Overview

Timeline and Budget

- Project start date: 09/01/03
- FY17 DOE funding: $200K
- FY18 planned DOE funding: $200K
- Total DOE funds received to date: $4.1M (over 16 years)

Additional funding: U.S. Department of Transportation (DOT) Federal Transit Administration (FTA)

Barriers

- Lack of current fuel cell vehicle (bus) performance and durability data
- Lack of current H2 fueling infrastructure performance and availability data

Partners

- Transit fleets: Operational data, fleet experience
- Manufacturers: Vehicle specs, data, and review
- Fuel providers: Fueling data and review
Relevance

• Validate fuel cell electric bus (FCEB) performance and cost compared to DOE/FTA targets and conventional technologies
• Document progress and “lessons learned” on implementing fuel cell systems in transit operations to address barriers to market acceptance

<table>
<thead>
<tr>
<th>Current Targets(^a)</th>
<th>Units</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lifetime</td>
<td>years/miles</td>
<td>12/500,000</td>
<td>12/500,000</td>
</tr>
<tr>
<td>Powerplant lifetime</td>
<td>hours</td>
<td>18,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Bus availability</td>
<td>%</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Roadcall frequency</td>
<td>miles between roadcall</td>
<td>3,500/15,000</td>
<td>4,000/20,000</td>
</tr>
<tr>
<td>Roadcall frequency</td>
<td>miles between roadcall</td>
<td>3,500/15,000</td>
<td>4,000/20,000</td>
</tr>
<tr>
<td>Roadcall frequency</td>
<td>miles between roadcall</td>
<td>3,500/15,000</td>
<td>4,000/20,000</td>
</tr>
<tr>
<td>Operation time</td>
<td>hours per day/days per week</td>
<td>20/7</td>
<td>20/7</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>$/mile</td>
<td>0.75</td>
<td>0.40</td>
</tr>
<tr>
<td>Fuel economy</td>
<td>miles per diesel gallon equivalent</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Approach

Data Collection/Analysis
• NREL uses a standard protocol for collecting existing data from transit partners
• Provides a third-party analysis
• Includes comparisons to conventional-technology buses in similar service (diesel, CNG, diesel hybrid)

Individual Site Reports
• Documents performance results and experience for each transit agency
• Builds database of results
• Reports published and posted on NREL website

Annual FCEB Status Report (milestone)
• Crosscutting analysis comparing results from all sites
• Assesses progress and needs for continued success
• Provides input on annual status for DOE/FTA targets

CNG = compressed natural gas
## Selected specifications for FCEBs included in data summary

<table>
<thead>
<tr>
<th>Bus Manufacturer</th>
<th>Van Hool</th>
<th>ENC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>A330</td>
<td>AFCB/Axcess</td>
</tr>
<tr>
<td>Bus length/height</td>
<td>40 ft./136 in.</td>
<td>40 ft./140 in.</td>
</tr>
<tr>
<td>Fuel cell OEM</td>
<td>UTC Power</td>
<td>Ballard</td>
</tr>
<tr>
<td>Model</td>
<td>PureMotion 120</td>
<td>FCvelocity–HD6</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Hybrid system</td>
<td>Siemens ELFA, Van Hool integration</td>
<td>BAE Systems HybriDrive</td>
</tr>
<tr>
<td>Design strategy</td>
<td>Fuel cell dominant</td>
<td>Fuel cell dominant</td>
</tr>
<tr>
<td>Energy storage – OEM</td>
<td>EnerDel</td>
<td>A123</td>
</tr>
<tr>
<td>Type</td>
<td>Li-ion</td>
<td>Nanophosphate Li-ion</td>
</tr>
<tr>
<td>Capacity</td>
<td>17.4 kWh</td>
<td>11 kWh</td>
</tr>
</tbody>
</table>

ENC = ElDorado National California
AFCB = American Fuel Cell Bus
OEM = original equipment manufacturer
### FCEB fleets included in data summary

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Abbreviation</th>
<th>Location</th>
<th>Bus Type</th>
<th># Buses</th>
<th>Data Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit</td>
<td>ACT</td>
<td>Oakland, CA</td>
<td>Van Hool</td>
<td>13</td>
<td>Fuel cell hours, fueling records, reliability</td>
</tr>
<tr>
<td>SunLine Transit Agency</td>
<td>SL</td>
<td>Thousand Palms, CA</td>
<td>AFCB</td>
<td>4</td>
<td>All</td>
</tr>
<tr>
<td>Orange County Transportation Authority</td>
<td>OCTA</td>
<td>Santa Ana, CA</td>
<td>AFCB</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Stark Area Regional Transit Authority</td>
<td>SARTA</td>
<td>Canton, OH</td>
<td>AFCB</td>
<td>5</td>
<td>Fuel cell hours only</td>
</tr>
<tr>
<td>Massachusetts Bay Transportation Authority</td>
<td>MBTA</td>
<td>Boston, MA</td>
<td>AFCB</td>
<td>1</td>
<td>Fuel cell hours and fueling records</td>
</tr>
<tr>
<td>University of California at Irvine</td>
<td>UCI</td>
<td>Irvine, CA</td>
<td>AFCB</td>
<td>1</td>
<td>All</td>
</tr>
</tbody>
</table>
Accomplishments and Progress
FCEB Numbers Expected to Grow

Currently in service: 33 FCEBs
Potential FCEBs by end of 2019: 71

New bus orders following standard procurement process

European FCEB programs: 46 active, with another 313 planned
Asia FCEB programs: 400 planned, potential for 2,000 more per year
Accomplishments and Progress
Top Fuel Cell Powerplant Exceeds 27,000 Hours

Top fuel cell powerplant (FCPP) >27,330 hours, surpassing DOE/DOT 2016 target; 12 FCPPs have more than 19,000 hours

In-service FCPPs

Total hours accumulated on each FCPP as of 2/28/18
Accomplishments and Progress
Fuel Economy

- Based on first year of data for each demonstration
- Gen 1: Six demonstrations of three FCEB designs
- Gen 2: Five demonstrations of two FCEB designs

Average fuel economy for Gen 2 designs 19% higher than Gen 1

Low point FCEB not a hybrid
Transit agencies typically fill the buses every day during a 6–8-hour window after the end of service.

Stations must be capable of back-to-back fueling of up to 40 kg per fill, although the average fill is 21 kg.

Agency goal of fueling in less than 10 minutes.

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### Summary of hydrogen use by demonstration site

<table>
<thead>
<tr>
<th></th>
<th>ACT</th>
<th>SL</th>
<th>UCI</th>
<th>OCTA</th>
<th>MBTA</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of buses</td>
<td>13</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Number of fueling days</td>
<td>1,794</td>
<td>2,371</td>
<td>342</td>
<td>607</td>
<td>142</td>
<td>5,256</td>
</tr>
<tr>
<td>Monthly H2 (kg)</td>
<td>309,463</td>
<td>96,665</td>
<td>8,580</td>
<td>4,240</td>
<td>1,680</td>
<td>420,628</td>
</tr>
<tr>
<td>Number of occurrences</td>
<td>14,814</td>
<td>4,581</td>
<td>319</td>
<td>222</td>
<td>118</td>
<td>20,054</td>
</tr>
<tr>
<td>Average daily fuel use (kg)</td>
<td>172.5</td>
<td>40.8</td>
<td>25.1</td>
<td>7.0</td>
<td>11.8</td>
<td>80.0</td>
</tr>
<tr>
<td>Average fill amount (kg)</td>
<td>20.9</td>
<td>21.1</td>
<td>26.9</td>
<td>19.1</td>
<td>14.2</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Reliability: Miles Between Roadcall

- Reliability trends are shown for two FCEB designs: AFCB and Van Hool (VH).
- Fuel cell system roadcalls are caused by balance of plant components, not stack issues.
- The higher trend for the Van Hool FCEBs is due to the increasing use of the buses and the competence level of the maintenance staff in preventive maintenance—better able to anticipate and repair issues before they cause an in-service failure.
Accomplishments and Progress
Maintenance Cost by System

• Cost for propulsion system repairs highest for AFCBs
• Propulsion issues include:
  – Cooling system leaks
  – Low-voltage batteries
  – Fuel cell BOP
• Other issues:
  – Air compressor
  – Suspension

- Cumulative cost from in-service date
- Labor @ $50/h
- Cost per mile sensitive to number of buses in a fleet

BEB = battery electric bus
BOP = balance of plant
PMI = preventive maintenance inspection
HVAC = heating, ventilation, and air conditioning
Accomplishments and Progress
Maintenance Cost Trends

Cumulative maintenance cost from start of service

1. Low miles and introduction of new technology leads to higher cost in early stage of FCEB introduction
2. Cost drops as miles increase—most repairs handled under warranty
3. Cost trends up with learning curve for troubleshooting and repair as agency staff take on more maintenance work
4. Costs decrease as mechanics become more familiar with technology
5. Parts cost increase as the Warranty period ends for some FCEBs
6. BEB maintenance work handled by on-site OEM staff; costs increase as agency takes over and warranty period ends
Accomplishments and Progress
Technical Issues Affecting Cost

• Majority of issues with fuel cell system due to balance of plant:
  – Air handling—blowers
  – Cooling—pumps, plumbing
• Electrical system: low-voltage batteries
  – Electric accessories can cause a continual drain that shortens battery life (includes IT equipment such as cameras and fareboxes)
  – Issue also affects BEBs
• Cooling system leaks
  – Significant labor to locate
• Added labor hours for troubleshooting problems
Accomplishments and Progress: Responses to Previous Year Reviewers’ Comments

• Project would benefit from the inclusion of additional bus projects.
  – Response: Sites are added as buses go into service within funding limits. NREL began collecting data on five new FCEBs at SARTA. SunLine is adding at least six new buses in 2018. Results from these buses will be added once we have sufficient data.

• Project would be improved by doing a comparison against battery buses as well as the baseline diesel or CNG, because batteries are the main competitor to fuel cells in the zero-emission bus space. Agencies will want to see what the comparative benefits are.
  – Response: We now have battery bus data and can make comparisons.

• Would like to see data on fueling cycles at the sites.
  – Response: We have included a slide to show fueling data summary (Slide 10).
Collaboration and Coordination

- Transit agencies (1) provide data on buses, fleet experience, and training and (2) review reports
  - California: AC Transit, SunLine, UC Irvine, OCTA
  - Massachusetts: MBTA
  - Ohio: SARTA

- Manufacturers provide some data on buses and review reports
  - Bus OEMs: New Flyer, ElDorado National
  - Fuel cell OEMs: Ballard, Hydrogenics, US Hybrid
  - Hybrid system OEMs: BAE Systems, New Flyer

- Federal Transit Administration provides funding to cover evaluations of both FCEBs and BEBs (follows same protocol)

- Other organizations share information and analysis results
  - California Air Resources Board, Center for Transportation and the Environment, CALSTART
Remaining Challenges and Barriers

• For technology validation and data collection project:
  – Continue data collection to track progress of newer-generation designs
  – Establish good relationships with additional transit agencies to add to the data set

• For industry to commercialize FCEBs:
  – Develop robust supply chain for components and parts to lower cost and downtime
    • Multiple component suppliers to stabilize supply
    • Standardize with conventional bus components to lower cost
  – Deploy larger fleets—large agencies have challenges introducing small fleets of advanced buses
    • Steep learning curve for staff
    • Larger fleets require commitment
  – Reduce cost, both capital and operating
    • Parts and labor increasing as fleets surpass warranty period
  – Competition with other zero-emission technologies
Proposed Future Work

• Remainder of FY 2018
  – Complete the following data analyses/reports:
    • SunLine AFCB Report, May 2018
    • 2018 Annual Status Report, September 2018
    • Preliminary reports on SARTA and OCTA (FTA-funded)
  – Provide feedback to DOE on technical issues with systems and components
  – Begin analysis of fuel cell truck projects

• FY 2019
  – Kick off new FCEB evaluations as buses go into service—target new designs from different OEMs
  – Complete individual site reports as scheduled
  – Complete annual crosscutting analysis across sites

Any proposed future work is subject to change based on funding levels.
Proposed Future Work

Current data collection includes a total of 25 FCEBs at six transit sites
New sites could add 44 buses and four new designs

Any proposed future work is subject to change based on funding levels.
Technology Transfer Activities

- Project provides non-biased evaluation of technology developed by industry
- Project documents performance results and lessons learned to aid market in understanding needs for full commercialization
  - Manufacturers
  - Transit agencies
  - Policymaking organizations
  - Funding organizations
- No technology (hardware/software) is developed through this project
### Summary: Progress Toward Targets

#### Summary of FCEB Data through February 2018

<table>
<thead>
<tr>
<th></th>
<th>2017 Fleet Average</th>
<th>2018 Fleet Max</th>
<th>2018 Fleet Average</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
<th>Target Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lifetime (years)</td>
<td>4.7</td>
<td>7.5</td>
<td>5.5</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bus lifetime (miles)</td>
<td>118,989</td>
<td>189,168</td>
<td>128,656</td>
<td>500,000</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>Powerplant lifetime&lt;sup&gt;a&lt;/sup&gt; (hours)</td>
<td>13,801</td>
<td>27,330</td>
<td>13,041</td>
<td>18,000</td>
<td>25,000</td>
<td>2016</td>
</tr>
<tr>
<td>Bus availability (%)</td>
<td>76</td>
<td>90</td>
<td>71</td>
<td>85</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Roadcall frequency&lt;sup&gt;b&lt;/sup&gt; (bus)</td>
<td>4,710</td>
<td>4,715</td>
<td>4,516</td>
<td>3,500</td>
<td>4,000</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Roadcall frequency (fuel cell system)</td>
<td>20,705</td>
<td>23,741</td>
<td>18,026</td>
<td>15,000</td>
<td>20,000</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Maintenance cost ($/mi)</td>
<td>1.03</td>
<td>0.56</td>
<td>0.53</td>
<td>0.75</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Fuel economy (mpd&lt;sub&gt;ge&lt;/sub&gt;)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.51</td>
<td>7.82</td>
<td>7.01</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Range (miles)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>247</td>
<td>357</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Fuel cell hours accumulated to date from newest FCPP to oldest FCPP. Does not indicate end of life.

<sup>b</sup> MBRC: average for current designs.

<sup>c</sup> Miles per diesel gallon equivalent.

<sup>d</sup> Estimated range based on fuel economy and 95% tank capacity. Transit agencies report lower real-world range.
Thank You

www.nrel.gov
Backup Slides
Accomplishments and Progress

Maintenance Cost: Parts and Labor

- Majority of FCEB cost is from labor—troubleshooting and training increase labor hours
- Parts costs are low while the buses are under warranty

- Cumulative cost from in-service date
- Labor @ $50/h

BEB = battery electric bus