EXHIBIT F

NSO

ASSISTANCE AGREEMENT

1. Award No.	2. Modification No.	3. Effective Date	4. CFDA No.
DE-EE0011347		10/01/2024	81.087

5. Awarded To
CABOT CORP
Attn: Catherine Stone
TWO SEAPORT LANE, SUITE 1400
BOSTON MA 022102019

6. Sponsoring Office
Energy Effcy & Renewable Energy
EE-1
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington DC 20585

7. Period of Performance
10/01/2024
through
09/30/2025

8. Type of Agreement
- ☐ Grant
- ☒ Cooperative Agreement
- ☐ Other

9. Authority
IIJA PL 117-58,2021
PL109-58 EPACT, 2005

10. Purchase Request or Funding Document No.
See Schedule

11. Remittance Address
CABOT CORP
Attn: CABOT CORPORATION
2 SEAPORT LANE
SUITE 1400
BOSTON MA 022102001

12. Total Amount
Govt. Share: $5,437,559.00
Cost Share : $1,359,390.00
Total : $6,796,949.00

13. Funds Obligated
This action: $5,437,559.00
Total : $5,437,559.00

14. Principal Investigator

15. Program Manager
Gregory J. Kleen
Phone: 240-562-1672

16. Administrator
Golden Field Office
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17. Submit Payment Requests To
VIPERS
https://vipers.doe.gov
Any questions, please contact by call/email 855-384-7377 or VipersSupport@hq.doe.gov

18. Paying Office
VIPERS
https://vipers.doe.gov
Any questions, please contact by call/email 855-384-7377 or VipersSupport@hq.doe.gov

19. Submit Reports To
See Attachment 2

20. Accounting and Appropriation Data
See Schedule

21. Research Title and/or Description of Project
BIL-Scalable, innovative manufacturing process for novel carbon supports for metal catalysts for MDV/HDV PEM fuel cells

For the Recipient		For the United States of America	
22. Signature of Person Authorized to Sign		25. Signature of Grants/Agreements Officer	
23. Name and Title	24. Date Signed	26. Name of Officer	27. Date Signed
		Paul C. Kingham	09/20/2024

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	UEI: C3BGEN6HC493 In addition to this Assistance Agreement, this award consists of the items listed on the Cover Page of the Special Terms and Conditions. The Project Period for this award is 10/01/2024 through 03/31/2028, consisting of the following Budget Periods: Budget Period 1: 10/01/2024 to 09/30/2025 Budget Period 2: 10/01/2025 to 12/31/2026 Budget Period 3: 01/01/2027 to 03/31/2028 In Block 7 of the Assistance Agreement, the Period of Performance reflects the beginning of the Project Period through the end of the current Budget Period. Additional future DOE funding and additional budget periods are not contemplated under this award. Funding for all awards and future budget periods is contingent upon the availability of funds appropriated by Congress for the purpose of this program and the availability of future-year budget authority. The Special Terms and Conditions for this award contain specific funding restrictions. Please review the applicable terms for procedures required to lift the restrictions. DOE Award Administrator: Josh Durant E-mail: joshua.durant@ee.doe.gov Phone: 240-562-1459 DOE Project Officer: Greg Kleen E-mail: gregory.kleen@ee.doe.gov Phone: 240-562-1672 Recipient Business Officer: Limeng Chen E-mail: limeng.chen@cabotcorp.com Phone: 978-435-5936 Recipient Principal Investigator: Paolina Atanassova E-mail: paolina.atanassova@cabotcorp.com Phone: 151-1480-4916 Continued ...				

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CONTINUATION SHEET	REFERENCE NO. OF DOCUMENT BEING CONTINUED	PAGE	OF
	DE-EE0011347	3	3

NAME OF OFFEROR OR CONTRACTOR

CABOT CORP

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	"Electronic signature or signatures as used in this document means a method of signing an electronic message that-- (A) Identifies and authenticates a particular person as the source of the electronic message; (B) Indicates such person's approval of the information contained in the electronic message; and, (C) Submission via FedConnect constitutes electronically signed documents." ASAP: NO: STD IMMEDIATE Extent Competed: COMPETED Davis-Bacon Act: YES PI: Atanassova, Paolina				

JULY 2004

Statement of Project Objectives (SOPO)

Project Title: **Advanced Low-PGM Cathode Catalysts with Self-Healing Properties for High Performing and Highly Durable MEAs**

Lead Institution**:** University of California, Irvine

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A. Project Objectives

The project aims to develop and deliver highly durable and manufacturable fuel cell MEAs with low-PGM novel cathode catalyst loading, enhanced mass activity at high operational potentials, improved high current density performance, and extended operational longevity at a reduced cos. The proposed program's level of performance will meet the M2FCT 2025 end-of-life MEA target: demonstration of 2.5 kW/g_{PGM} power output (1.07 A/cm^2 current density at 0.7 V; 749 mW/cm^2 at 0.7 V) after running a heavy-duty AST equivalent to 25,000 hours. The development of commercially viable Pt-alloy catalysts and analysis techniques for evaluating and ranking them as proposed here are based on fundamental principles and discoveries that were conceived in our laboratories. Mitigation of degradation processes is feasible only by materials design at atomic/molecular level, which is a signature of this project. To enhance the performance and durability of the cathode catalyst to meet the medium- and heavy-duty targets we will aim to: (1) drive nanoscale surface structures to mimic that of Pt(111)-skin, (2) induce ordering in the alloy to limit TM loss , (3) introduce Au to enable *self-healing*, (4) optimize the interface between water, ionomer, and the catalyst with molecular interfacial additives, (5) deploy nanoparticles on advanced carbon supports with selective anchors, and (5) integrate novel materials in to highly durable MEAs. The technical innovations proposed here rely on cutting edge fundamental discoveries at atomic/molecular scale that will be applied to the development of novel catalysts for highly durable *self-healing* MEAs. The outcome will be groundbreaking MEA performance which will meet or exceed the M2FCT and DOE Technical Target. The ***final deliverable*** of the project will be at least 6 MEAs for independent testing by the M2FCT core lab consortium. The delivered MEAs will meet/exceed the M2FCT 2025 end-of-life target.

B. Scope of Work

The project will be conducted in three *Budget Periods* of 12 months in length, total of 12 quarters. During all phases of the project a series of technical tasks will achieve the internal milestone, 3 SMART milestone and final deliverable. The two Go/No-Go decisions points will be reached by the end of first and second budget periods respectively. The project scope encompasses a combination of materials development and fabrication scale-up, optimized integration for improved material utilization, advanced performance, and manufacturability, novel in-situ diagnostics to feedback to materials development and integration tasks, and a focus on recyclability for materials recovery. The overall outcome of the three-year project will be improved MEA durability over the projected lifetime of heavy-duty vehicles, increased mass activity at high electrode potentials, enhanced performance at high current density, and decreased content of PGM. This will be accomplished by: (1) guided advanced synthesis, informed from well-defined 2D systems, of self-healing cathode catalysts, (2) development and integration of molecular interfacial modifiers to optimizing the catalyst/ionomer interface, (3) development of advanced carbon supports, (4) deployment of advanced in-situ characterization tools, and (5) fabrication and integration of new system components for highly durable MEAs. Developed materials will be deployed in the MEA cathodes with total PGM loading less than the DOE 2030 target of 0.3 mg_{PGM}/cm^2 and meet previously specified performance targets.

C. Tasks To Be Performed

Tasks Extended over All Budget Periods - Overall Project Management and Planning

The proposed program is a multi-institutional research effort that involves two universities and two companies. All partners in this project have extensive track record in collaboration, including on DOE-EERE-HFTO programs. The effort will be highly complementary and strictly coordinated with ongoing M2FCT Consortium of National Laboratories. The program will use both experimental and computational approaches to deliver groundbreaking enhancement in performance of hydrogen fuel cells. The effort will be executed by a multidisciplinary team with diverse expertise, the Project management will be codified with well-defined roles and responsibilities. The PI and co-Pis are responsible for overseeing the day-to-day research activities withing their own institutions. This includes overseeing regular scientific meetings; mentoring the students and postdocs; coordinating with the other participants in this project; writing research and communicating progress reports through emails and online bi-weekly meetings; and continually developing a well-defined set of scientific goals. The lead-PI will serve as the primary contact responsible for communications with the DOE Program Manager on behalf of all the personnel in this project. He will set the research agenda and will be responsible for the reports to the DOE Program Manager. Additionally, he will ensure that the annual operating plans, milestones, and project objectives are met on time and within budget.

Task 0.0 – Project Management and Planning: We shall develop and maintain the Project Management Plan (PMP). The content and organization of the PMP is identified in the Federal Assistance Reporting Checklist and Instructions. The initial PMP shall be provided within forty-five (45) days after award. The PMP will be updated and submitted as part of the continuation application prior to the initiation of each budget period. We shall manage and implement the project in accordance with the PMP.

Task 0.1 – Kick-Off Meeting: We will participate in a project kickoff meeting with the DOE within 30 days of project initiation.

Task 0.2 – Integration with M2FCT National Laboratories Consortium: The proposed research will be *fully integrated* and *highly complementary* to the existing a one-of-a-kind US National Laboratories research network, that was launched in 2020 as the Million Mile Fuel Cell Truck Consortium (M2FCT). The consortium will serve as a nucleus for linking the research efforts proposed here which will be focused on technical targets relevant for the polymer electrolyte fuel cells in heavy-duty vehicles.

BUDGET PERIOD 1 | Year-1

Task 1: Materials Discovery and Innovative Synthesis (Q1 – Q4)

Summary: This task aims towards novel low-PGM well-defined nanoparticles (NPs) with controlled size, composition, compositional gradient, shape, surface morphology and architecture by high-precision wet chemical solvothermal synthesis. Materials discovery will be performed from 2D towards 3D materials. 2D materials will be obtained by utilizing magnetron sputtering thin film deposition method to simulate different compositional gradient and surface morphologies with well-defined geometric surface area. Emphasis in synthesis will be placed on NPs with defect-free (111)-Pt-skin outermost surface over TM-metal-rich subsurface region in various architectures. Both subsurface and surface Au will be introduced into intermetallic ordered NPs, such as PtM_{IM}, $PtNM_{IM}$, including $AuTa_{IM}$ cores coated with Pt-alloy shells, etc.). We will explore synthesizing bimetallic, multimetallic, open-frame, porous, solid, and cage nanoarchitectures.

Subtask 1.1.1: Deposit sputtered Pt thin films on glassy carbon substrate to obtain extended 2D surfaces with well-defined geometric surfaces area for electrochemical evaluations by RDE and RDE-ICP/MS. Establish correlation between film thickness and dissolution rate.

Subtask 1.1.2: Utilize different sputtering protocols to produce Pt films with different surface morphologies, average grain size, and properties. Such 2D materials in the form of thin films will be used for detailed guidance for the design of complex structures and compositions in 2D at the nanoscale.

Subtask 1.1.3: Synthesize solid particles with distinct intermetallic phases with gold core. Adjust structural parameters of catalyst in accordance with results from Task 7.

Subtask 1.1.4: Synthesize nano particles (NPs) with controlled size, shape/morphology and composition. Obtain reproducible results for two distinct architectures.

Go/No-Go-1: Down select for further integration with carbon supports Pt-M NPs based on (i) intermetallic phases with gold core (from Subtask 1.3) and (ii) NPs with controlled size, shape and composition (from Subtask 1.4).

Task 2: Durable Catalyst Supports (Q1 – Q4)

Summary: Under this task we will study the new generation of Cabot FCX carbons as supports for ORR catalysts in RDE. A full suite of characterization (STEM, EDS, XPS, XRD, BET, SEM, Raman) will be performed on these catalyst supports (under Task 7) to confirm the initial characteristics provided by the manufacturer (see Table 1 of the Technical Volume).

Subtask 2.1.1: Determine physicochemical properties of the engineered carbon supports developed by Cabot Corp. such as surface chemistry, graphitization, specific surface area, and pore size distribution, suitable for durable and active ORR catalysts.

Subtask 2.1.2: Investigate effects of Pt-M/carbon ratio on activity of selected (Subtask 2.1.1) Cabot FCX series supports. The insights gained through this subtask will promote rational design of ORR catalysts and catalyst layers.

Subtask 2.1.3: Investigate and alter surface chemistry of selected (Subtask 2.1.1) Cabot FCX series materials. The role of surface chemistry (surface oxygen content and the character of the oxygen-carbon moieties) towards anchoring of Pt-M NPs and dispersion of ionomer in the catalyst layer.

Subtask 2.1.4: Introduce nitrogen and phosphorus dopants on the surface of selected (Subtask 2.1.1) Cabot FCX series materials.

Task 3: Modified Catalyst-Ionomer Interfaces (Q1 – Q4)

Summary: The objective of this task is to enhance the catalytic activity and durability of Pt-M catalyst by selected “molecular implants” on Pt (111) surface (Drexel) and 2D thin films (UCI).

Subtask 3.1.1: Pt (111) surface and 2D thin films will be modified by “molecular implants” such as melamine, melamine-formaldehyde co-polymer and caffeine and investigating its effect on catalytic activity and selectivity of ORR.

Subtask 3.1.2: Pt (111) surface and 2D thin films will be modified by “surface modifiers” - nanomaterials, pre-synthesized or obtained commercially, such as graphene, graphene oxide and “holey graphene” and study the effect on catalytic performance incl. local transport of O2.

Subtask 3.1.3: Pt (111) surface and 2D thin films will be modified by ionic liquids selected for their effect of the structure of the electric double layer, adsorption properties and modulation of ORR activity and selectivity. , such as graphene, graphene oxide and “holey graphene” and study the effect on catalytic performance including local transport of O2.

Subtask 3.1.4: Selection of Pt (111) and 2D thin films surface modifications studied in Subtask 3.1.1, 3.1.2 and 3.1.3 for their electrochemical performance for *in situ* ICP-MS durability studies.

Task 4: Advanced Catalyst Characterization (Q1 – Q4)

Summary: Continuous durability assessment in conjunction with structure-to-property correlations and feedback to nanocatalysts design.

Subtask 4.1.1: Development and demonstration of ICP-MS methods under RRDE electrochemical *in situ* tests for 2D materials.

Subtask 4.1.2: Evaluation of Au composition gradient in 2D materials and its effects on durability as studied by *in situ* ICP-MS /RRDE tests.

Subtask 4.1.3: Introduction of transition metal (Co, Ni) as intermetallic compound former with Pt in 2D materials and the effects of intermetallic structures on durability by *in situ* ICP-MS /RRDE tests.

Subtask 4.1.4: Integration of Au and transition metal intermetallic structures in 2D materials and the confirming their effect on advancing durability by *in situ* ICP-MS /RRDE tests.

Task 5: Advanced Component Integration (Q2 – Q4)
Summary: Component Integration based on several innovations proposed by UCI for MEA design for improved durability: (i) anchoring Pt to supports; (ii) use of molecular additives to decrease oxophilicity of Pt surfaces, and (iii) use of molecular additives for carbon support pore filling.
Subtask 5.1.1: Exploring anchoring strategies under development in Task 2 (N and P doping) to provide stabilization of Pt-M nanocatalysts on caron supports in MEA catalyst layers.
Subtask 5.1.2: Integration of interfacial molecular additives, developed in Task 3 ("molecular implants") in order to demonstrate advantages in durability under MEA testing conditions.
Subtask 5.1.3: Integration of ionic liquids selected in Task 3 for their protective effect on Pt dissolution demonstrating such effects for enhanced durability under MEA testing conditions.
Task 6: Electrode Component Distribution and Morphology Design (Q2 – Q4)
Summary: Electrode component distribution is critical for the MEA durability and morphology design is viewed here as a main method to ensure its performance predictability. Characterization methodologies developed under this task will be used in collaboration with various nodes at M2FCT (ORNL, ANL).
Subtask 6.1.1: Ingredients of the inks for electrode catalyst layer fabrication will be studies with the properties of select carbons and their morphologies will be in the focus of this rheology evaluation.
Subtask 6.1.2: Additives to improve dispersion and processability of the inks will be evaluated which includes specific alcohols (IPA NPA) and mild non-ionogenic surfactants.
Task 7: MEA Diagnostics for Accelerated Stress Testing (Q2 – Q4)
Summary: This task is about MEA Diagnostics for Accelerated Stress Testing. The tests will be performed according to DoE standards.
Subtask 7.1.1: Test MEAS with standard nitrogen-based protocol (0.6 V to 0.95 V) for 90,000 cycles and air-based protocol (0.675 V to 0.925 V) for 30,000 cycles.
Subtask 7.1.1: Develop a dynamic load cycling protocol based on the light-duty protocol.
BUDGET PERIOD 2 | Year-2
Task 1: Materials Discovery and Innovative Synthesis (Q5 – Q8)
Summary: This task aims towards novel low-PGM nano particles (NPs) with defined control and distribution of atomic structural ensembles and ordered compositional gradients. The results from BP1 will be used for further improvement.
Subtask 1.2.1: Synthesize nanoscale systems with defect-free (111)-Pt-skin facets over TM-rich subsurface region in various architectures, which will use subsurface and surface Au and intermetallic ordered compositional distributions.
Subtask 1.2.2: Synthesize solid particles with distinct intermetallic phases with gold core.
Subtask 1.2.3: Adjust structural parameters of catalyst in accordance with results from Task 7.
Task 2: Durable Catalyst Supports (Q5 – Q8)
Summary: Under this task we will integrate the Pt-M advanced catalysts NPs selected at the point of Go/No-Go-1 decision into at least two types of carbon supports. The objective of this study is to determine which support type: chemically modified or pristine (as obtained from Cabot Corp.) is advantageous for anchoring the advanced catalysts developed under Task 1.
Subtask 2.2.1: Atomic layer deposition (ALD) we will seed active materials and deposit protective metal oxide layers onto carbon supports.
Subtask 2.2.2: Investigate small molecules bonding to the surface of Pt-M/C catalysts will be studied with melamine- and dopamine-derived carbonaceous films coating over the Pt-M NPs will be studied and compared to commercial Pt-M/C catalyst benchmarks.
Subtask 2.2.3: Modifying carbon blacks with *1-pyrenecarboxylic acid* (PCA) in order to provide controlled surface carboxyl on the graphitic plane and simultaneously increase hydrophilicity of the support.

Subtask 2.2.4: Investigate effect of pyrolysis of small molecule coverage of the Pt-M NPs deposited on select carbon supports to obtain "holey graphene" structure locally covering the catalysts NPs integrated with the catalysts.

Go/No-Go-2: Down select for further integration with Pt-M NPs a strategy based on (i) advanced surface modified carbon blacks (as a result of Subtasks 2.2.1 and 2.2.2) and (ii) introduction of the pyrolytic step in the catalysts synthesis leading to "holey graphene" layer formation over the Pt-M NPs supported on the carbon blacks (from Subtasks 2.2.3 and 2.2.4).

Task 3: Modified Catalyst-Ionomer Interfaces (Q5 – Q8)

Summary: The objective of this task is to enhance the catalytic activity and durability of Pt-M catalyst nanoparticles (nanocatalysts) by pre-selected "molecular implants" or surface modifiers strategies on the specific nanocatalysts type selected in the Go/No-Go-1.

Subtask 3.2.1: Pt-M nanocatalysts will be modified by the method resulting from the evaluation of the Subtask 3.1.4 and its catalytic activity and selectivity in ORR will be studied by RRDE.

Subtask 3.2.2: Exploration of the effects of surface modifiers such as graphene, graphene oxide and "holey graphene" on catalytic performance of Pt-M nanocatalysts

Subtask 3.2.3: Studying the effects of "molecular implants" in the catalytic activity and selectivity of Pt-M nanocatalysts in RRDE

Subtask 3.2.4: Integrating ionic liquids and "holey graphene" as complex modifier of Pt-M nanocatalysts. Elucidating the local transport effects of overall catalytic activity and selectivity.

Task 4: Advanced Catalyst Characterization (Q5 – Q8)

Summary: Continuous durability assessment in conjunction with structure-to-property correlations and feedback to nanocatalysts design.

Subtask 4.2.1: Development and demonstration of ICP-MS methods under RRDE electrochemical *in situ* tests for nanocatalysts and demonstration of its utility based on the catalyst selected in Go/No-Go-1.

Subtask 4.2.2: Evaluation of Au as a core in Pt nanocatalysts and its effects on durability as studied by *in situ* ICP-MS /RRDE tests.

Subtask 4.2.3: Evaluation of Au as a underlayer in Pt nanocatalysts and its effects on durability as studied by *in situ* ICP-MS /RRDE tests.

Subtask 4.2.4: Introduction of transition metal (Co, Ni) as intermetallic compound forming with Pt-Au in nanocatalysts selected from Subtask 4.2.2 and 4.2.3 and the effects of intermetallic structures on durability as studied by *in situ* ICP-MS /RRDE tests.

Task 5: Advanced Component Integration (Q5 – Q8)

Summary: Focus study of specific adsorption of sulfonic acid groups and polymer backbone coverage at the Pt/ionomer interface to determine the mechanism of its detrimental impacts on activity and mass transport

Subtask 5.2.1: Integrating novel ionomers, such as HOPI with a better oxygen permeability to ensure higher power density performance, based on facilitated oxygen transport.

Subtask 5.2.2: Integrate interfacial molecular additives, developed in Task 3 in order to protect Pt from ionomer poisoning when new HOPI ionomers are used.

Subtask 5.2.3: Developing technology to selectively fill the meso-pores with poly-melamine formaldehyde (PMF) to improve proton conductivity, especially at lower relative humidity (RH), and protect Pt from dissolution in the meso-pores.

Subtask 5.2.4: Integrating the above solutions with MEA design for in situ ICP-MS testing for the development of new MEA based durability evaluation technique.

Task 6: Electrode Component Distribution and Morphology Design (Q5 – Q8)

Summary: This task introduces identical location micro-XRF method to monitor in-plane catalyst movement in MEA from BOL to EOL in order to understand catalyst aggregation during heavy-duty lifetime ageing.

Subtask 6.2.1: UCI will correlate micro-XRF and micro-XRD in order to demonstrate that locations where there are higher Pt loadings at the BOL have also the largest particles at the EOL and reveal local 'hot-spots' of increased Pt particle sizes for MEA durability diagnostics.
Subtask 6.2.2: UCI will develop standard operating procedure for identical location micro-XRF methodology and validate it with other *ex situ* microscopy methods.
Subtask 6.2.3: UCI will transfer this newly developed identical location micro-XRF methodology to the partners in M2FCT consortium.
Task 7: MEA Diagnostics for Accelerated Stress Testing (Q5 – Q8)
Summary: This task is about MEA Diagnostics for Accelerated Stress Testing. The tests will be performed according to DoE standards.
Subtask 7.2.1: Test MEAS with standard nitrogen-based protocol (0.6 V to 0.95 V) for 90,000 cycles and air-based protocol (0.675 V to 0.925 V) for 30,000 cycles.
Subtask 7.2.2: Test MEAs with light-duty protocol developed in Task 1.
Task 8: Feasibility Studies for High Volume and High Throughput MEA Manufacturing (Q6 – Q8)
Summary: Establish the feasibility studies for potential routes for MAE manufacturing in high volume.
Subtask 8.2.1: Identification of variables for MEA manufacturing.
Subtask 8.2.2: Evaluation of selected chemistries for high volume syntheses
Task 9: Sustainable and Recyclable MEA Design (Q7 – Q8)
Task This task is aimed for repurposing of membranes and highly durable catalyst layers, along with less toxic chemicals
Subtask 9.2.1: Evaluation of catalyst layer separation from the state-of-the-art MEA. Comparison between BOL and EOL
Subtask 9.2.2: Introduction of interlayers between membrane and catalyst, including molecular modifiers developed in Task 3, and their impact on separation process after EOL

BUDGET PERIOD 3 | Year-3
Task 1: Materials Discovery and Innovative Synthesis (Q9 – Q12)
Summary: This task aims towards novel low-PGM nano particles (NPs) with defined control and distribution of atomic structural ensembles and ordered compositional gradients in the needed quantity for MEA investigations.
Subtask 1.3.1: Scale up the best performing synthesis from BP 1 and 2 up to 5 g.
Subtask 1.3.2: Proof result of scale-up synthesis in comparison to small batch synthesis.
Subtask 1.3.3: Synthesize material needed for MEA testing (1 g)
Task 2: Durable Catalyst Supports (Q9 – Q12)
Summary: Under this task we will integrate the type of carbon support with the treatment strategy determined at the point of Go/No-Go-2 decision with the type of catalyst selected at the Go/No-Go-1 decision. The objective of this study is to optimize the integration of the support and catalyst technology for integration in the catalysts layer and MEA structures. The secondary objective is to investigate the paths for future scale up of both the advanced catalysts developed under Task 1 and advanced supports developed under Task 2. This should determine manufacturability of the cathode catalyst and will be the feed for the techno-economic analysis needed for the Market Transformation Plan.
Subtask 2.3.1: Investigation of the effects of Pt-M/Advanced Carbon catalysts morphology and surface chemistry of its wettability and ink preparation. Tuning catalyst morphology and surface chemistry to allow materials dispersion in colloidal suspension while retaining the aggregation ability in sub-colloidal aggregates and agglomerates. Selecting of the most appropriate technology catalysts layer formation in MEA fabrication process: printing, spraying, casting, etc.

Subtask 2.3.2: Synthesis of 1-5 g (total weight) batches of the of Pt-M/Advanced Carbon catalysts in laboratory conditions and verifying the activity and physicochemical properties of such batches remain identical/similar to the smaller (exploratory) batch synthesis performed throughout the first two years of the project.
Subtask 2.3.3: Supplying the partner DOE labs from M2FCT consortium with samples from the larger batches of the of Pt-M/Advanced Carbon catalysts for validation/verification testing and alternative methods of integration in MEA designs to establish the versatility of the catalyst across several FC technologies for heavy-duty truck stack applications.
Subtask 2.3.4: Conceptualizing the unit operations needed for industrial scale synthesis of the catalysts and determining the cost/production volume parameters for techno-economic analysis.
Task 3: Modified Catalyst-Ionomer Interfaces (Q9 – Q12)
Summary: The objective of this task is to develop reliable synthesis protocol for Pt-M nanocatalysts integration with the specific carbon support selected in the Go/No-Go-2.
Subtask 3.2.1: Pt-M nanocatalysts selected in Go/No-Go-1 will be integrated with carbon support selected in the Go/No-Go-2 and its catalytic activity and selectivity in ORR will be studied by RRDE.
Subtask 3.2.2: Exploration of the effects of surface modifiers such as graphene, graphene oxide and "holey graphene" on catalytic performance of the integrated catalysts resulting from Subtask 3.2.1 will be studied for transport effects in ORR under RRDE conditions.
Subtask 3.2.3: Exploration of the effects of "molecular implants" on catalytic performance of the integrated catalysts resulting from Subtask 3.2.1 will be studied for transport effects in ORR under RRDE conditions.
Subtask 3.2.4: The resulting catalysts from Subtasks 3.1.1, 3.1.2 and 3.1.3 will be evaluated for their electrochemical performance in ORR for *in situ* ICP-MS durability studies.
Task 4: Advanced Catalyst Characterization (Q9 – Q12)
Summary: Development of ICP-MS diagnostic too integrated with single MEA fuel cell testing capability for in situ monitoring of degrading processes in the catalyst layer.
Subtask 4.3.1: Development and demonstration of ICP-MS methods in conjunction with model catalysts layer formed in a realistic MEA configuration.
Subtask 4.3.2: Integration of ICP-MS setup with catalyst layer tested in gas-diffusion electrode configuration.
Subtask 4.3.3: Integration of ICP-MS setup with catalyst layer deposited on the polymer electrolyte membrane (CCM)
Subtask 4.3.4: Design and demonstration of *in situ* ICP-MS in fully assembled MEA operating under AST conditions and validation of the durability figures of merit with members of M2FCT consortium.
Task 5: Advanced Component Integration (Q9 – Q12)
Summary: The studies under this task aim to produce a base MEA integration platform that will utilize the catalysts and supports selected in Go/No-Go-1 and Go/No-Go-2 with the methods used for surface modification in Task 3 applied to the 3D structure of the catalyst layer in the MEA.
Subtask 5.3.1: Establishing reproducible protocols for filling mesopores of advanced Pt-M nanocatalysts supported on selected supports with ionic liquids
Subtask 5.3.2: Elucidating the mechanism of enhanced proton conduction / ionic conductivity as a prerequisite for enhanced catalyst performance over a broad range of current densities.
Subtask 5.3.3: Evaluation of the MEA fabrication methodology to reduce complexity in multi-step process integration for manufacturability.
Task 6: Electrode Component Distribution and Morphology Design (Q9– Q12)
Task Summary: Structural validation of electrode component distribution by ex situ FIB-SEM employed to contrast BOL to EOL MEA structures.

Subtask 6.3.1: Introduction of the FIB-SEM cross-section of the catalyst layers for morphology study at BOL and EOL conditions.
Subtask 6.3.2: Development of the FIB-SEM with EDS to determine individual chemical species distribution the cross-section of the catalyst layers for morphology study at BOL and EOL conditions.
Task 7: MEA Diagnostics for Accelerated Stress Testing (Q9 – Q12)
Summary: This task is about MEA Diagnostics for Accelerated Stress Testing. The tests will be performed according to DoE standards.
Subtask 7.3.1: Test MEAS with standard nitrogen-based protocol (0.6 V to 0.95 V) for 90,000 cycles and air-based protocol (0.675 V to 0.925 V) for 30,000 cycles.
Subtask 7.3.2: Test MEAs with light-duty protocol developed in Task 1.
Subtask 7.3.3: Test 3 MEAs for a duration of 1,000 operating hours with dynamic load cycling protocol and characterize MEAs every 200 cycles.
Task 8: Feasibility Studies for High Volume and High Throughput MEA Manufacturing (Q9 – Q10)
Summary: High throughput manufacturing is the final aim at this stage.
Subtask 8.3.1: Component integration with desirable precision and cleanliness
Subtask 8.3.1: Evaluation of roll-to-roll processes with alternative approaches in manufacturing
Task 9: Sustainable and Recyclable MEA Design (Q9 – Q12)
Summary: This final year the task will be focused solely on recycling
Subtask 9.3.1: Identification of alternative post-processing steps by chemical and physical separations without burning the membrane
Subtask 9.3.2: Evaluation of targeted corrosion and delamination
Subtask 9.3.3: Feasibility to employ Pt erosion approach in separating Pt NPs from CCM
Subtask 9.3.4: Implemented strategy for better separation of Deliverables in this project, 6 MEAs with targeted performance

Milestones and Deliverables
Milestone 1 (Q4): MEA with catalyst synthesized reaching power output of 0.65 A/cm^2 at 0.7 V (equivalent to 1.5 kW/g) after heavy-duty AST equivalent to 25,000 hours.
Milestone 2 (Q8): MEA with catalyst synthesized reaching power output of 0.87 A/cm^2 at 0.7 V (equivalent to 2.0 kW/g) after heavy-duty AST equivalent to 25,000 hours.
Milestone 3 (Q12): MEA with catalyst synthesized reaching power output of 1.07 A/cm^2 at 0.7 V (equivalent to 2.5 kW/g) after heavy-duty AST equivalent to 25,000 hours.
Milestone 4 (Q12): Proof of recycling more than xy % of Pt from membrane and reuse of membrane with the same performance as initial.
Deliverable 1 (Q12): 6 MEAs for testing

D. Project Management and Reporting
Reports and other deliverables will be provided in accordance with the Federal Assistance Reporting Checklist following the instructions included therein.

E. DOE MHK DATA REPOSITORY PLAN
All the data collected as well as key deliverables will be uploaded to the DOE Marine and Hydrokinetic Data Repository at: https://mhkdr.openei.org, respectively the EERE Project Management Center (PMC) according to the Data Management Plan.
Data produced under this Award will be treated according to the Intellectual Property Provisions.

UCI Statement of Work (SOW) for the Sub-Contract to Cabot Corp.

"*Scalable, innovative manufacturing process for novel carbon supports for metal catalysts for MDV/HDV PEM fuel cells*"
DOE Award: DE-EE0011347

UCI Performing Organization:	National Fuel Cel Research Center
UCI Team:	Prof. Plamen Atanassov – PI UCI subcontract
	Prof. Iryna Zenyuk – Director, National Fuel Cel Research Center
	Dr. Camille Roiron – postdoctoral researcher
	Dr. Bilal Iskandarani – postdoctoral researcher
	Loki (Jiazhe) Chen – graduate student researcher

Project Objectives (from the SOPO):

The objective of this project is to develop a scalable and innovative manufacturing process to produce carbon catalyst supports for the oxygen reduction cathode, which can enable high catalyst utilization and enhanced durability at low cost in Medium-Duty Vehicle/Heavy-Duty Vehicle Proton Exchange Membrane Fuel Cells (MDV/HDV PEMFCs). The expected outcome will be a scaled process that can produce 1200 kg/year of novel carbon support. The fuel cell Membrane Electrode Assembly (MEA) using the novel carbon catalyst support will reach power output of 1.07 A/cm^2 at 0.7 V (equivalent to 2.5 kW/gPGM) after M2FCT's heavy-duty accelerated stress test (AST), which is equivalent to 25,000 hours operation. The process will be demonstrated for commercial path towards 10 MT/year carbon support through production trials.

Technical Scope Summary (from the SOPO):

The stated objectives will be accomplished by: (1) developing and demonstrating a pilot-scale carbon support production line; (2) developing carbon support accelerated stress test (C-AST) to differentiate corrosion resistance of different carbons; (3) optimizing catalyst deposition process; (4) performing in-depth analysis of carbon support and MEA performance to provide feedback to the process design; and (5) optimizing the steam etching and graphitization process to increase process versatility, reduce production cost and minimize environmental impact.

This **UCI Statement of Work** is to be treated and understood as a contributed component effort of the **Statement of Project Objectives** (SOPO) for DOE Award: DE-EE0011347, negotiated by the Cabot Corp. as the Prime on this project.

Budget Period 1: UCI collaborates with Cabot on carbon AST development and catalyzation

Task 2.0: Carbon support accelerated stress test (C-AST) development. [M4-M12]
Task Summary: A carbon support accelerated stress test (C-AST) will be developed at UCI that can differentiate the corrosion resistance of different carbon supports.
Subtask 2.1: Develop C-AST test using Cabot provided carbon supports. [M4-M9]
Subtask Summary: C-AST test protocols development will be started with Cabot-provided existing steam etched graphitized carbon support .
Subtask 2.2: C-AST test protocol validation using carbon supports from task 1. [M6-M9]
Subtask Summary: After completion of subtask 1.3, the C-AST test will be further finetuned and validated using the carbon support produced in Task 1.

Subtask 2.3: Work with the Million Mile Fuel Cell Truck (M2FCT) Consortium and provide input to optimize AST. [M10-M12]
Subtask Summary: Working closely with M2FCT and provide input to optimize C-AST.
Milestone 2.1: C-AST protocol developed and validated. [M9]

Task 3.0: Catalysation process development by UCI in collaboration with JM and ink formulation optimization.
Task Summary: There is a risk that the current Pt deposition process and ink formulation will not be suitable for the novel carbon supports produced during this project. This task will tune existing and develop new wet chemical Pt catalysation processes suitable for large volume manufacturing of cathode catalysts using the new carbons created in Task 1. In addition, catalyst ink formulation will be optimized for the catalyst using the novel carbon support. Catalyst coated membranes (CCM) will be produced both at UCI and JM for MEA assembly and performance testing.
Subtask 3.1: Catalysation process optimization. [M4-M9]
Subtask Summary: This task will tune existing and develop new wet chemical Pt catalysation processes suitable for large volume manufacturing of cathode catalysts using the new carbons created by Cabot. The variables that will be closely controlled and quantified include: the carbon support surface area and porosity, the location of the Pt catalyst particles on the support, the particle size distribution of the Pt particles and, as a non-independent variable, the corrosion resistance of the carbon support.
Subtask 3.2: Ink formulation optimization. [M4-M9]
Subtask Summary: This task will optimize of catalyst ink formulation for the catalyst using the novel carbon support**.**
Subtask 3.4: MEA assembly and performance testing. [M10-M12]
Subtask Summary: MEA will be assembled using CCM from subtext 3.3 and performance testing will be carried out at UCI, JM and Bosch (validation).
Milestone 3.1: MEA with the carbon support has power output of 0.57 A/cm^2 at 0.7 V (equivalent to 1.25 kW/gPGM) after M2FCT's heavy-duty AST equivalent to 25,000 hours. (M12)

Subtask 4.3: Carbon catalyst support characterization. [M7-M12]
Subtask Summary: Key material characteristics including Brunauer-Emmett-Teller surface area (BET SA), total pore volume, pore size distribution (PSD) and crystallinity as defined by Lc and La value derived from X-ray diffraction (XRD) and Raman measurement respectively will be characterized at UCI.

Budget Period 2: UCI collaborates with Cabot, JM and Bosch on CCM and MEA development

Subtask 7.3: Optimized CCM production.
Subtask Summary: This task will finetune the catalysation process and catalyst ink formulation developed in task 3 to produce optimized CCM.
Subtask 7.4: MEA fabrication and testing.
Subtask Summary: The CCM from Subtask 7.2 will be used by UCI to fabricate MEAs for performance testing.
Subtask 7.5: MEA performance validation and aging mode modeling.
Subtask Summary: Several MEAs will be down selected based on their performance and performance verification and aging mode modeling will be performed.
Subtask 7.5.1: MEA performance evaluation and preliminary AST evaluation.
Subtask Summary: MEA performance evaluation will be carried out to provide baseline for 7.5.2

Subtask 7.5.2: Develop realistic aging protocols for stack-level degradation phenomena and parameterize aging model.
Subtask Summary: the following tasks will be performed: (1) Start-up cycling on SU/SD test stand. (2) Relevant load/unload aging, with LPT/drive cycle. (3) Parameterization of existing aging models and lifetime prediction modeling to demonstrate improvement in stack longevity.
Milestone 7.1: MEA with novel carbon support reaches power output of 0.76 A/cm^2 at 0.7 V (equivalent to 1.75 kW/gPGM) after heavy-duty AST equivalent to 25,000 hours. (M21)

Budget Period 3: UCI collaborates with Cabot in QC and aging models development

Subtask 8.3: Production quality control method development. [M37-M39]
Subtask Summary: Production quality control method will be developed (Subtask 8.3) which will include measurement of tapped density, BET SA, XRD, and Raman to quantify the variability in production.
Milestone 8.2: Carbon support production quality control method established (M39).

Task 9.0: stack-relevant aging characterization and lifetime prediction modeling. [M36-M42]
Task Summary: Stack-relevant aging characterization and parameterization of new aging models and lifetime prediction modeling will be developed to demonstrate improvement in stack longevity.
Subtask 9.1: Stack-relevant aging characterization. [M36-M41]
Subtask Summary: Stack-relevant aging characterization, model refinement, and lifetime prediction will be performed using MEAs from Subtask 8.1.
Subtask 9.2: Aging models and lifetime prediction model development. [M41-M42]
Subtask Summary: The aging model will be parameterized and exercised to predict lifetime and demonstrate improvement in stack longevity.
Milestone 9.1: Aging models and lifetime prediction models developed. [M42]