

FOIL BEARING SUPPORTED COMPRESSOR-EXPANDER

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R&D DYNAMICS CORPORATION

DOE PROJECT AWARD #DE-EE0009617

MAY 6TH-9TH, 2024

DOE FUEL CELL R&D FOR HEAVY-DUTY APPLICATIONS

PROJECT ID: FC349

2024 ANNUAL MERIT REVIEW AND PEER EVALUATION MEETING

Project Goals

Develop a fuel cell system Compressor-Expander for heavy-duty vehicle applications. It must meet the following requirements:

- Flow 143 to 285 g/s of air at a compressor ratio up to 2.5 efficiently over a wide operating range.
- Be highly reliable and have a long service life.
- Be versatile to allow broad usage across many fuel cell platforms
- Be able to be mass-produced at lower cost.

Overview

Timeline and Budget

Project Start Date: May 1, 2022

Project End Date: May 1, 2025

Total Project Budget: \$2,000,000

- Total Federal Share: \$1,600,000
- Total Cost Share: \$400,000
- Total DOE Funds Spent*: \$1,330,300
- Total Cost Share Funds Spent*: \$332,575

*As of 10/31/2023

Barriers

- Meeting the efficiency for the Compressor-Expander at the required pressure ratio.

Targets

- 75% compressor efficiency and 70% expander efficiency at 285 g/s and a pressure ratio of 2.52.
- System cost less than \$3,000 at 100,000 units/year.
- Durability of 25,000 hours under various loads.

Partners

- Industry Collaborator: Loop Energy
- University Collaborator: University of Texas – Dallas

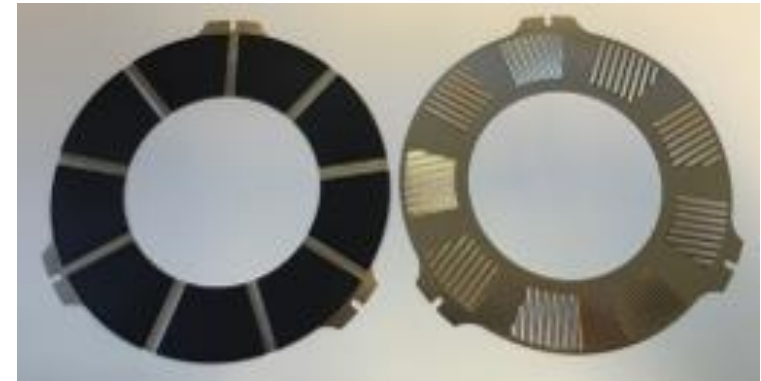
Potential Impact

- The Compressor-Expander is the key component of the balance of plant in a hydrogen fuel cell.
- The foil bearing supported Compressor-Expander being developed under this project will allow automotive and heavy-duty truck fuel cell manufacturers to deliver small, efficient, and extremely reliable fuel cell air management systems to their customers at a reasonable price.
- Successful completion of this project will create significant additional manufacturing jobs at R&D Dynamics and their partners/subcontractors.

Technology	Advantages
Oil-free foil air/gas bearings	No oil contamination, increased reliability, high vibration & shock capacity, smaller size/weight, no scheduled maintenance, quieter operation, and high start-stop cycles
Centrifugal compressor and turbine	Higher efficiency and smaller size/weight
Surge bypass and variable turbine nozzles	High efficiency over wide operating range
Drive with silicon carbide (SiC) switches	Higher switching frequency, higher operating temperature, and smaller size

Approach

- High speed centrifugal compressor/expander
- Supported on oil-free foil air/gas bearings
- Surge bypass and variable turbine nozzles
- Sensorless permanent magnet motor (DCPM)
- Motor drive with silicon carbide (SiC) switches
- Smaller size and weight



Milestone Review

	SOPO Date of Completion	Milestone	Status	Comment
BP1	August 2022	Preliminary Design	100%	Completed!
	January 2023	Detailed Design & Analysis	100%	Completed!
	January 2023	CE & Drive Drawings	100%	Completed!
	May 2023	Test Rig Design and Manufacturing	100%	Completed!
	May 2023	CE & Drive Manufacturing	100%	Completed!
	November 2023	CE & Drive Assembly and Development Testing	65%	Currently performing development testing on CE
	May 2024	Budget Period 1 Go/No-Go Decision Point		
BP2	May 2025	Cost Estimate and Production Plan		
	May 2025	Durability Protocol Testing		

Performance Targets

Characteristic	2030 Targets	Basis	Today's Values	Mitigation Strategy
Compressor Efficiency*	a=77%, b=69%, c=46%	Predicted Performance Map	a=73%, b=75%, c=68%	Test rotor, compare against prediction, and then iterate
Turbine Efficiency*	a=70%, b=80%, c=0%	Predicted Performance Map	a=72%, b=68%, c=0%	Test rotor, compare against prediction, and then iterate
Motor Efficiency*	a=95%, b=95%, c=80%	Power meter	a=97%, b=TBD, c=TBD	
Drive Efficiency*	a=97%, b=97%, c=80%	Power meter/thermal balance	a=98%**, b=TBD, c=TBD	
System Weight	<125 kg	<0.50 kg/kWe, 250kWe System	CE: 45.4 kg	
System Volume	<62.5 L	<0.25 L/kWe, 250 kWe System	CE and Drive: 34.8 L	
System Cost	<\$3,000	\$12/kWe, 250 kWe System, @ 100,000 units	\$25,000 (prototype unit)	Switching manufacturing paths for cheaper point price
Performance	Pressure rise and flow at each Operating Point			

*DE-FOA-0002446: 100% flow is a, 50% flow is b, Idle flow is c

**neglecting conduction losses between the drive and motor

Budget Period 1 Go/No-Go Decision Point:

One compressor expander system demonstrated on bench with path to Coefficient of Performance > 1.1 (Compressor Isentropic Power ÷ Total Input Power). And pathway toward DOE targets listed in Section C Table 1 (shown above here).

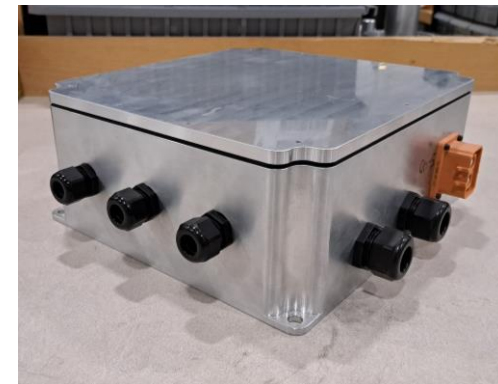
Safety Planning & Culture

- This project was not required to submit a safety plan to the Hydrogen Safety Panel (HSP)
- R&D Dynamics holds safety meetings and performs safety audits quarterly to ensure employees are properly trained, workspaces are clean, and protective equipment is being used
- Safety information is clearly incorporated into all assembly and test procedures
- Safety incidents are reported to Management; Engineering is responsible for mitigating the causes of any safety incidents to prevent them from recurring

Accomplishments & Progress

Budget Period 1: 2022-2023 (Since Last AMR)

- Completed detailed design of solid models and drawings for all CE components and assemblies in Solidworks
- Completed manufacturing for all CE components and assemblies
- Finished assembly work for the CE
- Built test stand in dedicated lab space, integrated instrumentation and electronic controls into custom LabVIEW VI
- Internally developed motor drive for testing with CE. Received alternate motor drive from UT Dallas
- Ran CE up to 65 kRPM on our test stand and measured the performance of motor drive and compressor



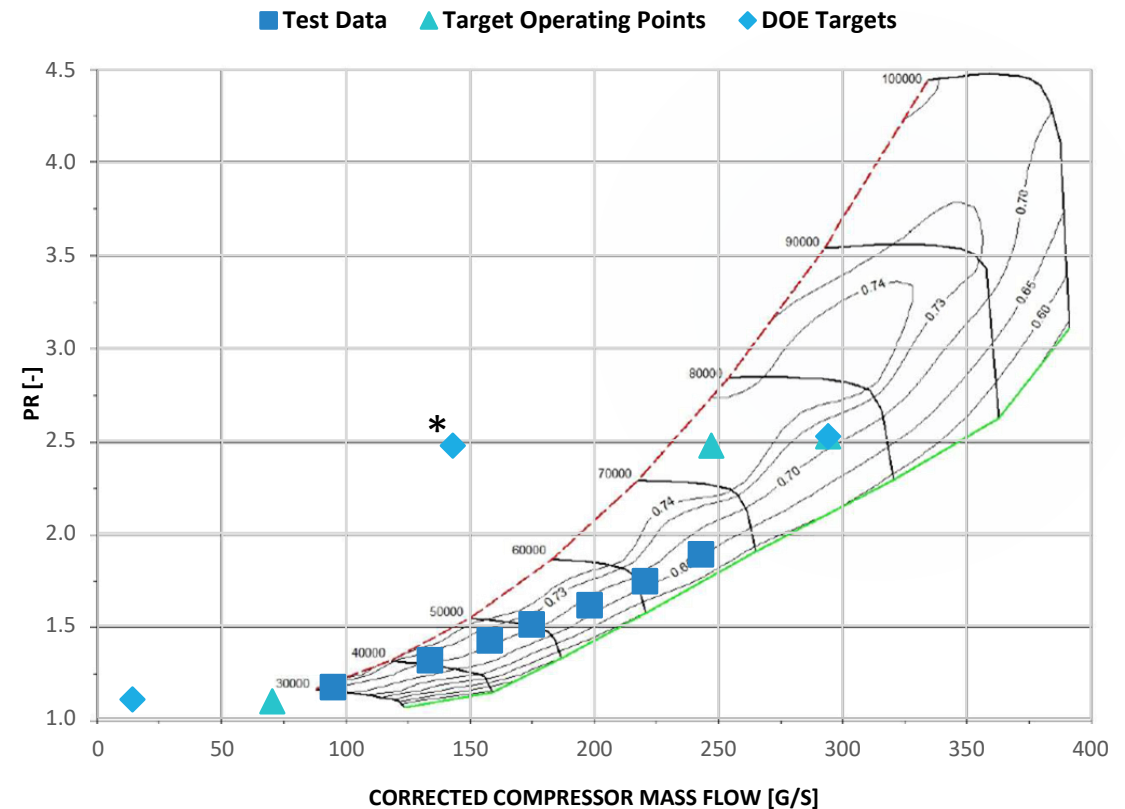
Accomplishments & Progress

Data at left shows an operating curve for CE

Test parameters:

- Backpressure device completely opened for minimal flow restriction
- VATN area maximized for minimal flow restriction
- Maximum speed for test was 65 kRPM
- Tested VATN position represents minimum expected compressor and turbine efficiency. Decreasing VATN area will increase both compressor and turbine performance. Data collected to date should be treated as off-design, showing minimum expected performance with respect to pressure ratio, efficiency, and COP.

COMPRESSOR PRESSURE RATIO VS. CORRECTED MASS FLOW



*Fuel Cell Program has de-emphasized the 50% flow point for project progress tracking based on stakeholder feedback

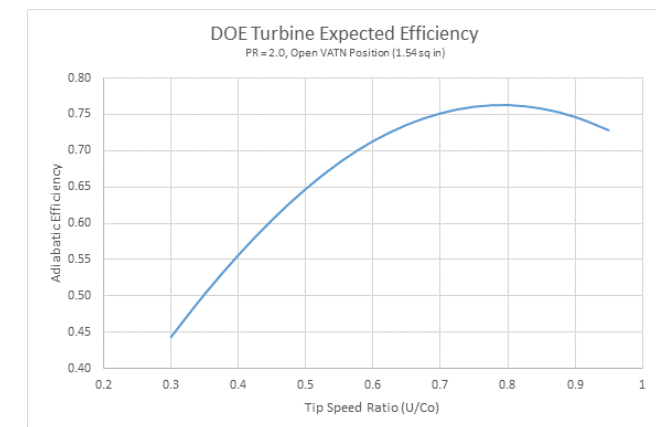
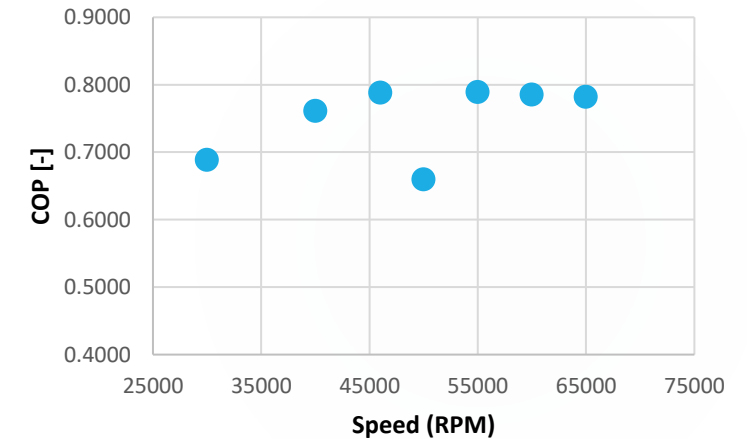
Accomplishments & Progress

*Data recorded during same test as on previous slide

$$COP = \frac{\text{Compressor Isentropic Power}}{\text{Total Input Power}}$$

Speed [RPM]	DC Power Input [kW]	Compressor Isentropic Power [kW]	COP [-]	Compressor Isentropic Efficiency [%]	Rig Diff. Pressure [psid]	Compressor Outlet Temp [°F]
30,000	1.8	1.24	0.6884	69.40	0.31	103.75
40,000	4.1	3.12	0.7608	63.63	0.60	137.10
46,000	6.1	4.81	0.7882	61.25	0.75	162.96
50,000	9.5	6.26	0.6594	62.43	0.90	179.67
55,000	10.6	8.36	0.7890	63.54	1.02	202.02
60,000	13.9	10.91	0.7852	61.80	1.19	230.12
65,000	17.8	13.92	0.7819	60.97	1.36	261.41

COP vs. CE Speed



Reviewer Comments

Reviewer Comment: The proposed work is a logical sequence. However, it is unclear how durability over 25,000 hours will be assessed. An accelerated stress test is perceived as necessary. R&D Dynamics Corporation is a foil bearing pioneer. However, performance data for other applications were not reported, which could support an assessment of the risk level of the proposed work.

- **R&D has defined a durability test plan that will simulate 25,000 hours of operation. This includes 10,000 start/stops, 5,000 cycles between 25% and 100% speed, and 1,000 on/off power cycles among other tests.**

Reviewer Comment: R&D Dynamics Corporation has shown excellent progress toward addressing the critical barriers of efficiency, mass, and cost in fuel cell system CE development. The project is exceeding many of the performance targets in CE efficiency, mass, and volume. Cost metrics are pending. Also, the total power of the fuel cell system air CE does not seem to be noted.

- **R&D will be conducting a cost estimate and production plan during the next phase of the program. R&D has estimated the required input power at each operating point. At our maximum pressure ratio and flow, we expect the input power to be approximately 32 kW.**

Reviewer Comment: The basic design has been completed. It would be helpful to see the model of efficiency and the performance diagram and intended operation points for HD fuel cell system applications, as well as the design verification test plan.

- **We've included some of our efficiency and performance maps on the previous slides along with our test data. R&D has a detailed test plan with objectives to map the compressor, characterize the VATN, and validate maximum operating conditions.**

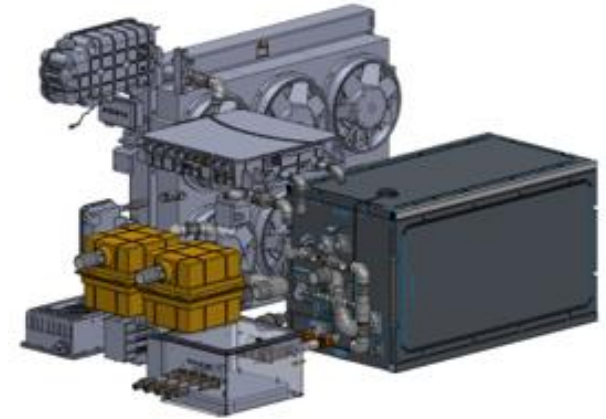
Collaboration & Coordination

Loop Energy

- At the end of the program, Loop Energy will perform field testing on their bench
- Assisted in developing CE specification at onset of program

University of Texas – Dallas

- Developed alternate motor drive for testing with CE.



Remaining Challenges and Barriers

Challenges

Meeting the efficiency targets for the Compressor and Expander at all operating points.

- Progress towards meeting these targets can be made by iterating the design of the impellers and their related components

Meeting the durability targets for the entire unit.

- A durability testing protocol has been developed by R&D which will simulate the 25,000 hours that the unit must survive in the field

Barriers

Meeting the volume cost targets for the entire unit.

- More work is required to determine alternate manufacturing paths to bring down component costs while maintaining the necessary performance of the CE and Drive

Proposed Future Work

FY 2024

- Run the CE to its maximum speed, 80 kRPM
- Optimize test setup and controls scheme for CE to better meet performance requirements
- Fabricate hardware to assemble (3) Drive development units
- Complete cost estimate and production plan
- Perform durability protocol testing on the CEs and Drives, including:
 - 10,000 Start/Stops of the CE from a stop to idle speed
 - 1,000 On/Off power cycles of the Drive electronics
 - 200 hours of maximum flow rate and pressure testing
 - Noise levels measured at idle from a distance of (1) meter

Program formally ends November 1st, 2024

- Beyond the DOE-funded timeline, R&D will market this CE and Drive to automotive OEMs for use in Hydrogen Fuel Cell vehicles

Summary

- Project awarded May 1st, 2022
- Foil air/gas bearings offer increased reliability, high vibration & shock capacity with lower lifetime maintenance cost
- Centrifugal compressors and turbines provide the highest efficiency and smallest size/weight
- Higher switching frequencies and operating temperatures with SiC switches in the Drive provide greater efficiency and reliability
- Detailed design of the CE and Drive models and drawings completed
- Parts manufacturing and component assemblies completed for the CE
- Fabricated and assembled dedicated test stand with a custom LabVIEW VI
- Tested CE to speed of 65 kRPM while measuring compressor performance data, compressor achieved corrected mass flow of 243 g/s at a 1.88 pressure ratio