MT011
Ground Support Equipment Demonstration

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Overview | Program

- 15 fuel cell cargo tractors
- Memphis airport for 2 years
- H2 station on airport ramp

Timeline

- Project Start Date | 1/1/13
- Project End Date | 3/31/18
- Percent Complete | 76%

Barriers

- Aggressive load profile
- Airport emissions
- Exposure to elements

Budget

- Total Funding | $4.996M
- DOE Share |$2.497
- Partners Share | 50.03%
- Funding in FY16 | $0
- Funding in FY17 | $462k

Partners

- Plug Power
- FedEx Express
- Charlatte America
- Memphis-Shelby AA
- Memphis Fire Services

Overview | Cargo Tractors

Deployment in Airport Cargo Transport

- 50,000 lbs. towing capacity
- 24/7 outdoor operation
- Run Time: 4 hours at max haul capacity
- Refuel time: 3-4 minutes
- Engines fit existing cargo tractor
  - Require very little mods (air exchange)

Approach | GSE Commercialization

PROVE SUITABLE FOR OPERATIONS

Demonstrate fuel cells can operate in airport environments
- Handle energy-intensive duty cycle of cargo transport
- Contend with high shock and vibe
- Operate outdoors 24/7
- Unaffected by diesel emissions of other airport assets
- Use of hydrogen vs. diesel is transparent to operators
- Does not alter cargo transport operations at airport

DEMONSTRATE AND QUANTIFY VALUE

Demonstrate value proposition of cargo tractors
- Quantify fuel savings $ - hydrogen vs. diesel
- Articulate other benefits of hydrogen
- Prove acceptable payback period with a CapEx premium

SCALE IMPROVES ECONOMICS

Expand hydrogen-driven airport asset portfolio
- Define what other assets are candidates for conversion to hydrogen
- Define a H2 infrastructure solution for large-scale airport conversion

EXTEND REACH

Redefine the airport as the center of a hydrogen ecosystem
- Use breadth of hydrogen airport assets as baseline captive fleet
- Expand to tethered fleets that use the airport as a home base
- Create additional value by scaling H2 consumption to lower pricing
- Establish a repeatable model that enables smaller airports as candidates

Approach | Delivered Liquid Hydrogen

Liquid hydrogen was chosen as the best economical solution for the demonstration based on:

- **Size of the fleet (15 x 4-8 kg/day = 60-120 kg/day)**
- **Ability to scale the fleet beyond the demonstration**

Specifications

- **H2 Capacity: 15,000 gallons (4,000 kg)**
- **Liquid temp: -253 deg C**
- **Pressure: Liquid - 5 PSI / Gas – 125 PSI**
- **Gaseous Storage: 60 kg (scalable)**
- **Gaseous Fuel Pressure: 350 bar (5,000 PSI)**
- **Dispensing Time: 1 kg/min**

As more hydrogen fuel is amortized over the CapEx, the all-in price drops.

As more hydrogen is needed, little is needed to expand the site to accommodate greater fuel demands.

Memphis Airport Ramp

Approach | Hydrogen Economics

Supply Method	Comments	Price ($/kg) Fuel Only	Trucks	Usage (kg/mo)	Price ($/kg) Fuel + Infra
Gaseous	- Inefficient, generally lower volumes (200 kg) - Generally lower pressure (2400 PSI), partial fills	$12.00	5	800	$15.75

Supply Method	Comments	Price ($/kg) Fuel Only	Trucks	Usage (kg/mo)	Price ($/kg) Fuel + Infra
Liquid	- 20x more efficient than gaseous tube trailers - Liquid tanks can hold ~4,000 kg	$5.00	100	16,000	$6.25

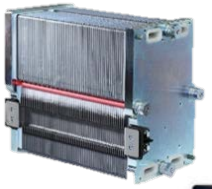
Supply Method	Comments	Price ($/kg) Fuel Only	Trucks	Usage (kg/mo)	Price ($/kg) Fuel + Infra
Onsite	- Eliminates delivery (40-60% of cost)	$1.75	500	120,000	$4.25

Approach | All-Inclusive Offering

GENKEY

Full solution drives ROI and customer adoption

ProGen Stack



GenDrive System

ProGen Stack Module

GENDRIVE

Fuel cell solution for Material Handling

GENFUEL

Complete Hydrogen infrastructure

GENCARE

Complete Service & Maintenance

Approach | Value Proposition

Value Prop Drivers
- Energy efficiency: 45% FC vs. 20% diesel
- Energy recovery via regenerative braking
- Decreased maintenance costs

Ancillary Benefits
- Data to evaluate EV performance
- Prognostics - see issues before they happen, less downtime
- Less noise - operator health benefits

Market Drivers
- Zero emission regulations
- Cost of compliance, creating more costly exhaust abatement
- Trend toward EV autonomy

Elimination / Reduction of Diesel Tractor Maintenance Items
- Oil changes
- DPF (Diesel Particulate Filter) changes
- Starters (policy to turn off tractor when getting off)
- Brakes (Regenerative braking eliminates or minimizes replacement interval)
  - *Typical route is 1.8 miles including 10-12 stops.*
  - *Diesel tractors require brakes to stop 40,000 lbs. from 10-15 mph to a stop.*

Approach | Value Proposition

2017 goal: To vet the assumptions in the value proposition with real world data

- **Volume pricing optimization (QTY 100, 1000) on a range of EV cargo tractors**
- **Maintenance savings – fuel cell vs. diesel**
- **Achievable regenerative braking (energy recaptured**
- **Data-driven diesel tractor idle time**

Fuel Savings for GSE Hydrogen-powered Cargo Tractors

Usage	days/yr	312

Hydrogen		H2-Liq	H2-SMR
Energy to Wheels	kWh	75.0	75.0
Regenerative Braking*	%	20%	20%
Energy Consumed	kWh	60	60
Fuel Cell Efficiency	%	45%	45%
Hydrogen Content	kWh/kg	33.3	33.3
Hydrogen Consumed	kg	4.0	4.0
Hydrogen	$/kg	$6.25	$4.25
Annual Fuel Cost	$	$7,808	$5,309
Ann. Fuel Savings	**$**	**$2,790**	**$5,289**
Ann. Maint. Savings	**$**	**$1,000**	**$1,000**
OpEx Reduction	**%**	**35.8%**	**59.3%**
CapEx Premium (est.)	**$**	**$25,000**	**$25,000**
Estimated Payback	**yrs**	**6.6**	**4.0**

Diesel		Diesel
Energy to Wheels	kWh	75.0
Idle Time*	$	25%
Energy to Wheels	kWh	93.8
Diesel Engine Efficiency	%	20%
Diesel Content	kWh/gal	37.95
Diesel Consumed	gal	12.4
Diesel	$/gal	$2.75
Annual Diesel Cost	$	$10,598

**Assumptions need to be verified*

Approach | Commercialization

			
Asset Type	Cargo Tractor	Belt Loader	Outdoor Forklift
Example Make/Model	Charlatte CT5E	TUG 660E	Caterpillar 2EC25
Fuel Cell Solution • Architecture • Power (kW) • Voltage (VDC)	GenDrive • FC Dominant • 22 kW • 80V	GenDrive • FC Dominant • 5-10 kW • 48V	GenDrive • FC Dominant • 8-12 kW • 48V
H2 Consumed @ 350 bar	4-8 kg/day	2 kg/day	2 kg/day
Required Development	• Beta → Product • Improvements to serviceability • Service interface	• Packaging for battery compartment with different aspect ratio (short, long and wide)	• Weatherproofing – wind driven rain, snow • Possible scaling up to Class 4 or 5

Approach | Commercialization

			
Asset Type	Cargo Loader	Spotter Truck (Yard Dog)	Class 5 Delivery Van
Example Make/Model	TLD TXL-838-REGEN	Capacity	Workhorse EGEN
Fuel Cell Solution • Architecture • Power (kW) • Voltage (VDC)	GenDrive Battery Charger • Battery Dominant • 5-10 kW w. Boost Conv. • 160V	GenDrive • FC Dominant • 20 kW w. Boost Conv. • Truck V	GenDrive • FC Dominant • 20-30 kW w. Boost • 48V
H2 Consumed @ 350 bar	10 kg/day	20-25 kg/day	10-12 kg/day
Required Development	• Bolt-on battery charging unit • Boost converter to 160V • CAN communication	• Integration with truck batteries and BMS • H2 storage placement • CAN communication	• Beta → Product • Match truck voltage and power requirement • H2 storage placement

Approach | H2 in EV Cargo Vehicles

Customer behavior in commercial applications drives the need to use hydrogen as part of the EV solution

Heavy Utilization - High Energy Intensity - Inability to Pause Operations

1 kg/day

Material Handling Forklifts

- Saves ~13 min. every shift with refueling in work cell
- Enables 24/7 3-shift ops with single asset

4-8 kg/day

Ground Support Equipment

- Tows 50,000 lbs. in energy-intensive shifts
- No stop during 4 hr. shift

10 kg/day

Class 5 Delivery Trucks

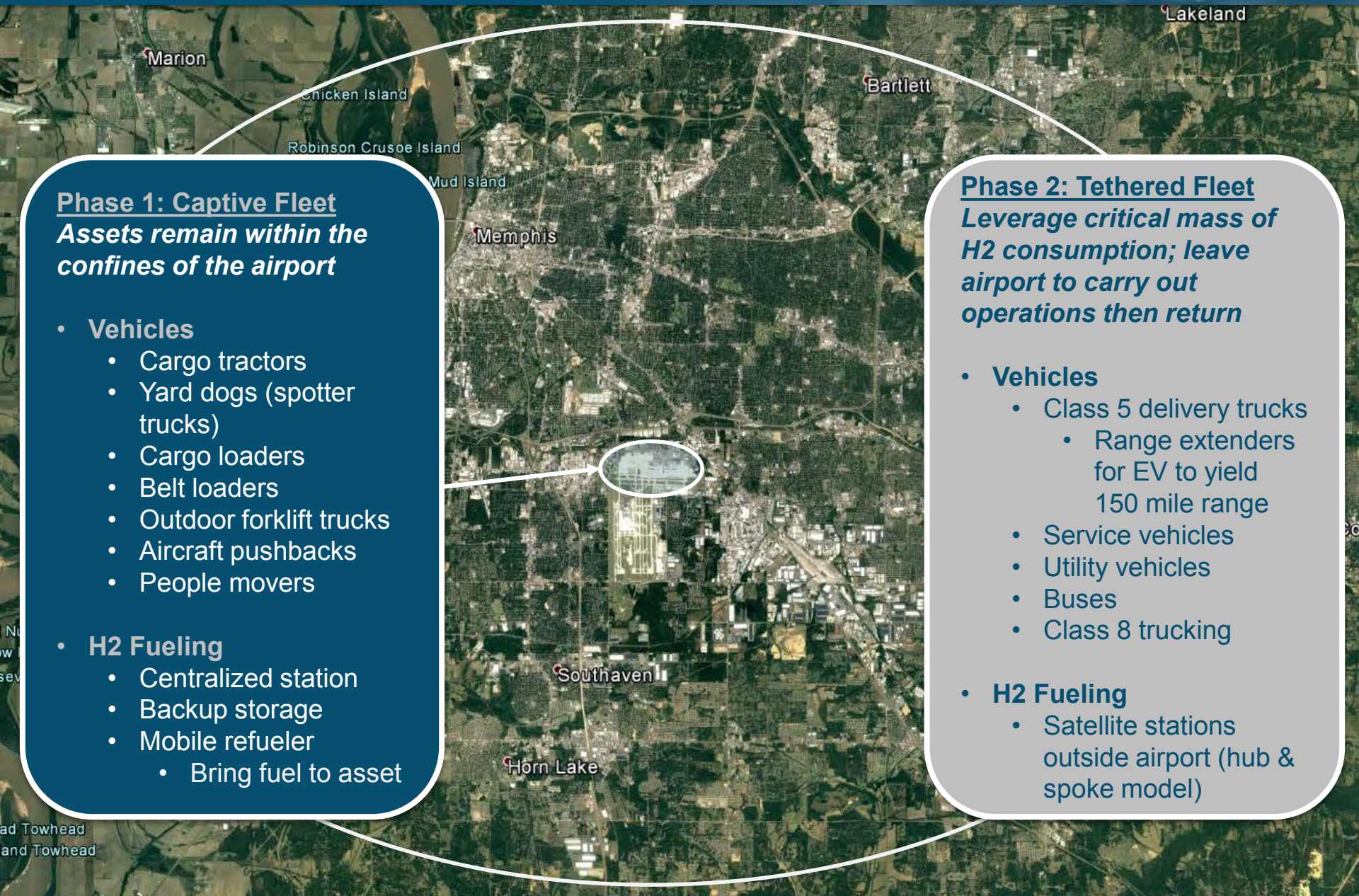
- Satisfies the need for 150 miles before refueling
- Does not diminish the cargo payload

20 kg/day

Class 8 Trucks

- Extends route capability
- Enables EV for aggressive load profiles

Approach | H2 Ecosystem for Airport Cargo



Phase 1: Captive Fleet

Assets remain within the confines of the airport

- **Vehicles**
  - Cargo tractors
  - Yard dogs (spotter trucks)
  - Cargo loaders
  - Belt loaders
  - Outdoor forklift trucks
  - Aircraft pushbacks
  - People movers
- **H2 Fueling**
  - Centralized station
  - Backup storage
  - Mobile refueler
    - Bring fuel to asset

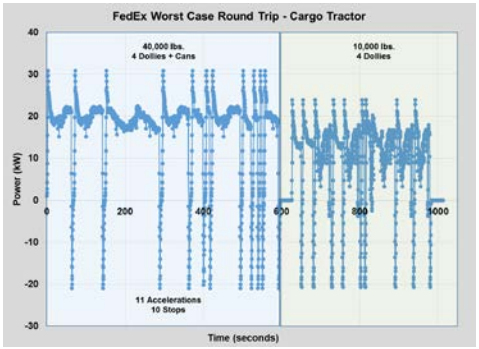
Phase 2: Tethered Fleet

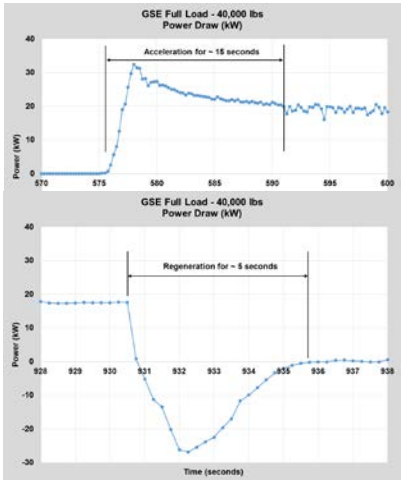
Leverage critical mass of H2 consumption; leave airport to carry out operations then return

- **Vehicles**
  - Class 5 delivery trucks
    - Range extenders for EV to yield 150 mile range
  - Service vehicles
  - Utility vehicles
  - Buses
  - Class 8 trucking
- **H2 Fueling**
  - Satellite stations outside airport (hub & spoke model)

Accomplishments | Development

Requirements Gathering

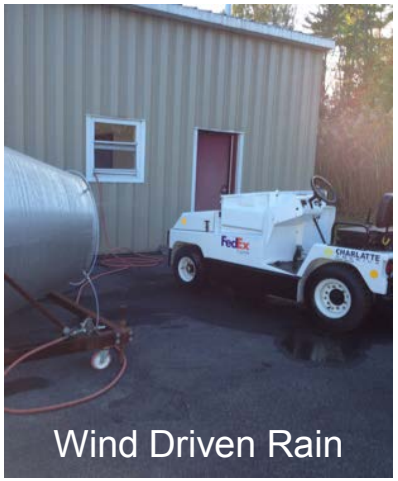




Bench Prototype

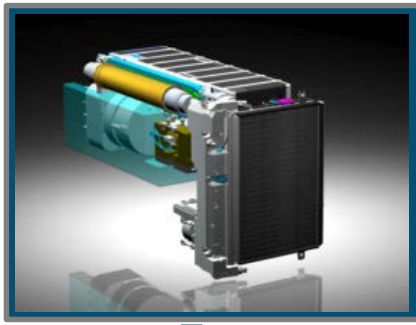
Alpha Prototype Design & Test

Stress Testing



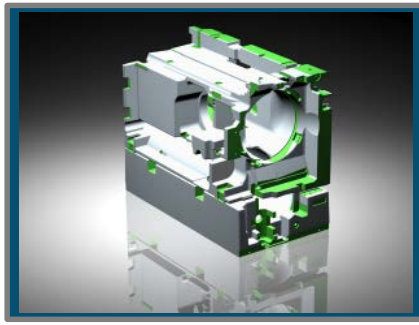
Accomplishments | Fuel Cell Design

Drop-in-Place Replacement For Battery



Fuel Cell System
- Stack (power)
- Battery (transients)

H2 Tank
- Energy (run time)



Ballast
- Weight (traction)

- *Drawbar: 5,000 lbs.*
- *Towing Capacity: 40,000 lbs.*
- *Voltage: 80VDC*
- *Power: 22 kW*
- *100% Outdoor Operation*
- *H2 Storage: 3.6 kg*
- *Hybrid PEM FC / Li-Ion Battery*
- *4,000 lbs.*

Accomplishments | Safety Planning

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System safety architecture used in 14,800+ fielded GenDrive units

- Safety Documentation
  - GSE System Requirements Document
  - GSE Safety Concept
  - Answers to PNNL Hydrogen Safety Team review
  - DFMEA on all subsystems
  - Safety HAZOP
- Safety Testing
  - Battery vibration
  - System vibration
  - Hydrogen ventilation testing
  - H2 tank test (1.25x working pressure)
  - Factory Acceptance Testing (FAT)
- Fueling Safety
  - Switches in receptacles to prevent drive-aways
  - Protective housing for receptacle
- Training
  - Safety – FedEx fire department
  - Operator
  - Service

Site safety architecture used in 40+ fielded GenFuel H2 Infrastructure sites

- GenFuel safety documentation
- GenFuel service manual
- 3rd party review of infrastructure
- GenFuel System Components
  - Infrared flame detectors
  - Hydrogen sensors in dispenser
  - E-stops
  - Pressure relief valves
  - Pressure relief routes to vent stack
  - Burst discs on all cryogenic lines
- Automatic notifications - FedEx fire dept., Memphis fire dept.
- Safety Testing
  - Factory acceptance test of dispenser – 1.25x working pressure
  - Line pressure test
- Safety Code Compliance & Permitting
  - Memphis-Shelby County Airport Authority
  - Memphis Fire Service Bureau
- First responder training

Accomplishments | System Performance

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March 2015: GSE deployed with 3rd party stacks at Memphis airport

May 2016: Fleet pulled due to poor stack performance

October 2016: System design completed with Plug stack

February 2017: Redeployment of small fleet with Plug stacks

Metrics Achieved in 2016

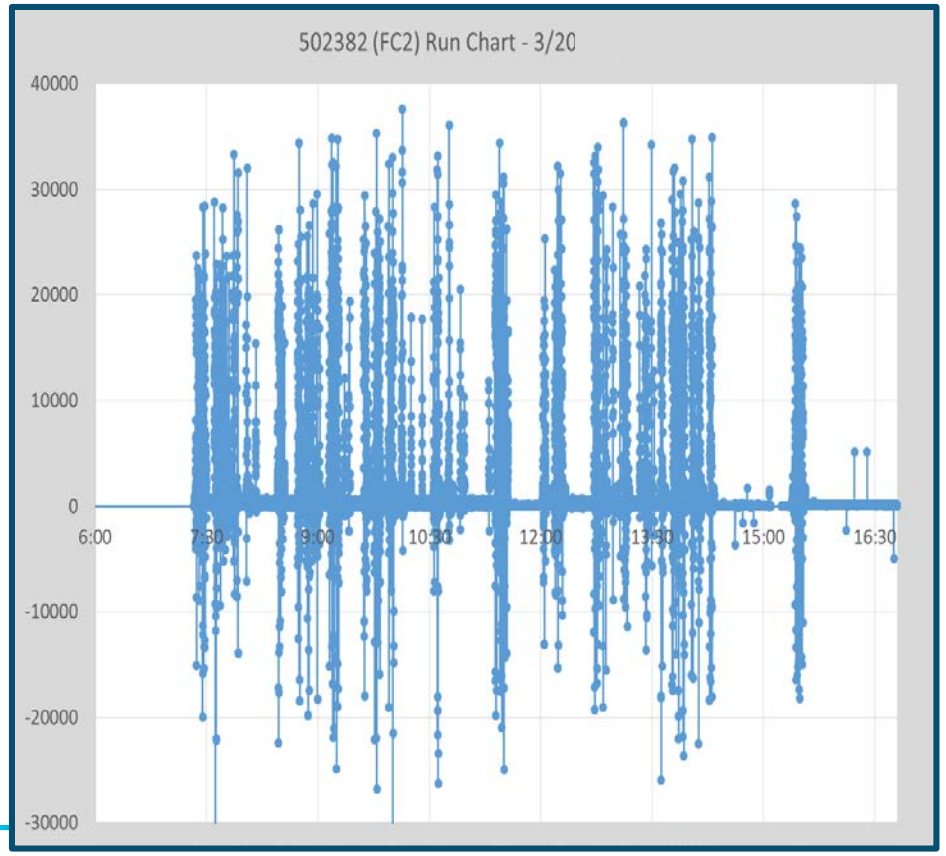
- Power: 5,000 lbs. drawbar capacity
- Run time: > 1 shift
- Speed rating: 10 mph
- Outdoor operation with no non-recoverable issues
- Hydrogen Fills: 350 bar

Metrics to Prove in 2017

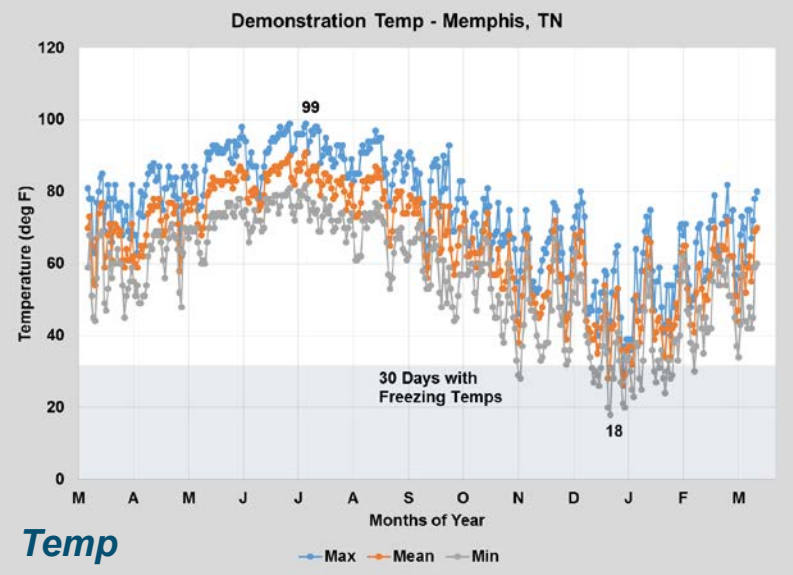
- Availability: > 80%
- Reliability (MTBF) > 100 hours

Availability Metrics:

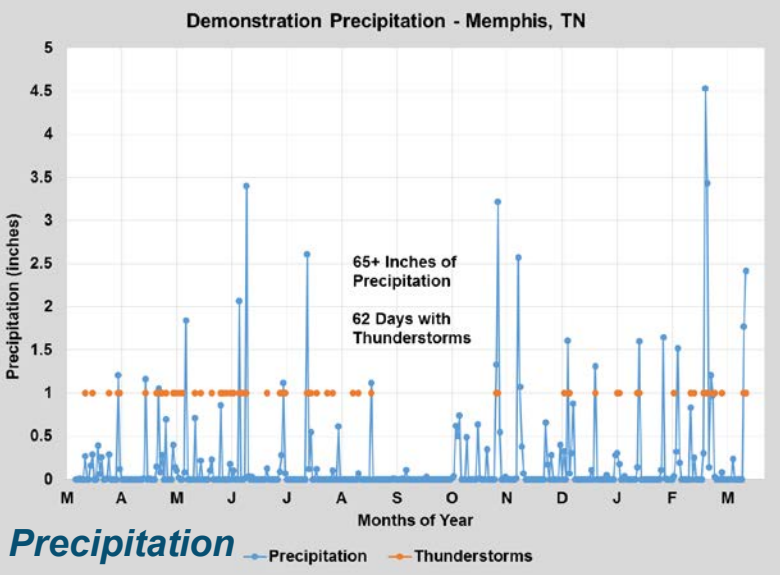
- February 95.9%
- March 97.2%
- April 97.0%



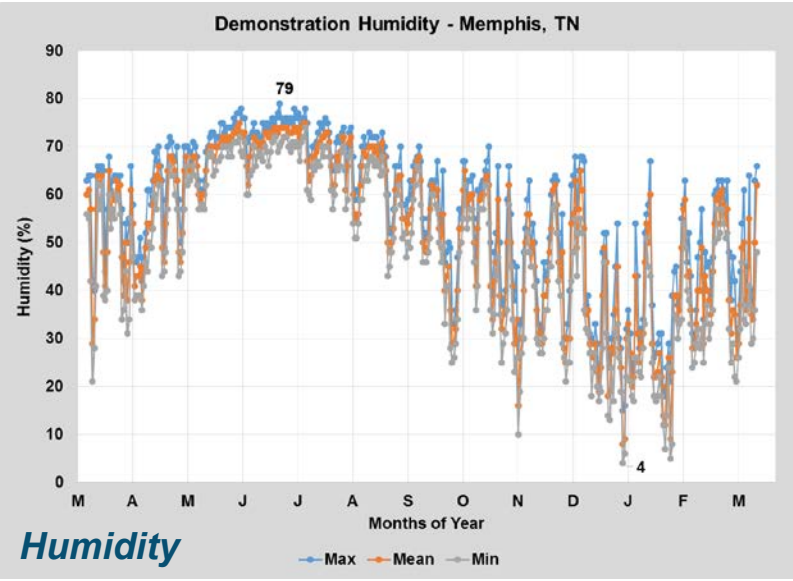
Accomplishments | Experience



Temp



Precipitation



Humidity

Shock and vibe

Challenges | Lessons Learned – MHE/GSE

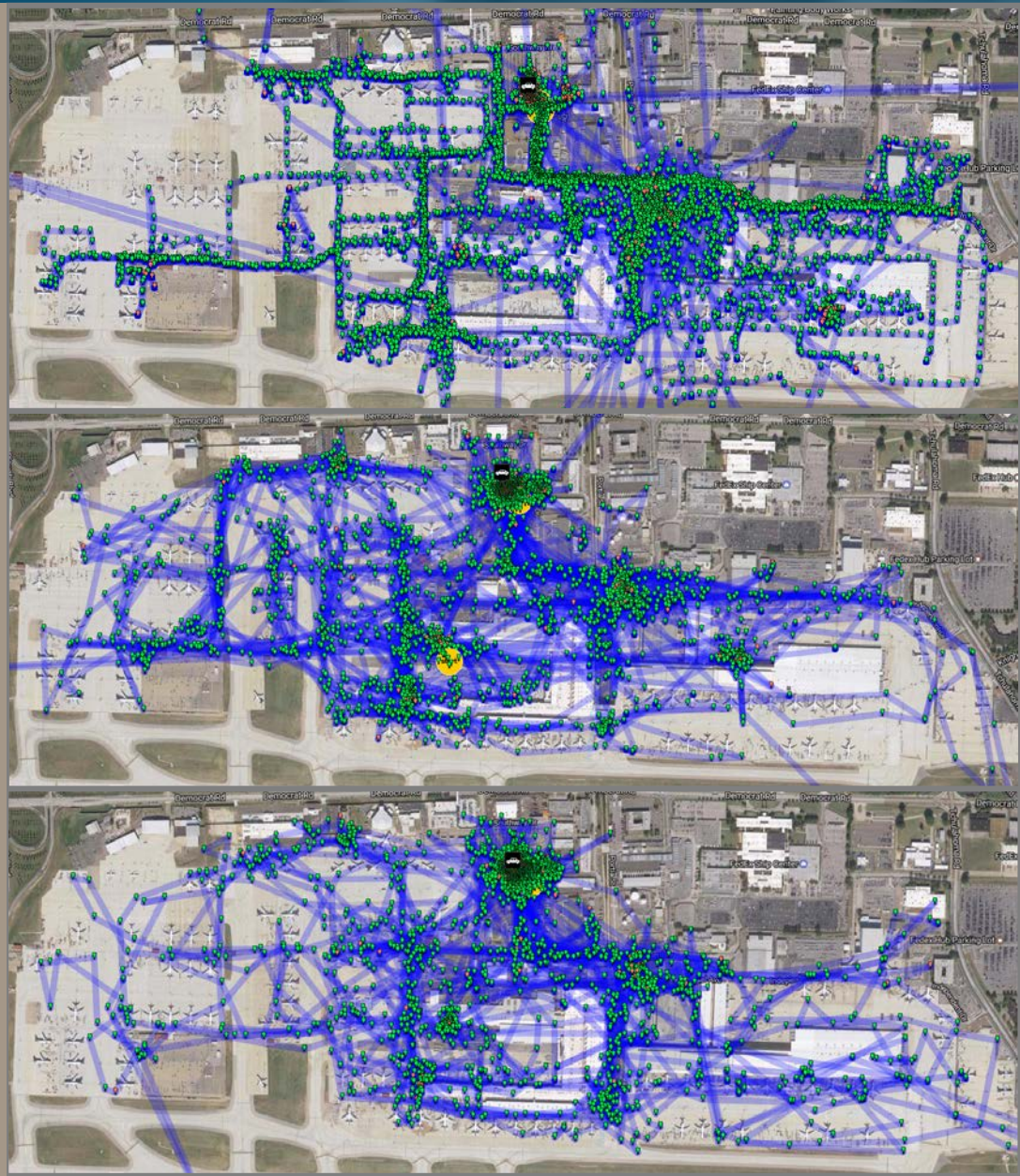
Lesson #1: Tractor is able to handle the full extent of the application

Usage throughout airport / all applications

- Prep 4-dolly strings
- Tow 40,000 lbs. from planes to sort
- Input cans into sorting facility
- Tow 40,000 lbs. from sort to planes

Takeaways

- No issues operating outdoors 24/7
- Operate worst route for full shift without needing to refuel
- Weatherproofing is successful



Challenges | Lessons Learned (GSE/MHE)

Lesson #2 | The More Used, the Cheaper Hydrogen Becomes

- **Infrastructure is amortized over more molecules of hydrogen**
- **Adding more vehicles (not just tractors) improves the value prop for all hydrogen vehicles.**

Hydrogen All-In Price Reduction Sensitivity to Volume						
Freight Tractor Fleet Size	#	15	25	50	75	100
Freight Tractor Usage	kg/day	4	4	4	4	4
Total Fleet Usage	kg/day	60	100	200	300	400
Total Fleet Usage	kg/month	1800	3000	6000	9000	12000
Molecule Price	$/kg	$5.00	$5.00	$5.00	$5.00	$5.00
Infrastructure Site Price	$/month	$20,000	$20,000	$20,000	$20,000	$20,000
All-In Price per kg	$/kg	$16.11	$11.67	$8.33	$7.22	$6.67

Lesson #3 | Need the Appropriate Suite of Vehicles

- **Customers don't want to deal with multiple types of fuel for different vehicles/assets**
- **Need to drive hydrogen usage – impact shown in the chart above**

Lesson #4 | H2 Fuel / Infrastructure Must Be Part of the Freight Solution

- **Customers not familiar with hydrogen as a fuel**
- **If an issue arises, a customer wants one throat to choke**
- **Managing infrastructure ensures construction/permitting coincides with FC deployment**

Lesson #5 | Being "Green" Alone Doesn't Sell

- **There isn't a line item in the value prop for emissions reduction**
- **Business case must be based on clear value prop (ex. fuel savings, lower maintenance)**
- **However, one environmental impact to economics can be lower cost of compliance**

Challenges | Lessons Learned (GSE/MHE)

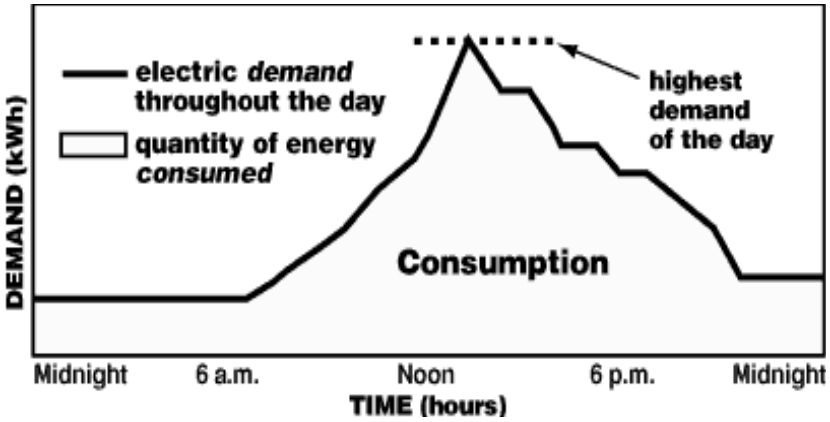
Lesson #6 | Some customers don't fully appreciate the impact that demand charges have on the total cost of ownership of electric equipment.

Electricity Usage ($ = Total Usage x $ / kW-hr)

- Removing electricity from battery charging
- Reduced rate of remaining electricity (the more you use, the higher the incremental cost)

Peak Demand ($ = Peak Usage x $ / kW max)

- Cost associated with meeting peak loads.
- Typically based on max power used during any 15-minute to 30-minute window throughout the month



Case Study

- A freight site with 50 EV freight trucks
- 80 kWh battery
- 50 kWh usable (20% to 90% SOC)
- Electricity Price: $0.12/kWh
- Demand Price: $10/kW

Constraints

- Standard charge time: 8 hrs.
- Standard = 1.6 ratio max/avg. charge
- Fast charge time: 2 hrs.
- Fast charge = 5.6 ratio max/avg. charge

Annual Electricity Price – Standard Charge

- Consumption Price: $188k
- Demand Price: $103k (35% of total)

Annual Electricity Price – Fast Charge

- Consumption Price: $188k
- Demand Price: $362k (66% of total)

Challenges | Lessons Learned (GSE/MHE)

Lesson #7 | Hydrogen to Vehicle

- Customers want to concentrate on their operations
- Customers will not change the behavior by bringing vehicles to fueling locations
- This damages the value proposition due to wasted operator labor

Lesson #8 | Financing

- Fuel cells are generally more costly than incumbent technologies
- Higher CapEx creates impediments to adoption when managing the P&L
- Financing fuel cells and infrastructure changes it to an OpEx expense

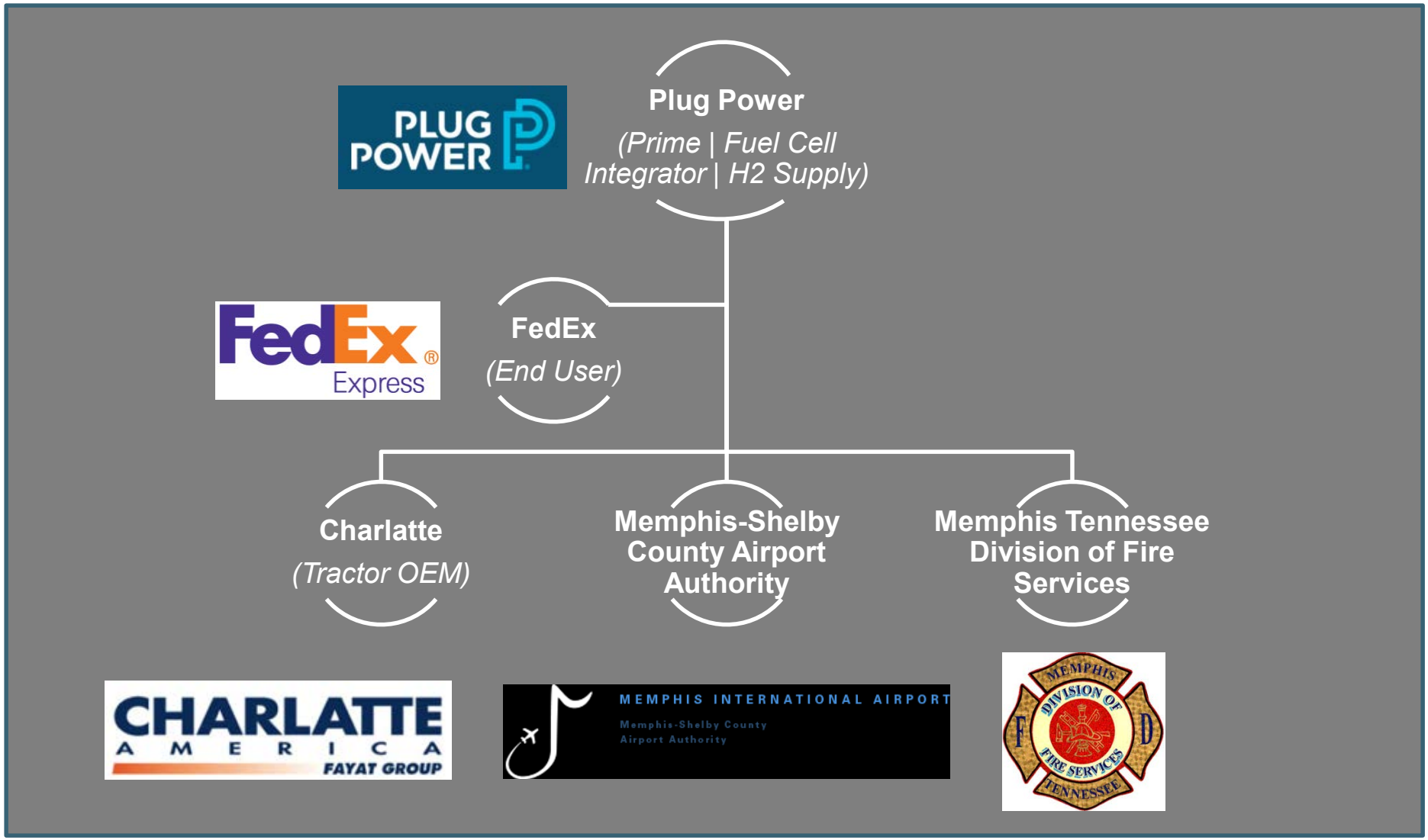
Lesson #9 | Service

- Programs are required to teach service technicians new technology
- Skills to teach include hydrogen safety / higher voltage safety

Lesson #10 | Look to Use Preferred Vendors

- Provides the same look and feel to the operators
- With only a different in drivetrain, operators don't know the difference
- Customers want to feel secure in continuity of service parts
- Customers also want to know the vehicle ruggedness is proven over 15-20 years

Collaborations | Program Team



Future Work

Vetting the Value Proposition

- Vetting the assumptions
  - *Diesel fuel consumption / idle time / annual operating hours*
  - *Diesel tractor maintenance – specifically starters, brakes, oil changes*
  - *Diesel maintenance interval*
  - *Fuel cell maintenance*
- System/Tractor Improvements
  - *Optimizing efficiency (lower kWh usage per shift)*
  - *Optimizing regenerative braking (recover max energy)*

Run Time with Plug stack-based System

- 4 seasons of operation | precipitation, temp fluctuations, etc.
- Long-term durability | effects of months of shock & vibe
- Expand the fleet to full 15 tractors (9 as of late April 2017)
- Increased usage by FedEx operators (training required)

Service: Feedback from FedEx service technicians

- FedEx technicians performing PMs
- Integrate into FedEx SOPs and management system

Summary

Objectives

- Cost-competitive
- More energy-efficient
- Reduce consumption of diesel
- Lower carbon emissions
- Decreased energy expenditures
- Validate value proposition

Actions

- Alpha prototype fully tested in 2013
- Beta prototype fully tested in 2014
- Hydrogen installation in Q4 2014
- Site permitted in March 2015
- GSE V1 0 deployed in April 2015
- 3rd party stack performance did not meet req's
- Redesigned GSE using Plug stack in 2016
- Redeployed small fleet in February 2017
- Demonstrated 96% availability with Plug stack
- Continued expansion in 2017 to full fleet

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