleeper walls

Technical Accomplishment – Impact of Insulation Package I

Reduced heating and cooling loads by 26% and 20%, respectively

- **E-A-R™ Thermal Acoustic Systems Insulation Package I**
  - Installed in sleeper walls and roof
  - 26% reduction in heating load
  - 20% reduction in A/C load

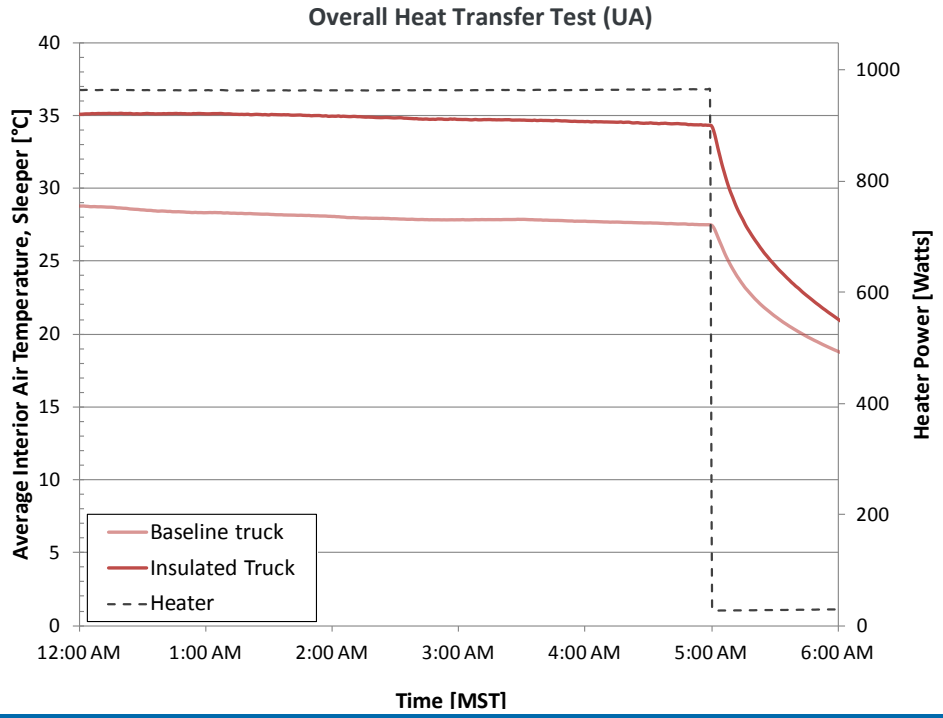


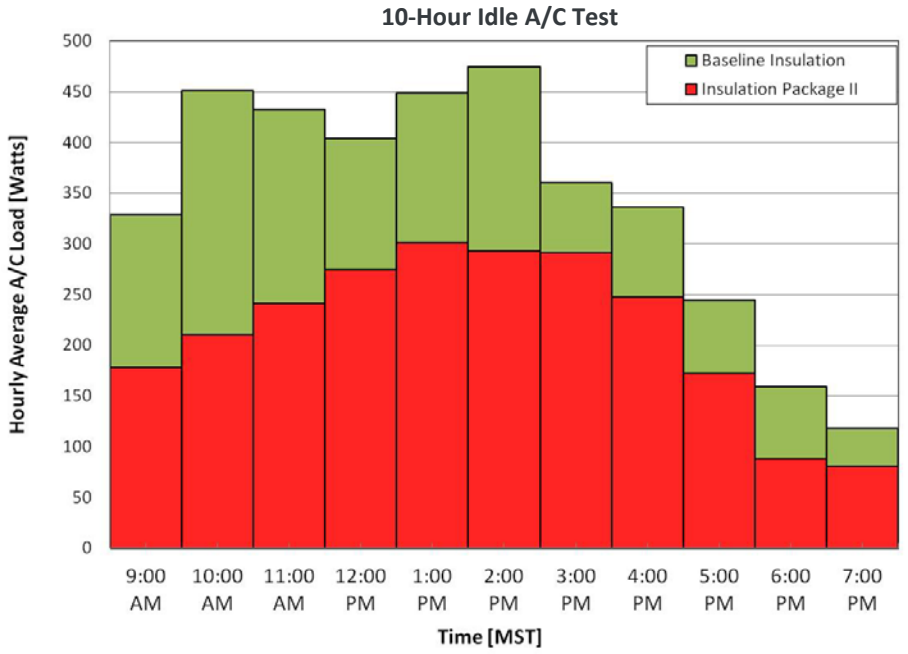


Technical Accomplishment – Impact of Insulation Package II

Reduced heating and cooling loads by 36% and 34%, respectively

- **E-A-R™ Thermal Acoustic Systems Insulation Package II**
  - Installed in sleeper walls and roof
  - Added insulation in channels
  - 36% reduction in heating load
  - 34% reduction in A/C load

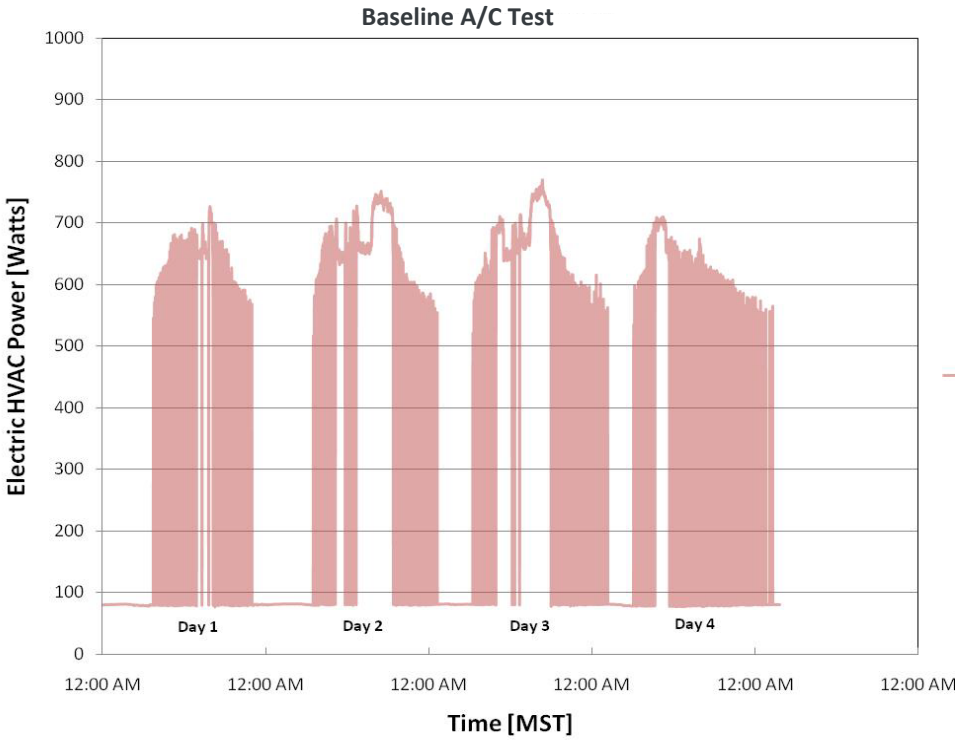




Technical Accomplishment – Idle Reduction System

Identified opportunities to reduce battery pack capacity by 23%

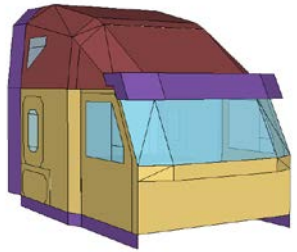
- Dometic Electric A/C System
  - Battery or shore-powered A/C system
  - Batteries charge from alternator
  - Provides 10 hours of idle-free cooling
  - Identified opportunities to reduce battery capacity by 23%, ~ 1 battery



Test Configuration	Battery Energy Reduction
Solar Reflective Film	7%
Insulation Package I & Film	20%
Insulation Package I	15%
Insulation Package II	23%

Collaboration

- 21st Century Truck Partnership
- Kenworth
  - Fully instrumented and tested for thermal-load measurements
  - Developed, validated, and released CoolCalc model
- Volvo Trucks
  - Completed thermal testing
  - Developed CoolCalc model, validation in progress
- Daimler Truck, Super Truck Program
  - Completed thermal testing of Super Truck
  - Developed and validated CoolCalc model
- Oshkosh Truck
  - CoolCalc Beta testing
  - CoolCalc modeling
- 3M Renewable Energy Laboratory
  - Evaluated solar reflective film
- Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems
  - Evaluated insulation packages
- Dometic Environmental Corporation
  - Evaluated electric A/C system



Proposed Future Work

- **FY12**
  - Improve CoolCalc and add functionality for partner implementation
  - Apply CoolCalc model to characterize technologies over a range of operating conditions
  - Complete validation of Volvo model
  - Interface with A/C model to characterize fuel impacts
  - Evaluate advanced technologies on test bucks and heavy vehicles
  - A/C emulator test bench, UA, thermal soak
  - Characterize technologies identified by CoolCalc analysis
- **FY13**
  - Work with industry partners to evaluate and implement advanced thermal and idle load reduction technologies
  - Move toward in-use demonstration and evaluation
  - Quantify fuel savings and economic trade-offs for technologies over a wide range of use and weather conditions

Summary

- **DOE Mission Support**
  - Overcome barriers to the adoption of market-viable and efficient thermal management systems that keep the cab comfortable without the need for engine idling, helping to reduce the 838 million gallons of fuel used for truck hotel loads every year
- **Approach**
  - Work with industry partners to develop effective, market-viable solutions using a system-level approach to research, development and design
  - Address thermal load reduction of the cab, effective delivery of conditioning to the occupants for thermal comfort, and the use of efficient equipment

Summary

- **Technical Accomplishments**
  - CoolCalc
    - Refined interface and improved robustness
    - Released with user guide to industry partners
    - Developed and began validation of a model for Volvo
    - Applied model to characterize technologies
  - Truck Testing
    - 36% reduction in heat loss for insulated truck
    - 34% reduction in idle A/C load for insulated truck
    - Characterized impact of solar reflective film
    - Identified opportunities to reduce idle A/C system battery capacity by 23%
- **Collaborations**
  - Volvo – testing, analysis, and CoolCalc model development
  - Daimler – supported Daimler's Super Truck program through testing and analysis
  - Kenworth – extended Cooperative Research and Development Agreement (CRADA), CoolCalc beta testing
  - Oshkosh – CoolCalc beta testing and application
  - 3M – evaluated solar reflective film technology
  - Aearo Technologies LLC / E-A-R™ Thermal Acoustic Systems – tested commercial and advanced insulation packages
  - Dometic – evaluated no-idle, battery-powered A/C system

1

Contacts

Special thanks to:

- **Lee Slezak & David Anderson**
  Advanced Vehicle Technology Analysis and Evaluation Vehicle Technologies Program

For more information:

Principal Investigator:
Jason A. Lustbader
National Renewable Energy Laboratory
Jason.Lustbader@nrel.gov
303-275-4443

Image References

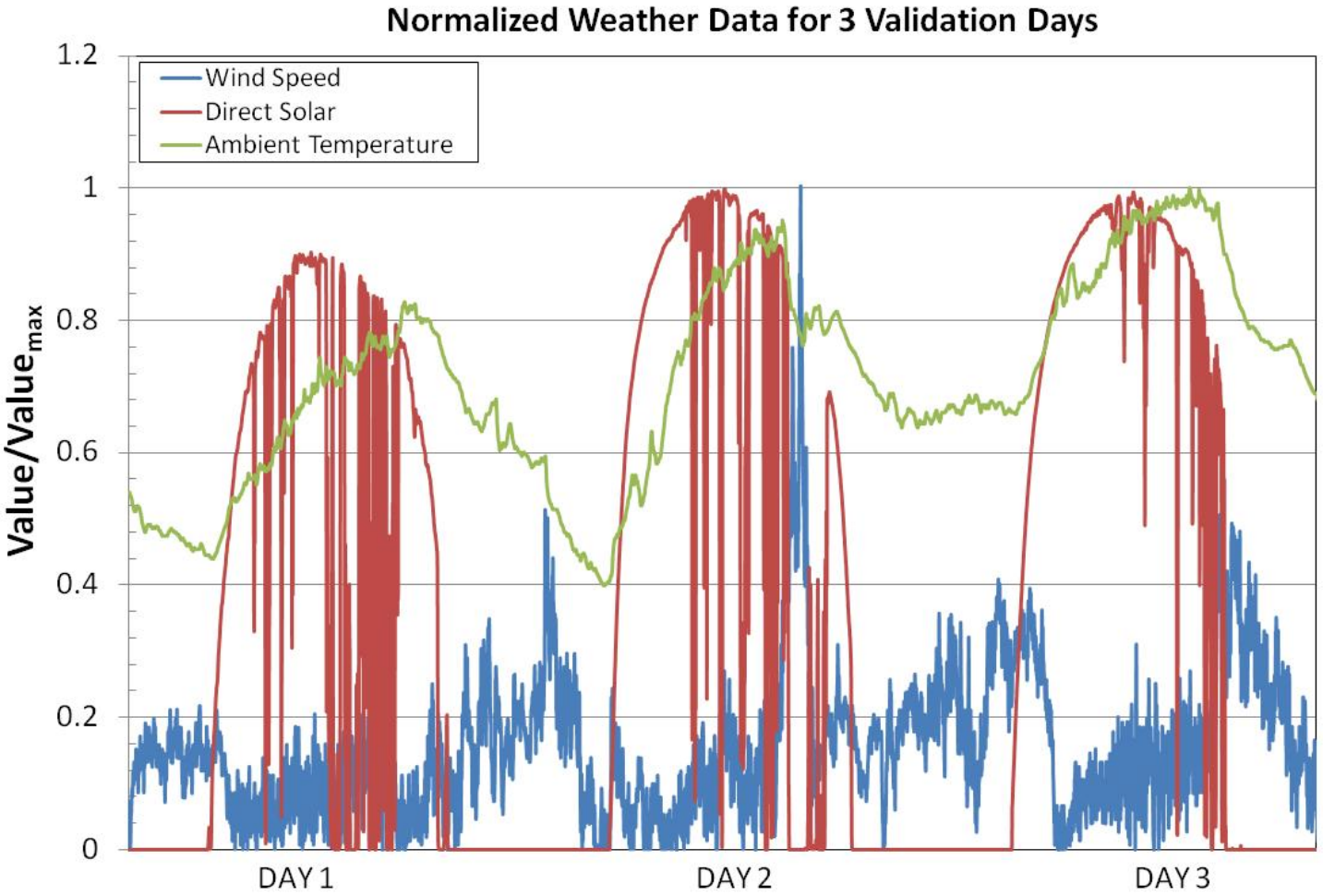
- **Slide 1**
  1. Photograph of NREL's Vehicle Test Pad (VTP), NREL photographer Dennis Schroeder, 2011
- **Slide 3**
  1. Photograph of Volvo truck, Ken Proc, 2009
- **Slide 6**
  1. Photograph of Kenworth truck, Ken Proc, 2009
  2. Aerial photograph of VTP, Travis Venson, 2011
  3. Photograph of Volvo truck, Travis Venson, 2010
  4. Photograph of Freightliner truck and Volvo test bucks, Travis Venson, 2012
- **Slide 9**
  1. Photograph of VTP, NREL photographer Dennis Schroeder, 2011
- **Slide 12**
  1. Photograph of trucks on VTP, Ken Proc, 2009
  2. Thermal image, Travis Venson, 2010
  3. Photograph of electric A/C system courtesy of Dometic, 2011
- **Slide 14**
  1. Photograph of Volvo truck, Travis Venson, 2011
- **Slide 20**
  1. Thermal images (3), Travis Venson, 2011
- **Slide 21**
  1. Photograph of truck insulation package I, Travis Venson, 2011
- **Slide 22**
  1. Photograph of truck insulation package II, Travis Venson, 2011
- **Slide 23**
  1. Photograph of electric A/C system courtesy of Dometic, 2011
- **Slide 24**
  1. Photograph of Kenworth truck, Ken Proc, 2009
  2. Photograph of Volvo truck, Travis Venson, 2010
  3. Photograph of Daimler truck, Travis Venson, 2011
  4. Aerial photograph of VTP, Travis Venson, 2011
- **Slide 27**
  1. Daimler Super Truck Logo, Courtesy of Daimler Trucks, 2011
- **Slide 28**
  1. Photograph of VTP, NREL photographer Dennis Schroeder, 2011

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Technical Back-Up Slides

Technical Back-Up Slide – Normalized Validation Weather

Three validation days with varying weather conditions were used



Day 1:
Cloudy
Low wind
Low temperature

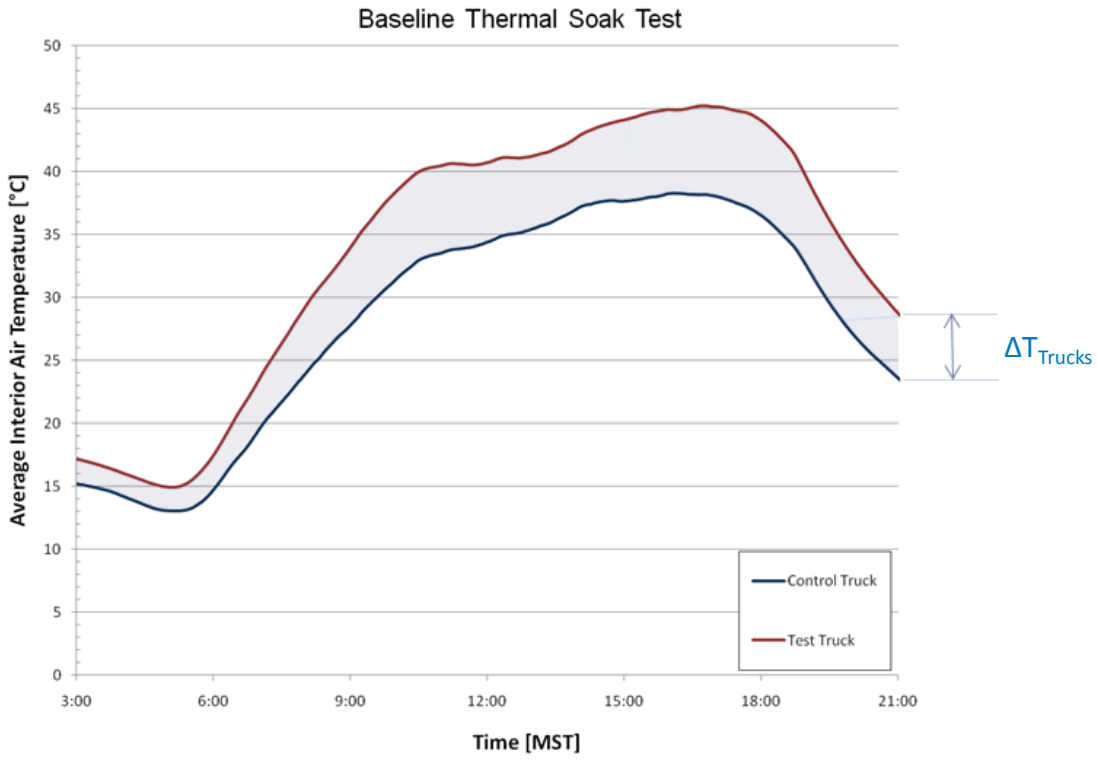
Day 2:
Sunny → cloudy
Late wind peak
Avg. temperature

Day 3:
Few clouds
Variable wind
High temperature

Technical Back-Up Slide – Baseline Test Process

Validate CoolCalc truck models and calibrate control truck performance to baseline test truck

1. Acquire 3 or more days of data
2. Characterize daily averages ΔT_{trucks} profile
3. Adjust measured control truck data by ΔT_{trucks}
4. Validate process with other days



$$\Delta T_{Trucks} = T_{Test} - T_{control}$$

Technical Back-Up Slide – Test Procedures, Infiltration and IR Imaging

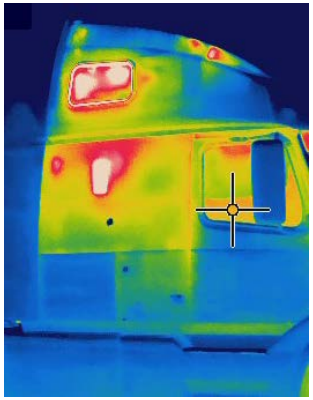
Infiltration tests characterize air leakage while infrared imaging identifies opportunities to reduce heat loss

Infiltration Test

- **Purpose**
  - Characterize air changes per hour (ACH)
  - Data are used as CoolCalc input
  - Measure of air leakage in truck
- **Test Methodology**
  - Inert gas (SF_6) released in cab
  - B&K gas analyzer measures PPM of SF_6 (3-hour period minimum)

Infrared Imaging

- **Purpose**
  - Characterize high heat loss paths in cab construction
  - Used to identify insulation opportunities
- **Test Methodology**
  - Outdoor, overnight
  - Heater on inside cab (1,200 W)
  - Infrared camera

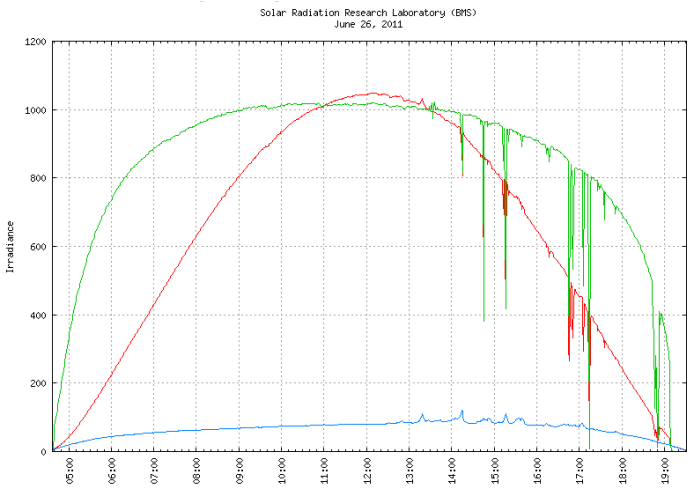


Technical Back-Up Slide – Test Procedures, Thermal Soak and UA

Are used to characterize thermal performance of commercially available and advanced technologies

Thermal Soak

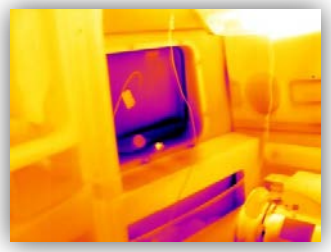
- **Purpose**
  - Characterize impact of solar load on vehicle temperatures
- **Test Methodology**
  - Vehicle exposed to solar loads (800-1,000 W/m^2) in an engine-off configuration
  - Low wind speed (< 5 m/s)



Overall Heat Transfer (UA) Test

- **Purpose**
  - Very similar to TMC RP 422A
  - Characterize impact of insulation
- **Test Methodology**
  - Outdoor, overnight test (no solar)
  - Heater inside cab/sleeper
  - Heater power at 1,000 watts (Q_{heater})
  - Interior and exterior air temps measured ($\Delta T = T_{air,\,truck} - T_{air,\,ambient}$)
  - Overall heat transfer (UA) calculated

$$UA = \frac{Q_{heater}}{\overline{T}_{air,truck} - \overline{T}_{air,ambient}}$$



Technical Back Up-Slide – Test Procedures, Idle A/C Test

A/C testing is used to directly link thermal management to idle reduction

- **Purpose**
  - Determine A/C system power required to maintain set point temperature
  - Characterize thermal load reduction technologies impact on idle reduction

- **Test Methodology**
  - Outdoor, daytime test
  - Electric A/C set point of 73°F
  - Weather conditions are measured
  - 24 hours of data are collected at set point, 10-hour rest time used
  - Sleeper curtain closed
  - A/C power is measured