EXHIBIT C

Control Number: 2792-1619

TECHNICAL VOLUME

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

FOA Number: **DE-FOA-0002792**

Area of Interest 1: Hydrogen and Fuel Cell Technologies in Support of Hydrogen Shot

Topic 4: M2FCT: High Performing, Durable, and Low-PGM Catalysts/Membrane Electrode Assemblies (MEAs) for Medium- and Heavy-duty Applications

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• Project Overview:

Background: Hydrogen technologies are the prevailing choice to effectively address the urgent needs to decarbonize the energy sector, electrify transportation, and modernize the electric grid. Nevertheless, for the nation to widely use hydrogen profound improvements in existing electrochemical technologies are urgently needed. Specifically, the efficiency, durability, and cost of materials that effectively catalyze electrochemical reactions in fuel cells are considered major hurdles, primarily the cathodic oxygen reduction reaction. 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.

This project will be led by the University of California, Irvine (UCI) and will rely on unique expertise and capabilities at UCI and team members at Drexel University, Cabot Corporation, and Bosch Research Technology Center North America, while strategically utilizing the M2FCT Consortia's testing, modeling and characterization capabilities. UCI has a long legacy in hydrogen technologies, including its own hydrogen fueling station available for public use, the busiest refueling station in the nation. Moreover, UCI hosts National Fuel Cell Research Center (NFCRC), and recently established the Horiba Institute for Mobility and Connectivity (HIMaC), which are uniquely equipped facilities for research and development of fuel cell technologies.

Project Goal: The project will aim to develop and deliver highly-durable and manufacturable fuel cell membrane electrode assemblies (MEA) with low-PGM novel cathode catalyst loading, improved mass activity and high current density at high operational potentials as well as extended operational longevity at a reduced cost. 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; 750 mW/cm^2 at 0.7 V) after running a heavy-duty AST equivalent to 25,000 hours.

DOE Impact: DOE EERE funding would enable the collaboration and integration of expertise and technological advancements required to reach the aggressive targets set in this proposed project. It is only through synchronization of these efforts by the listed institutions and the M2FCT Consortia that these targets for heavy duty vehicles can be met.[1] DOE EERE funding will facilitate the combination of atomic level fundamental insight, unique materials development strategies, targeted device integration, and next generation operando diagnostics to yield greatly improved device-level performance. The proposed project will deliver unprecedented improvement in functionality, focused on durability, performance and cost, and will address strategic needs that will secure U.S. leadership in fuel cell technology. Moreover, DOE EERE funding of this project will enhance national research infrastructures that will be based on strong ties with National Laboratories within the M2FCT Consortia and multiple universities, including Minority-Serving Institutions (MSIs) such as UC Irvine.

• Technical Description, Innovation and Impact:

Relevance and Outcome: This project goes beyond conventional durability requirements and targets development of robust MEAs for medium- and heavy-duty truck applications with over 25,000 hours lifetime. The focus will be improved durability over the projected lifetime, increased mass activity at high electrode potentials, enhanced performance at high current density, while decreasing PGM content. This will be accomplished by the combination of unique fundamental insight and technological advances established by the PIs who have a long legacy of research and development in fuel cell technology. The approach relies on utilization of fundamental properties of well-defined two-dimensional (2D) interfaces to direct rational synthesis of advanced nanoparticle (NP) fuel cell catalysts, customized characterization tools, implementation of novel carbon supports, interface modification by selected molecular implants, and advanced design and fabrication of MEAs. Developed materials will be deployed in the MEA cathodes with total PGM loadings below the DOE 2030 target of 0.3 mg_{PGM}/cm^2. *The outcome of the project* will be at least 6 MEAs for independent testing and evaluation by the M2FCT core lab consortium. The delivered MEAs will meet the M2FCT 2025 end-of-life target: 2.5 kW/g_{PGM} power output (1.07 A/cm^2 current density at 0.7 V; 750 mW/cm^2 at 0.7 V) after running a heavy-duty AST equivalent to 25,000 hours.

The outcome will be pursued through nine tasks: (1) high precision synthesis of nanoparticles with defined control and distribution of atomic structural ensembles and ordered compositional gradient for Pt-transition metal (TM) alloys; (2) design and implementation of advanced carbon-based support materials; (3) modifications of catalyst-ionomer interfaces by selected molecular implants; (4) advanced component integration strategies; (5) advanced electrochemical and structural catalyst characterization; (6) electrode component distribution and morphology design; (7) electrochemical MEA diagnostics for in-operando characterizations and accelerated stress testing; (8) feasibility studies for high volume and high throughput roll to roll MEA manufacturing; (9) sustainable MEA design aimed for recyclability, repurposing of membranes and highly durable catalyst layers.

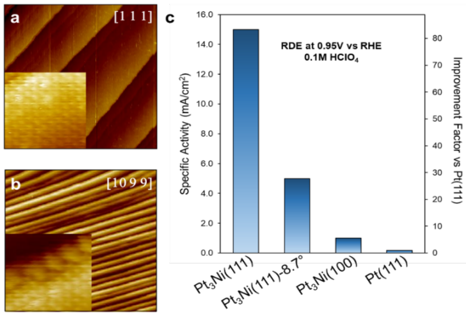


Figure 1. Pt$_3$Ni(111)-skin surfaces: STM images of Pt-skin surface with long terraces (**a**); and vicinal surface; **b)** along with ORR activities at 0.95 V; **c)**. *unpublished* [3]

Feasibility: The technical feasibility of the proposed program is based on the core synergy between the *four* major fundamental discoveries that have been achieved in our laboratories and will be applied towards novel catalyst design and transferred into high performing MEA electrodes.

The first discovery reflects the roles of atomic surface structure and subsurface composition towards the overall catalyst performance. Our preliminary studies on extended 2D surfaces with high precision revealed the true performance of materials can be achieved by removing irregularities and structural defects in catalytic surfaces. Single crystalline Pt$_3$TM(111) alloys are the most active materials for the cathodic oxygen reduction reaction (ORR) in fuel cells.[2] They are characterized by a segregated pure Pt-skin surface with (111) spatial arrangement of the topmost atoms and a subsurface that is enriched in TM (Co, Ni, Fe). Initially we reported a one-order of magnitude enhancement in ORR activity when compared to Pt(111). More recently, however, improved experimental precision through optimized crystal preparation, i.e. limiting the presence of surface defects, and electrolyte purification to remove all trace-level impurities have shown that TMs and the Pt-skinned (111) compositional profile yield even greater activity improvements. Combined atomic-scale surface images and electrochemical measurements, Fig. 1, show that defect-free Pt(111)-skinned Pt-TM alloy surfaces yield and ORR activity enhancement of 80-fold vs. pure Pt(111) at 0.95 V, and 250-fold vs. Pt/C, due to altered electronic/adsorption properties of Pt-skin.[3] Moreover, the RDE-ICP/MS durability measurements confirmed that Pt(111) surfaces provide ultimate stability for both Pt-topmost and subsurface TM atoms due to high coordination. This example amplifies the necessity of working with 2D surfaces in high-precision mode, which will provide new insight and the development of design rules, during the execution of this project, for advanced nanoscale catalyst development. This discovery defines the first target: *synthesize Pt-alloy nanocatalysts bounded by defect-free Pt(111)-skin surface facets with a high-precision synthesis protocol for controlled NPs size/dispersion, shape, morphology, and compositional gradient.*

The second discovery relates to the mitigation of Pt dissolution through the incorporation of Au atoms in the subsurface.[4] Addition of Au in the near-surface region induces favorable structuring of Pt topmost atoms towards a (111)-surface geometry as demonstrated with thin films. During operation, differences in surface energies between the subsurface Au and surface Pt atoms cause the dissolved Pt atoms to be replaced by Au, passivating and stabilizing

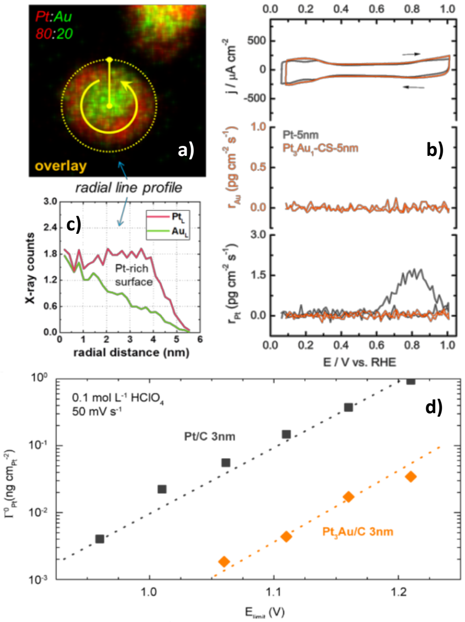


Figure 2. PtAu/C NP: **a)** elemental mapping and **c)** line profile, which **b)** eliminates Pt dissolution. **d)** Pt dissolution over wide potential range is improved 50-fold for PtAu. [4]

the low coordinated defects on catalyst surfaces. This amounts to a *self-healing effect* by supplying highly stable Au atoms to occupy surface sites with low-coordination numbers. Some Au atoms can spillover to the surface due to affinity to segregate over Pt and differences in surface energy, but that would have minimal impact on ORR activity. For nanocatalysts developed using insight from 2D films, the dissolution rates normalized to electrochemically active surface area were followed by *in situ* RDE-ICP/MS. Substantial dissolution of Pt is observed for small Pt/C NPs due to a large number of low-coordinated surface atoms from corner and edge sites. Strategic placement of Au within PtAu NPs **eliminates Pt dissolution**, as shown in Fig. 2. The PtAu NPs were preliminarily evaluated in 50 cm^2 MEAs with only 20% loss in mass activity after 30K cycles AST, compared to over 60% losses for corresponding Pt/C. Our atomic level insight will guide the design of highly durable catalysts aimed towards (111)-like surface structures and well-defined Au atom positioning. *These findings will be applied towards a broad spectrum of catalysts with strictly controlled physical parameters in which the difference in surface energies can alter morphology towards highly coordinated surface atoms.*

The third discovery relates to the enhancement in durability and reduction in TM loss when moving from a random Pt-TM alloy solid-solution to an ordered intermetallic compositional profile.[5] Intermetallic structure further promotes the beneficial effects of Pt-alloys described above, enhancing both specific activity and durability through reinforced formation of a larger fraction of stable (111)-like surfaces. A representative example from our systematic studies of the structure-function properties of PtCo, is shown in Figure 3. [6]

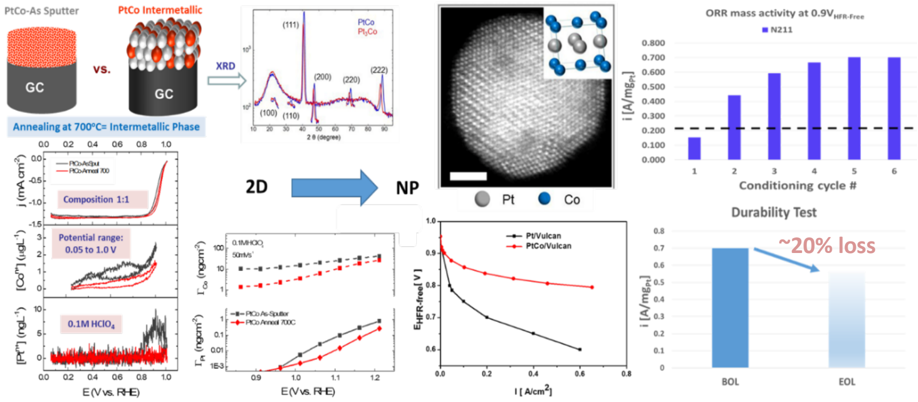


Figure 3. Electrochemical and structural characterization: **(left)** XRD, RDE, and RDE-ICP/MS of as-sputtered vs. intermetallic extended 2D thin film of PtCo; **(right)** HRTEM and MEA evaluations of PtCo intermetallic NPs. *unpublished* [6]

Initial evaluations were done with PtCo intermetallic thin films. From RDE-ICP/MS measurements, we found that the intermetallic structure offers a unique combination of properties that resulted in *improved activity and durability* with suppressed dissolution of both Pt and Co. This result is the first of its kind to offer proof that durability of the non-Pt transitional metal can be improved by structure, again by closely packed (111) surfaces. These results guided the synthesis of monodisperse PtTM intermetallic NPs which were scaled up to be successfully tested in 50 cm^2 MEAs for both activity and durability. Intermetallic PtCo NPs exhibited high mass activity of 0.7 A/mg_{Pt} at 0.9 V with 20% loss after 30K cycle AST. *Utilization of intermetallic structures will be used in the proposed project and will be employed across the entire volume of NPs and/or in the NP core, with addition of Au as well as other metals that might mitigate dissolution through a similar mechanism.*

The fourth discovery relates to the optimization of the interaction between water, ionomer, and catalyst achieved with molecular interfacial modifiers. Carefully selected and designed organic species can limit the degree of ionomer poisoning from physical aggregation and specific adsorption as well as delay the onset of Pt oxidation, enhancing ORR activity and catalyst durability.[7] A series of initial studies have been done in our laboratories ranging from measurements on well-defined 2D to NPs. These results point to the enormous potential for implementation of selected molecules in MEA. The initial MEA studies of

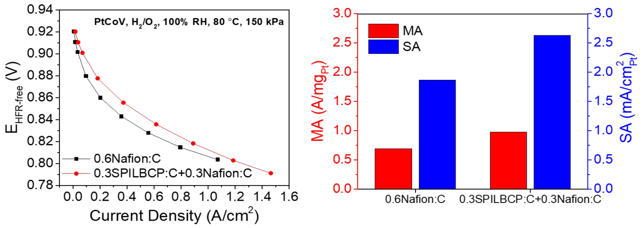


Figure 4. MEA results with PtCo/V modified by SPILBCP: **left)** polarization curves with SPILBCP (red) and without (blue) in H_2/O_2. **right)** mass and specific activities at 0.9 V. *unpublished* [6]

these interfacial modifiers were done with ionic liquids (IL) and melamine molecular implants. In both cases, the MEA with molecular modifiers overperformed baseline Pt/C MEA in the entire potential range and indicated that not only current density but also durability can be improved. Preliminary MEA results with sulfonated poly ionic liquid block copolymer (SPILBCP) is shown in Fig. 4, and reveals huge effects on both mass and specific activity. *The results are obtained with PtCo intermetallic NPs supported on Vulcan, and demonstrate how a synergistic approach, which is proposed here, will lead towards unprecedented improvements in catalyst material development and MEA performance.*

The integration of four key discoveries defines strategies in materials design for catalyst activity and durability improvements. This targeted and synergistic effort, together with capabilities of the M2FCT Consortium, will yield active and durable MEAs, meeting the M2FCT 2025 end-of-life target.

The following research activities aimed to synthesize, integrate and characterize low-PGM catalyst in MEAs will evolve from the four central discoveries that define the approach of this program:

Task 1 | Materials Discovery and Innovative Synthesis will aim towards novel low-PGM NPs with defined control and distribution of atomic structural ensembles and ordered compositional gradients. The first step in targeted synthesis will be reliance on well-defined extended 2D materials in the form of thin-films, which will be used to bridge the gap between experimental and modeling efforts and provide detailed guidance for the design of complex structures and compositions in 3D at the nanoscale.[4] They will serve as a foundation for assessing the electrochemical functionality associated with controlled active site density, surface and subsurface structures and compositions, compositional gradients, surface defects (adatoms, kinks, step-edges, etc.) on precisely defined geometric surfaces areas.

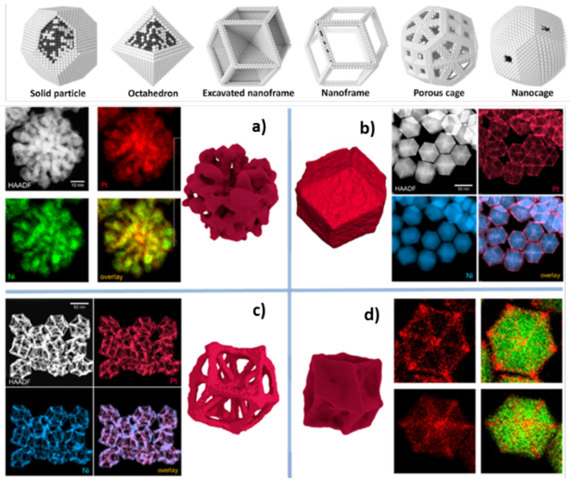


Figure 5. High precision synthesis of NPs with controlled size, shape, composition (green-Ni, blue-Co, red-Pt) through innovative chemical synthesis: a) porous structure; b) solid particles; c) radial nanoframes and d) excavated nanoframes. [9]

High-precision wet chemical solvothermal synthesis will be employed in pursuit of nanoscale systems with defect-free (111)-Pt-skin facets over TM-metal-rich subsurface region in various architectures that will utilize subsurface and surface Au as well as intermetallic ordered compositional distributions (PtM_{IM}, $PtNM_{IM}$, $AuTa_{IM}$ cores coated with Pt-alloy shells, etc.). We will explore synthesizing bimetaillic, multimetallic, open-frame, porous, solid, and cage nanoarchitectures.[8] In case of solid particles, the structure will be tuned towards distinct intermetallic phases due to significant durability benefits. To approach those well-defined nanoscale materials, advanced protocols will be applied. Most wet chemistry methods for NP synthesis with controlled shape, size, and composition are explored at the milligram scale. To address the demand in quantity of novel materials for MEA investigations, high-precision synthesis will be done by one-pot synthesis. We demonstrated, Fig. 5, that advanced nanoscale catalysts with Pt-skin surfaces developed in discovery lab can be scaled up to several grams.[9] In addition, the flow reactor synthesis is available at Argonne National Laboratory through the M2FCT, as we showed in our previous effort this could be a superior way for manufacturing large quantities of NPs (Fig. 5).

Task 2 | Durable Catalyst Supports will be developed by several strategies to meet targeted performance and mitigate carbon corrosion. The catalysts and supports will be engineered by Cabot and UCI as a synergistic construct by modifying the advanced carbon through alteration of its basic/acidic properties, adsorption and ion-exchange capacity, and hydrophilicity/hydrophobicity. In addition, emphasis will be on highly homogeneous dispersion (equal number of particles per volume of catalyst) of NPs on carbon support with well-defined specific surface area, controlled porosity, graphitization, and enhancing electrochemical durability.[10] This will be achieved through introduction of controlled defects with defined surface concentration and/or functionalizing the carbon with N, P, B. Both strategies will yield strong/selective anchoring of metallic NPs, improving

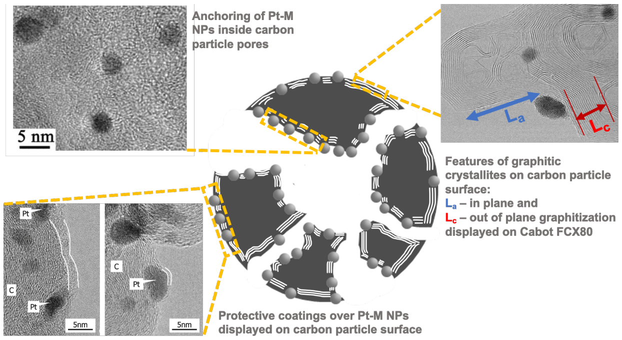


Figure 6. Carbon support by design: anchoring NPs inside carbon pores with highly graphitic surfaces, which can be additionally modified, e.g., graphene layer over NPs can be used for anchoring and tuning of activity and durability.

dispersion and enhancing durability. Additionally, conductive metal oxides, carbides and/or nitrides will be used as additive components of advanced composite carbon supports with the goal of further enhancing the strength of the metal-support interaction through hetero-poly-epitaxy. These tandem systems will mitigate migration, agglomeration, and detachment of NPs. Carbon architecture development and manufacturing scale-up will be executed by Cabot and UCI. Table 1 lists initial series of engineered "FCX" carbon blacks by Cabot, which will be used as a starting set for selecting, integrating and modifying catalyst supports. A common strategy to mitigate carbon corrosion is using supports with higher degrees of surface graphitization, since they contain less defects and edges than amorphous carbon and are more corrosion resistant. The porous network along with size distribution is intrinsic to the function and durability of carbon supports. Hierarchical mesoporosity is desirable for novel carbons, as it promotes mass transport and homogenous ionomer coverage in pores. The support's porous structure can be modified independently of surface chemistry, allowing for the stability and activity benefits of highly graphitic carbons. Fig. 6 shows synergistic approach that will be pursed in this project.

Table 1. Physical Characteristics of New Generation of FCX Carbons

Sample	BET Surface Area (m²/g)	Crystallinity XRD L_C (Å)	Crystallinity Raman L_a (Å)	Micropore volume (cm³/g)	Mesopore volume, 2-10 nm (cm³/g)	Mesopore volume, 10-50 nm (cm³/g)	Macropore Volume (cm³/g)	Total pore volume (cm³/g)
FCX 80	73	60	67	0.01	0.04	0.10	0.19	0.34
FCX 200	158	16	31	0.02	0.06	0.12	0.22	0.42
FCX 300	246	21	36	0	0.12	0.44	0.77	1.33
FCX 200	208	22	36	0	0.10	0.35	0.51	0.97
FCX 400	396	15	30	0.04	0.14	0.69	0.85	1.73
FCX 800	890	13	27	0.20	0.16	0.87	0.95	2.18
FCS 200	201	60	26	0.02	0.10	0.16	0.18	0.46
FCX 650	630	22	19	0.01	0.39	0.64	0.74	1.78
FCX 500	506	23	20	0.01	0.31	0.55	0.54	1.42
FCX 1100	1053	15	23	0.11	0.37	0.72	1.02	2.22
FCX 800	809	20	24	0.02	0.32	0.44	0.71	1.49
FCX 1000	998	16	21	0.03	0.10	0.19	0.42	0.74
FCX 450	443	36	21	0.01	0.19	0.43	0.57	1.21

Task 3 | Modified Catalyst-Ionomer Interfaces by selected molecular implants will be explored on 2D surfaces and nanocatalysts by introducing molecular additive layer(s). The composition and structure of these molecular interfacial additives will be targeted to optimize interactions between reactants, water, solid electrolytes, and the catalyst surface while maintaining fast transport of reactant(s), electrons, and ions to the surface. In this task we will look at the role of the chemical composition and individual/molecular ensemble structure in modulating ORR kinetics, mitigating detrimental interactions between catalyst and solid electrolytes, affecting catalyst durability, and facilitating ionic and gaseous transport to and from the active sites. Significant effort will be placed on integration of these with nanocatalysts in MEA electrodes with the goal of enhancing performance and operational longevity of not only the catalyst but also the interfacial modifying additives. Integration methodologies to be assessed include specifically adsorbed molecules, viscous liquid interlayers, incorporation into ionic polymers (i.e. S-PILBCP ionomers), and thin film hydrogels. An ideal interfacial additive will have limited blocking of the active surface, but sufficient structural and chemical integrity to remain at the interface during long duration fuel cell operation. The molecular additives must be chemically stable and allow facile tuning of its functional properties through chemical modifications. Their spatial distribution in-plane and out-of-plane must be varied to allow precise control over overlapping

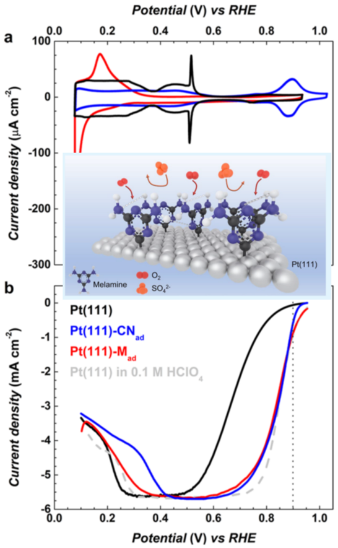


Figure 7. Pt(111) modified by melamine molecules achieves the same ORR activity in sulfuric acid and deflects impact of sulfates on the ORR. [11]

double-layer and diffusion layer thicknesses, without compromising effective charge, ion, and reactant transport to the surface. An example in Fig. 7 depicts how negative effect of strongly adsorbing anions on the ORR rate was reversed by melamine molecules.[11] The same species have been used on nanoscale Pt surfaces, and the approach has been extended to MEA electrode.[12,13] Targeted selection and decoration of catalyst surfaces with molecular implants including ionic liquids, melamine, melamine formaldehyde, caffeine, graphene, etc., will alter the ionomer/catalyst interface, improve ORR kinetics, and slow degradation during AST.

Task | 4 Advanced Catalyst Characterization of catalyst layers will rely on continuous durability assessment in conjunction with their structural properties. This Task is essential for the whole project and is composed of three pillars: durability analytics, aging prediction algorithm, and AST validation based on BOL and EOL. The durability analytics is focused on the degradation mechanism of the catalyst, support, and ionomer/membrane, including quantification of degradation products. That will be executed by combination of customized analytical methods such as electron microscopy (available at UCI and Oak Ridge through the M2FCT), synchrotron X-ray spectroscopy methods (ANL through the M2FCT), ICP-MS, GC-MS, AFM-Raman, micro-XRF, that are coupled with RDE and MEA. Our *in situ* RDE-ICP-MS can detect sub-picogram amounts of dissolved Pt (ppt range or 10^{-6} atomic monolayer) and other elements from a single potential scan.[4] Over the lifetime of an MEA, Pt and TM dissolution have direct impact on the particle size ripening that is routinely observed after AST protocols. Insights into atomic scale quantities of degradation products are crucial input for the aging prediction algorithm. This protocol will enable extrapolation from the quick (several hours) evaluation of durability to the performance prediction beyond 25,000 hours. The core of this algorithm, which was developed in our lab, relies on degradation analysis from each component, obtained from the durability analytics. It also relies on AST validation from the traditional AST protocol in combination with the long-term drive cycle protocol that simulates real-world driving conditions. Establishing an experimental routine and data analysis will expedite assessment of catalyst layer durability beyond 25,000 hours. Integration of our unique set of operando characterization protocols, centered on our achieved detection limit of 4×10^{-13} $g_{Pt}/cm^2_{(geo)}$ (or normalized as 5×10^{-6} $ng/\mu C_{Hupd}$), will give a detailed picture of the degradation mechanisms of various electrode components, facilitating the development of extrapolated degradation profiles and potential new mitigation strategies. Importantly, true in-situ corrosion rates will be determined through quantification of the scavenging effect of the porous carbon matrix, estabilishing an *intrinsic dissolution rate* Γ^0 (ng/cm^2_{Pt})[4], which is normalized to electrochemically active surface area. Degradation of the electrode layers will be delineated, and total degradation will be decoupled into the contributions that originate from dissolution of NPs, carbon corrosion, and ionomer degradation based on synergistic in-situ studies from RDE | MEA-ICP/MS.**Task 5 | Advanced Component Integration** will rely on several innovations proposed by UCI for MEA design aimed at 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. Pt *dissolves at higher rates from micro- and meso-pores*, which are ionomer-free, indicating that ionomer acts as a protection layer.[14] However, specific adsorption of sulfonic acid groups and polymer backbone coverage at the Pt/ionomer interface have detrimental impacts on activity and mass transport. We have shown that novel ionomers, such as HOPI have similar SO_3^- adsorption, but exhibit better power densities due to porous backbones, which enables high oxygen transport.[15] Our approach is to integrate interfacial molecular additives, developed in Task 3 in order to: i) protect Pt from ionomer poisoning, ii)

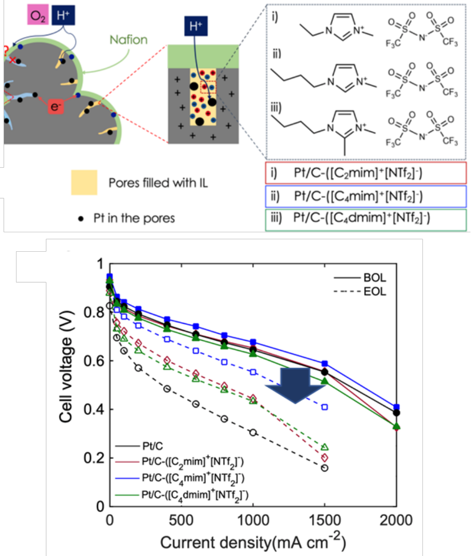


Figure 8. A schematic of IL filled meso-pores and structure of ILs. Polarization curves at the BOL and EOL durability improvement for MEAs with ILs after 30k AST cycles. [14]

fill meso-pores to improve proton conductivity, especially at lower relative humidity (RH), and protect Pt from dissolution in the meso-pores. Preliminary work indicates that molecular additives, such as poly melamine formaldehyde (PMF) have potential to reduce SO_3^- adsorption, resulting in higher mass activity. PMF is a poor proton conductor, therefore it is necessary to have optimized coating on Pt with PMF. UCI will investigate various ink compositions with PMF and various ionomers (including HOPI) to find an optimal composition, where PMF thinly coats Pt, protecting it from SO_3^- poisoning but also enabling oxygen and proton transport. To solve a challenge of higher rates of Pt dissolution from meso-pores, these pores will be filled with molecular additives. Our recent work significantly improved proton transport for CCMs with ionic liquids in meso-pores, resulting in higher power densities for Pt supported on high surface area carbons.[14] Furthermore, filling mesopores with ionic liquids reduces Pt dissolution, Fig. 8, which likely slows down Ostwald ripening. This might be due to shift of onsite growth of PtO to higher potentials for Pt covered by ionic liquids, as Pt dissolution is proportional to the amount of PtO present on the surface. One of the potential advantages of pore filling with ionic liquids or other molecular additives is the potential to engineer the ionic conductivity of those additives, providing protonic transport at dry conditions.

Task 6 | Electrode Component Distribution and Morphology Design; Standard methods of characterization will be used for this project in collaboration with various nodes at M2FCT (ORNL, ANL). In addition, UCI introduced identical location micro-XRF method to monitor in-plane catalyst movement in MEA from BOL to EOL, Fig. 9, to understand catalyst aggregation during heavy-duty lifetime ageing. The technique can extend to quantification of TM distribution in-plane, along with Pt. UCI has also correlated micro-XRF and micro-XRD results showing that locations where there are higher Pt loadings at the BOL have also the largest particles at the EOL, indicating that inhomogeneous Pt distribution is undesirable as it leads to local 'hot-spots' of increased Pt particle sizes, Fig. 9. In the through-plane direction catalyst and ionomer distribution at BOL and EOL will be quantified with glow discharge optical emission spectroscopy (GD-OES), which was never applied to the fuel cell field; with the ability to determine through-thickness Pt loading distribution in the z-direction, and quantify whether Pt-band is formed within the membrane and its distance from the catalyst layer. Combined insights from this Task will identify weak-spots in electrode component distribution along with its morphology and provide feedback to Tasks 1-3 to guide improvements in materials design.

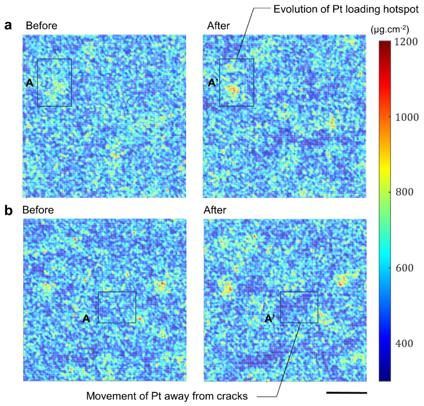


Figure 9. Identical location maps of Pt distribution by micro-XRF: **a)** inlet and **b)** outlet at the BOL and after 90k heavy-duty AST. [15]

Task 7 | MEA Diagnostics for Accelerated Stress Testing will be adopted from M2FCT protocols. These include standard nitrogen-based protocol with UPL of 0.95 V and LPL of 0.6 V for 6 s cycle for 90k cycles and air-based protocol with UPL of 0.925 V and LPL of 0.675 V with 60 s cycle for 30k cycles. Carbon corrosion protocols are extended to higher UPL. In addition, we will develop a dynamic load cycling protocol that is based on the light-duty protocol developed in European ID-FAST project, where a representative drive cycle based on several hours of customer fleet data was used.[16] The protocol is more difficult to implement with standard test stands due to variations of temperature, humidity, pressure and load dynamically. At UCI we have customized a test-stand to operate with 4 humidifiers for fast switching between RHs. These dynamic protocols include performance at high and low loads and also with short and long stops, as well as cold soaks. The short stop and cold soak represent stopping of vehicles and will need to be reduced for heavy-duty truck operation, as these are rare events compared to light-duty. UCI will test 3 down-selected MEAs for a duration of 1,000 operating hours for the dynamic load cycling protocol and characterize MEAs every 200 cycles. In parallel with initial testing at UCI, evaluation of MEAs with selected materials developed in this program will be executed by M2FCT MEA fabrication and testing capabilities at NREL, LANL, and later at RTC Bosch. Catalyst materials will be supplied by UCI for durability evaluation with M2FCT's AST protocols. Based on the comparison between BOL and EOL performance critical structural parameters of electrode layers will be tuned in Task 1-4.

Task 8 | Feasibility Studies for High Volume and High Throughput MEA Manufacturing will be continuously performed among the team members, particularly with industry partners Cabot Corp. and RTC Bosch. Several key parameters will be assessed: i) feasibility of scaling up chemistry of novel highly durable low-PGM catalyst developed in this project; ii) evaluation of MEA component integration with desirable precision at high volume and high throughput; iii) different approaches in MEA manufacturing will also be considered in comparison to roll-to-roll process; iiii) techno-economic evaluation of catalyst production and component integration at industrial scale by roll-to-roll approach (cost of chemicals and processes, timing and facilities). This Task will address complex chemistries, component integration and fabrication processes in large scale manufacturing.

Task 9 | Sustainable and Recyclable MEA Design will be aimed for repurposing of membranes and highly durable catalyst layers. Currently, membranes and catalyst layers cannot be separated after the PEFC operation due to the high degree of adhesion between the catalyst layer and membrane. Various interlayers between membrane and catalyst layer will be explored, including molecular modifiers and modified carbon-ionomer composites to enable catalyst layer detachment from the membrane at the EOL. Post-processing steps to separate the catalyst layers from the membrane at EOL will be investigated, including chemical and physical separation processes to enable extraction of Pt and TM from the catalyst layers without the complexity of burning or dissolving the membrane. Additionally, methods for targeted corrosion and delamination of the catalyst layers will be thoroughly evaluated. UCI has previously showed a method for making Pt nanoparticles through erosion by applying alternating voltage with a specific frequency. 1M KOH electrolyte was used and we showed that Pt particle size can be controlled by potential amplitude of alternating voltage.[17] The method is fairly fast and results in Pt particles of uniform size. We will extend this method to Pt erosion from CCMs. Mixed metal oxide meshes will be used on both anode and cathode size to mount CCM between these to conduct current. Then a three electrode setup will be used to erode Pt from the CCM and create Pt nanoparticles in solution. We will also use dispersed carbon in electrolyte to deposit Pt nanoparticles from used CCM onto carbon support. This erosion method has only previously been used on Pt wires and meshes and has not been applied to Pt dispersed on carbon support. The advantage of the method is that it is fast, does not require any solvents or ionic liquids and can be done with power supplies and signal generators. There is also a flexibility of how Pt particles will be deposited, whether on GDL, on carbon support or other supports. This method also preserves membrane, which can be reused after dissolution of ionomers.

Innovation and Impacts: Breaking the current stagnation in MEA performance requires addressing a range of interconnected materials and operational problems. These include: insufficient catalyst durability; Pt and TM dissolution at high potentials needed to reach high H_2 utilization for heavy-duty applications; PFSI-based ionomer poisoning of Pt via sulfonic acid group adsorption and dense backbone aggregates leading to oxygen transport resistance; ionic conductivity limitations at high T and low RH; limited understanding of ionomer degradation pathways, especially for 90k catalyst AST; standard AST protocols may not be representative for the entire heavy-duty drive-cycle; pyrometallurgical methods for PEFC materials recovery is expensive and releases toxic fluorine compounds from perfluoronated components. 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. In the design and development of NPs, catalyst support, and molecular interfacial additives for catalyst-ionomer modification we use a collaborative integration of our innovative developments. 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 and introduce Au to enable *self-healing*, (3) optimize the interface between water, ionomer, and the catalyst with molecular interfacial additives, (4) deploy nanoparticles on advanced carbon supports with selective anchors, and (5) integrate novel materials into highly durable MEAs. The entire approach will be executed with substantial amount of novelty in material design and unique characterization processes. 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 overall relevance of this project is reflected through the impact on the DOE EERE Hydrogen Fuel Cell Technologies Office (HFCTO) Program, particularly by addressing critical technical barrie*rs to fuel cell commercialization. This is also in line with the mission of the HFCTO to enable the widespread commercialization of hydrogen and fuel cell technology targeting medium- and heavy-duty trucks. Moreover, the outcome of this project has the potential to dramatically reduce dependence on foreign oil by promoting sustainable energy resources and creating and maintaining a domestic manufacturing base and workforce, specifically for hydrogen technologies. Additionally, this project has 6 PIs, and 3 of them are female researchers, emphasizing the inclusive agenda described separately in the Diversity, Equity, and Inclusion Plan (DEIP) document.

- **Workplan and Market Transformation Plan**

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 cost. We will accomplish this through: (1) development of novel, highly active, and stable cathode catalysts, (2) integration of molecular interfacial additives to enhance kinetic performance, optimize the catalyst/ionomer interface, and improve catalyst durability, (3) design and scaled-up manufacturing of advanced carbon supports, (4) combined integration efforts to maximize MEA performance, (5) advanced in-situ diagnostics to aid material design and fabrication, and (6) focus on manufacturability and recyclability of MEAs for material economy. 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 outcome 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.

Scope Summary: 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.

WBS and Task Description Summary: The three year workplan breakdown to accomplish the objectives will be executed simultaneously in nine tasks: Task 1 - *Materials Discovery and Innovative Synthesis*: 2D materials and modeling guided high-precision synthesis of *self-healing* nanoparticles with defined size, shape, composition, morphology, and distribution of atomic structural ensembles as well as ordered compositional gradients for Pt-transition metal (TM) alloys; Task 2 - Durable Catalyst Supports: design and implementation of advanced carbon-based support materials with defined physical properties, pore size, and NP-anchoring sites; Task 3 - Modified Catalyst-Ionomer Interfaces: modifications of catalyst-ionomer interfaces by selected molecular interfacial modifiers for improved performance and durability; Task 4 - Advanced Catalyst Characterization: customized structural and electrochemical methods for catalyst characterization; Task 5 | Advanced Component Integration in MEA is aimed at improved durability by i) anchoring NPs to supports; ii) use of molecular interfacial modifiers to decrease oxophilicity of NPs surfaces, and iii) use of molecular interfacial modifiers for carbon support pore filling to increase Pt utilization and reduce dissolution; Task 6 - Electrode Component Distribution and Morphology Design by identifying weak-spots in electrode component distribution in 3D, novel highly durable electrode morphologies will be designed; Task 7 - MEA Diagnostics for Accelerated Stress Testing electrochemical MEA diagnostics for in-operando characterizations and accelerated stress testing; Task 8 - Feasibility Studies for High Volume and High Throughput MEA Manufacturing for roll to roll processes and beyond; Task 9 | Sustainable and Recyclable MEA Design is aimed for recyclability and repurposing of membranes and highly durable PGM catalyst layers.Detailed task descriptions can be found in the SOPO document.

Milestone Summary: The project will have a number of internal progress-measure milestones devoted to each Task and sub-Task, and they are listed separately in the SOPO document. In addition, the project will have three SMART milestones in total, i.e., one SMART milestone per year.

The first SMART milestone will be to employ selected material developed in this project in 50 cm^2 MEA, with 0.3 mg$_{PGM}$/cm^2 total loading at 250 kPa in H_2/air, 65% RH, 1.52 kW/g$_{PGM}$, 0.65 A/cm^2 and 455 mW/cm^2 at 0.7 V following 25,000 hour equivalent heavy-duty AST.

The second SMART milestone will be to employ selected material developed in this project in 50 cm^2 MEA, with 0.3 mg$_{PGM}$/cm^2 total loading at 250 kPa in H_2/air, 65% RH, 2.03 kW/g$_{PGM}$, 0.87 A/cm^2 and 609 mW/cm^2 at 0.7 V after 25,000 hour equivalent heavy-duty AST.

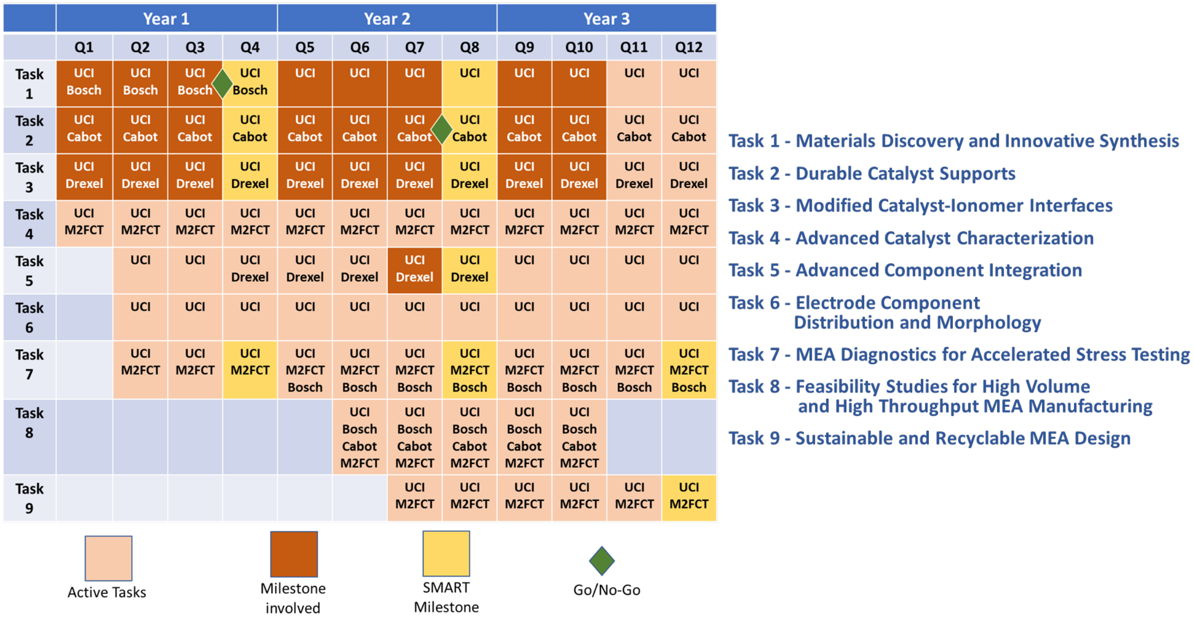
The third SMART milestone will be the embedded in the End of Project Goal listed below.

Go/No-Go Decision Points: *First*: At Q4 in Task 1, based on durability/activity performance it will be decided whether to move exclusively with shape-controlled hollow NPs or solid NPs. *Second:* At Q8 it will be determined if the support of choice will be mesoporous carbon or highly graphitized carbon with anchoring sites. Based on that, the two winning choices will be pursued in Q9-12 of the project.

End of Project Goal: The third SMART milestone is 50 cm^2 MEA, with 0.3 mg$_{PGM}$/cm^2 at 250 kPa in H_2/air, 65% RH, 2.5 kW/g$_{PGM}$, 1.07 A/cm^2 and 750 mW/cm^2 at 0.7 V following 25,000 hour equivalent heavy-duty AST; additional deliverables: 6 MEAs for independent testing by the M2FCT.

Project Schedule: This is a three-year project with multiple tasks of which timelines are summarized in Table 2, including internal milestones, SMART milestones and Go/No-GO decision points:

Table 2. Project schedule for all Tasks.



	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1	🟧 UCI Bosch	🟧 UCI Bosch	🟧 UCI Bosch ◆	🟨 UCI Bosch	🟧 UCI	🟧 UCI	🟧 UCI	🟨 UCI	🟧 UCI	🟧 UCI	UCI	UCI
Task 2	🟧 UCI Cabot	🟧 UCI Cabot	🟧 UCI Cabot	🟨 UCI Cabot	🟧 UCI Cabot	🟧 UCI Cabot	🟧 UCI Cabot ◆	🟨 UCI Cabot	🟧 UCI Cabot	🟧 UCI Cabot	UCI Cabot	UCI Cabot
Task 3	🟧 UCI Drexel	🟧 UCI Drexel	🟧 UCI Drexel	🟨 UCI Drexel	🟧 UCI Drexel	🟧 UCI Drexel	🟧 UCI Drexel	🟨 UCI Drexel	🟧 UCI Drexel	🟧 UCI Drexel	UCI Drexel	UCI Drexel
Task 4	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT
Task 5		UCI	UCI	UCI Drexel	UCI Drexel	UCI Drexel	🟧 UCI Drexel	🟨 UCI Drexel	UCI	UCI	UCI	UCI
Task 6		UCI	UCI	UCI	UCI	UCI	UCI	UCI	UCI	UCI	UCI	UCI
Task 7		UCI M2FCT	UCI M2FCT	🟨 UCI M2FCT	UCI M2FCT Bosch	UCI M2FCT Bosch	UCI M2FCT Bosch	🟨 UCI M2FCT Bosch	UCI M2FCT Bosch	UCI M2FCT Bosch	UCI M2FCT Bosch	🟨 UCI M2FCT Bosch
Task 8						UCI Bosch Cabot M2FCT	UCI Bosch Cabot M2FCT	UCI Bosch Cabot M2FCT	UCI Bosch Cabot M2FCT	UCI Bosch Cabot M2FCT		
Task 9							UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	UCI M2FCT	🟨 UCI M2FCT

□ Active Tasks
🟧 Milestone involved
🟨 SMART Milestone
◆ Go/No-Go

Task 1 - Materials Discovery and Innovative Synthesis
Task 2 - Durable Catalyst Supports
Task 3 - Modified Catalyst-Ionomer Interfaces
Task 4 - Advanced Catalyst Characterization
Task 5 - Advanced Component Integration
Task 6 - Electrode Component Distribution and Morphology
Task 7 - MEA Diagnostics for Accelerated Stress Testing
Task 8 - Feasibility Studies for High Volume and High Throughput MEA Manufacturing
Task 9 - Sustainable and Recyclable MEA Design

Project Management: The proposed program is a multi-institutional research effort that involves two universities and two companies. 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 prime institution, UCI, is a federally recognized Hispanic-Serving Institution (HSI) and Asian American and Native American Pacific Islander-Serving Institution (AANAPISI). The UCI team consists of three faculty members from the School of Engineering, Department of Chemical and Biomolecular Engineering bridging fundamental design to guided nanoscale synthesis to advanced characterization and MEA fabrication. Of the three faculty members, two are professors, and one is female associate professor. Drexel University, Cabot Corporation and Bosch RTC North America are partner institutions that bring in new and prior interdisciplinary collaborations to the team.

Roles and Responsibilities: Prof. Vojislav Stamenkovic (UCI), 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. He will be involved in the strategic planning of research directions, day-to-day operations, and interfacing with researchers and participants, including internal and external report preparation, data management, highlights, publications as well as ensuring oversight of safety in the laboratories and facilities at UCI. He will be involved in all phases of this project, including all Tasks.

Prof. Plamen Atanassov (UCI) is a co-PI and will be conducting experimental work related to carbon supports in Task 2, including activities in Tasks 3-5. He will develop novel carbon structures, functionalize carbon supports and will work on anchoring sites to attach NPs developed in Task 1. Atanassov will work closely with Cabot to identify advanced carbon structures that will be fabricated by Cabot. Development of carbon materials is a unique activity across M2FCT and selected advanced highly durable carbon materials developed in this program could be deployed across the Consortium.

Prof. Iryna Zenyuk (UCI) is a co-PI and will be conducting a series of experiments with materials developed in Task 1-3. She will evaluate integration of advanced low-PGM catalysts in MEAs, and will be engaged in Tasks 4-7 and Task 9. She will be working closely with Bosch RTC to explore additional testing protocols for MEA durability assessment. In addition, she will be performing BOL and EOL experiments by micro-XRF and GD-OES to assess NP distribution across electrode layers. These methods will be offered to M2FCT as additional capability for Consortium researchers. Prof. Zenyuk will explore MEA recycling methodolog to enable extraction of Pt and membranes by novel approaches in MEA fabrication after EOL.

Prof. Joshua Snyder (Drexel University) is a co-PI and will be conducting a number of experiments with 2D and 3D catalytically active surfaces with different molecules, such as caffeine, melamine, ionic liquids, polymerized ionic liquids, ionic liquid hydrogels, etc. to assess correlation between surface coverage of these molecules and electrochemical properties, including durability evaluations in RDE. He will be engaged in Tasks 3 and 5, and he will look at the role of the chemical composition and individual/molecular ensemble structure in modulating ORR kinetics, mitigating detrimental interactions between catalyst and solid electrolytes, affecting catalyst durability, and facilitating ionic and gaseous transport to and from the active sites. He will work on methodologies to apply and optimize transfer of molecular implants to MEA electrodes.

Dr. Christina Johnston (Bosch RTC North America) is a co-PI and will be coordinating activities of this project within Bosch. These efforts will address activities in Tasks 1, such as supporting computational modeling of well-defined 2D multi-metallic systems with self-healing properties and corresponding nanostructures. In addition, Dr. Johnston will perform and synchronize efforts within Task 7 related to industry AST methodologies based on Bosch's internal screening tools derived from stacks on-road and representative drive cycles. Performance will be evaluated using low and high current density polarization curve data, specifically mass and specific activity extraction from O_2/H_2 and high current density under H_2/Air operation. Bosch's internal analytics team will perform alloy-specific aging evaluation techniques to determine the extent of the novel catalyst's degradation independently of other components, and will compare the outcome to M2FCT's ageing protocols.

M.E. Qian Ni (Cabot Corporation) is a co-PI and will be providing a series of carbon supports with controlled properties and perform analytical evaluations of the carbon materials. She will develop a variety of carbon supports designed to provide controlled combinations of properties to evaluate the impact of fabrication processes on electrochemical performance, including surface enhancement treatment via scalable processes. M.E. Ni and Cabot will focus on supplying the carbon materials to support the feasibility studies for high volume and high throughput MEAs, as well as for evaluation and benchmarking. Dispersion quality of carbon support materials will be tested in proxy catalytic ink formulation. M.E. Ni will be primarily engaged in activities in Task 2, and also Task 5.

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 PIs will employ mentorship strategies and exchanges that promotes collaboration, especially amongst the postdocs, graduate students, and investigators. This project will be interconnected with M2FCT Consortium, and therefore, early pairing between point of contact at national laboratory with university graduate students and postdocs will be established to facilitate utilization of M2FCT capabilities at Argonne, Oak Ridge, NREL and LANL. Of particular interest will be the utilization of electron microscopy at ORNL, MEA testing capabilities at NREL and LANL, and X-ray spectroscopy at the beam line at Argonne.

Additionally, Data Management Plan will be established through a data sharing platform at UCI’s Campus Research Storage Pool (CRSP) that is accessible to all team members through a temporary UCI-net ID. The website and CRSP will be used for data sharing, dissemination, and the archival of meeting presentations and publications. Data sharing will also be provided to the M2FCT platforms.

Market Transformation Plan: High performing MEAs with the requisite durability to meet the demands of heavy-duty operation are an existing obstacle to fuel cell stack production and wide deployment of fuel cell technologies. The derived insight and materials and integration/fabrication outcomes will address many of the existing limitations. Additionally, the focus on material integration, MEA manufacturability, and materials recovery, as well as our specified industrial collaborations, will yield a project outcome that is tailored for direct integration into existing business plans and expand MEA manufacturing capabilities in United States for heavy-duty applications. Success of this project will be communicated through industry partners in this program, which will additionally facilitate market penetration and evaluation. Intellectual property licensing will be the first tier in exploring dissemination of the project outcomes. In addition, UCI has an established mechanism for early start-up enterprises with direct access to investors, space and facilities for initial activities. Timelines for an early launch could be even before official end of the project, considering the enormous potential to deliver groundbreaking performance of MEAs based on the four discoveries that are the foundation in development of highly durable and high performing MEAs.

• Technical Qualifications and Resources

The PI and Project Team have extensive experience and track record in the field of fuel cells. **UCI: Prof. Vojislav Stamenkovic (PI)** has over 20 years of experience in the design and development of electrochemical materials, holds over 20 patents on fuel cell catalysts, he is recipient of the DOE Hydrogen and Fuel Cells Award, and he has been named since 2018 as a Highly Cited Researcher by Clarivate Web of Science for his influential work in electrocatalysis. **Prof. Plamen Atanassov** has over 25 years of experience in the catalyst development with outstanding track record in the design of carbon-based materials with specific focus on the electronic and structural properties of carbon materials. **Prof. Iryna Zenyuk** has over 13 years of experience in fuel cell technology and has influential track record in advanced modeling, fabrication and characterizations of single cells; **Drexel University: Prof. Joshua Snyder** has over 15 years of experience in electrochemical technologies, and he pioneered approach in ionic liquids at electrochemical interfaces. **Bosch RTC North America:** is a projected large-scale supplier of FCEV stacks and supporting systems to OEMs and is interested in novel catalysts with superior performance and durability characteristics for integration into internally fabricated MEAs or into MEAs produced by a partner or supplier. **Dr. Christina Johnston**, Senior Project Manager will be the technical point of contact as she has been in the field of fuel cells for over

15 years, leading multiple projects, focusing on all aspects of fuel cells from atomic to stack level. **Cabot Corporation:** has over 20 years history of developing and commercializing carbons for energy applications, especially carbon supports for fuel cells, and has become an international developer and scaled commercial supplier of carbons for fuel cells. **M.E. Qian Ni**, Senior Engineer at Cabot Corporation, has over 10 years of experience in research and development of advanced conductive carbons for Lithium-ion batteries and fuel cell applications, and has led multiple projects, from idea through manufacturing scale up to commercial adoption, and has been responsible for various workstreams of DOE funded programs at Cabot.

Facilities: Applicants have access to equipment needed to engage in the proposed effort through both the established research facilities and laboratories in their own institutions, and M2FCT Consortia capabilities. The proposed project will be mainly executed at University of California, Irvine, where the majority of the proposed activities will take place in the Stamenkovic, Atanassov and Zenyuk research laboratories, as well as within the Horiba Institute for Mobility and Connectivity (HIMaC), National Fuel Cell Research Center (NFCRC) and Interdisciplinary Science and Engineering Building, consisting of various lab clusters for surface science, electrochemical testing, materials synthesis and wet labs with ventilated hoods. The PIs have office space for Ph.D. students located in the proximity of the laboratories. The following equipment is available: Electrochemical Testing and Characterization laboratory with multiple Autolab digital potentiostats. Perkin Elmer Inductively Coupled Plasma Mass Spectrometer is integrated in the electrochemical laboratory for in situ durability studies. Surface Characterization and Modification laboratory is equipped with various surface specific ultra-high vacuum techniques, such as XPS, AES, LEIS, including physical vapor deposition tools for thin film deposition by AJA magnetron sputtering system. Chemical Synthesis Lab for colloidal solvo-thermal fabrication of nanoscale materials is equipped with custom made glassware and furnace to accommodate experimental requirements. It has 300 square feet and provides equipment and expertise in advanced manufacturing technologies with emphasis on high precision synthesis. HIMaC analytical laboratory with 1) GD-Profiler 2 glow discharge optical emission spectroscopy, 2) LabRAM HR Evoluton nano - AFM-Raman/TERS spectrometer, 3) XGT-9000 micro-X-ray fluorescence and 4) SZ-100 Particle size analyzer will be utilized and offered to other M2FCT researchers to expand existing capabilities of Consortia. In addition, UCI's Irvine Materials Research Institute (IMRI) provides a wide range of state-of-the-art techniques including structural and chemical characterization, 3D imaging, surface analysis, physical property measurements, and material synthesis. The equipment list for material characterization required for this study includes scanning electron microscopy systems (FEI Quanta 3D FEG Dual Beam SEM, FEI Magellan XHR SEM, Hitachi S-4700 SEM), a line laser scan (Tencor FLX-2320A), transmission electron microscopy (JEOL 2100F), micro X-ray CT (Xradia VersaXRM 410), etc. See http://www.imri.uci.edu for the complete list.

The PI and co-PIs have documented successes in leading and teaming in DOE funded research, executing the most complex tasks, and achieving proposed targets. The applicants have previous successful DOE collaborations and possess the requisite complimentary expertise for completion of the proposed work. Time commitment to this project for each PI is outlined in the budget, while the roles and the work to be performed by each PI is listed in the Workplan and SOPO document. Business arrangement between the applicant and each PI is defined in the budget and SOPO. Various tasks and efforts will be integrated and managed in accordance with the management plan. All PIs are equally participating in the scientific and technical decision-making processes. The results obtained will be publicly disclosed in the form of peer reviewed articles, M2FCT reports, and conference presentations. Intellectual property is defined through the subcontract documents between institutions. Communication channels among the participants will be in the form of bi-weekly meetings on the progress made, and results will be shared electronically through designated shared drives. The PIs may expedite further development of the materials developed in this program, and all parties are open to engage in the planning process of various forms of commercial deployment.

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