

CALSTART Project Results for National Fuel Cell Bus Program Awards



*Clean Transportation
Technologies and Solutions*

2009 Fuel Cell Seminar & Exposition
Fuel Cells: The New Generation of Green Power
Palm Springs, CA
November 18, 2009

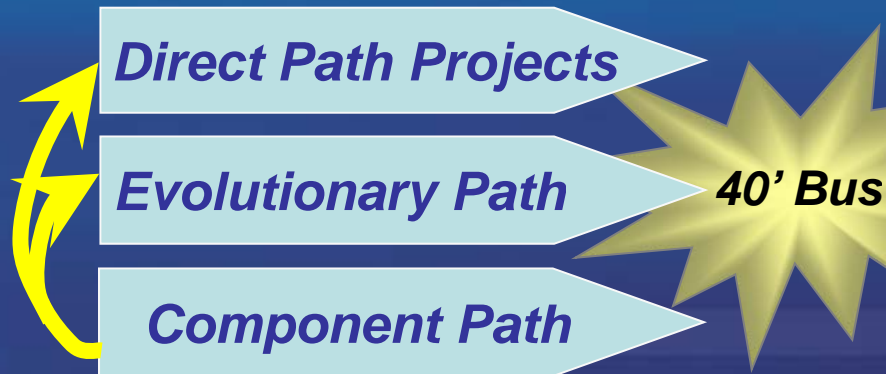
Lawrence Wnuk PhD, Senior Director



Transit H₂ Multi-Path Strategy – Technical & Commercial Goals



System Developments



Components Development

- Durability – 4 to 6 Years/
20,000 to 30,000 hours
- Reliability >90% Available
- Bus Cost – <5x Comparable
Size Transit Bus
- Fuel Efficiency – 2x
Comparable Transit Bus
- Emissions – Exceed 2010
EPA Standards
- Enhance Public Acceptance



CALSTART National FC Bus Programs



AC Transit HyRoad



SunLine AFCB



BAE Systems BUS 2010



US Hybrid Components



IAM



BDC



Direct Path Vehicle & Systems Development

Full Scale Designs are Technology Focus

- *Transit Bus - 40'*
- *Heavy Duty Fuel Cell Power Plant*
- *Hybrid Design with Energy Storage*
- *High Efficiency Drive Systems*
- *FC Bus Targeted Electronic Designs*
- *Weight Reduction*
 - *Vehicle and Sub-systems*



*AC Transit HyRoad Program
- Van Hool, UTC Power*





AC Transit HyRoad

- Putting Technology on the Road



Direct Path Project in Oakland

- Accelerated Testing of Fuel Cells for Transit
 - Team - AC Transit, ISE, UTC Power
 - AC Transit - Accelerated Fuel Cell bus operations underway
 - UTC Power - Engineer next generation
- Fuel Cell ... reliability increase 2 - 4 times





AC Transit HyRoad Program - Accelerated Service Shows Results



Performance

- **198,000 Miles**
(as of 09/30/09)
- **72% to 100%
Better Fuel
Economy**



- **3 Buses Continuing to Perform Accelerated In-Service Testing**
- **Battery Subsystem Hindered Test Trials – Two Stage Mitigation**
- **FC Reliability/Durability Improvements on 4,000 hr Fuel Cell**
 - **New Fuel Cell Program 6,000 hr with incentives if 10,000 hr achieved**
 - **Current performance warranty at 8,000 hours**

Manufacturing process and design improvements



Enhanced HyRoad Program

- Adds Improved Buses



- **Enhanced Program – 8 lighter buses, new FC, batteries**
- **New buses are 6,000 lbs lighter than current generation (only 2,000 lbs heavier than a standard diesel bus ~ 30,000 lbs)**
- **Innovations**
 - Light weight, hi tech exterior sheet metal
 - Light weight cooling system cover
 - Combination rear cap, exhaust outlet, and ventilation outlet
 - New fiberglass passenger bench seats with vital mechanical and electronic equipment installed under bench
 - Roof cover system with light weight, high tech sandwich panels
 - Latest generation drive system components installed low in the vehicle to improve handling and ride dynamics.
 - New lighter, higher efficiency HVAC unit for in passenger compartment temperature control and Hybrid System battery pack cooling.
- **New Infrastructure Facility Funded and In Planning**





American Fuel Cell Bus (AFCB) – Direct Path Program



- **New purpose design fuel cell bus**
 - North American chassis
 - Lightweight bus body/chassis design for H₂ fuel components
 - U.S. sourced drive components
 - Latest-generation U.S. sourced fuel cell
 - New power electronics and advanced energy storage
 - Unique hi-efficiency accessory electronics
- **Zero Emission Bus vehicle demo in a very hot climate**



Evolutionary Path Vehicle & Systems Development



Scalable Designs/Applications are the Focus

- *Variety of Buses and Lengths*
 - Shuttle, School and Transit
 - 20', 30', 40' and 60' Articulated
- *Scalable Fuel Cell Power Plant Hybrids or APU Designs*
- *Conventional Internal Combustion Engine (ICE), Battery or H₂ ICE*
- *Scalable Drive Systems*
- *Selected Subsystem Designs*
- *Targeted Industry Software*



BUS 2010 Program
- BAE Systems
- Hydrogenics





BUS 2010 Evolutionary Path - Enhancing a Successful HEV

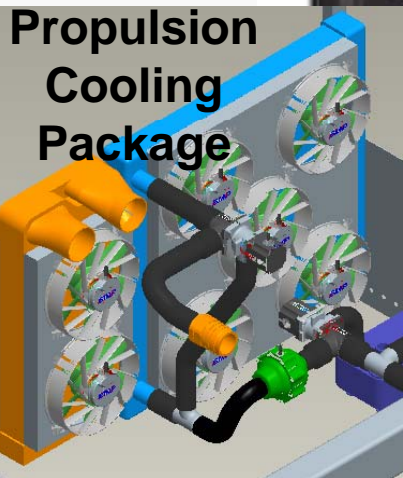


Hydrogenics Fuel Cells for APU and H₂ Storage System



Propulsion Control Electronics

Lithium-Ion Energy Storage System



Better fuel economy

Lower emissions

Reduced maintenance

Better reliability

Path to future

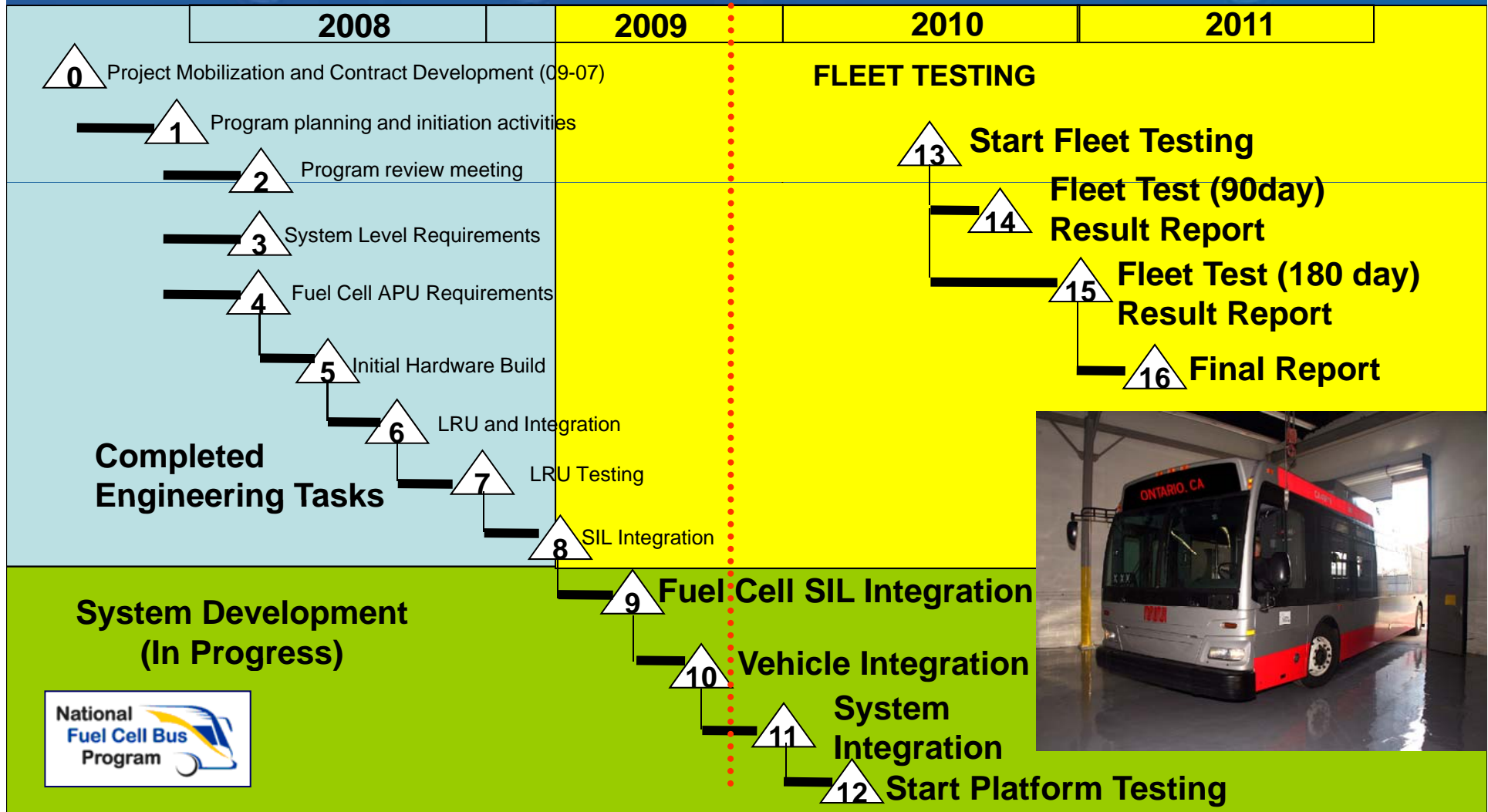


BAE Systems BUS 2010 - On-Track for Vehicle Integration



• On-Time, Within Budget

BAE SYSTEMS





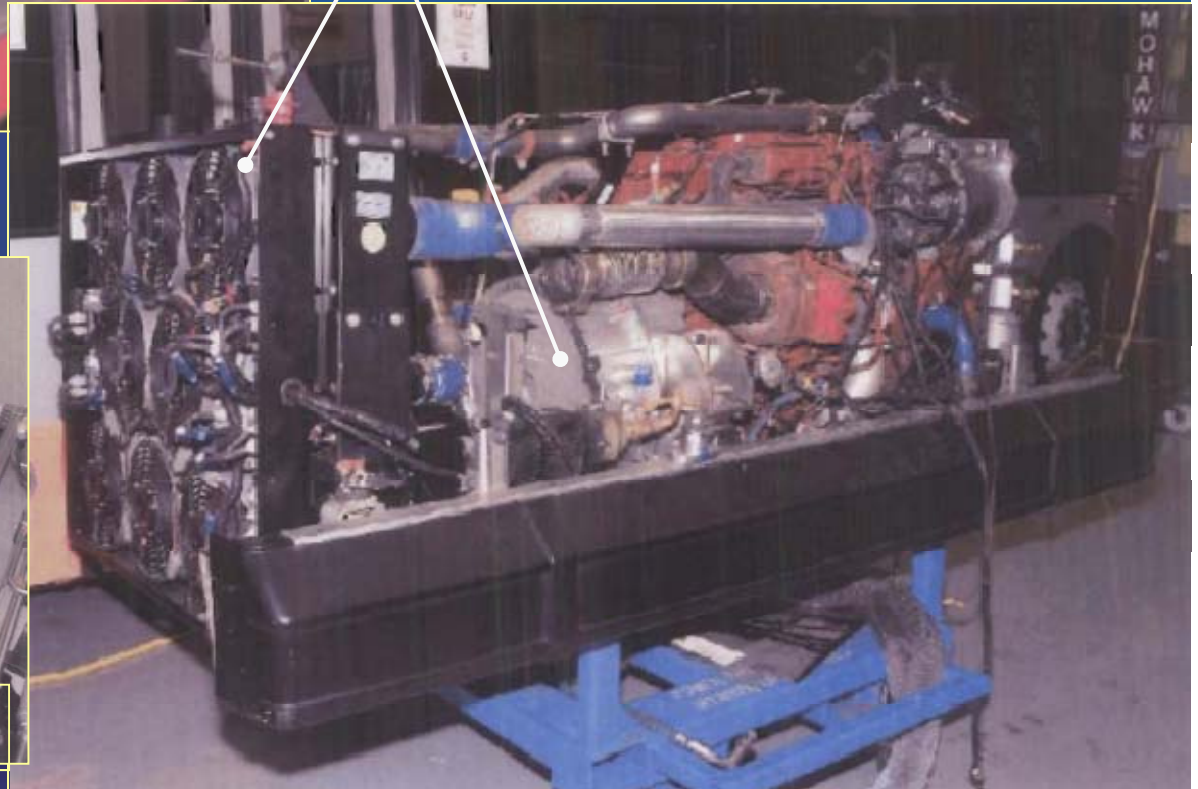
Vehicle Integration of Major Sub-systems



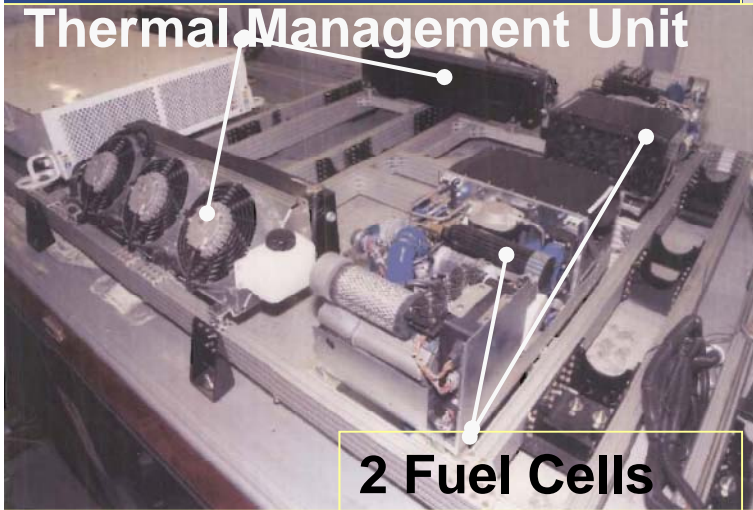
Roof Mounted H₂ Storage System



Power Plant Assembly with Propulsion Cooling Package / Integrated Starter Generator



Partial APU Rack Assembly, Thermal Management Unit



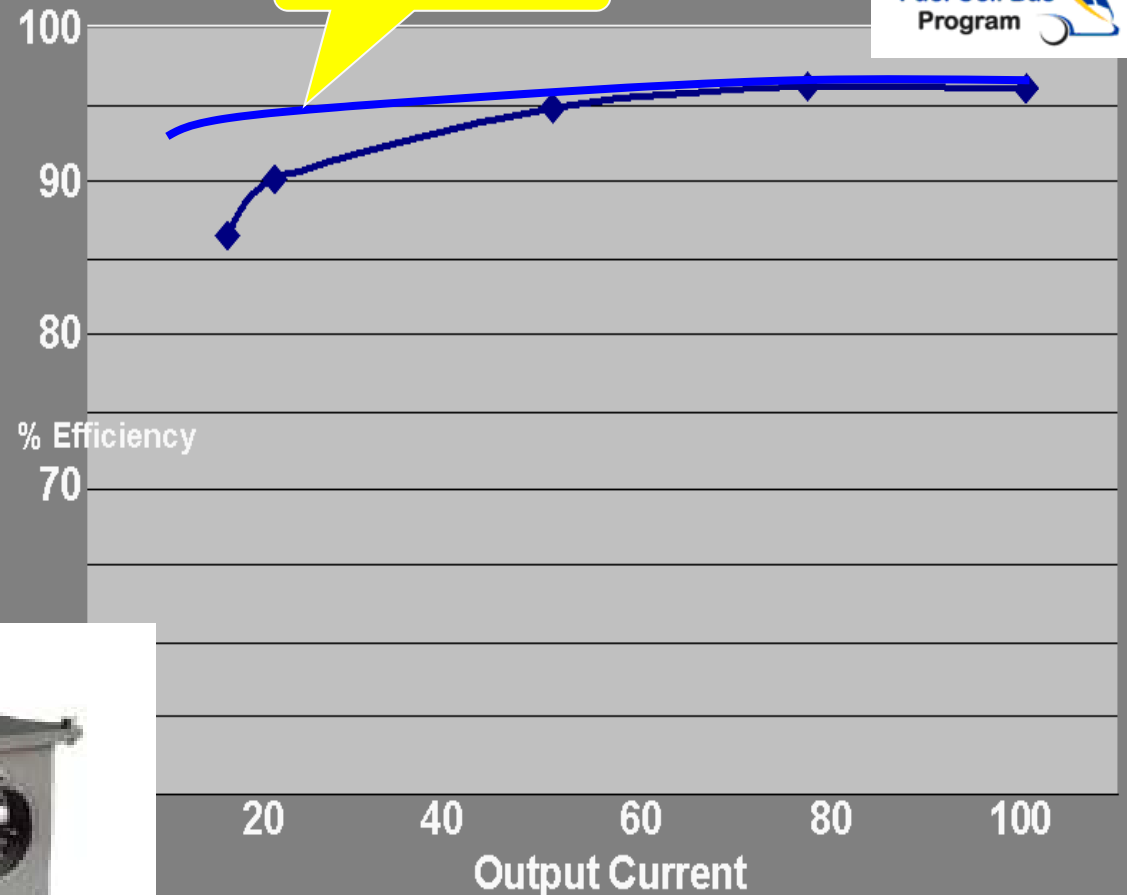
2 Fuel Cells



US Hybrid Efficient, Low-cost, Compact, Bi-directional DC-DC(BDC) Converter



- \$60/kW in low production
- 150-300VDC / 300-600VDC Input Voltage Range
- 400A Input Current
- Output
 - $V_{in} < V_{out} < 900$ VDC
 - Power 60 kW to 200 kW



Component Path Project
Replaces functions now custom designed for fuel cell and electric drive buses



BDC Plug-n-Play Electronics Component for Multiple Applications



US Hybrid BDC Configuration

COM Port: 1.00

Send Configuration: OK

Flush RX Port: OK

Request Current Configuration: OK

CAN Baud Rate: 2 (0 - 125 kb/s, 1 - 250 kb/s, 2 - 500 kb/s, 3 - 1 Mb/s)

Broadcast Rate (ACK rate is 4X slower): 4 (0 - 1 Hz, 1 - 2 Hz, 2 - 4 Hz, 3 - 10 Hz, 4 - 20 Hz)

Broadcast Mode: 2 (0 - No CAN, 1 - Send Sta, 2 - Full Broa, 3 - Full Broa)

Min Battery Voltage: 0.00 V

Max Battery Voltage: 200.00 V

Max Battery charging cu: 200.00 V

BDC Mode

Software Version: 0

Desired Output Voltage: 0.00

Output Voltage: 0.00

Isolation Voltage: 0.00

Power On

BDC Control Mode: 0

Listen Only (No CAN TX)

Minimum Battery Voltage: 0.00

Maximum Battery Voltage: 200.00

Max Output Current (Chg): 200.00

Max Output Current (Load): 200.00

Max Battery Current (Chg): 200.00

Max Battery Current (Load): 200.00

Battery Current: 0.00

Battery Current 1: 0.00

Battery Current 2: 0.00

Battery Current 3: 0.00

Output Current: 0.00

Output Power: 0.00 W

Control Mode: 0 (0 - CAN, 1 - Analog, 2 - Preset)

Converter mode: 0 (0 - Buck/Boost, 1 - Buck, 2 - Boost)

BDC On:

PWR_ON Present:

UV Batt:

OV Batt:

VHV Error:

CAN Lost:

- Programmable, plug-and-play, with diagnostics
- User reconfigurable via RS232 interface
- Tailored unit performance, speeds, simplifies integration
- User performs Configuration Management





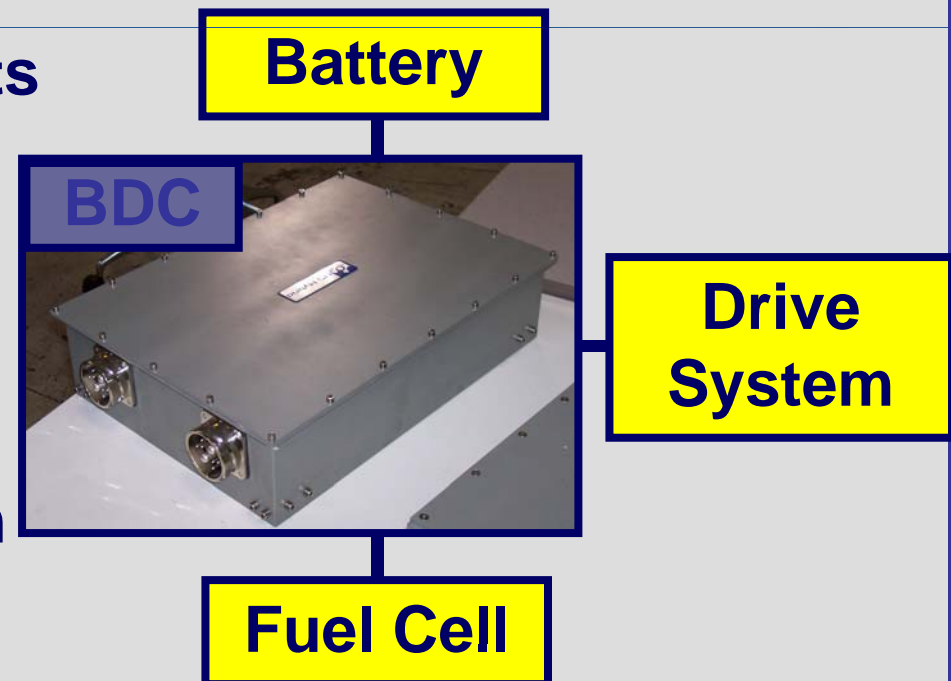
High-frequency, multi-phase DC-DC Power Conversion – Why Important



BDC fast dynamic response & current/voltage mode agility optimizes energy flow between fuel cell, energy storage and drive system

In-Service Trials Demonstrate BDC Power Converter

- **Smooths Fuel Cell Transients Improving FC Durability**
- **Fast Response Captures More Regen Energy**
- **Low Standby Power & High-Efficiency Reduces System Cooling Requirements**
- **Features Together Improves Vehicle Fuel Economy**





Component Program - US Hybrid Integrated Auxiliary Module (IAM)



- Low cost, \$55/hp for motor drives and \$15/A for DC-DC
- Single Unit eases vehicle integration, increases reliability
- 94% Rated Efficiency, for Motor Drives and DC-DC Converter
- Motor Control
 - Speed, torque and Sensor-less
 - Hydraulic and/or Air System Pressure Regulation
 - CAN Command or Analog
- Configuration User Managed



Input: 250-450, 500-700 VDC

Cooling: Liquid WEG < 60°C

Motor Drive 1
10 hp

Hydraulic System

Motor Drive 2
10 hp

Air System

DC-DC Converter
200A

12/24 VDC
Aux Battery

16





IAM High-frequency Switched Power Stages

- accepts wide input dynamic voltage range



US Hybrid IAM Characteristics	
DC-DC	200A , 28.7 VDC
Line regulation ($\pm 10\%$ Input)	1 % Output
Load regulation (10- 90%)	1 % Output
Turn-on rise time	Soft-start, 300 ms typical
Storage Temperature	-40°C to +85°C
Dimensions	43 x 33 x 13 cm

- Simplifies vehicle integration of auxiliary motors
 - Single enclosure
- Lowers cost and increases reliability by eliminating some
 - high voltage wiring
 - high voltage connectors
 - separate water-cooled enclosures
- IAM price $< 1/3$ for comparable functionality today
 - Even in low quantity production
- Enhances vehicle fuel economy
 - Vehicle CAN control allows efficient operation and control of the auxiliary loads





Achievement Highlights to Date



- **Two Component Programs Completed**
 - Electronics Price Point Close DOE 2015 Goals
 - Contributes to Vehicle Efficiency and Fuel Economy
 - Next Step, More On-Road Testing
- **Fuel Cell Performance**
 - Reliability (Availability) Above 95%
 - Durability has Increased to 8,000 hrs, Continuing to Grow
 - Needs More On-Road Testing
- **Public Acceptance Very Positive**
- **Over-all Poised for the Next Step**
 - Beyond Demo Stage
 - On-Road Pilot Production Fleets (10's of Buses) Needed
 - Supplier Focus on Production Configurations to further Reduce Cost and Increase Durability/Reliability



FTA FCB Goals and Objectives Commercialization Focus



- Durability – 4 to 6 Years/
20,000 to 30,000 hours
- Reliability >90% Available
- Bus Cost – <5x Comparable
Size Transit Bus
- Fuel Efficiency – 2x
Comparable Transit Bus

40' Bus

Accomplishments

- UTC – 4 + yrs/8,000 hrs
w/10,000 hr incentives
- Reliability >90% UTC FC
Stack demonstrated,
bus has a way to go
- BUS 2010 achieves
– Component achieves
- Fuel Efficiency – 1.7x
AC Transit FC Bus vs a
Diesel Bus





Clean Transportation Technologies and SolutionsSM



www.calstart.org