PEM Fuel Cell Systems for Commercial Airplane Systems Power

Project ID #MT002

Sandia National Laboratories

Lennie Klebanoff*

Joe Pratt*†

Karina Munoz-Ramos

Abbas Akhil

Dita Curgus

Ben Schenkman

*Co-Principal Investigators

†Presenter

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Project Overview

Timeline

- **Project start date: 7/1/2010**
- **Project end date: 3/31/2011**
- **Percent complete: 100%**

Partners

- **Boeing**
- **Hydrogenics**

Barriers

- **System Weight & Volume**
- **Cost**
- **Efficiency**

Budget

Total project funding:

- **DOE share:**
  - FY2010: $400,000
  - FY2011: $0
- **Contractor share: $0**

Relevance

- **The Department of Energy is broadening the application scope of its Fuel Cell Technologies Program to include:**
  - Commercial aircraft
  - Airport ground support equipment
- **This project assesses:**
  - Feasibility of using proton exchange membrane (PEM) fuel cell systems on a commercial airplane, and
  - The impact of such a system on:
    - Other airplane systems
    - Overall flight performance

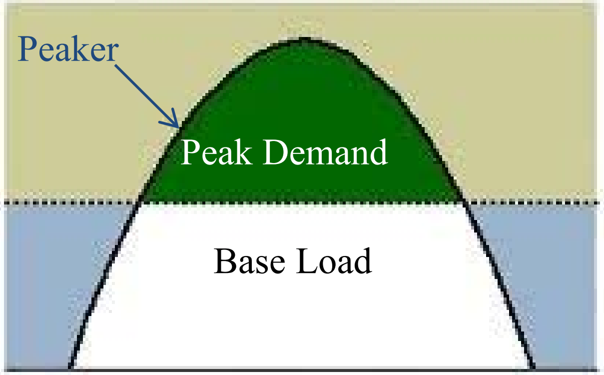
Presentation Outline

- ❖ Approach
- ❖ Results
- ❖ Summary
- ❖ Collaborations and Acknowledgements

We looked at on-board PEM fuel cell systems designed to provide power for any combination of three possible electrical loads.

Galley (20-60 kW)
Used during taxi, takeoff and climb, and cruise.

In-flight Entertainment (IFE, 20 kW)
Used during all phases of flight.



Peaker Power (2 x 75 kW)
Used during Descent and Landing phase only.

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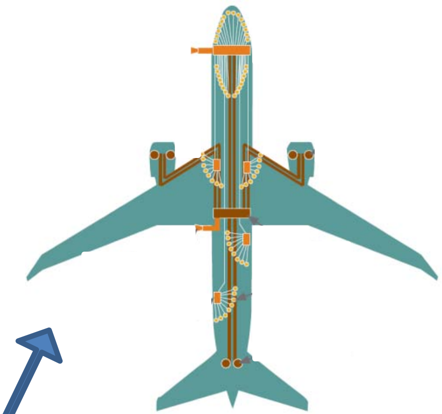
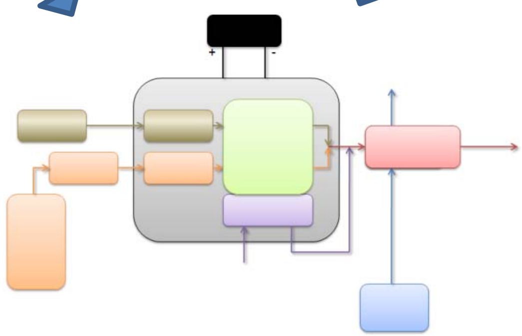
This study is comprised of three components, each of which depend on each other and all of which affect airplane performance.

Hardware Requirements and Sizing

Electrical Architecture Design





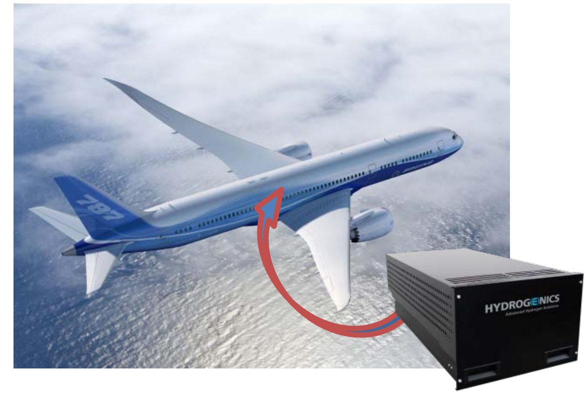
Thermodynamic Systems Analysis

Airplane Performance

Our analysis reveals the differences between the base airplane and the airplane with the fuel cells.

Base Airplane

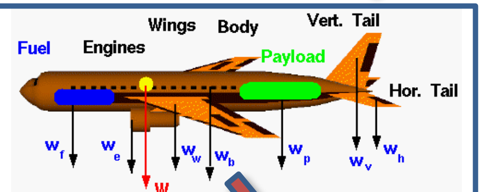
Airplane with fuel cell



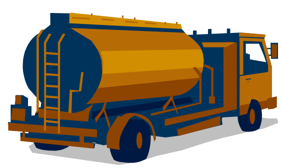
Compare

Find

Change in Empty Mass



Change in Drag



Change in Required Fuel

- Base mission (SFO ↔ JFK, 5 hrs): **7,500 gallons** (23,000 kg) of jet fuel used.
- On this flight, about **200 gallons** (625 kg) will provide 500 kW of electricity.

Significant reductions to the electrical system demands on jet fuel may be small when compared to the overall airplane fuel consumption.

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We base hardware sizes on representative commercially available components that meet performance requirements.

- **Proton Exchange Membrane Fuel Cell:**
  - 149 W/kg and 103 W/L for current technology.
    - Hydrogenics HYPM-12 linearly scaled with actual power.
  - 650 W/kg and 650 W/L used for forecast analysis
    - DOE 2015 target of integrated transportation fuel cell power systems operating on direct hydrogen.

- **Hydrogen tank:**
  - 5.8% gravimetric density, 17.0 gH_2/L for current technology.
    - 350 bar (5,000 psi) compressed gas storage.
  - 7.5% gravimetric density, 70 gH_2/L used for forecast analysis
    - DOE Ultimate target of on-board H_2 storage for light duty vehicles.

- **Other components modeled:**
  - Heat exchangers
  - Cooling water pump
  - Blowers
  - Tubing and ducting
  - Pressurized gas regulator

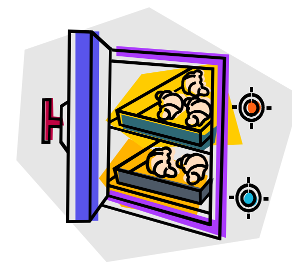
The waste heat produced by the fuel cell could be used for a variety of on-board needs.

Heat Output Mechanisms:

- Hot cooling water (90% of total)
- Cathode exhaust (10% of total)
- Un-reacted H_2 (< 1%)

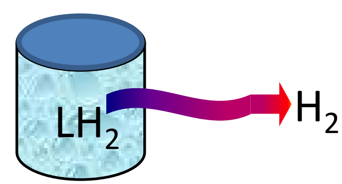
- Absorbed by airplane's cooling system

On-board Heat Uses:



- Food preparation

- Hot water

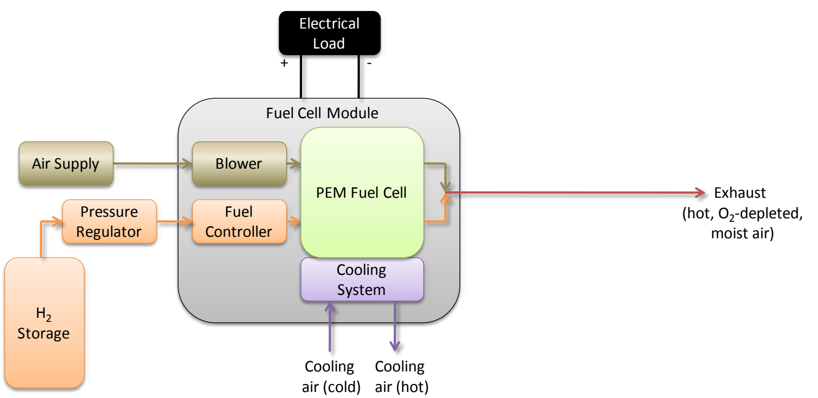


- Liquid H_2 pre-heating (only for LH_2 systems)

- Engine fuel pre-heating

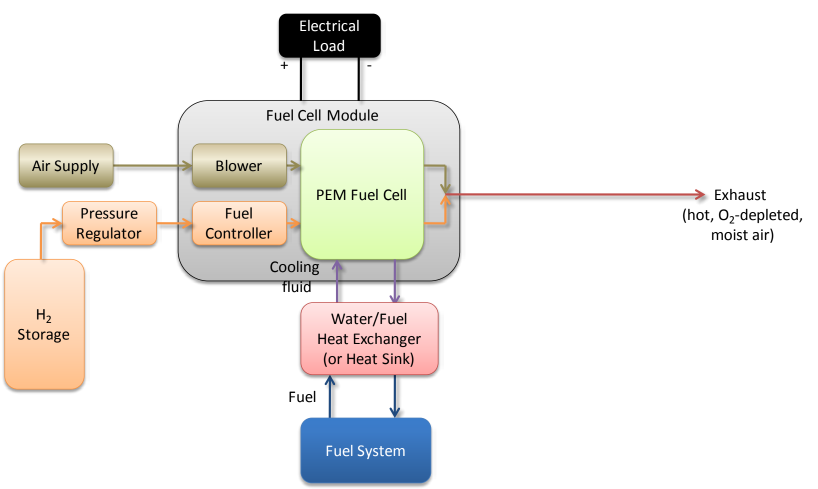
The primary differences in system configuration are the methods of utilizing the waste heat.

Case 1a: Air Cooled

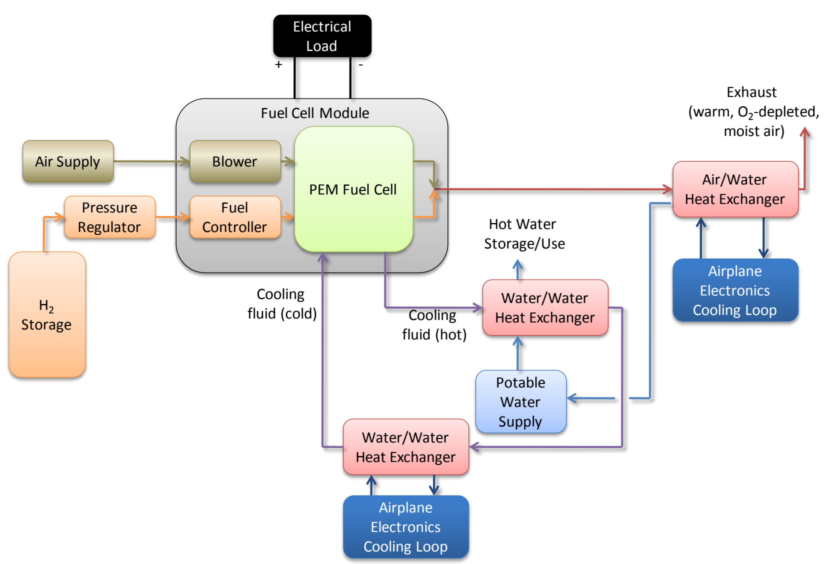


In all, 11 configurations were analyzed. Here is just a sample of the system configurations considered.

Case 6a: Fuel Cooled



Case 3b: Water Cooled, Limited Hot Water, Max Water Recovery



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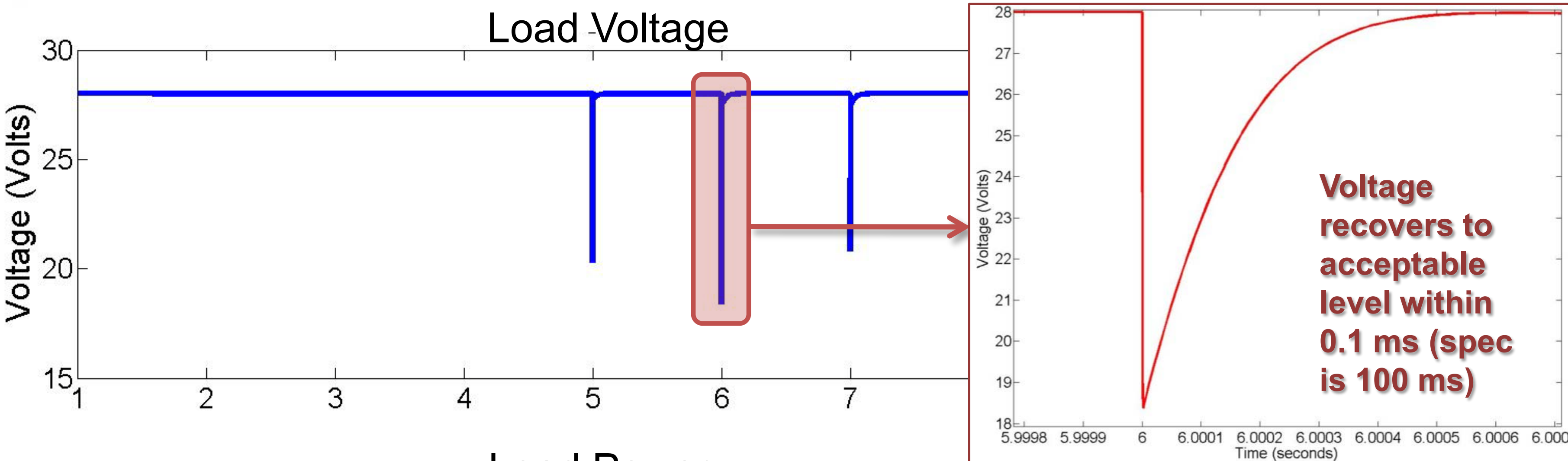
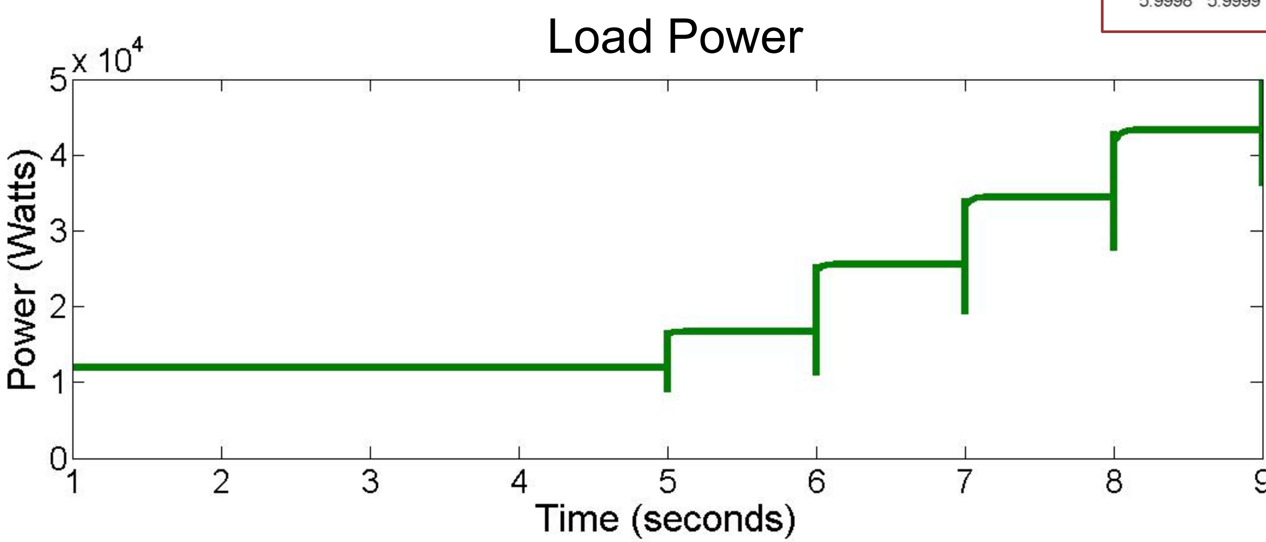
Electrical modeling and simulation shows the fuel cell performs all required electrical functions.

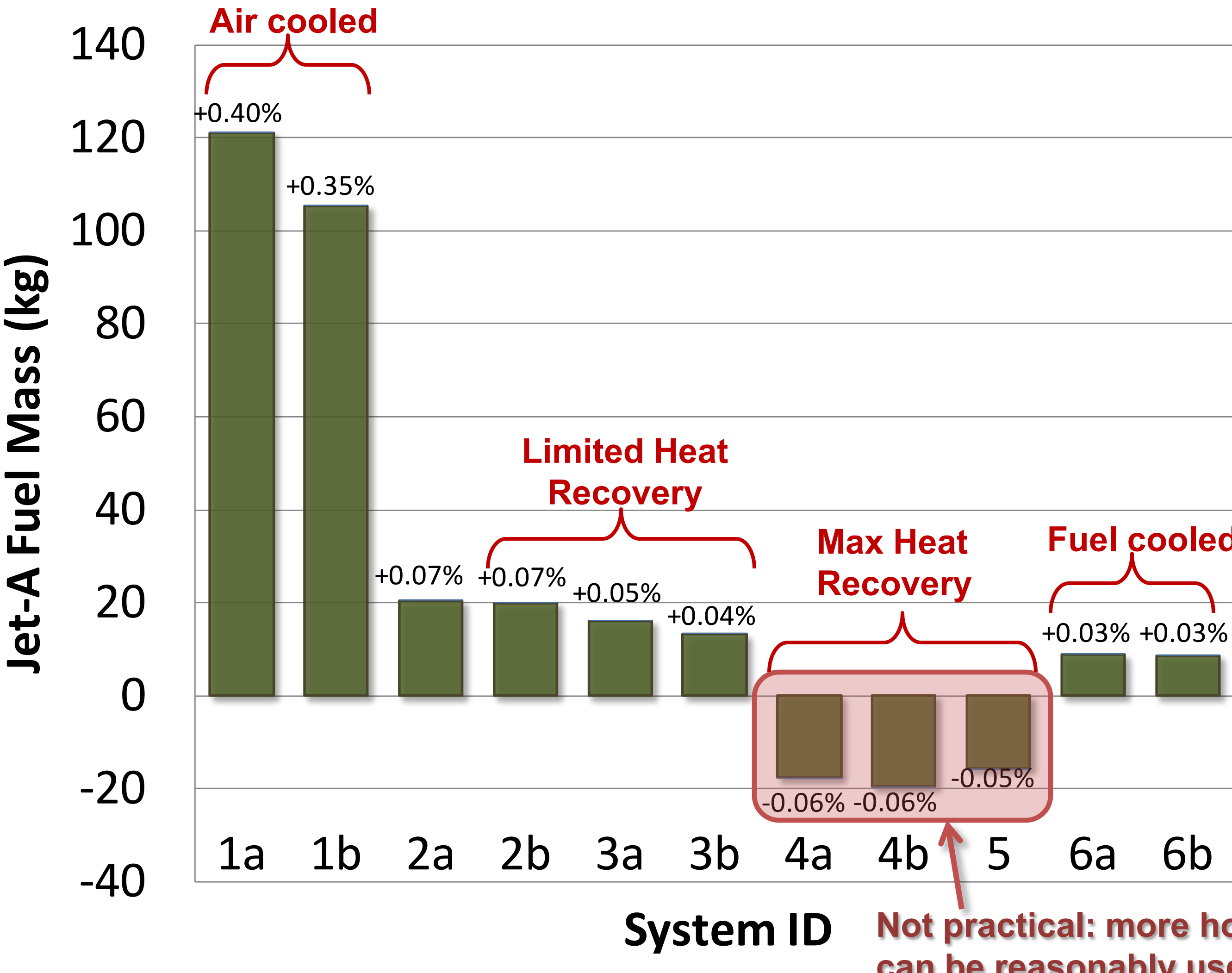




- Voltage remains relatively constant at 28VDC
- Fuel cell is capable of meeting load demand and transient requirement.

Simulation results shown for the galley case, IFE and Peaker also have similar satisfactory responses.

Putting everything in terms of a change in required fuel reveals that fuel-cooling is the best performing realistic configuration.



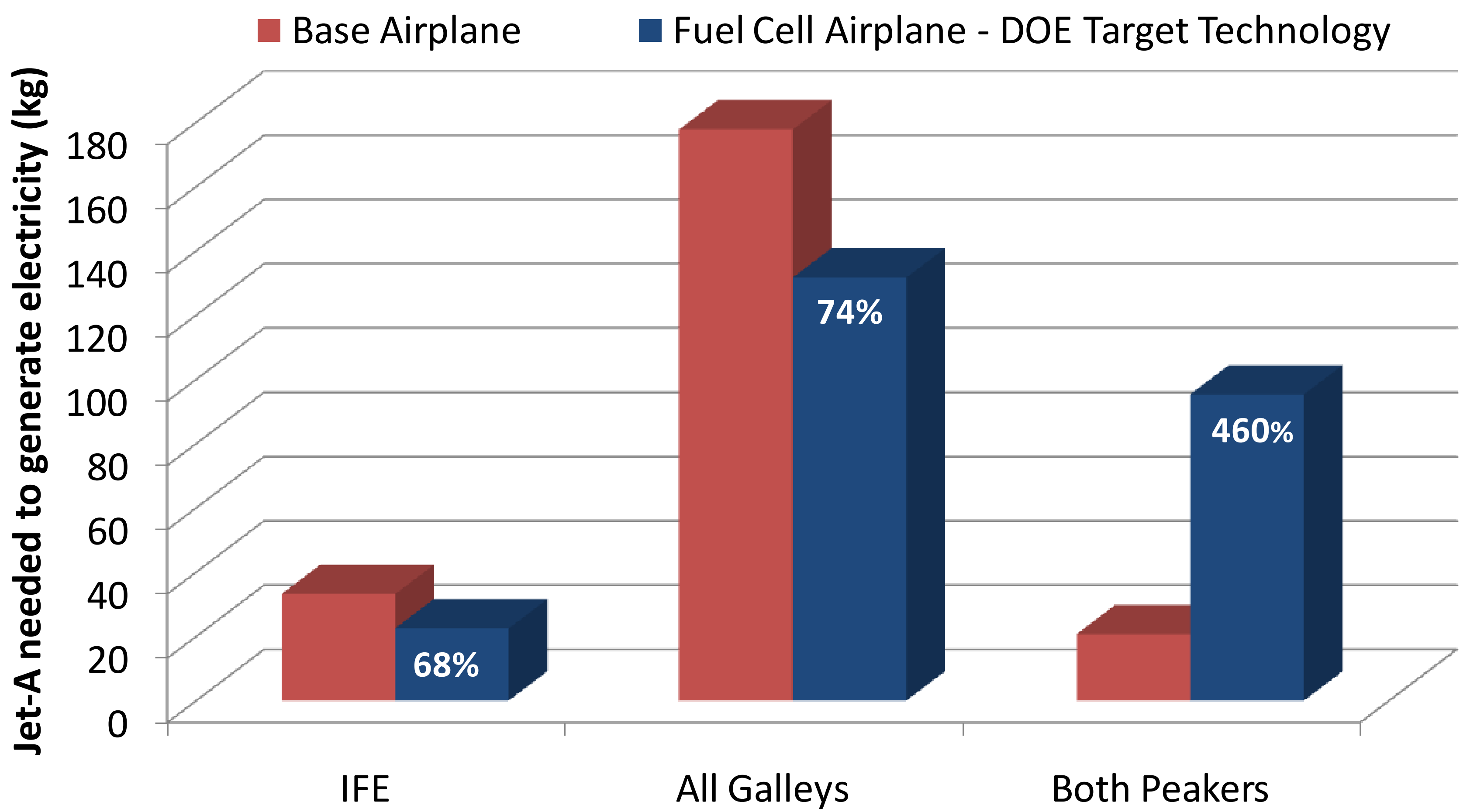
Load: 20 kW IFE

Case Legend

1a: Air cooled, no heat recov.
1b: Air cooled, heat recov.
2a: Water cooled, no heat recov.
2b: Water cooled, air heat recov.
3a: Water cooled, limited heat recov.
3b: Water cooled, limited heat recov., water recov.
4a: Water cooled, unlimited heat recov.
4b: Water cooled, unlimited heat recov., water recov.
5: Water cooled, hydrogen furnace, unlimited heat recov.
6a: Fuel cooled
6b: Fuel cooled, water recovery

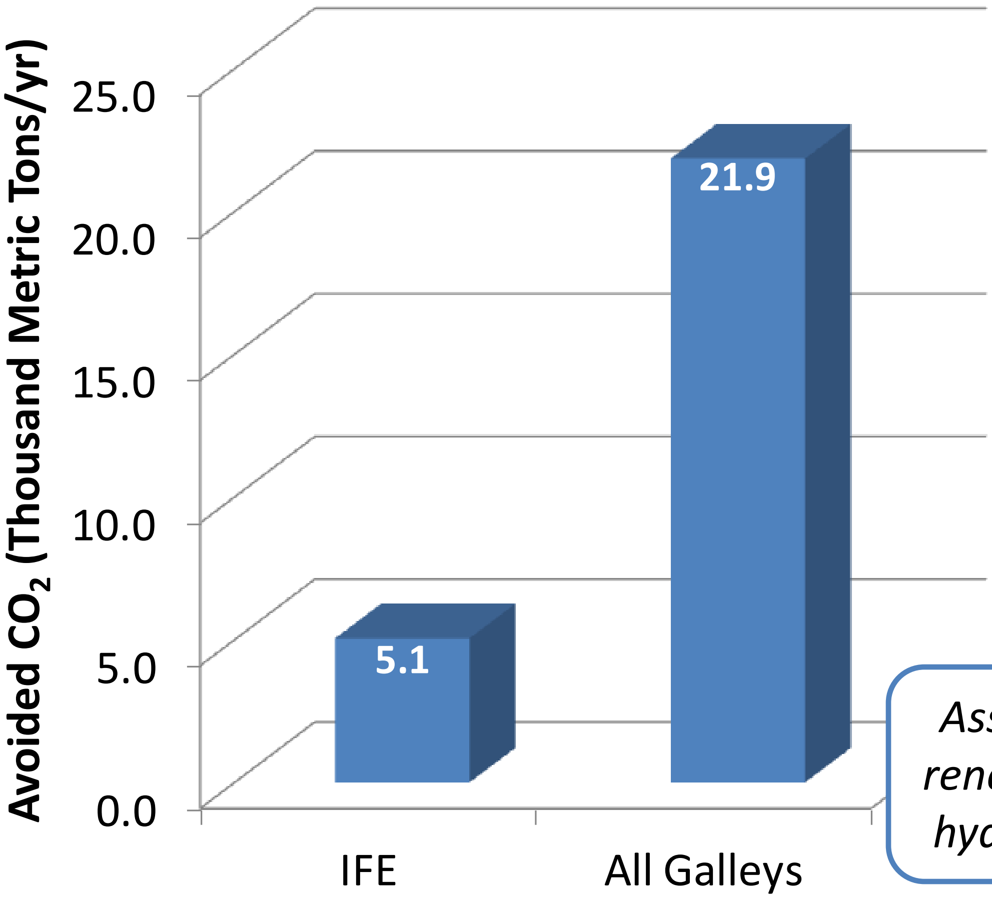
Results shown for currently available fuel cell and H_2 storage technology

A jet fuel-cooled system using DOE targets for both the PEM fuel cell and H_2 storage could enable a ≅30% reduction in the fuel required to generate electricity.



Data for Jet fuel-cooled fuel cell system using DOE-target fuel cell and hydrogen storage technology

Outfitting 1,000 airplanes with a PEM fuel cell system for the IFE and all galleys could avoid 27,000 metric tons of CO_2 per year.



Assumes renewable hydrogen

Data is for 1,000 airplanes, each flying 750 hrs/yr.

- **Boeing currently has > 800 orders for 787.**
- **787-class market projected to be 4,400 airplanes by 2029.**
- **Total commercial airplane fleet projected to be 36,300 by 2029.**

Data for Jet fuel-cooled fuel cell system using DOE-target fuel cell and hydrogen storage technology.
Airplane order and projections data from: www.boeing.com/commercial

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Summary

- **Fuel cells can perform the required electrical functions for galley, IFE, and peaker power, even in transients.**
- **It is very important to make use of the waste heat (hot water or fuel heating).**
- **Using current fuel cell and hydrogen storage technologies requires the airplane to carry more fuel.**
- **Fuel cell and hydrogen storage technologies meeting the DOE targets could lead to airplane fuel savings and avoided CO_2 emissions.**

- ***A PEM fuel cell system on-board a commercial airplane is technically feasible, performs well electrically, and is a flexible power source.***
- ***With technology improvements and an airplane designed for a fuel cell (and vice-versa), on-board PEM fuel cell systems will provide electrical and performance benefits to the airplane.***

Collaborations and Acknowledgements

Supported by DOE – EERE

Pete Devlin and Nancy Garland (Market Transformation)

Boeing Commercial Airplanes

(Actual airplane systems, requirements, and performance knowledge and specifications)

Joe Breit with

Trevor Laib, Andy Bayliss, Casey Roberts, and Farhad Nozari

Hydrogenics

(PEM fuel cell performance and operation data)

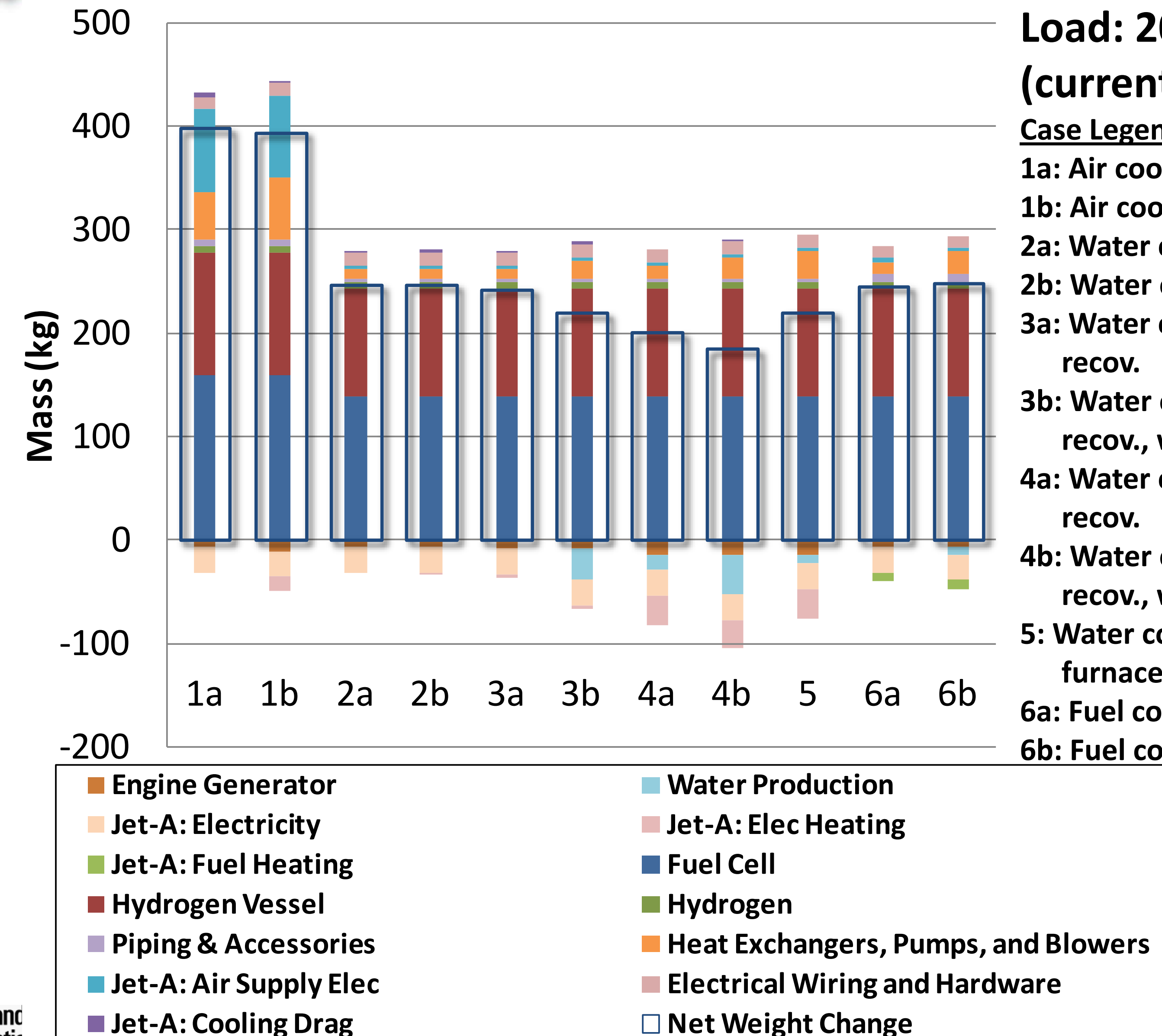
Ryan Sookhoo

Sandia

Andy Lutz

Technical Backup Slides

Mass contributions of all systems in screening study.



Load: 20 kW IFE (current technology)

<u>Case Legend</u>

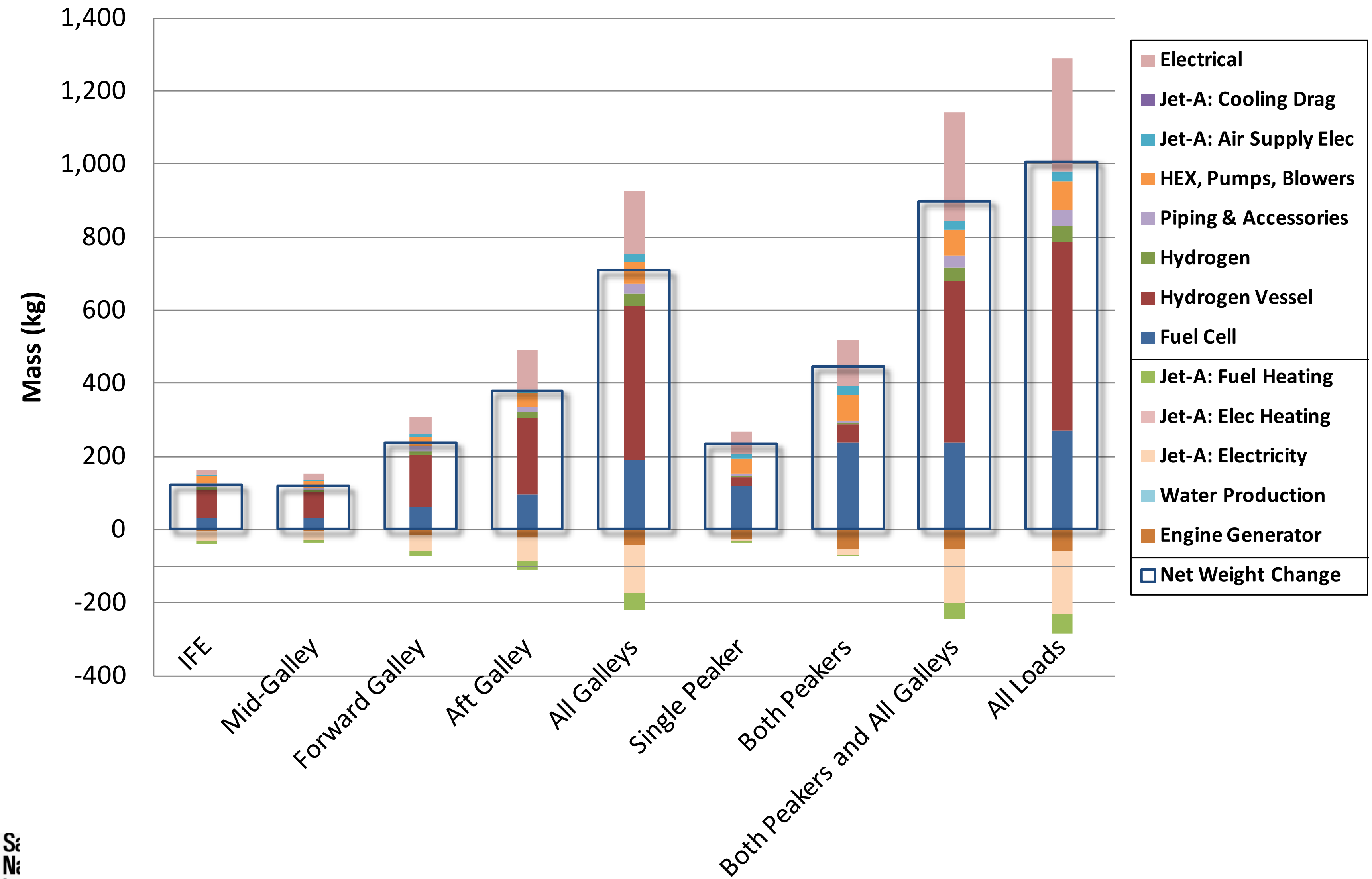
- 1a: Air cooled, no heat recov.
- 1b: Air cooled, heat recov.
- 2a: Water cooled, no heat recov.
- 2b: Water cooled, air heat recov.
- 3a: Water cooled, limited heat recov.
- 3b: Water cooled, limited heat recov., water recov.
- 4a: Water cooled, unlimited heat recov.
- 4b: Water cooled, unlimited heat recov., water recov.
- 5: Water cooled, hydrogen furnace, unlimited heat recov.
- 6a: Fuel cooled
- 6b: Fuel cooled, water recovery

The details of three configurations selected through the screening analysis are shown here.

Case ID	2a	3b	6a
Description	Simple water cooled	Water cooled, limited hot water, water recovery	Fuel cooled
Overall System Efficiency (HHV)	40.9%	46.4%	81.9%
Waste Heat Use	None	Hot water: 0.225 gpm @ 60 °C.	Fuel pre-heating
Water Recovery	None	0.027 gpm (0.1 LPM); 30.8 L	None
Cooling Load on Airplane	20 kW heat rejected to PECS	17.4 kW heat rejected to PECS	None
Net System Weight (kg)	245.4	218.6	244.5
Total System Volume (L)	596.6	605.8	605.0
Net Change in Jet-A required (kg)	+20.3	+13.1	+8.8
Net Change in Jet-A required (% of total mission fuel)	+0.07%	+0.04%	+0.03%

Data shown are for the screening case:
20 kW IFE load, fuel cell and hydrogen located in the fairing, with current technology.

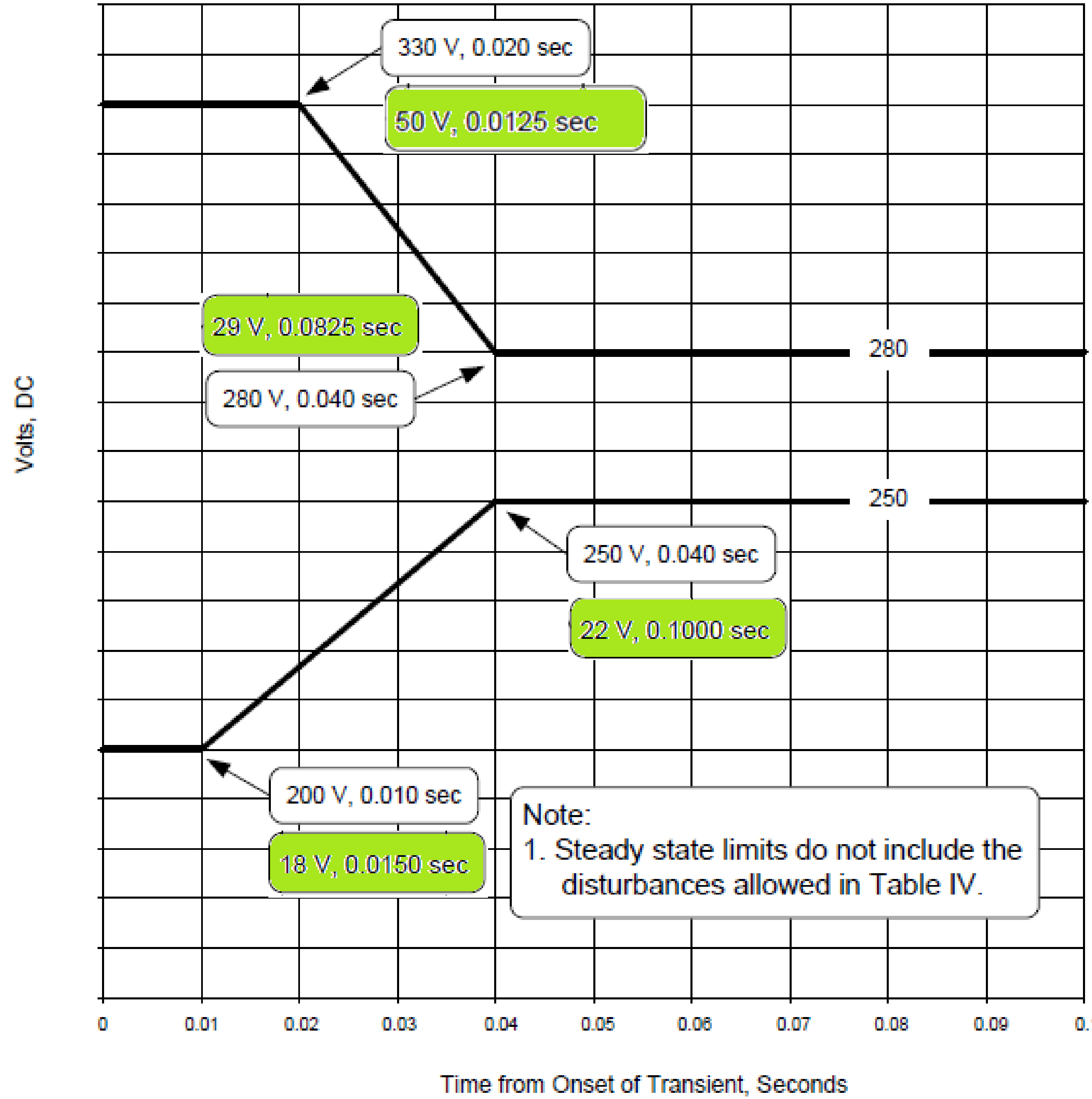
Mass contributions for all applications for system configuration 6a (jet fuel cooled) using DOE-targets for the fuel cell and hydrogen storage technologies.



MIL-STD-704F is widely used as the electrical transient standard which aviation electrical systems must meet.

28 VDC

270 VDC



The peaker circuit, tied into the existing electrical system, also shows acceptable electrical behavior.

- **MIL-STD-704F standards are met**
- **Fuel Cell operates as a peaker: operating only when generator can no longer meet power demand**
- **Capacitor in DC-DC Converter allows for fuel cell load following**