2015 DOE Hydrogen and Fuel Cells Program Review

Roots Air Management System with Integrated Expander

Project ID: FC103

Principal Investigator: Dale Stretch
Eaton Corporation
June 10, 2015

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Overview

Timeline

- Project Start Date: 07/05/2012
- Project End Date: 12/31/2015
- % Complete: 75%

Budget Period	Start Date	End Date
1	07/05/2012	12/31/2014
2	01/01/2015	12/31/2015

Budget

- Total Funding Spent (as of 2/28/15): $1,570,048
- Project Value: $2,660,533
  - DOE Share: $2,128,424
  - Cost Share: $532,109 (20%)
- Funds Obligated: $2,660,533
  - Funding for FY14: $683,569
  - Funding for FY15: $614,638

Barriers & Technical Targets:

- Air management system drive cycle efficiencies, power & cost
- Cost Target: 2017 = $500
- Input Power at Idle: 2017 = 200 W_e
- Compressor/Expander Eff. @ 25% flow > 65/70%
- Motor/motor controller Eff. @ 100% flow > 90%
- Comp./Expander $Power_{in}$ @ 100% flow < 8/14kW

Partners

- Prime: Eaton Corporation
- Subcontractors
  - Ballard Power Systems
  - Kettering University
  - Electricore, Inc.
- Technical Support
  - Argonne National Lab
  - Strategic Analysis

Relevance

Problem Statement:

- For Proton Exchange Membrane (PEM) fuel cells to achieve acceptance in the vehicle market, cost , reliability, and efficiency must be improved.
  - Current systems have trouble meeting all these objectives
  - This program is designed to move these objectives further ahead

Primary Objectives:

- Demonstrate key improvements to compressor/expander efficiency, including:
  - Compressor/expander efficiency at 25% flow of >65/70% by 2017 (baseline = 62/64%)
  - Combined motor/controller efficiency at 100% flow of >90% by 2017 (baseline = 80%)
  - Compressor/expander input power at 100% flow of <8/14 kW by 2017 (base = 11/17 kW)

Secondary Objectives:

- Conduct a cost reduction analysis, 2014 goal is to achieve $700 cost
- A fully tested and validated (TRL 7) air management system hardware capable of meeting 2017 Project Targets shown in table by project conclusion

$$\text{Barriers} = \frac{\text{2015 Target – 2011 Baseline}}{\text{2011 Baseline}}$$

Flow	Characteristic	Units	Baseline 2011	2015 Project Target		Eaton Test Results	Barriers Objective vs. 2011 Baseline	
				Lower	Upper			
100% (see notes a & b)	Input power with expander	kWe	11.0		8.0	12.1	-27%	10%
	Input power without expander	kWe	17.3		14.0	15.5	-19%	-10.4%
	Combined motor & motor controller efficiency	%	80.0	90.0		95.0	12%	19%
	Compressor efficiency	%	71.0	75.0		57.5	5.6%	-19%
	Expander efficiency	%	73.0	75.0		59.0	9.6%	-19%
25% (see notes c)	Input power with expander	kWe	2.3		1.0	1.6	-57%	-30%
	Input power without expander	kWe	3.3		2.0	1.9	-39%	-42%
	Combined motor & motor controller efficiency	%	57.0	80.0		75.0	40%	32%
	Compressor efficiency	%	62.0	65.0		58.5	4.8%	-5.6%
	Expander efficiency	%	64.0	70.0		44.5	9.4%	-30%
Idle (see notes d)	Input power (1.2 Pressure Ratio) with expander	kWe	600.0		200.0	300.0	-67%	-50%
	Input power (1.2 Pressure Ratio) without expander	kWe	765.0		200.0	300.0	-74%	-61%
	Combined motor / motor controller efficiency	%	35.0	70.0		40.0	100%	14%
	Compressor efficiency	%	61.0	60.0		34.1	-1.6%	-44%
	Expander efficiency	%	59.0	60.0		0.0	1.7%	-100%
n/a (see notes e, f & g)	Turndown ratio (max/min flow rate)	none	20.0	20.0		130.0	0.0%	550%
	Noise at maximum flow dB(A)	dB(A)	n/a		65.0	95.6	n/a	n/a
	Transient time for 10 - 90% of maximum airflow	sec	1.0		1.0	1.0	0.0%	0%
	System volume	liters	15.0		15.0	12.0	0.0%	-20%
	System weight	kg	22.0		15.0	23.5	-32%	6.8%
	System cost	$	960.0		500.0	815.0	-48%	-15%

Notes given in backup section of presentation

Baseline Eff. #'s are adiabatic

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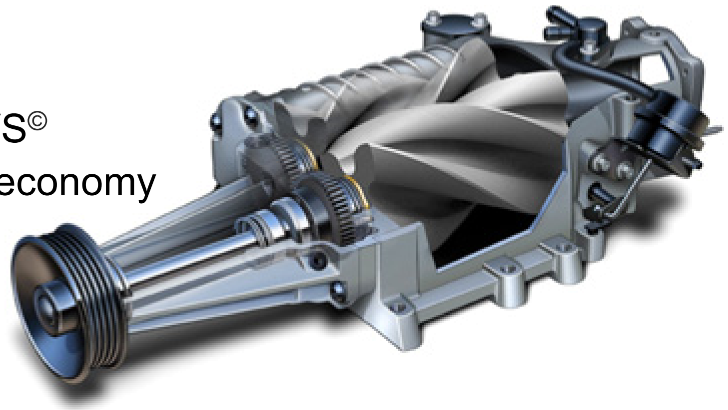
Approach

Hypothesis: An Eaton TVS© Roots blower with integral motor and TVS© Roots expander will create value for PEM fuel cell customers by significantly improving the efficiency, reliability, and costs of the air supply system as compared to the current state of the art.

Approach:

- Leveraging the broad efficiency map of Eaton's TVS© compressor to improve the overall drive cycle fuel economy
- Integrating the expander, compressor and motor to reduce system cost and increase system efficiency (new approach, similar to a traditional turbocharger)



- Reducing part count, thus cost, by incorporating overhung expander and motor rotors such that 4 bearings and 2 shafts are used
- Operating at lower speed to leverage lower cost bearings and improve system reliability
- Developing a net shape plastic expander to lower manufacturing costs

Approach – Budget Period 1-3

Period 1 – Develop Compressor/Expander with Integrated Motor

- ✓ Developing CFD capability to accurately model roots compressors & expanders which gives the ability to model many designs to more quickly meet performance and efficiency targets
- ✓ Design & build a roots blower mule to be used to ascertain the optimized expander & compressor inlet, outlet and unit size more quickly and with less full hardware builds
- ✓ Optimize compressor & expander
- ✓ Argonne National Lab will model and analyze compressor and expander performance data and Ballard's FC module data to determine the optimal compressor expander combination to maximize FC module performance
- ✓ Develop compressor/expander assembly with integrated motor – drive for reduced cost

Period 2 – Subsystem validation

- ✓ Prototype Compressor/Expander with Integrated Motor
- ✓ Compressor/Expander with Integrated Motor Performance and Validation Testing at Eaton

Period 3 - Validation Testing of System on 80kW FC Module

- <u>Demonstration of roots based air system performance within the overall Hydrogen and Fuel Cells Application</u>
  - Design & prototype complete system into integrated Ballard FC Stack
  - Compressor/Expander Validation Testing on Ballard Module
  - Correlate test results to ANL FC model
  - Determine Production Cost Estimates based on final design

Approach
Milestones & Deliverables

Deliverable and Milestone Log

Deliverable 1.0	Project kick-off presentation with revised project management plan	7/17/2012
Deliverable 1.1	Draft Safety Plan	10/04/2012
Deliverable 2.0	Concept design of the compressor/expander assembly with integrated motor	7/3/2013
Year 1 DOE Review	**Conduct a project review with DOE and report on project progress against GO/NO-GO Criteria**	**7/5/2013**
Deliverable 3.0	Final prototype design of the compressor/expander assembly with integrated motor	3/4/2014
Deliverable 4.0	Compressor/expander validation test plan	3/4/2014
Deliverable 5.0	Compressor/expander validation test report **	12/25/2014
Deliverable 6.0	OEM Integration and Test Plan	12/02/2014
Year 2 DOE Review	**Conduct a project review with DOE and report on project progress against GO/NO-GO Criteria**	**12/02/2014**
Deliverable 7.0	OEM validation test report	9/31/2015
Deliverable 8.0	Validated air management hardware	11/31/2015
Deliverable 9.0	System cost and manufacturability study	12/31/2015
Deliverable 10.0	Final Report and Presentation	12/31/2015
**Deliverable will include the test results taken on the test matrix developed with ANL and approved by DOE. This test will include dynamic tests, discharge pressures > 3 atm, and full map from idle to 100% flow.		

In progress

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Accomplishments and Progress

Table 1.1-1 Project Targets & Results

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Notes given in backup section of presentation

Roots Eff. #'s are isentropic vs Baseline Eff. #'s are adiabatic

Pressure ratio of compressor run at 2.4 instead of 2.5 (temperature too high to run 2.5)

■ Tests results exceeded 2015 Targets ■ Tests results did not meet 2015 Targets

DOE Original Objective/Goal

Eaton's Actual Achievement

■ Progress made since 2011

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Accomplishments and Progress

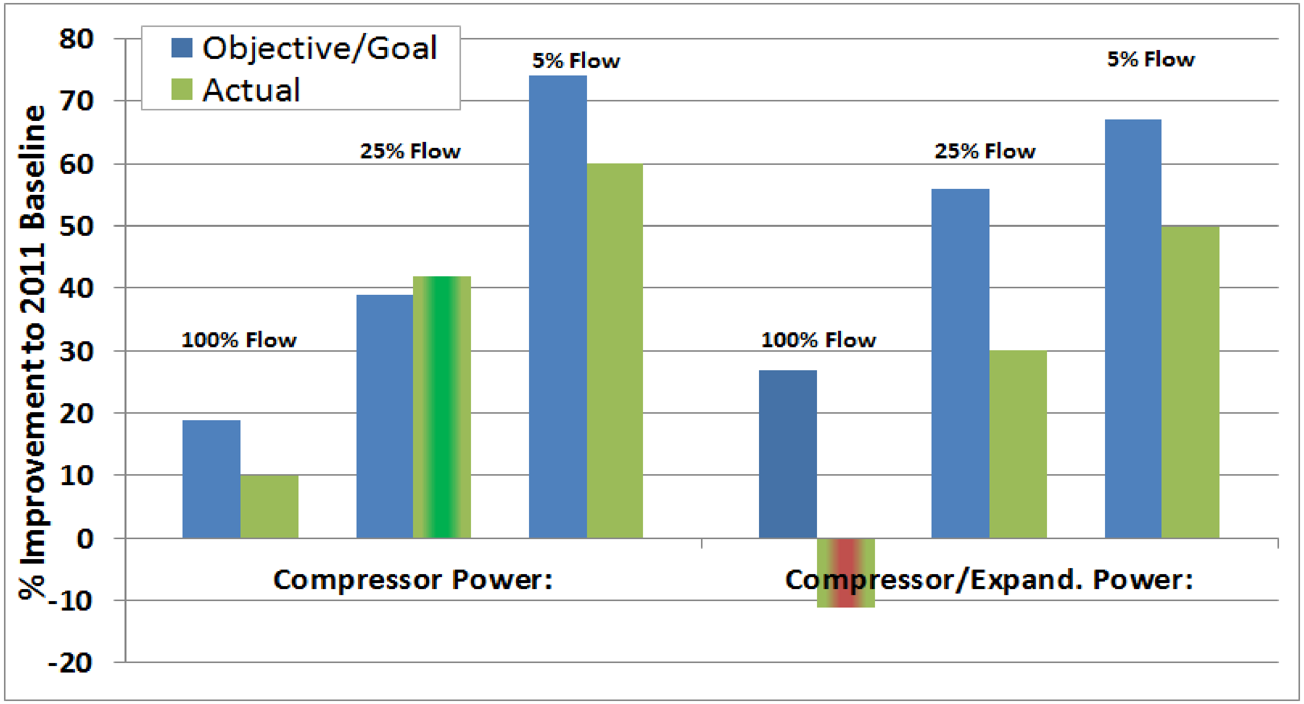
Barriers – Did Eaton improve on 2011 Power Performance?

Reduction in Power	Flow	Units	2011 Status	2014 Eaton Test Results	DOE 2017 Target
Compressor Power	100%	kWe	17.3	15.5	14
	25%	kWe	3.3	1.9	2
	5%	We	765	300	200
Comp./Expand. Power:	100%	kWe	11.0	12.1	8
	25%	kWe	2.3	1.6	1
	5%	We	600	300	200

Centrifugal Compressor

<u>Conclusions</u>:

- DOE requested greater low to midrange performance
- Eaton's strategy optimized system for lower power levels, so
  - Mid-range power consumption has improved
  - Top end power consumption slightly up for Comp./Expand.



Accomplishments and Progress

Barriers – Did Eaton improve on 2011 Eff. Performance?

Increase in Efficiency	Flow	Units	2011 Status	2014 Eaton Test Results	DOE 2017 Target
Motor Efficiency:	100%	%	80	95	90
	25%	%	57	75	80
	5%	%	35	40	70
Compressor Efficiency:	100%	%	71	57	75
	25%	%	62	58	65
	5%	%	61	34	60
Expander Efficiency:	100%	%	73	59	80
	25%	%	64	44	70
	5%	%	59	0.0	60

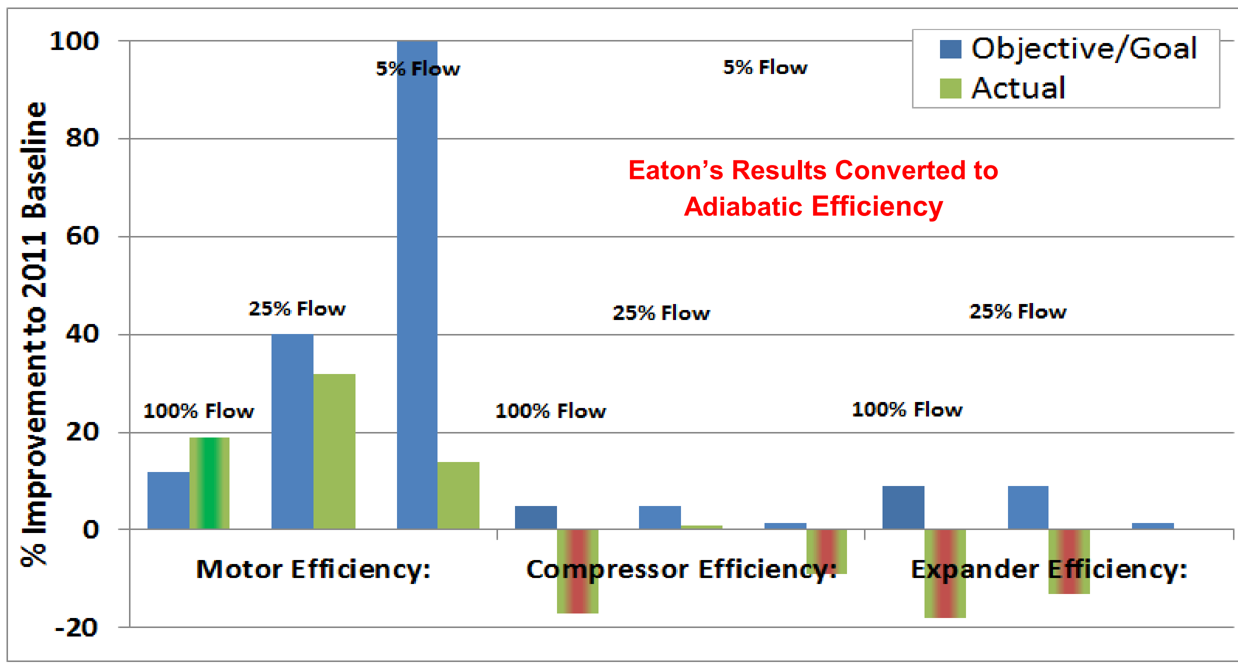
Adiabatic Eff. (2011 Status, compressor and expander) — Centrifugal Compressor

Isentropic Eff. (2014 Eaton Test Results, compressor and expander)

Adiabatic Eff. (DOE 2017 Target, compressor and expander)

Conclusions

- DOE requesting greater efficiency improvements for:
  - motor low & mid range
  - comp. & expand. high range
  - motor compared to comp. & expand.
- Motor efficiencies are higher for the roots compressor application due to lower shaft speeds
- Roots compressor efficiencies comparable to centrifugal but over a broader operating range
- Expander efficiencies appear to be less for the roots compared to the centrifugal



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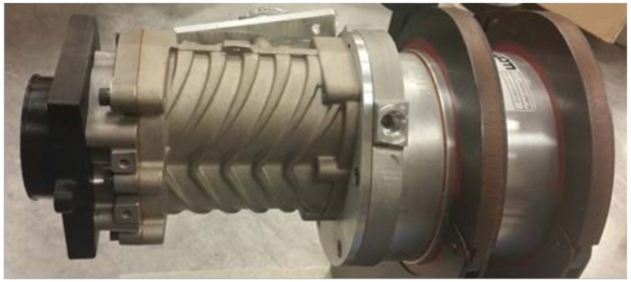
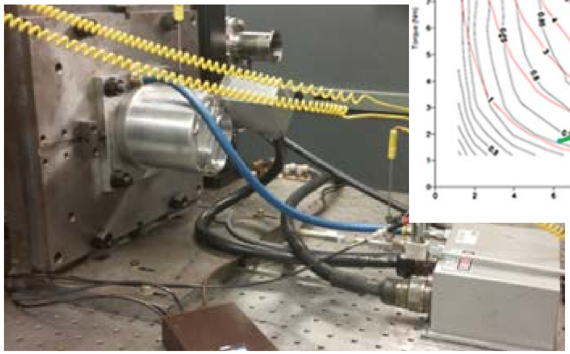
Accomplishments and Progress
Compressor & Motor, Design & Testing

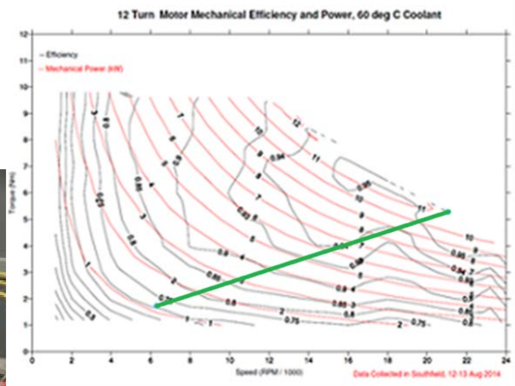
Design
- Built & Tested four compressor configurations
  - A 260 & 250 compressor design
  - Two low thermal growth, 3 & 4-lobe, compressor designs
  - Compressor tuned for best efficiency at its mid-range

Test
- The 3-lobe 250 compressor with aluminum rotors proved to have the best compressor performance
  - Data given in table for 3 spec. points
- Data shows that the compressor
  - has a fairly broad efficient range
    - ✓ 66% between 35% flow and 80% flow
  - provides good operating performance for an application with broad operating range

	Mass Flow	PR	kW	rpm	Eff.	Temp
100%	92	2.4	14.8	22000	59%	166C
25%	23	1.5	1.4	6000	63%	86C
Idle	4.6	1.2	0.23	2000	56%	60C







Design
- 12 Turn motor with assembly that includes:
  - Motor bearings
  - Water cooling passages
  - Mating surfaces for mounting the expander and compressor

Test
- Map presents
  - power supplied to the compressor/expander assembly
  - all mechanical & electrical losses in the motor, controller
- Air system operational points mapped in green
- Data shows that the motor is
  - ~95% efficient at 100% operating point
  - ~75% efficiency at 25% operating point
  - ~40% efficiency at idle

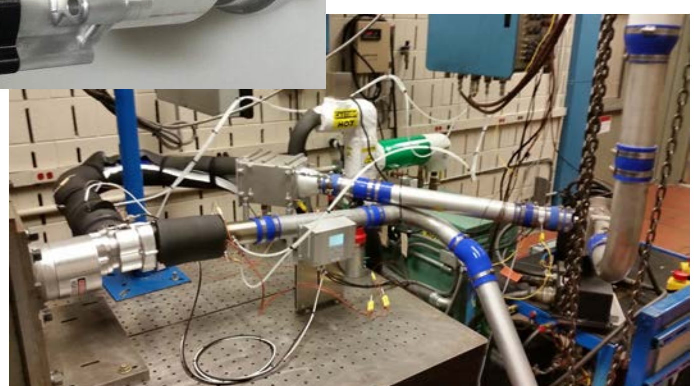
Accomplishments and Progress
Expander Design & Testing

Design

The 210 expander design, fabricated & tested – layout shown below

- Original path was to use all plastic parts, housing, rotors & covers
- Backup plan was to use all aluminum, this became the primary path when large rotor clearance diminished performance

210 Expander



Test

The 3-lobe aluminum expander proved to have the best expander performance

- Unit on test shown below left
- Dry & RH data shown below
- Data for 3 spec points as tested
- This expander has a fairly broad efficient range
  - >50% from 100% to 45% flow

Expander Testing – Dry Testing

	Mass Flow	PR	kW	rpm	Eff.	Temp
100%	88	2.2	3.6	9200	58	-43
25%	23	1.4	0.32	2300	39	-20
Idle	4.6	<1.2	--	--	--	--

Expander + Motor Testing – with Relative Humidity

	Mass Flow	PR	kW	rpm	Eff.	Temp
100%	88	2.2	3.8	10300	59	-24
25%	23	1.4	0.35	2800	44	-10
Idle	4.6	<1.2	--	--	--	--

Expander + Motor Testing – Dry Humidity

	Mass Flow	PR	kW	rpm	Eff.	Temp
100%	88	2.2	3.4	9300	55	-43
25%	23	1.4	0.29	2400	38	-18
Idle	4.6	<1.2	--	--	--	--

Accomplishments and Progress
Optimizing System Performance

System Layout:

The current layout is an Expander/Motor/Compressor system with the expander on one end and the compressor on the other end

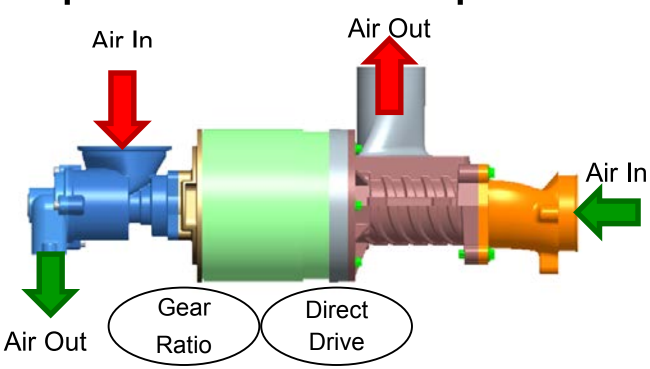
System consists of a 250 compressor, a 210 expander, & a 12 turn motor & controller

- Compressor & expander numbers related to volume displaced
- Compressor & expander designs implemented Eaton's TVS technology

Each unit can be separated from the system as a whole without disassembly

A gear reduction between the motor and expander is utilized to match the operating speed with the compressor

Expander Motor Compressor

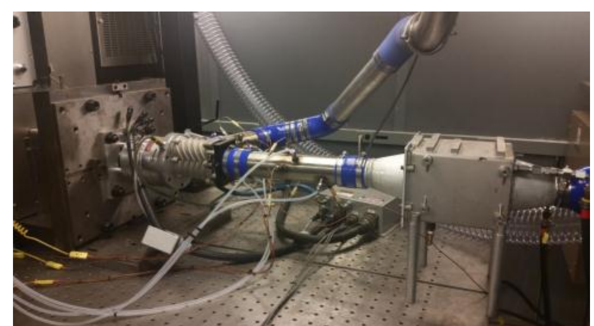


Expander Motor Compressor

Testing on dynamometer with & without expander

- Results indicate the mechanical power produced by the expander directly translates into electrical power saved at the system level

	Mass Flow @ Comp.	PR @ Comp.	Power With Expander (kW)	Power Without Expander (kW)
100%	92	2.4	12.1	15.5
25%	23	1.5	1.6	1.9
Idle	4.6	1.2	0.4	0.4



Accomplishments and Progress
Expander Helical Plastic Rotor

Low Fuel Cell outlet temperatures allow for the use of low cost plastic housings and rotors

- Designed helical plastic rotors
  - Designed & analyzed helical support structure
  - Optimized fiber orientation for injection ports.
- Molded rotors – Figure 3
  - Aluminum support structures were press fit onto the steel rotor shafts
  - Loaded into the injection molding machine for polymer overmolding
  - Right hand and left hand rotors were molded
  - Rotors were finished with an coating which reduces rotor-to-rotor & rotor-to-housing clearances.
- Assembled & tested complete plastic unit – Figure 4
  - Tested with no failure to a pressurized or 1.5 bar & rotation speed of 12000 rpm

Figure 4

Figure 3

Accomplishments and Progress
Costing Eaton Fuel Cell Cathode Air System

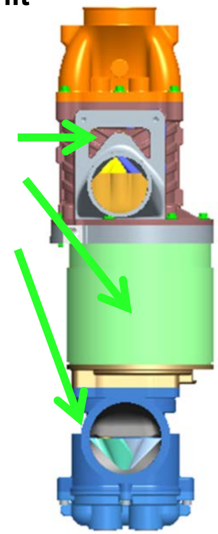
Costing completed in concert with Strategic Analysis

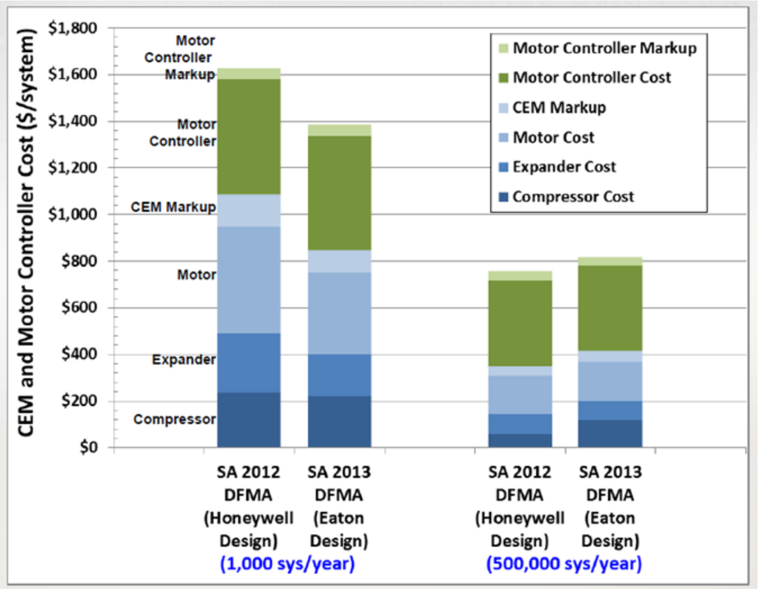
- estimated light & heavy duty applications
- Assembly and manufacturing markup are included in estimate
  - 15% on compressor & expander
  - 10% on motor & controller
- Eaton provided SA with cost estimate on motor & controller
- Progress has been made on cost
  - $815 vs $960
  - Improvements needed to achieve $500
- Most expensive part is the motor & controller – 71% of total cost
  - Compressor & Expander cost = $236.74
  - Motor & Controller cost = $579.23

Strategic Analysis & Eaton Cost Summary

Eaton 5-shaft V250 Compressor/V210 Expander/Motor Unit

Part No.	Component	Qty	Cost
1	Compressor	1	$116.34
2	Motor	1	$166.69
3	Expander	1	$77.32
4	Controller	1	$360.49
	Assembly		$11.33
	Markup		$83.80
Total			$815.97





Based on Annual Production Rate of 500,000 systems/year

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Responses to Last Year Reviewers' Comments

1. Some originally proposed concepts have been abandoned, such as common shafts…
   - Moving away from common shafts was driven by the significant loss of expander efficiency at low operating speeds.
   - Eaton reviewed the SA cost study & estimated the cost impact of using 5 shafts + gearing
     - 7-10% for compressor/expander system or between 2-3% for the complete system
   - Since there was a minimum cost impact, Eaton chose to:
     - target efficiency advancements, better matching of expander to compressor
     - over cost, equal expander compressor speeds (2 shaft design)

2. It is not clear whether plastic molding will be successful…
   - Testing has shown that plastics have opportunity to be successful but it is true that it is not quite ready for production
   - Fabrication process, plastic shrinkages and consistent molding is still needing development to be ready for production

3. Project is not very innovative…
   - 1st known application of roots expanders utilized to recuperate energy into a roots compressor
     - This required optimizing the expander to closely match the shaft speeds of the compressor

   - Demonstrated that roots compressor/expander air systems outperforms incumbent technology over a broader speed range
     - Primarily driven by lower speed operation and higher motor performance
     - Demonstrated roots compressor performance comparable to incumbent, peak performance is lower but performance island is broader
     - Demonstrated roots expander performance is slightly lower than incumbent
   - Demonstrated that the TVS© Roots air management system performs better than incumbent due to:
     - motor efficiencies that are higher for roots compressor as a result of their lower operating speeds
     - comparable compressor efficiencies between roots & centrifugal over operating range
     - minimal loss in expander performance

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Collaborations

Ballard

Relationship: Industry Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Provide Fuel Cell OEM input into the design and specification of the air management system. Integrate, test and validate the Eaton compressor/expander with a 75kW Ballard HD6 stack

Kettering

Relationship: University Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Provide critical analytical support includes expander CFD analysis, Critical Speed Analysis of compressor/expander design, and Critical Speed Analysis iterations of Eaton's compressor only

Electricore, Inc.

Relationship: Industry Sub-contractor within DOE Hydrogen and Fuel Cells Program

Responsibility: Administrative Program Management

Argonne National Lab

Relationship: Federal Laboratory Sub-contractor outside DOE Hydrogen and Fuel Cells Program

Responsibility: Provide critical simulation and modeling support of the fuel cell system to assist in optimizing the roots air system with the Ballard HD6 module

Strategic Analysis

Relationship: Industry Sub-contractor outside DOE Hydrogen and Fuel Cells Program

Responsibility: Develop fuel cell system cost utilizing manufacturing cost of roots based air management system

Key Remaining Barriers

RISK: Critical speed may be too low with overhung expander rotors.
LIKELIHOOD: No Longer Applicable IMPACT: Rotor contact, System redesign, cost impacts
ORIGIANAL MITIGATION PLAN: Analyze design to drive improvement before parts are made. Using light weight rotor material or support rotors on independent shafts and bearings. ACTUAL MITIGATION requirement to balance the expander size with system efficiency drove the implementation of a step up gear. The gearing eliminated the possibility of dual shaft, overhung design.
RISK: Material compatibility with exhaust de-ionized water.
LIKELIHOOD: Medium IMPACT: Material selection impacted
MITIGATION: Appropriate material selections will be used for all expander parts exposed to the working fluid. Eaton has significant experience with corrosion resistant coating for wetted components in roots blowers used for hydrogen recirculation. Continue to monitor during Fuel Cell Testing to determine impact.
RISK: Direct coupling of the expander to the compressor may result in FC stack pressure and flow rate control issues. System might not operate at optimal conditions.
LIKELIHOOD: Medium IMPACT: System efficiency reduction and cost impact
MITIGATION: Outlet/bypass valve will be add to maximize control while maintaining effective energy transfer.
RISK: Dry sump gearing will not meet durability requirements
LIKELIHOOD: Low IMPACT: Premature gear wear resulting in rotor contact
ORIGIANAL MITIGATION PLAN: Appropriate gear design, hardness and coating to prevent premature ware. Contingency will be to go back to wet sump. UPDATE: Went with wet sump configuration.

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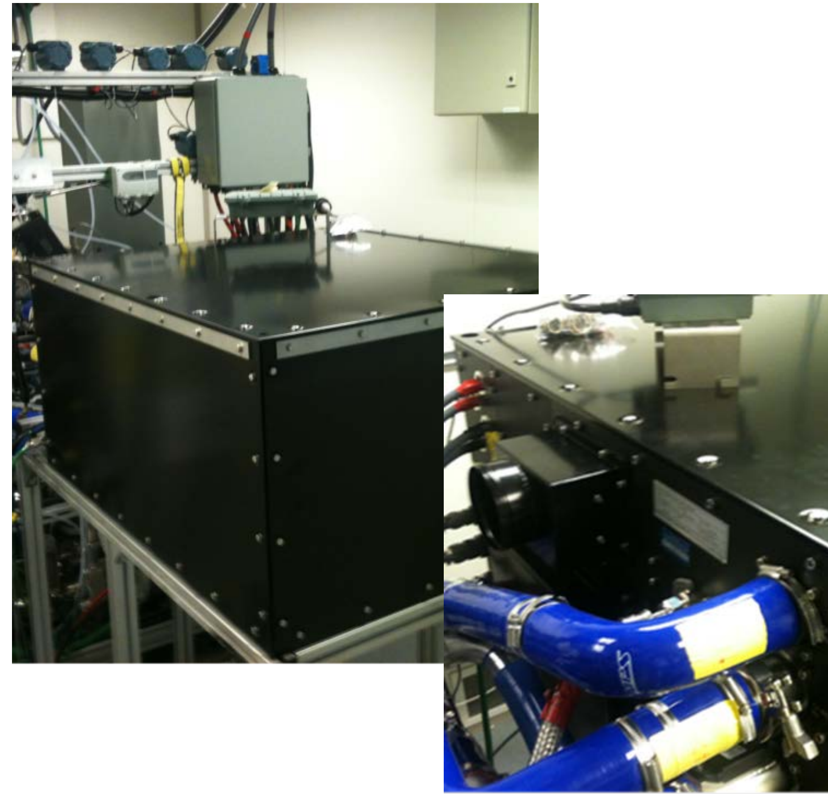
Proposed Future Work

Conduct Performance and Validation Testing at Ballard

- **Develop Test Plan / Determine Test Criteria**
- **Integrate Design, Build, & Debug Unit on Ballard Stack**
  - Design and integrate expander bypass valve & develop expander bypass valve control strategy if needed
- **Compressor/Expander Validation Testing On Ballard Stack**
  - Durability test as per Sub-Task 5.1
- **Document Test Results and Review Ballard Testing**



Ballard built and tested the HD7 fuel cell that will be used for the air management system testing

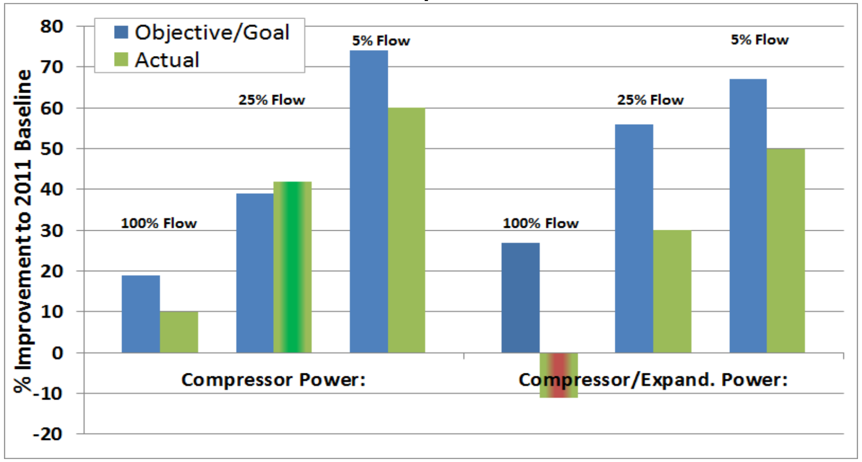
- Benchmarked performance in 2014

Summary
Milestone & Deliverable Details

- All Budget Period #2 Project Deliverables & Milestones were completed
  - ✓ Deliverable 3.0: Final prototype design of the compressor/expander assembly with integrated motor
    - ✓ Milestone: Prototype Compressor/Expander with Integrated Motor
  - ✓ Deliverable 4.0/5.0: Compressor/expander validation test plan & report
    - ✓ Milestone: Test and Validate Design Concept
    - ✓ Milestone: Go/No-Go Criteria - evaluate system design for efficiency and cost as compared to the 2017 targets and ANL model predictions
    - ✓ From Test Plan Document – 1)Dry Expander Map per 3.1.2, 2) Motor Map per 3.1.3, 3) Dry Compressor Map per 3.1.4, 4) Dry & Wet Expander/Motor per 3.1.5, 5) Dry & Wet Dyno/Motor/Compressor per 3.1.6, 6) Acceleration Test Procedure - #AS 127038, 7) Compressor Acoustic Noise Test - #AS 127454, 8)System Weight & Displaced Volume
  - ✓ Deliverable 6.0 OEM Integration and Test Plan
  - ✓ Milestone: Production Cost Estimate
  - ✓ Milestone: Year 2 Review

- Advancements were made at improving the technology & power consumption
  - ✓ At the component level:
    - ✓ demonstrated that roots compressor value was advanced from baseline
    - ✓ demonstrated that roots compressor + expander value is on par or slightly better than baseline, depending on duty cycle
  - ✓ Demonstrating that plastic use has potential to improve roots compressor value for customers

2011 to 2017 Improvement Goals



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Summary
Technology Advancement

- Improve roots expander technology – See Project Target Table
- Improve supercharger CFD modeling capability
  - Reduced modeling clearance capability by ~400%
  - Compressor & expanders models are now analyzed with correct clearances
- Develop plastic expander for purpose of driving down expander costs
  - Developed straight lobed & helical lobe expander
  - Straight lobe & helical lobe expander performed without failure
  - Expander testing was able to operate at 1.5 PR & 12,000 rpm
- Develop roots compressor/expander matching for improved waste heat recovery
  - Matched compressor & expander performance at all operating speeds.
- Develop high compression ratio (3.0) roots compressor with minimal efficiency losses using low thermal growth material
  - Developed low inertia compressor lobes with minimal thermal growth material
  - Fabrication process prevented complete evaluation - learned many lessons on how to fabricate correctly. 2nd attempt will have a much higher level of success.

Budget Period 1 & 2 activities enabled significant technology advancements that will yield increased value to Eaton, its partners, and FC customers.