

High Temperature Air-Cooled Power Electronics Thermal Design



Scot K. Waye
Principal Investigator
National Renewable Energy Laboratory
Annual Merit Review and Peer Evaluation Meeting

June 18, 2014

Washington, D.C.

PR-5400-61355

Project ID: APE019

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Overview

Timeline

Phase II Start Date: FY10

Project End Date: FY14

Phase II Complete: 80%

Budget

Total Project Phase II Funding:

DOE Share: \$1,700K

Funding Received in FY13: \$450K

Funding for FY14: \$450K

Barriers

- Cost – Eliminate need for secondary liquid coolant loop and associated cost and complexity
- Weight – Reduce unnecessary coolant, coolant lines, pump, and heat exchangers for lower system-level weight
- Performance – Maintain acceptable device temperatures while reducing complexity and system-level parasitic power

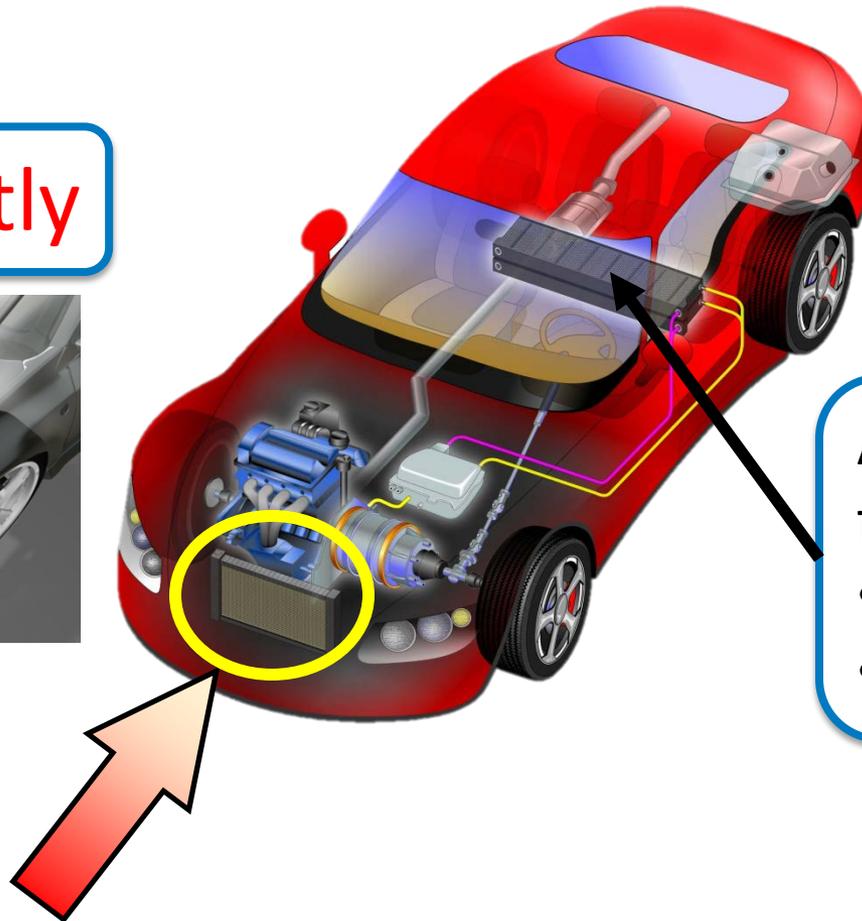
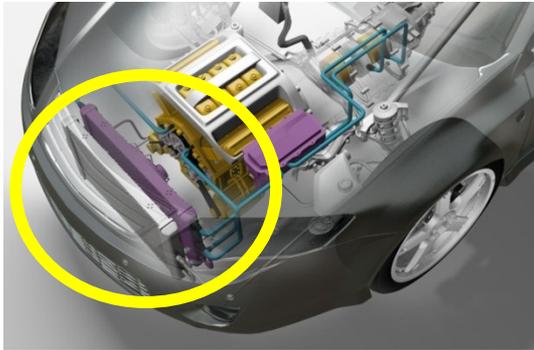
Partners

- Sapa Extrusions North America (aluminum extrusion/manufacturing)
- General Electric Global Research (previous air jet work)
- Oak Ridge National Laboratory (ORNL)
 - Madhu Chinthavali

Project Perspective

All vehicles are air cooled

Just indirectly



Air cooling a goal for batteries:

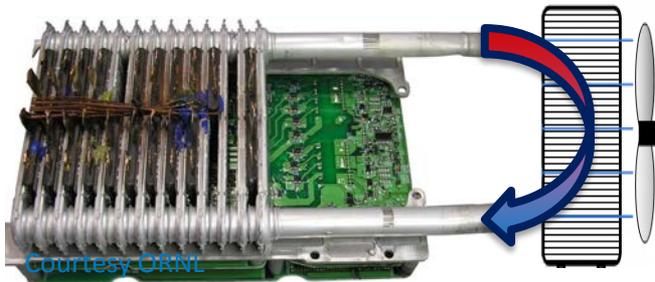
- Simple
- Direct

State of the Art

Indirect Air Cooling via Liquid Cooling

Intermediate liquid cooling loop rejects heat to air

LS 600H 2008



Camry 2007



Direct Air Cooling

Has been done before



Low Power

Honda Insight (12 kW)



Low Power Density



DOE Advanced Vehicle Testing Activity (Idaho National Laboratory)

AC Propulsion (150 kW)

Prototype: not in vehicle

Mitsubishi SiC Inverter (50 kVA/L, 400 V output, 156 kVA)

SiC = Silicon Carbide

Project Objective

Develop air-cooled thermal management system solution that contributes to:

- Accelerating electric drive vehicle adoption
- Eliminating intermediate cooling loops
- Meeting DOE's APEEM 2015 technical targets (12 kW/kg, 12 kW/L)
- Supporting *EV Everywhere*

FY14 Project-Specific Goals

- Build and demonstrate module-level thermal (NREL) and electrical (ORNL) design (10 kW)
- Conduct detailed analysis and proof of concept at system level to show progress relative to DOE's technical targets

Project Overview

Advantages

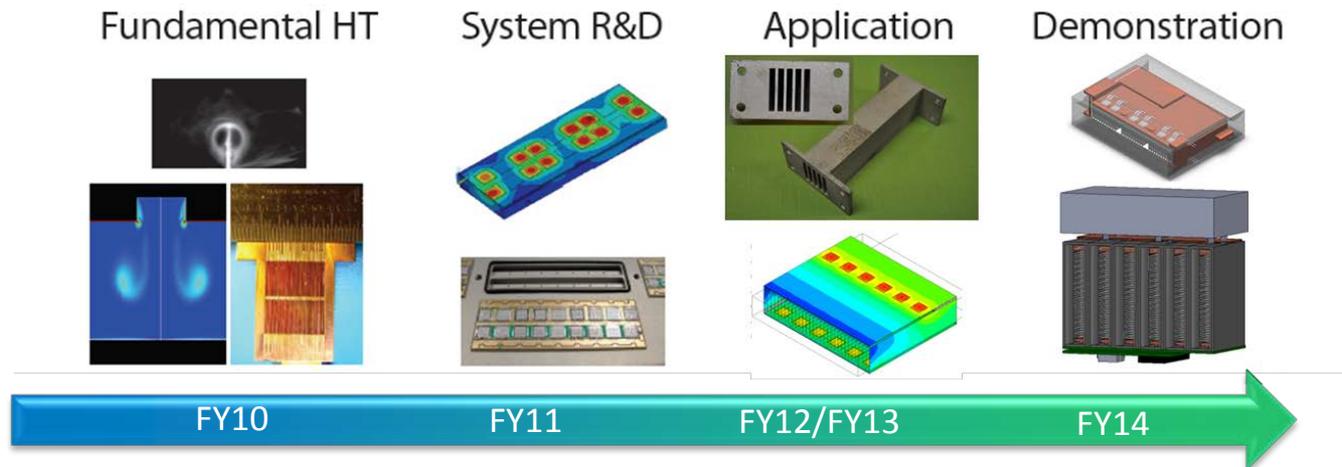
- Rejecting heat directly to air can **eliminate** intermediate liquid-air loops
- Attractive for high-temperature device (wide bandgap) applications
- Air is benign, is not carried, and does not need to be replaced
- Air is a dielectric and can contact the chip directly
- No global warming potential

Challenges

- Air is a poor heat-transfer fluid
 - Low specific heat
 - Low density
 - Low conductivity
- Potential parasitic power of fan
- Not yet used in high power production vehicles
- Filtering, fouling, fan noise

Project Pathway

This collaborative research with ORNL is on track to demonstrate an air-cooled inverter for 30-kW continuous, 55-kW peak power

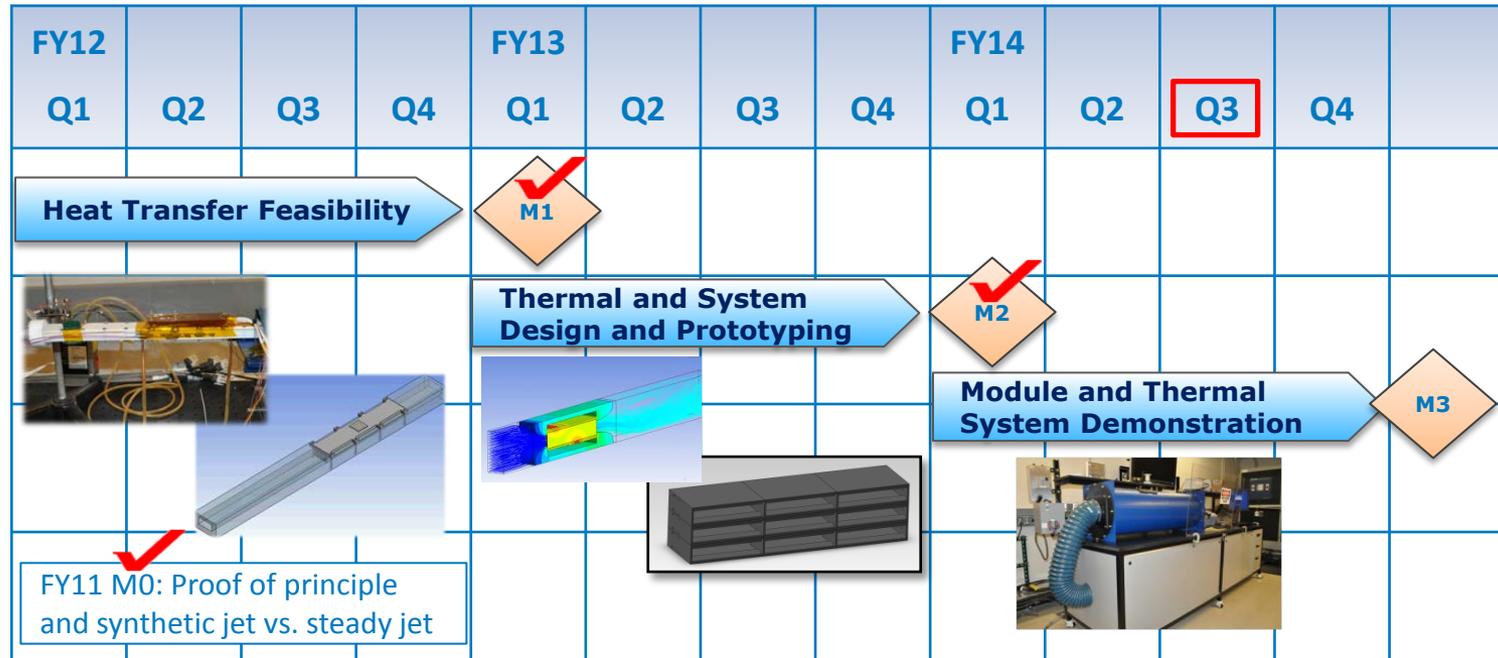


Air-cooled inverter technology can meet 2015 DOE targets (12 kW/kg, 12 kW/L) and provides pathways to meet 2020 targets with acceptable parasitic loads



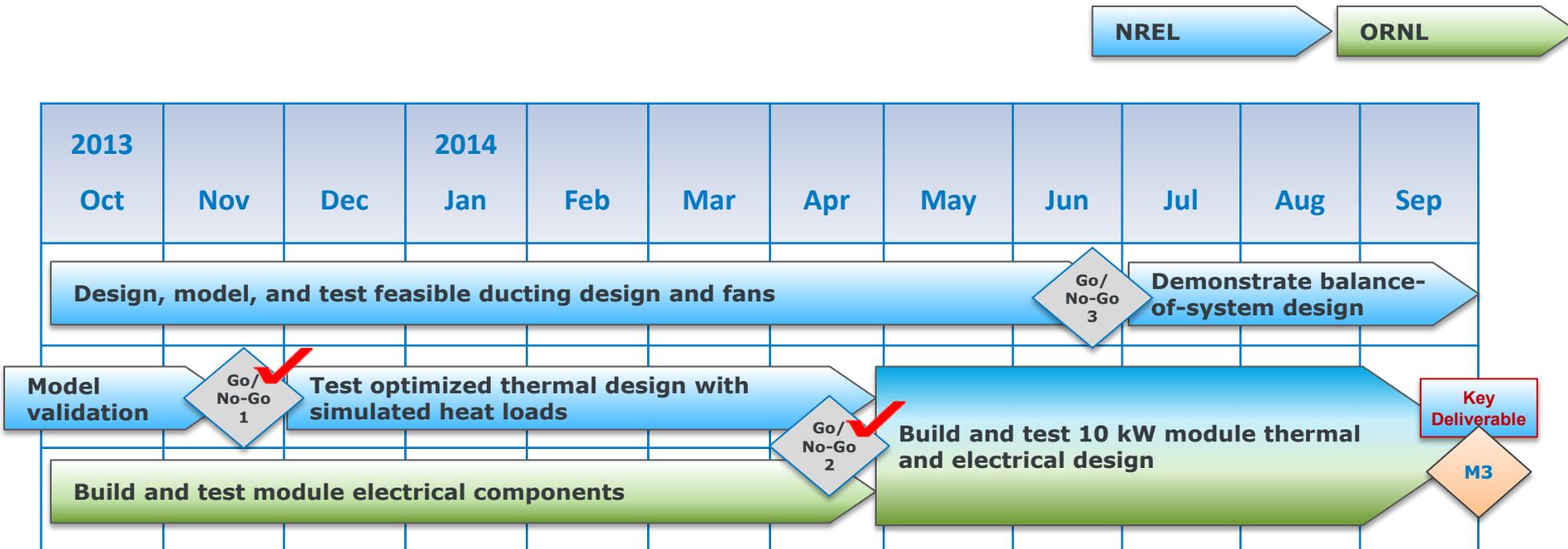
Opens path to **adoption by industry** as an alternative to standard liquid-cooled system that lowers weight, volume, and cost

Project Summary: FY11 – FY14



Deliverable/Milestone	Go/No-Go
M1 (NREL): Heat transfer feasibility study M1 (ORNL): Device-level evaluation	Heat transfer accomplished with reasonable flow and pressure loss? 
M2: Build and test thermal module and initial balance of system M2: Module electrical design	Demonstrated design on track to meet targets? 
M3: Demonstrate operating module and thermal system M3: Electrical inverter design and module build	Met targets for module level (10 kW)?

FY14 Tasks to Achieve Key Deliverable

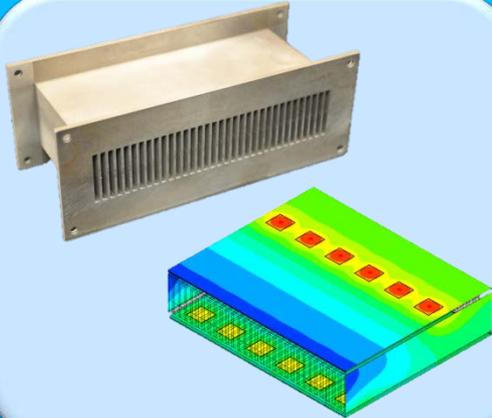


Go/No-Go 1: Down selection of optimized design meets targets? ✓

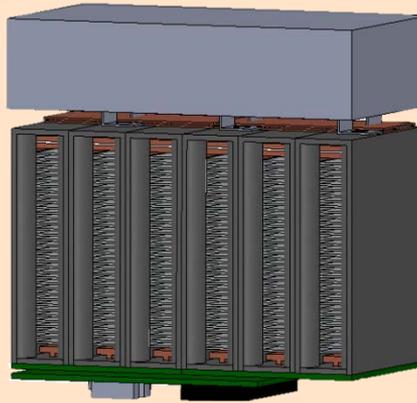
Go/No-Go 2: Module thermal/electrical design on track to meet targets? ✓

Go/No-Go 3: Balance-of-system design on track to meet air flow requirements?

Key Deliverable, M3: **Demonstrate operating 10-kW module and deliver system metrics (inverter power density, specific power, parasitic power)**



Cooling Technology



Packaging



Balance of System

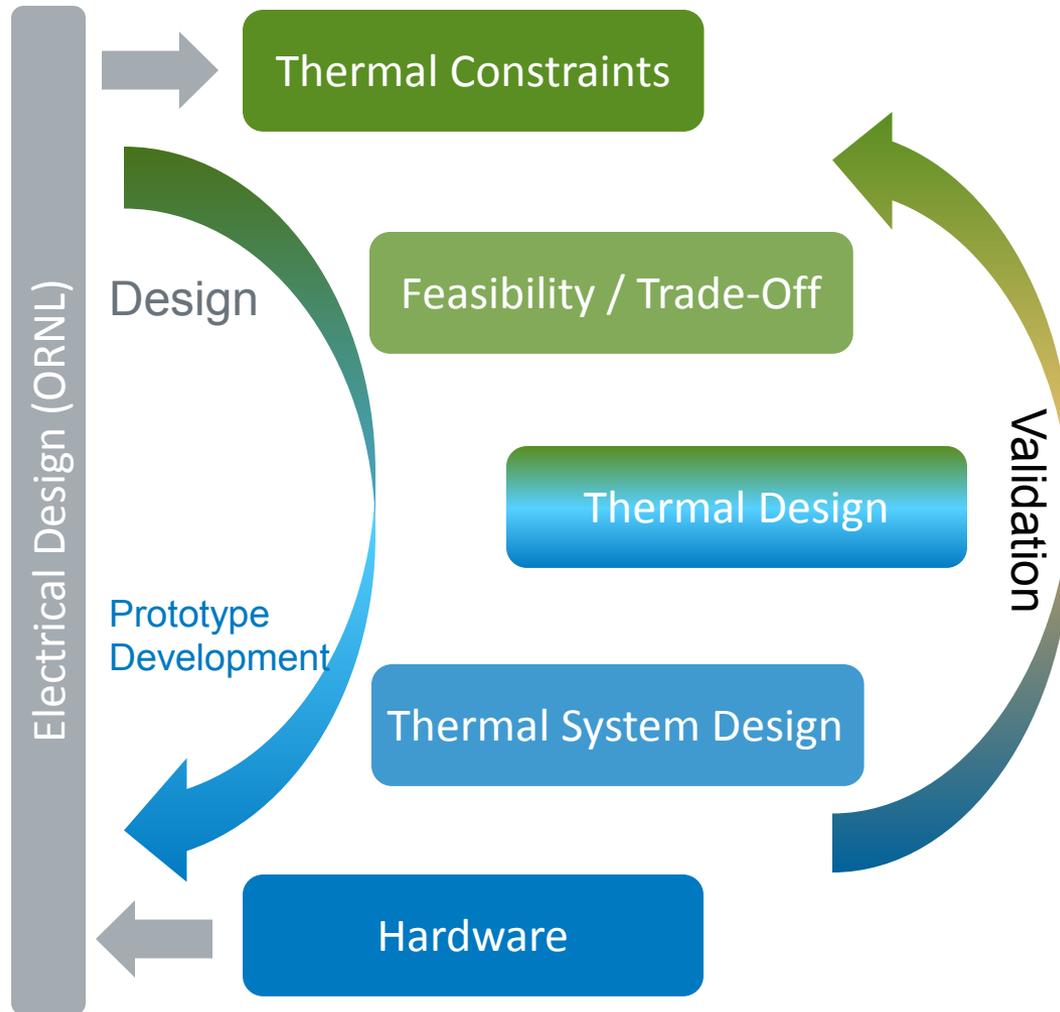


- Maximum Temperatures
- Device Efficiency

- Inverter Components
- Under-hood Location

- Parasitic Power (Fan)
- Air Source

High-Temperature Air-Cooled Inverter



- **Electrical Design:** Device type and location; electrical duty cycles; temperature-dependent losses, efficiency
- **Thermal Constraints:** Maximum junction temperature; heat generation; coolant temperature
- **Feasibility / Trade-Off:** Modeling; extrapolate to inverter scale
- **Thermal Design:** Sub-module testing and model validation; fan/ducting testing; optimization
- **Thermal System Design:** Balance-of-system analysis; full system models
- **Hardware:** Module prototype, improve design; balance-of-system testing

Module Optimization to Inverter

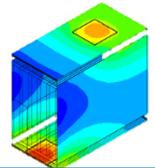
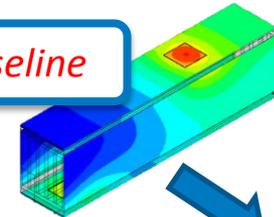
Heat dissipation for 55-kW peak power

From conservative analytical analysis ~ 2.7 kW heat (95% efficient)

2 devices

- Fixed device heat generation and temperature (175°C)
- Parametrically optimized geometry by varying air flow rate using computational fluid dynamics (CFD) – ANSYS Fluent

Baseline



Optimized

- Extrapolated sub-module modeling and testing results to module level

- Added in balance-of-inverter components†

Capacitor

9 modules

Capacitor

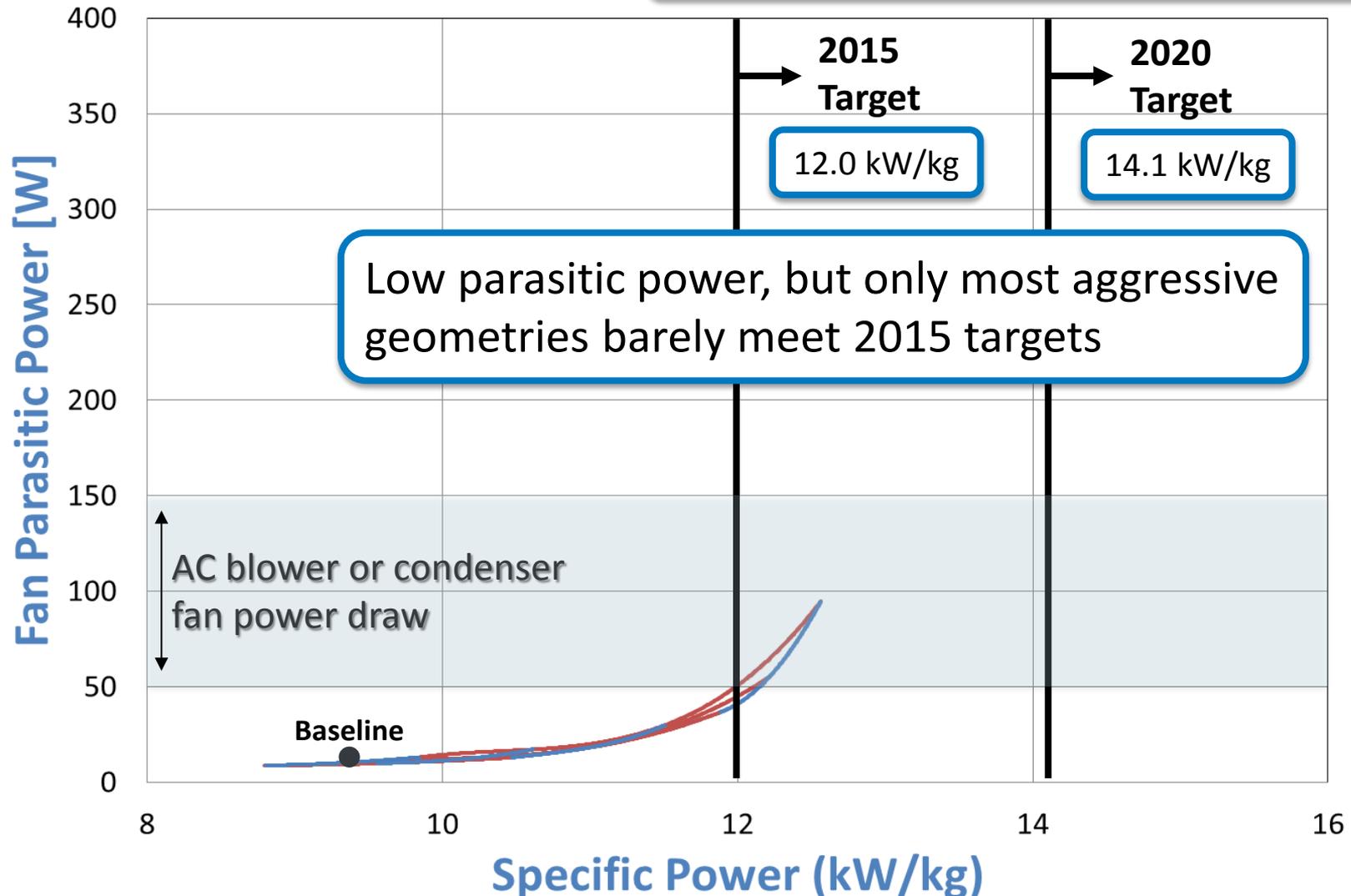
6 modules

- †Casing volume adjusted for fin geometry
- †Capacitor ~1.13 L*, ~1.62 kg*
- †Gate driver + control board ~0.88 L*, ~0.42 kg**

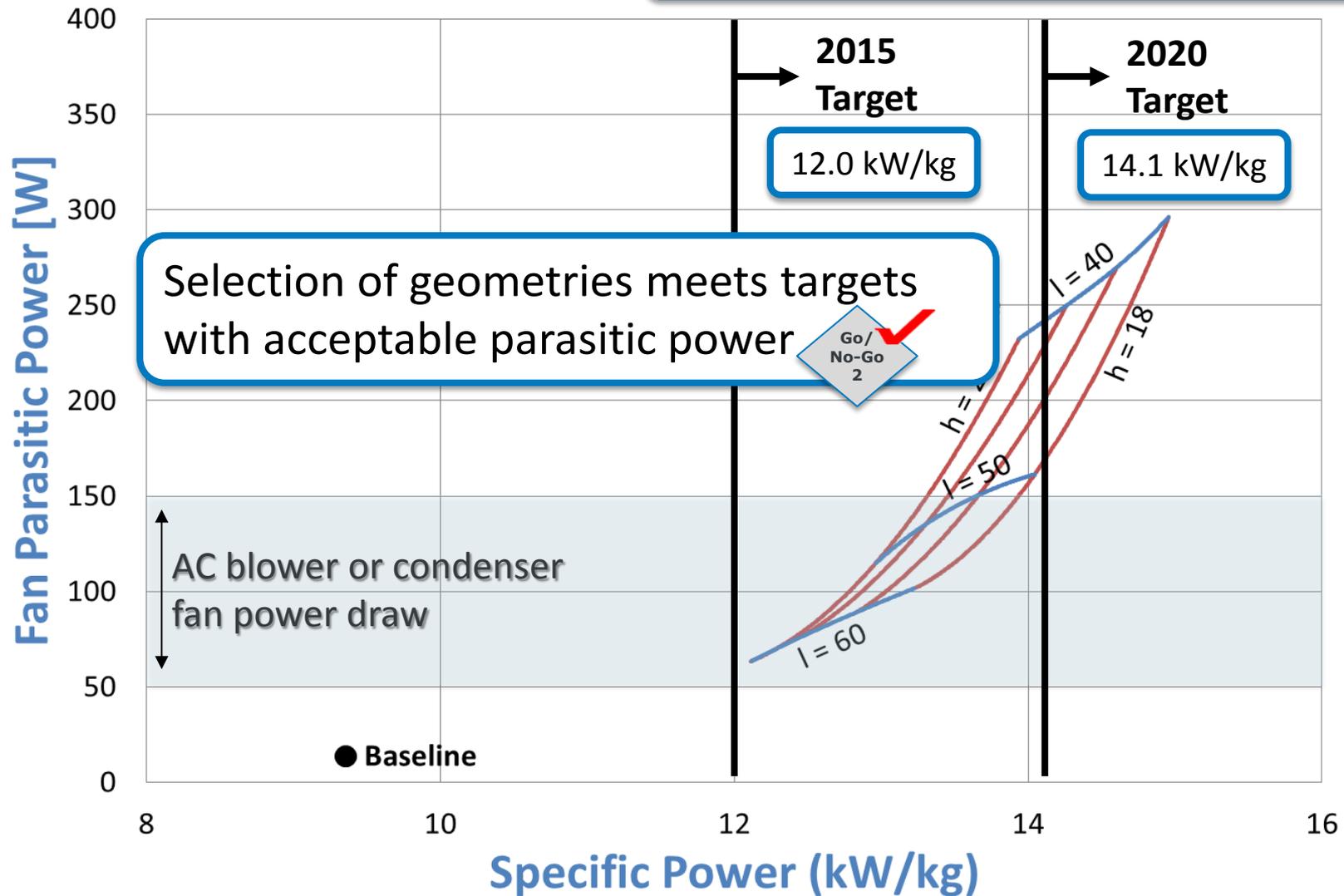
* Assumption provided by ORNL; ** NREL assumption based on similar device measurement

DBA = direct-bond-aluminum

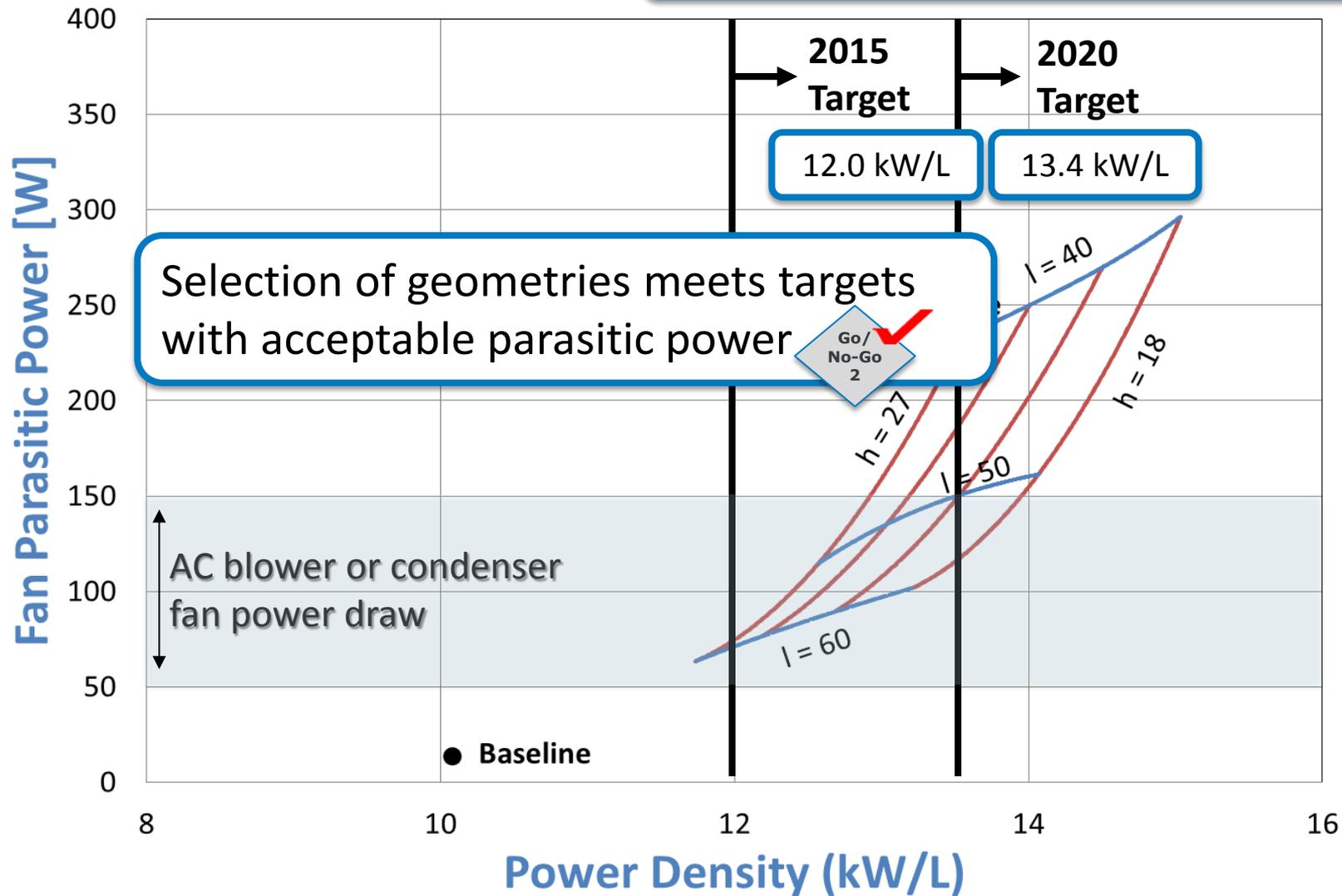
Each geometry represents one CFD simulation



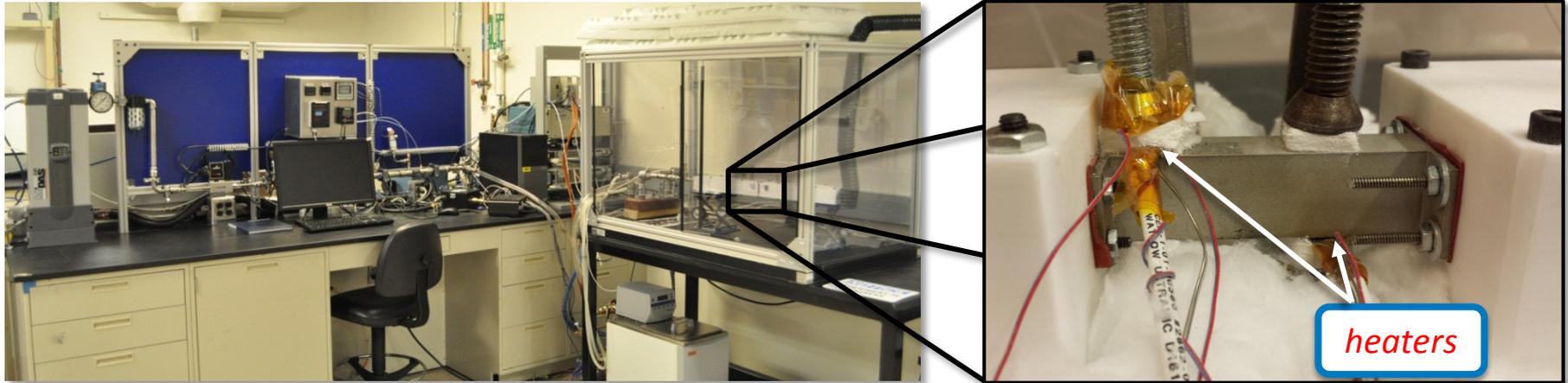
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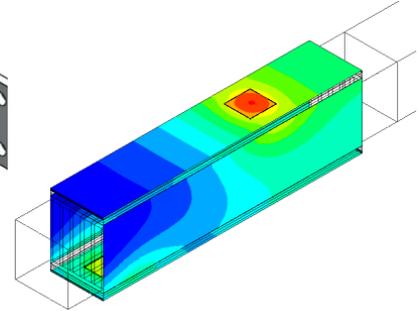
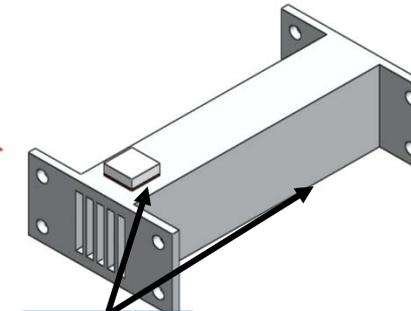
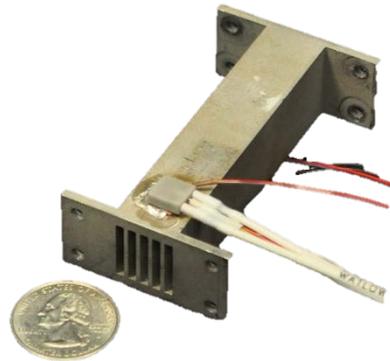
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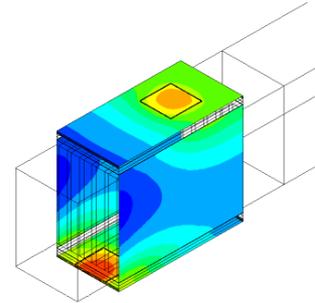
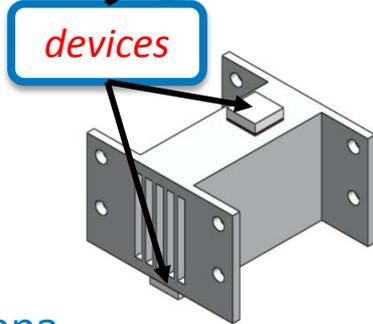
Heat Exchanger Experiments



Baseline



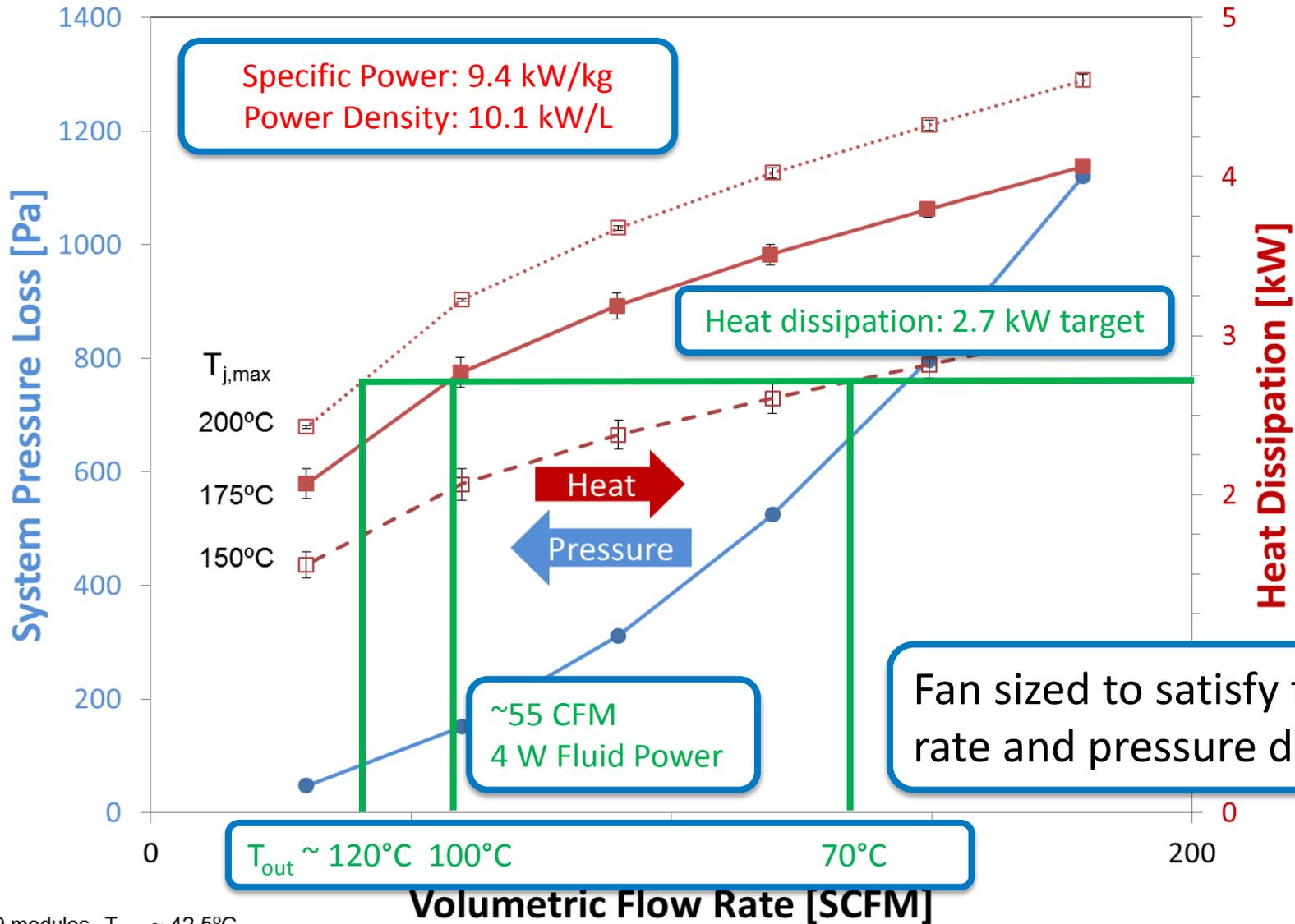
Optimized



devices

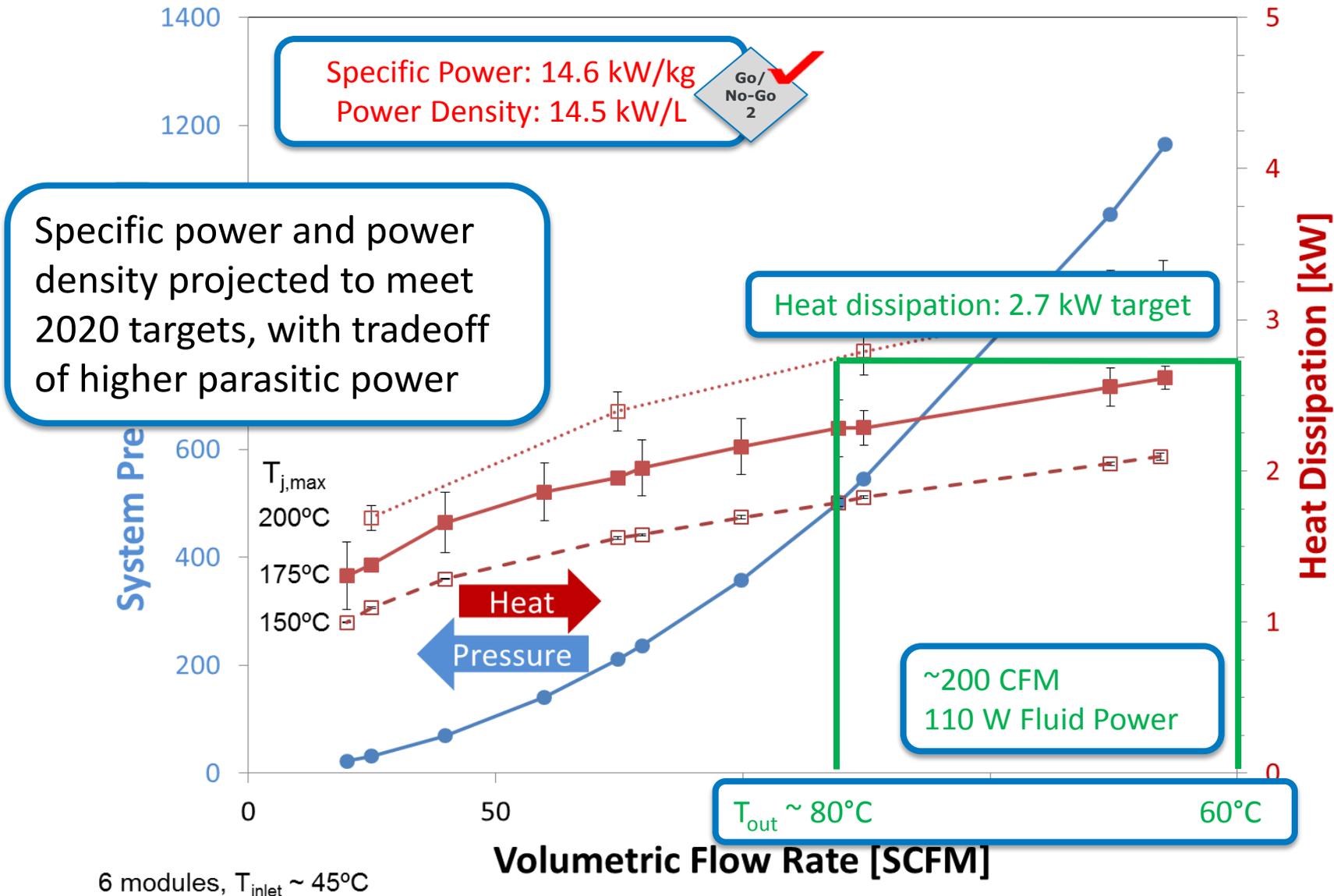
Prototypes provided by Sapa

Heat Dissipation for Baseline Case (9 modules)



9 modules, $T_{inlet} \sim 42.5^\circ\text{C}$

Heat Dissipation for Optimized Case (6 modules)



6 modules, $T_{inlet} \sim 45^{\circ}\text{C}$

Responses to AMR FY13 Reviewers' Comments

Feedback: The reviewer indicated that this is a good team, but felt that a **vehicle manufacturer should be added to the team to get industry input**. This reviewer suggested that this would help the project to become easier to manufacture and get industry acceptance.

Response: We have a strong collaboration with ORNL. NREL is addressing thermal issues, and ORNL is focused on the electrical design. On the thermal work, NREL is collaborating with Sapa Extrusions North America to aid in manufacturing concerns regarding extruded aluminum, a potential method for simple and inexpensive cooling channels. ORNL is working with device manufacturers and other partners on the electrical design. We have met with OEMs and first-tier suppliers through on site visit presentations to get feedback on the direction of the research and to address the advantages, challenges, and potential applications for vehicle platform adoption. We are addressing the barriers and constraints that they have brought up in these meetings.

Feedback: The reviewer suggested that **future work should produce a proof-of-concept of a working prototype** and address practical application issues.

Response: This fiscal year, the focus has been shifted from modeling and analysis to direct experimentation and proof-of-concept. Baseline and optimized sub-modules have been tested with data extrapolated to module and inverter level. An optimized module has also been manufactured and will be tested this fiscal year. One module heat sink will be tested for thermal performance at NREL, while another was sent to ORNL so they could mount the electrical topology and test the electrical design.

Feedback: The reviewer observed that **this project is very relevant to future wide-band applications** because cooling requires significant energy that reduces the EV drive efficiency.

Response: We agree that air cooling is better used on high-temperature application, where the large temperature difference helps overcome the shortcomings of air properties. Wide-band-gap devices provide an emerging opportunity for air cooling as they can be run at higher temperatures. They are more efficient, but with smaller areas, the heat flux is still a challenge. We believe air cooling will be a potential effective alternative to traditional cooling strategies.

Collaboration and Coordination

Collaborations

- **Industry:** Sapa Extrusions North America
 - Provided aluminum channel heat exchanger prototypes
 - Offered guidance on manufacturability for various designs and direction on reducing material and manufacturing costs
- **Federal Laboratory:** Oak Ridge National Laboratory (Madhu Chinthavali)
 - Building and testing electrical topology
 - Provided device information, estimated heat loads, balance-of-inverter component sizing, and design constraints
- **University/Industry:** WBG Institute (outside Vehicle Technology Office)
 - Developing relationships with industry and university partners for potential application of technology

Coordination

- **Industry:** Domestic OEMs and inverter suppliers
 - Contributed feedback on research and potential applications through direct one-on-one meetings

OEM = original equipment manufacturer

Remaining Challenges and Barriers

Cooling Technology

- Demonstrating prototype that meets technical targets

Packaging

- Showing how balance-of-inverter components complete efficient inverter packaging
- Under-hood location considerations for vehicle platforms

Balance of System

- Parasitic power requirements
- Comparison of weight, volume, and cost of necessary components (i.e. ducting, fans) compared to liquid-cooled loop

Electrical and Thermal Module (10 kW)

M3

Build 10-kW module ✓

Demonstrate 10-kW module (thermal performance)

Build 10-kW module ✓

Demonstrate 10-kW module (electrical performance)

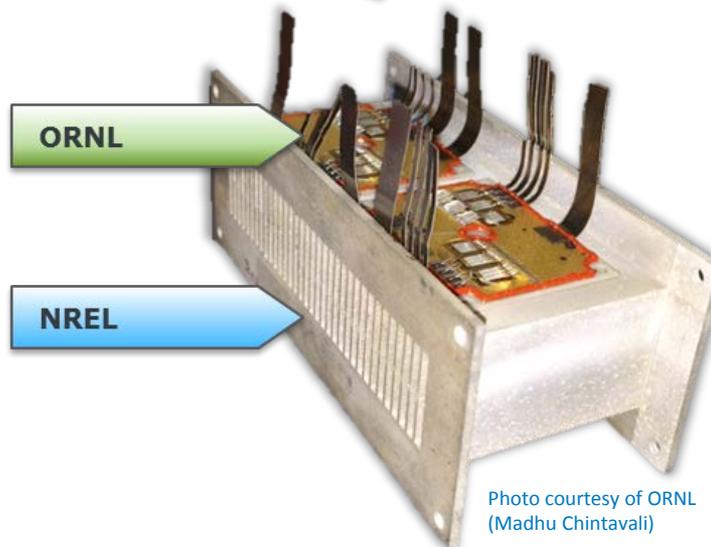
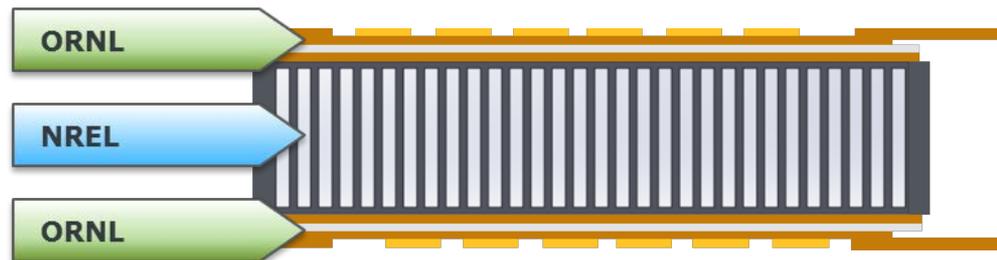
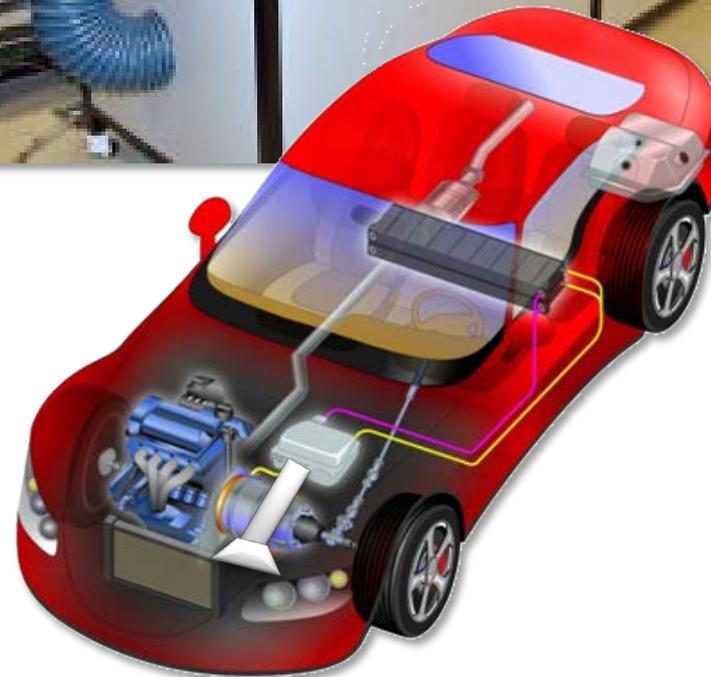


Photo courtesy of ORNL (Madhu Chintavali)

M3

Build and test sample system to measure and characterize parasitic load



Summary

DOE Mission Support

- Overcome barriers to accelerate adoption of low-cost air-cooled heat exchangers for power electronics, especially for high-temperature (i.e. WBG) devices; air remains the ultimate sink

Approach

- Create system-level understanding and designs addressing advanced cooling technology, packaging, and balance of system
- Develop solutions from fundamental heat transfer, then system-level design, to application – culminating in demonstration of concept

Collaborations

- ORNL developed electrical topology and is testing with NREL air-cooled heat exchanger and provided balance-of-inverter component sizing and characterization and device loss (heat dissipation) direction
- Sapa Extrusions North America provided aluminum heat exchanger prototypes and guidance on manufacturing constraints to control cost
- Met with OEMs and 1st tier suppliers to obtain feedback on air-cooling applications and overcoming barriers and constraints for adoption

Summary

Technical Accomplishments

- Optimized thermal design showing candidate designs that meet DOE power density and specific power technical targets with acceptable parasitic loads
- Demonstrated baseline and optimized module design thermal performance and, using balance-of-system assumptions, projected to meet 2015 DOE technical targets
- Built module-level (10-kW) heat exchanger that will be tested in FY14

Maximum Junction Temperature – 175°C	2015 Target	2020 Target	Baseline (9 modules)	Baseline (6 modules)	Optimized (9 modules)	Optimized (6 modules)
Power Density [kW/L]	12.0	13.4	10.1	12.8	11.8	14.5
Specific Power [kW/kg]	12.0	14.1	9.4	12.7	11.1	14.6
Fluid Power [W]	N/A	N/A	4	34	70	110

Acknowledgments and Contact

Acknowledgments:

- Susan Rogers and Steven Boyd
U.S. Department of Energy
- Andrew Wereszczak
Oak Ridge National Laboratory

Team Members:

Matt Musselman

Charlie King

Kevin Bennion

Madhu Chinthavali (ORNL)

For more information contact:

Principal Investigator

Scot K. Waye

Scot.Waye@nrel.gov

Phone: (303) 275-4454

APEEM Task Leader

Sreekant Narumanchi

Sreekant.Narumanchi@nrel.gov

Phone: (303)-275-4062

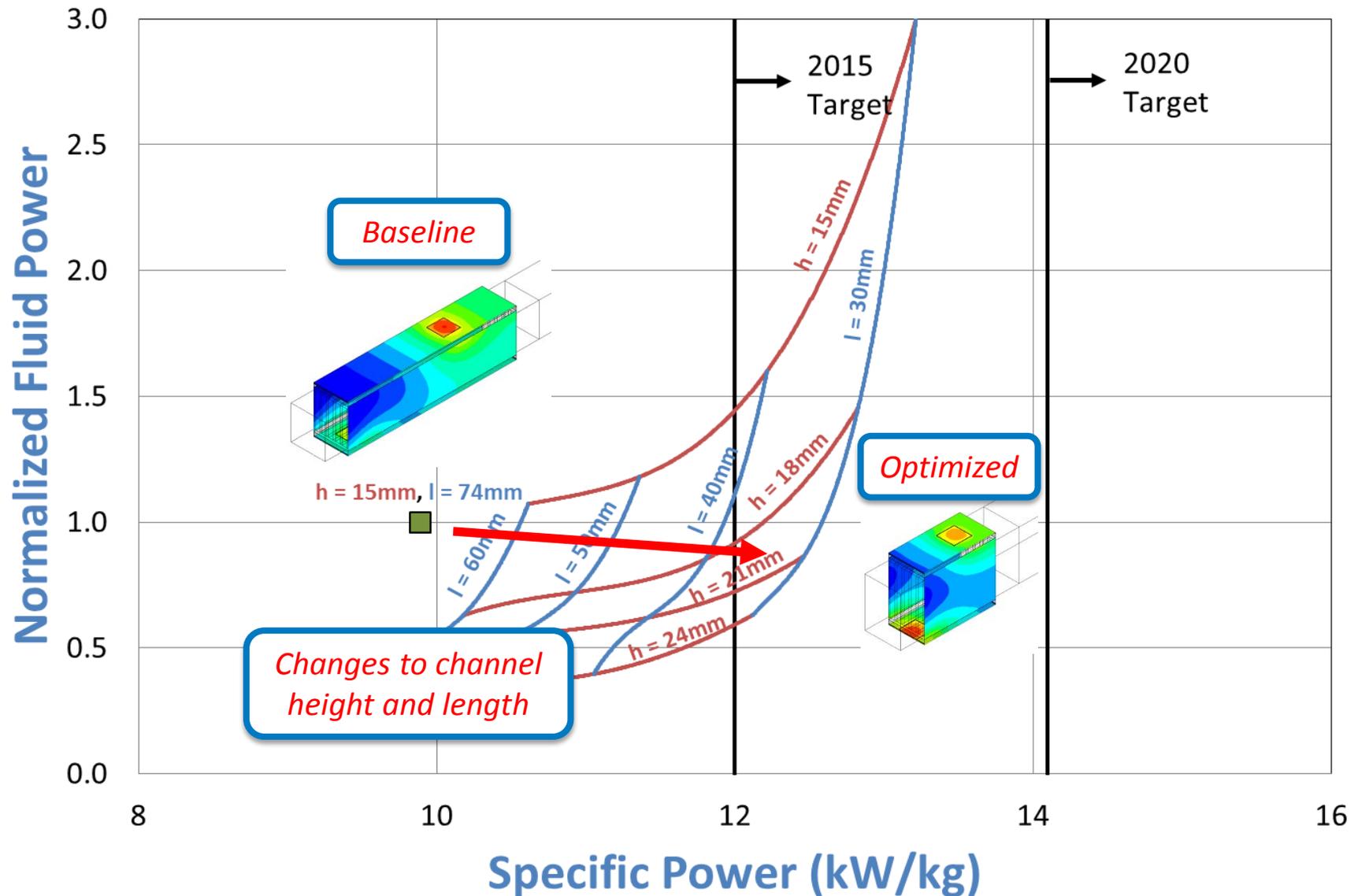


Technical Back-Up Slides

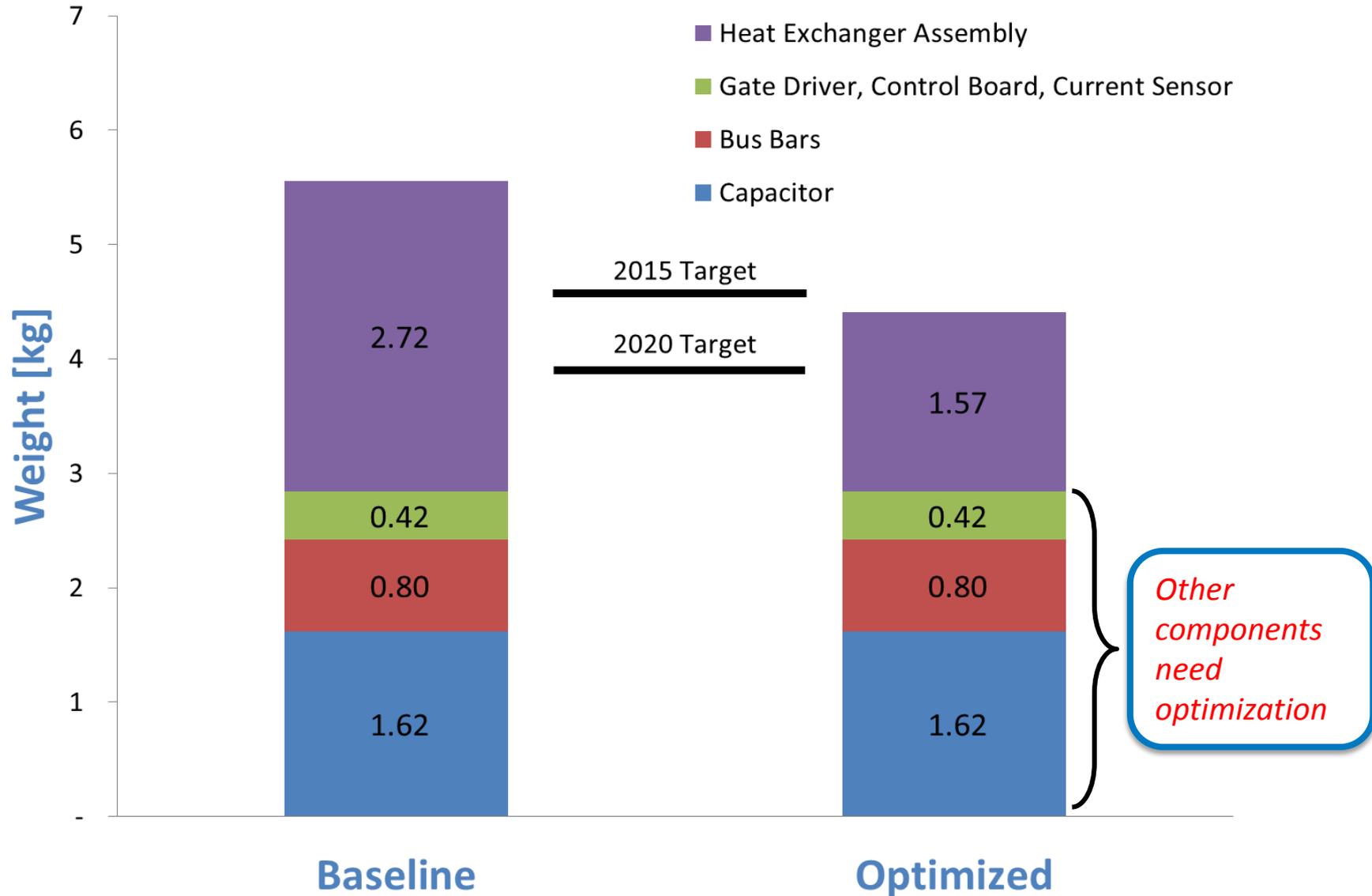
Optimized Geometries Improve Specific Power

On track to meet DOE 2015 technical target

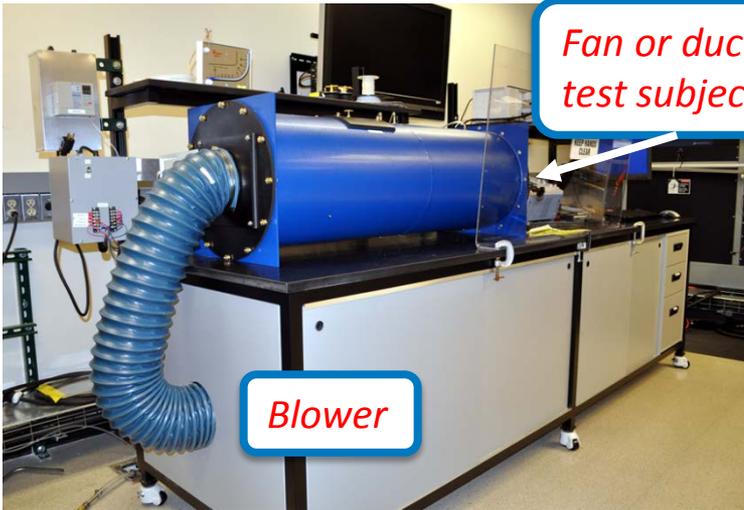
FY13 – Go/No-Go 1



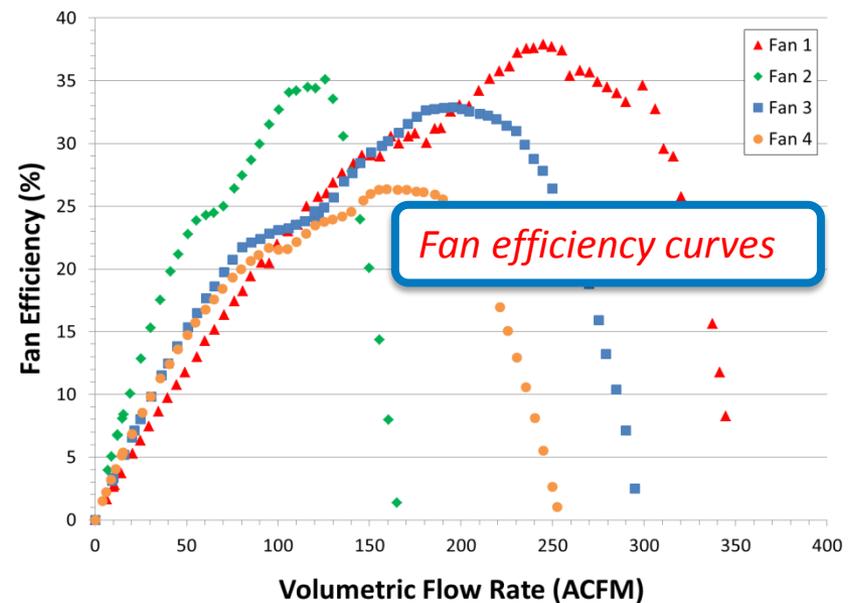
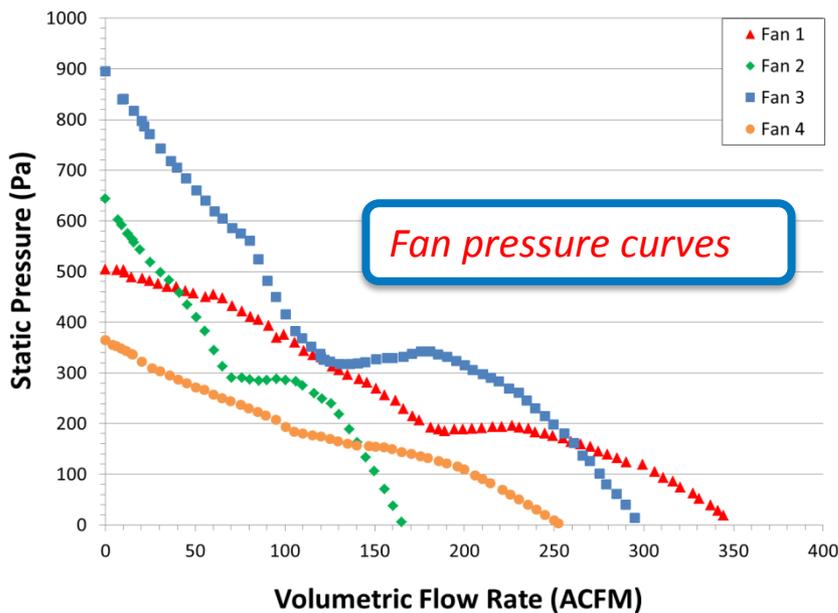
Component Contributions to Inverter Weight



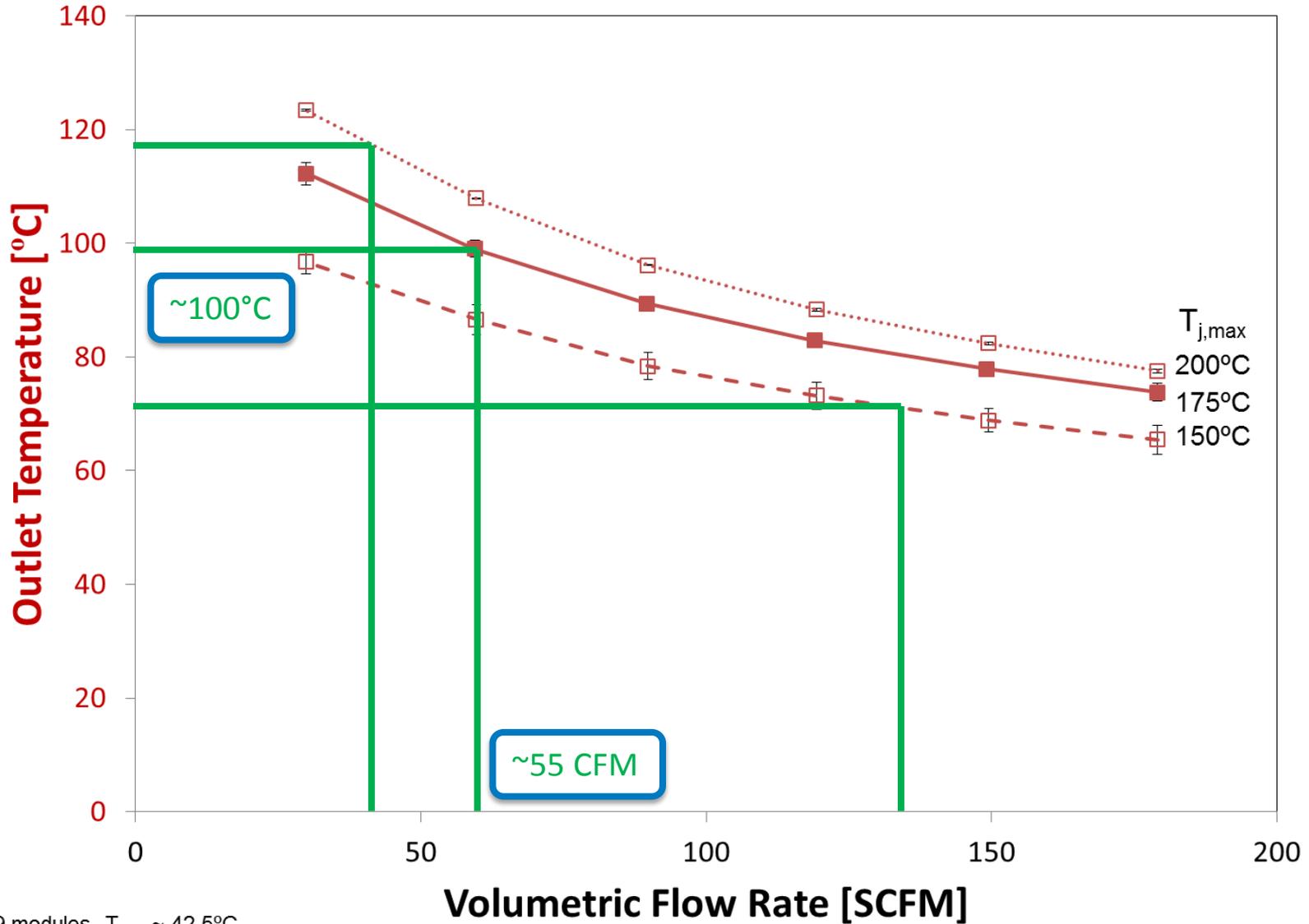
System Level Test Bench



- Meets Fan Test Standard
 - ANSI/AMCA 210-07
 - ANSI/ASHRAE 51-07
- Range: 5–500 CFM
- U_{95} Flow: ± 1.5 CFM
- U_{95} Pressure: ± 1.6 Pa

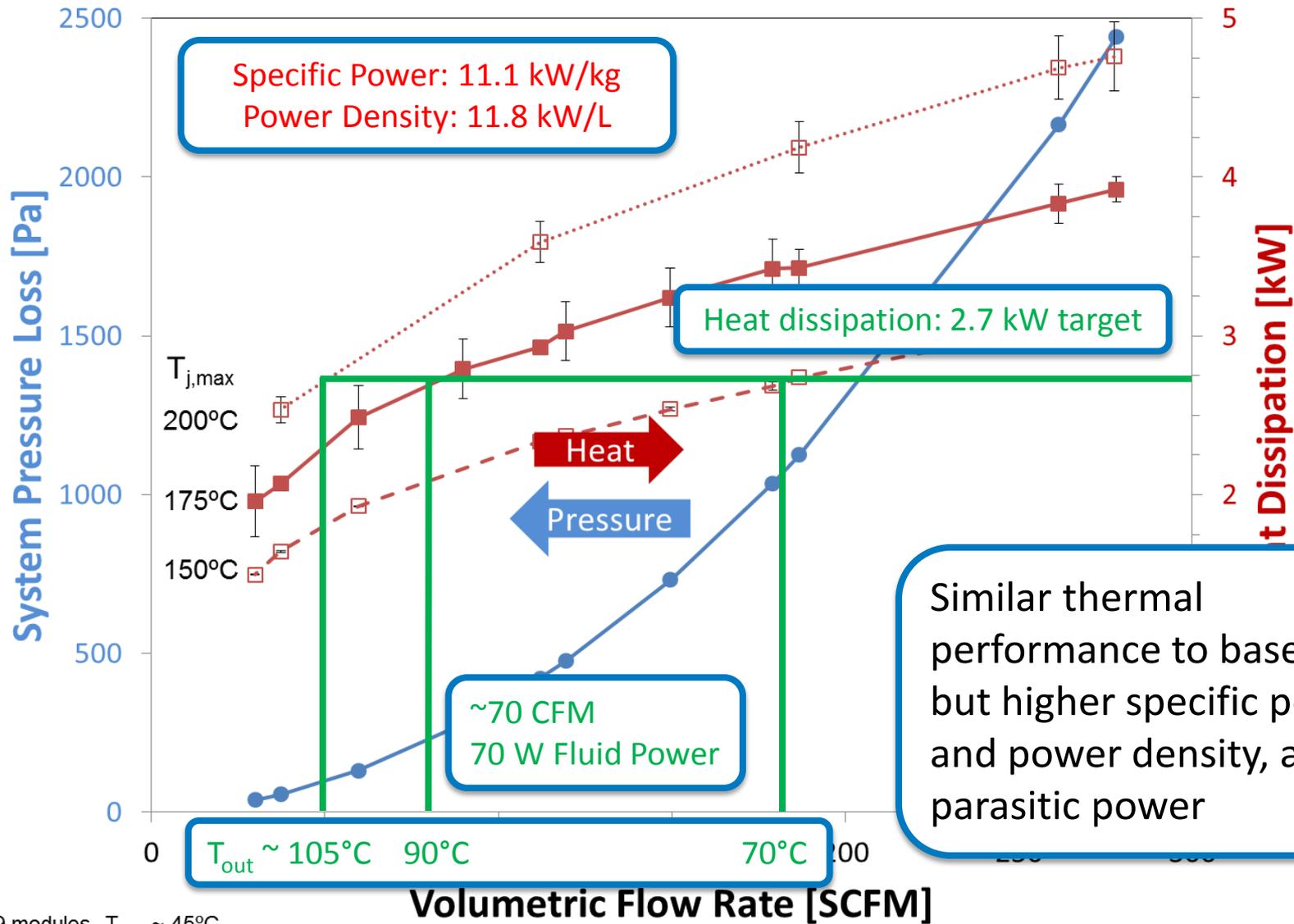


Air Outlet Temperature for Baseline Case



9 modules, $T_{inlet} \sim 42.5^\circ\text{C}$

Heat Dissipation for Optimized Case (9 modules)



9 modules, $T_{inlet} \sim 45^\circ\text{C}$