



NEO GRAF™
— SOLUTIONS

Development of Low Cost, Thin Flexible Graphite Bipolar Plates for Heavy Duty Fuel Cell Applications

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AMR Project ID: FC347

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Project Goal

- The goal is to reduce bipolar plate assembly (BPA) graphite costs by ~90% to enable a BPA cost of $\leq \$5/\text{kW}$ for next-generation heavy-duty fuel cell applications.
- Graphite costs will be reduced through development of thin and durable flexible graphite BPAs with low graphite basis weight (i.e., areal density) and very low concentration of leak-causing impurities.
- Thinner BPA design also yields higher volumetric cell and stack power densities.
- This will be a critical advancement in BPA technology and substantial progress towards meeting 2030 system level heavy-duty truck targets of $\$80/\text{kW}$ system cost and 25,000-hour durability.

NeoGraf Solutions, Lakewood, Ohio



Flexible Graphite



Flexible Graphite
BPA



*Courtesy of
Ballard Power Systems*

Overview

- **Timeline and Budget**

- Project Start Date: May 1, 2022
- Project End Date: Dec 31, 2025
- Total Project Budget: \$2,053,946
 - DOE Share: \$1,643,157
 - Cost Share: \$410,789
 - DOE Funds Spent*: \$309,672
 - Cost Share Funds Spent*: \$77,418

* As of 3/8/24

- **Partners**

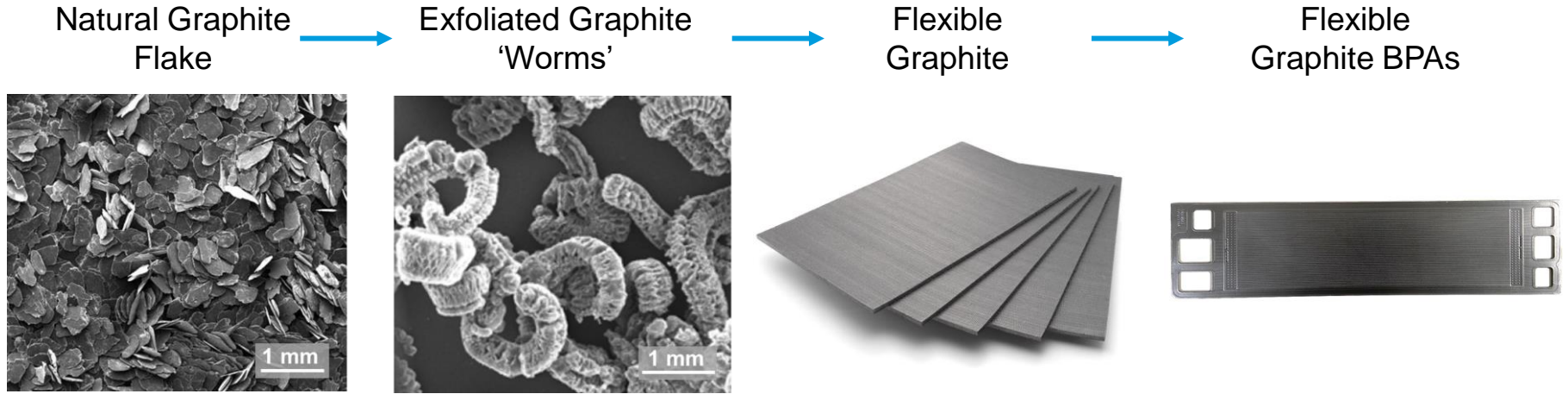
- Project Lead: NeoGraf Solutions, LLC
- Ballard Power Systems
- Strategic Analysis, Inc.
- Norley Carbon & Graphite Consultants, LLC

- **Barriers & Targets**

- Barrier Addressed: BPA yield loss due to leaks related to inclusions.
- Key Target: Reduce concentration of impurities in graphite to achieve BPA leak failure rate of <5% due to inclusions.

A no-cost time extension of seven months was granted in December 2023.

Background – Flexible Graphite BPAs

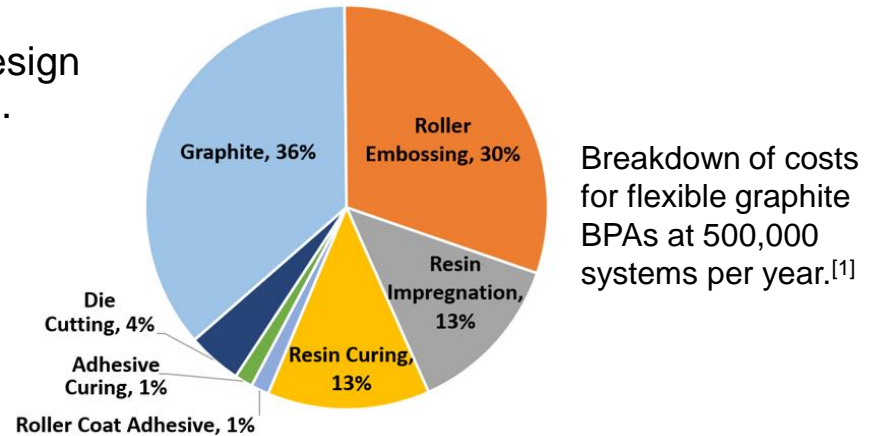


- Natural graphite flake is treated with a combination of chemicals, exfoliated in a high temperature furnace to produce vermicular expanded graphite or “worms”, and densified to produce flexible graphite.
- Flexible graphite is embossed, resin impregnated, and assembled into BPAs.

Potential Impact

- Flexible graphite BPAs already meet the durability, corrosion resistance, and other technical requirements for heavy-duty fuel cell applications. Further work is needed to meet the DOE target of $\leq \$5/\text{kW}$ BPA cost.
- A previous study of flexible graphite BPA costs projected that graphite is the largest cost driver at high production volumes.^[1] The amount of graphite, together with overall BPA thickness, must be reduced to meet cost targets.
- An additional benefit gained from a thinner BPA design is higher volumetric cell and stack power densities.

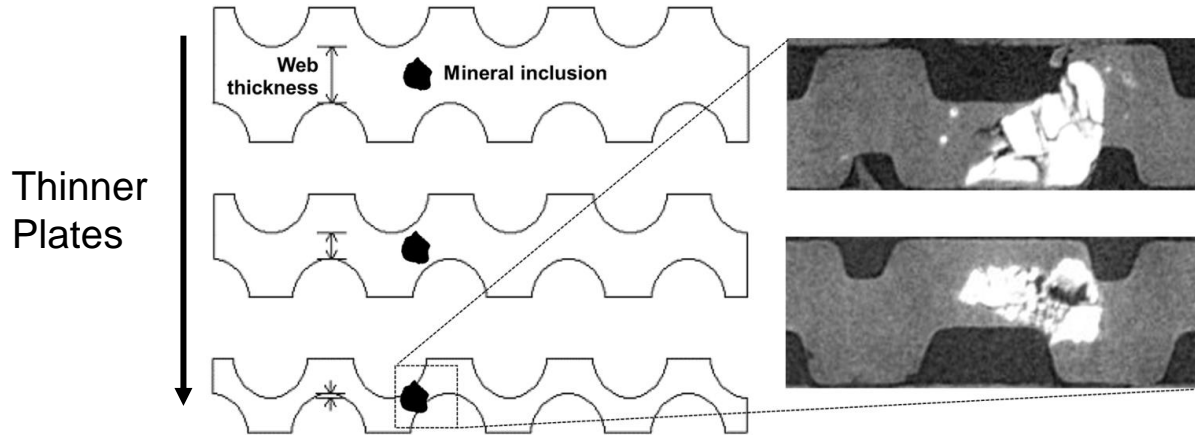
DOE 2030 Goal: Heavy-duty truck targets of \$80/kW system cost and 25,000-hour durability.



^[1]“Making the Case for Graphite Bipolar Plates”, Brian James (Strategic Analysis, Inc). Fuel Cell Seminar & Energy Exposition, Nov. 2019.

Potential Impact

- Technical Barrier: Plate thickness is limited by the size of mineral inclusions (i.e., 'ash') in the graphite, as inclusions may cause pinhole defects and leaks. As BPA thickness decreases, leak failures due to inclusions become more frequent.
- Impact: Flexible graphite costs for BPAs will be drastically reduced through the development of low basis weight, thin flexible graphite with very low amount of leak-causing impurities.



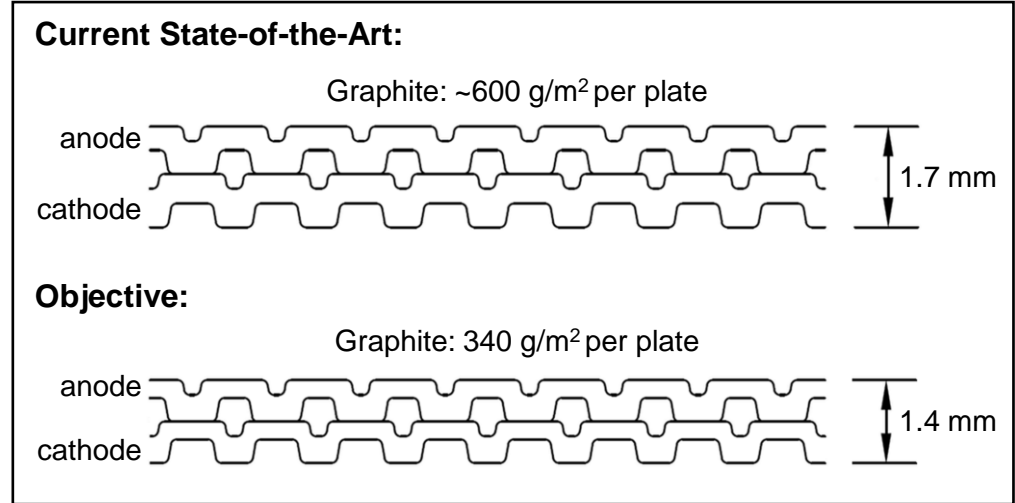
Two sources of ash:

- Natural impurities
- Process contaminations

Need to reduce the amount of ash particles larger than ~200 μm .

Approach & Key Objectives

- Technical Approach:
 - Develop technologies to eliminate inclusions in flexible graphite.
 - Evaluate impact of flexible graphite improvements on BPA leak failure rates.
- Key Objectives:
 - Reduce BPA thickness and graphite basis weight.
 - Achieve a leak failure rate due to inclusions of <5% in thin plates.
 - Demonstrate BPA performance through short stack testing and accelerated materials testing.
 - Provide detailed cost estimates of the BPA concept through manufacturing cost analysis.



Approach: Tasks and Final Goals

Budget Period 1

Task 2 - Alternative graphite feedstocks ✓

Task 4 - Graphite process improvements ✓

Task 5 - Pilot-scale clean exfoliation furnace ✓

Task 3 - Preliminary cost and manufacturability analysis ✓

Task 1 - Baseline thin plate production and evaluation ✓

✓ **Previously completed**
✓ **In progress**

Go/No-Go: Demonstrate <5% BPA leak failure rate due to inclusions. June 30, 2024.

Budget Period 2

Task 6 - Full-scale graphite production improvements

Task 8 - Manufacture large set of BPAs and evaluate performance

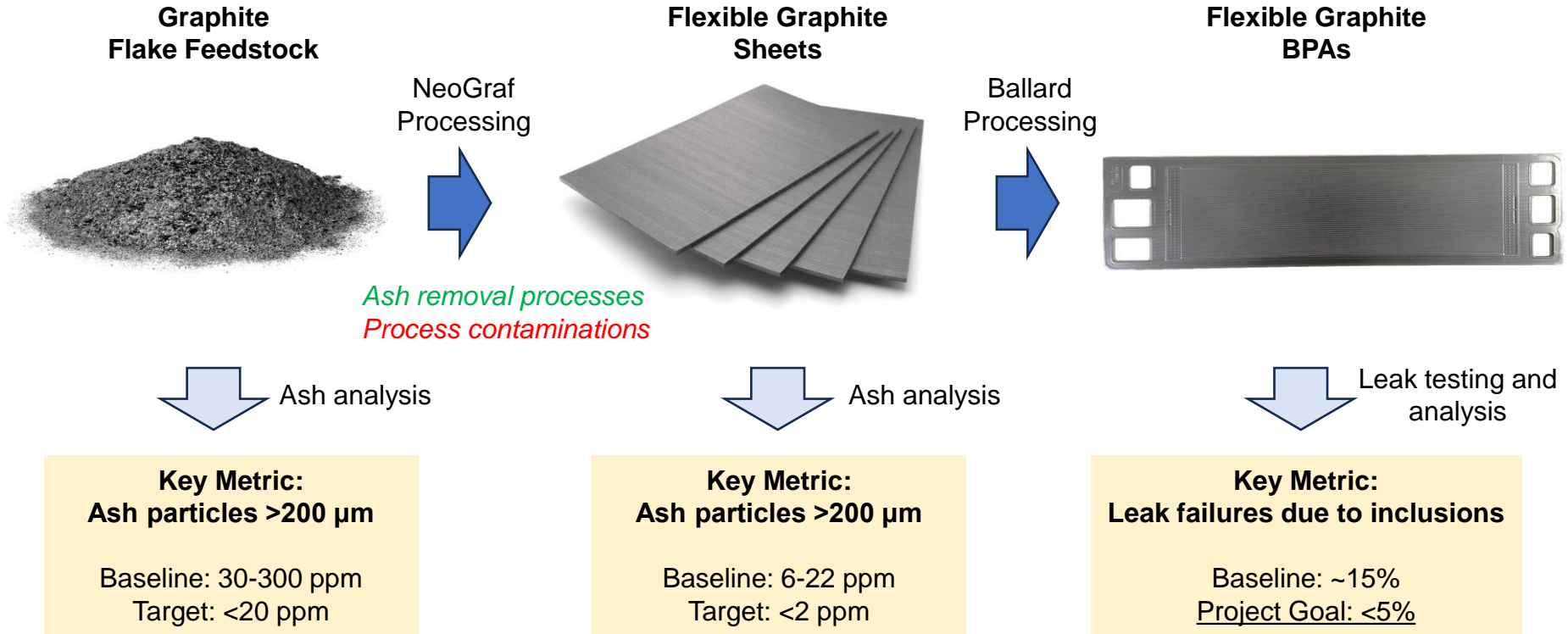
Task 7 - Detailed cost and manufacturability analysis

Final Goals:

- Achieve <5% BPA leak failure rate due to inclusions in a large production batch.
- Report on durability and performance tests in a fuel cell short stack.
- Deliver 6+ BPAs for independent testing and evaluation by M2FCT.
- Provide detailed cost estimates of the BPA concept.

Task 9 - Team meetings & reports ✓

Approach: Analysis and Key Metrics



Approach: Safety Planning and Culture

- This project was required to submit a safety plan to the Hydrogen Safety Panel (HSP).
- A revised plan was submitted which addressed HSP feedback regarding:
 - Hazard analysis
 - Hydrogen risk planning
 - Hydrogen safety system design
- Work is performed within the established safety cultures at NeoGraf and Ballard.
 - Process improvements and equipment modifications in Tasks 4 and 5 went through formal Management of Change (MOC) procedures.
 - Pre-start safety meetings were held with operators, engineers, and process managers before trial work began.
 - A safety management audit was conducted during a key production trial.



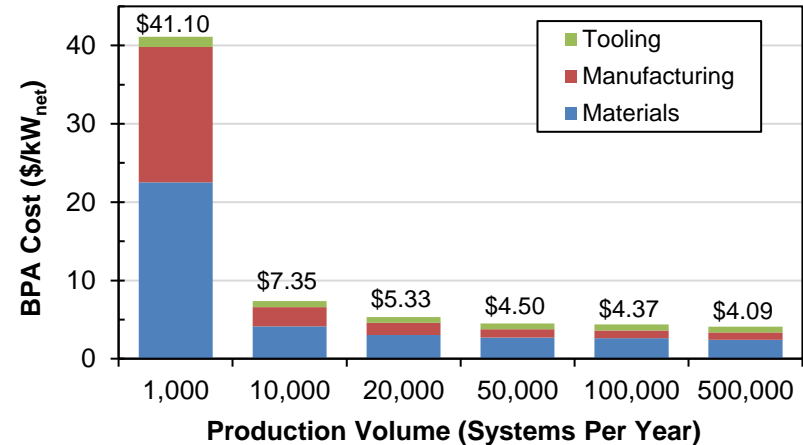
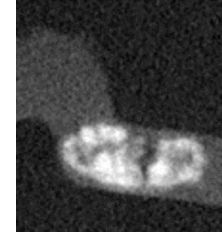
Previous Accomplishments

- Task 1 – Produced BPAs from low basis weight flexible graphite and evaluated baseline impurity levels and BPA leak failure rates.
- Task 2 – Identified four alternative graphite flake feedstocks with low amount of ash particles >200 μm , and good compatibility with the flexible graphite production process.
- Task 3 – Preliminary cost analysis conducted by Strategic Analysis projected that BPA cost of <\$5/kW is achievable with the proposed thin plate design.

Flexible Graphite Roll



XCT image of a leak-causing ash inclusion



Task 2: Alternative Graphite Feedstocks

- Setbacks:

- None of the initial four graphite flake candidates were obtained in ton-scale quantities.
- Suppliers were generally unable to match the quality of the initial lab-scale samples, in terms of amount of ash particles >200 μm .

- Progress:

- Evaluated 14 additional samples and found six new materials that meet the key metric target.
- Ton-scale orders for four new materials were placed in late 2023 / early 2024.
- NeoGraf is working closely with suppliers to ensure suitable graphite flake is obtained.

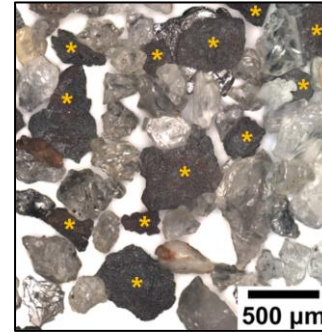


Key Metric:
Ash particles >200 μm

Baseline: 30-300 ppm
Target: <20 ppm

Task 2: Purification of Graphite Feedstocks

- Problem:
 - Graphite flake often contains small amounts of iron-rich, ferromagnetic particles.
 - Ballard has found BPA leak failures caused by iron-rich inclusions in this project.
- Progress:
 - NeoGraf identified a high-throughput magnetic separation technology suitable for removing iron-rich particles from graphite flake.
 - Two tons of graphite flake were purified using rented equipment, removing ~75% of iron particles >200 μm .
- Next steps:
 - Flexible graphite will be produced using the purified flake and will be analyzed for inclusions.



* Iron-rich impurities present in graphite flake



Electromagnetic filter removes iron-rich impurities from graphite flake

Task 4: Eliminating Potential Process Contaminations

Accomplishments
and Progress

Problem

- Silica sand used to seal the graphite exfoliation furnace is a potential source of contamination.
- Silica is nearly indistinguishable from naturally-occurring quartz present in graphite.

Natural Graphite
Impurities



Silica
Sand



Solution

- Replace silica with zirconia, which has higher density and is easily identifiable (e.g., by Raman microscope).
- Zirconia is an effective sealing material which does not contaminate the graphite product.

Zirconia
Sand



**No zirconia was found
in flexible graphite.**

- Ash collects in long, horizontal ductwork sections and is challenging to clean out.

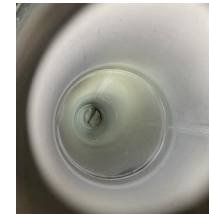


Graphite/ash residue
in old ductwork



- New steep ductwork and ash catch-box were installed.
- Ash does not build up in new ductwork.

New
ductwork



**No residue collects
in new ductwork.**

Task 4: BPAs from Improved Flexible Graphite

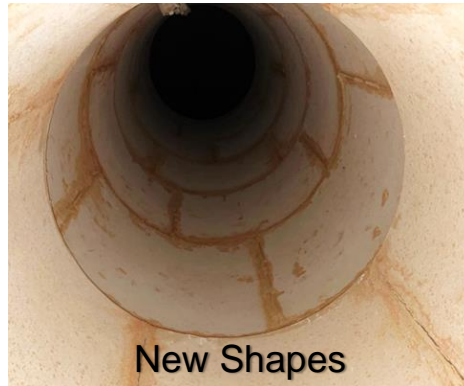
- Flexible graphite was produced after implementing the process improvements.
- The 'baseline' graphite flake used was relatively clean, with only 30 ppm of ash particles >200 μm .
- Ballard produced BPAs and conducted leak testing and analysis.
- Preliminary result: 256 leak-tight BPAs were produced, five BPAs failed leak testing due to possible or confirmed inclusions.
- Next steps: Additional BPAs are being produced and tested to increase the confidence in these results.

	Graphite Flake Feedstock	Flexible Graphite	Flexible Graphite BPAs
Key Metric:	Ash particles >200 μm (ppm)	Ash particles >200 μm (ppm)	Leak failure rate due to inclusions (%)
Baseline:	30-300	6-22	15
Target:	< 20	< 2	< 5
Task 4 Result:	30	1.8	1.9 (preliminary)

Satisfies Go/No-Go milestone (<5% leak failure rate due to inclusions). To be verified.

Task 5: Improved Exfoliation Furnace Refractory

- Problem:
 - Conventional refractory bricks have poor abrasion resistance. Abraded particulate may contaminate the graphite product stream and cause leaks in the BPAs.
- Progress:
 - Graphite exfoliation furnace was rebuilt with high strength, abrasion resistant refractory shapes.
 - Precast shapes have fewer mortar joints, which are prone to erosion, compared to bricks.



- Next Steps:
 - Complete production trials with new furnace and compare results to old bricks.
 - If product has reduced amount of ash particles $>200 \mu\text{m}$, it will be sent to Ballard for BPA production and testing.

Comment	Response
Supply chain evaluation for new sources of feedstock material is potentially omitted. It would be helpful to know where the sources are located, whether the supply is limited, and whether there are any logistical or price issues.	NeoGraf buys graphite flake from around the world and always considers supply chain factors when selecting sources. Multiple materials from North American-based suppliers have been evaluated for this project.
The understanding of what particle inclusion can be tolerated is based solely on leak rates. The actual impacts on performance, efficiency, and degradation are missing.	Other impacts of inclusions are part of a large historical dataset that Ballard has accumulated over decades. In this project, the focus is the beginning of life yield, which has been identified as a key factor in making thin graphite plates more feasible.
The project could use more work on understanding where some of the metrics originate and whether those metrics are appropriate.	The key metrics have been refined based on project learnings and are included in this presentation.
There should be more collaboration with national labs to better characterize the nature and origin of impurities.	LANL (through M2FCT) initially characterized impurities for the project. We now rely on in-house analytical equipment at NeoGraf and Ballard, as well as third-party laboratories.
Lack of coordination with M2FCT is a weakness.	Julian Norley represented our team at the M2FCT meeting in Aug. 2023 and participated in a bipolar plate roundtable. M2FCT will have a more significant role in Budget Period 2.

Collaboration and Coordination

Partner	Type	Project Role	Specific Contributions to Date
NeoGraf Solutions, LLC	Industry, Prime	Lead the development and manufacturing of next-generation flexible graphite.	Managed project progress and deliverables. Conducted graphite developmental work in Tasks 1, 2, 4, and 5.
Ballard Power Systems	Industry, Sub	Lead BPA and short stack production, as well as leak failure rate and performance evaluations.	Completed production of BPAs from baseline materials and evaluation of leak failure rate due to inclusions. Evaluated Task 4 materials.
Strategic Analysis, Inc.	Industry, Sub	Conduct manufacturing cost analysis of the proposed BPA concept.	Completed Task 3, the preliminary cost and manufacturability analysis.
Norley Carbon & Graphite Consultants, LLC	Industry, Sub	Provide technical guidance to NeoGraf Solutions for their development tasks.	Advised on all work to date. Represented the project at the M2FCT meeting in Aug. 2023 and participated in a bipolar plate roundtable.
Million Mile Fuel Cell Truck (M2FCT) Consortium	National Laboratory	Test and utilize appropriate accelerated stress tests, use system-modeling efforts to assess the proposed technology's impact on heavy-duty fuel cell cost and performance.	M2FCT technical efforts will begin in Budget Period 2.

Remaining Challenges and Barriers

- It is very likely that the Go/No-Go decision point will be met by demonstrating <5% BPA leak failure rate due to inclusions, but additional testing is needed to increase confidence in the results.
- Additional work is needed to secure a consistent, production-scale source of graphite flake with less than 20 ppm of ash particles >200 µm.
- Later, challenges may arise while integrating the new graphite flake feedstocks, optimized graphite exfoliation process, and improved furnace design.

	Graphite Flake Feedstock	→ Flexible Graphite	→ Flexible Graphite BPAs
Key Metric:	Ash particles >200 µm (ppm)	Ash particles >200 µm (ppm)	Leak failure rate due to inclusions (%)
Baseline:	30-300	6-22	15
Target:	< 20	< 2	< 5
Task 4 Result:	30	1.8	1.9 (preliminary)

Satisfies Go/No-Go milestone (<5% leak failure rate due to inclusions). To be verified.

Proposed Future Work

- FY 2024 Remainder

- Make and test additional BPAs using flexible graphite from Task 4 to validate the promising results.
- Produce flexible graphite from alternative graphite flake sources (Task 2).
- Complete trials using the improved graphite exfoliation furnace (Task 5).
- Form BPAs from flexible graphite made in Tasks 2 and 5 and analyze leak failure rates.
- Key Milestone: Go/No-Go Review
- Begin Budget Period 2:
 - Scale up the optimized flexible graphite manufacturing process.
 - Detailed manufacturing cost analysis.

- FY 2025

- Demonstrate full-scale flexible graphite production with new graphite flake feedstock, optimized graphite exfoliation process, and improved graphite exfoliation furnace.
- Form final BPAs using optimized flexible graphite and evaluate leak failure rate.
- Begin short stack evaluations.

Any proposed future work is subject to change based on funding levels.

Summary

- Previously, the preliminary cost analysis by Strategic Analysis found that the thin BPAs developed in this project can meet the DOE's BPA cost target of $\leq \$5/\text{kW}$ for heavy-duty applications.
- Progress was made in identifying high-purity graphite flake feedstocks and eliminating potential sources of process contaminations.
- It is very likely that the Go/No-Go decision point will be met by demonstrating $<5\%$ BPA leak failure rate due to inclusions.
- Additional work is needed to secure a consistent, production-scale source of graphite flake with less than 20 ppm of ash particles $>200 \mu\text{m}$.
- Expected outcome: Advance the state-of-the-art for flexible graphite BPAs towards meeting the performance, durability, and cost targets set by the DOE.