NEOGRAF™ 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 ≤$5/kW for next-generation heavy-duty fuel cell applications.
- Graphite costs will be reduced through the 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.
- Higher volumetric cell and stack power densities will also result from the thinner BPA design.
- This will be a critical advancement in BPA technology and substantial progress towards meeting 2030 system level heavy-duty truck targets of $80/kW system cost and 25,000-hour durability.

NeoGraf Solutions in Lakewood, Ohio

Flexible Graphite

Overview

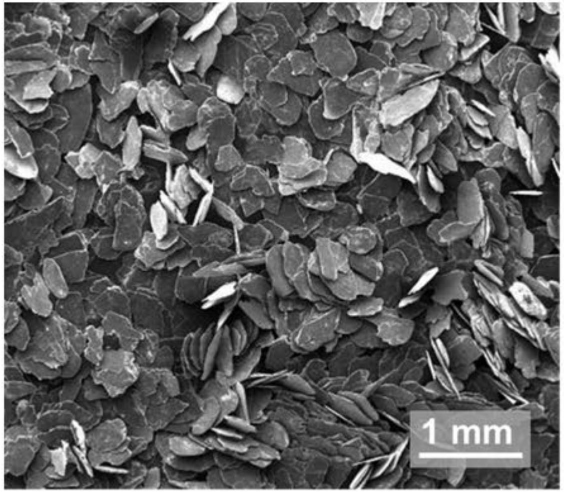
- **Timeline and Budget**
  - Project Start Date: May 1, 2022
  - Project End Date: May 31, 2025
  - Total Project Budget: $2,053,946
    - DOE Share: $1,643,157
    - Cost Share: $410,789
    - DOE Funds Spent*: $131,839
    - Cost Share Funds Spent*: $32,960

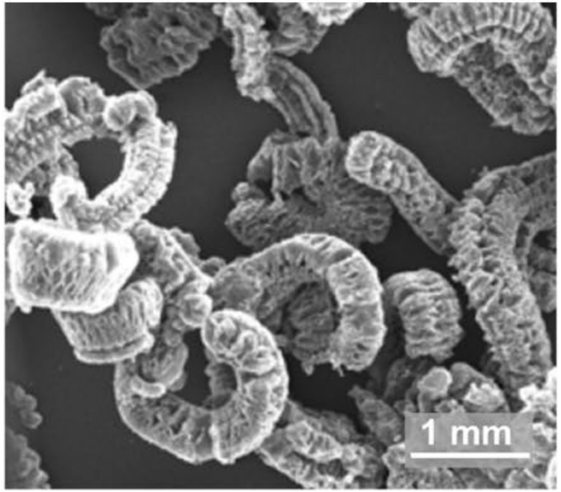
  * As of 4/14/23

- **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 ash inclusions.
  - Key Target: Reduce concentration of ash inclusions to achieve BPA leak rate of <5%.

Background – Flexible Graphite Production

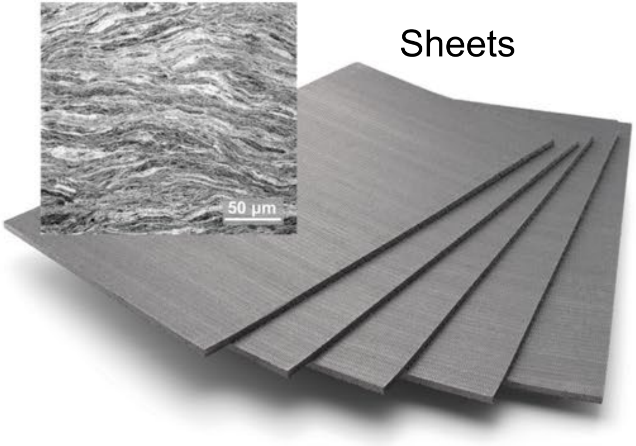
Natural Graphite Flake → Exfoliated Graphite ‘Worms’ → Flexible Graphite





Cross-section

Sheets

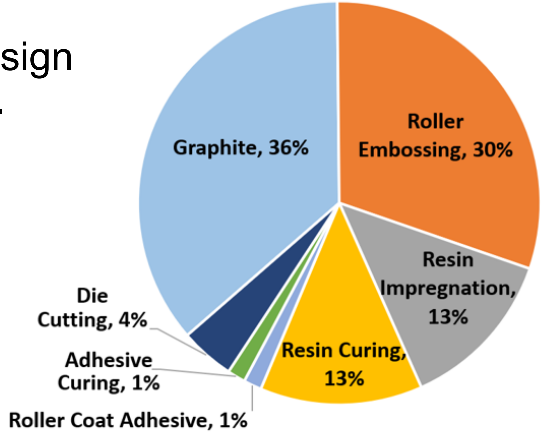


Natural graphite flake is treated with a combination of chemicals, exfoliated in a high temperature furnace to produce vermicular expanded graphite or “worms”, and densified to produce flexible graphite sheet.

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 ≤$5/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.

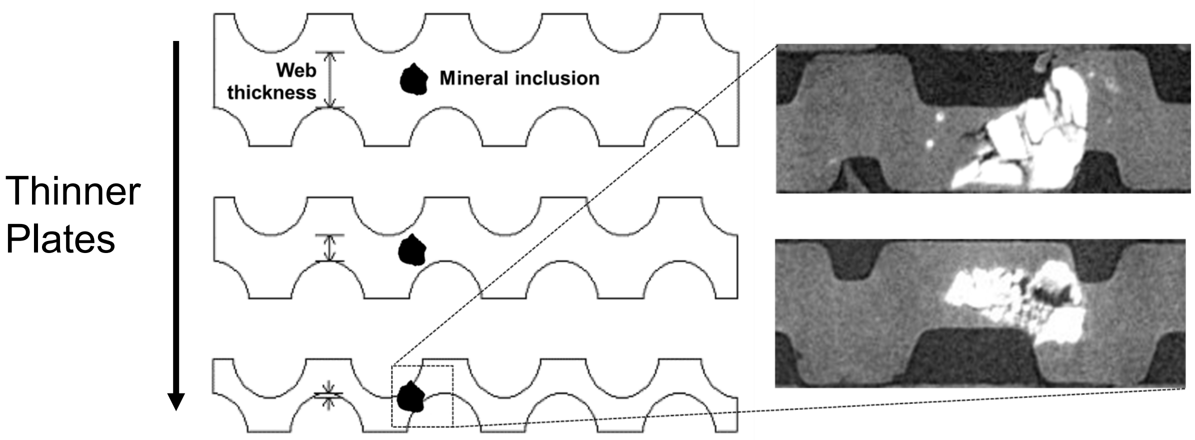


Breakdown of costs for flexible graphite BPAs at 500,000 systems per year.[1]

[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’ impurities) in the graphite, as inclusions may cause pinhole defects and leaks in the finished BPAs. As BPA thickness decreases, leakage failure due to inclusions becomes 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 content of leak-inducing impurities.

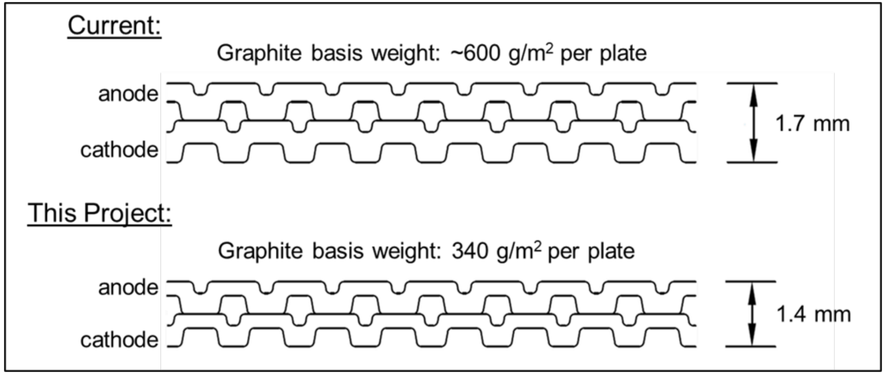


Need to reduce:
- Ash content
- Ash particle size

Two sources of ash:
- Natural impurities
- Process contaminations

Approach

- Technical Approach:
  - Develop technologies to eliminate leak-causing inclusions in flexible graphite introduced from two main sources, raw material impurities and process contaminations.
  - Evaluate impact of flexible graphite advancements on BPA leak failure rates.
- Key Objectives:
  - Reduce BPA thickness from approximately 1.7 mm to 1.4 mm while decreasing the graphite basis weight from the current state of ~600 g/m^2 to 340 g/m^2.
  - Eliminate impurities in the graphite BPAs to achieve a leak failure rate due to inclusions of <5% in thin plates.
  - Demonstrate BPA performance through short stack testing at heavy duty conditions and accelerated materials testing.
  - Provide detailed and transparent cost estimates of the BPA concept through a manufacturing cost analysis.



Approach – Tasks and Final Goals

Budget Period 1

Task 1 - Baseline Thin Plate Production and Evaluation

Task 2 - Alternative Graphite Feedstocks

Task 4 - Graphite Process Improvements

Task 5 - Pilot-Scale Clean Exfoliation Furnace

Task 3 - Preliminary Cost and Manufacturability Analysis

Go/No-Go: Demonstrate <5% BPA leak rate due to inclusions.

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 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 – Milestones (1/2)

Milestone #	Description	Completion Month*	Status
1	Produce thin, low basis weight flexible graphite sheets	M1	Complete
2	Produce continuous roll of flexible graphite at low basis weight	M1	Complete
3	Complete baseline leak rate dataset for BPAs produced from low basis weight graphite material	M9	Complete
4	Identify two or more alternative graphite feedstock candidates	M8	Complete
5	Produce flexible graphite from alternative feedstock materials	M15	In progress
6	Complete leak rate dataset for BPAs produced using flexible graphite from alternative feedstock materials	M18	Not started
7	Complete preliminary DFMA® BPA cost analysis and report on findings	M7	Complete
8	Report on impact of expansion furnace conditions on the degree of ash carryover	M10	Complete
9	Implement a new ash separation process and report on its efficacy to reduce the ash content in flexible graphite	M12	In progress
10	Select, deploy, and evaluate a new furnace sealing material	M12	In progress

*** Planned month of completion is shown for future milestones.**

Approach – Milestones (2/2)

Milestone #	Description	Completion Month*	Status
11	Complete BPA leak rate dataset for material produced in process optimization studies	M15	Not started
12	Deliver the design for a clean pilot scale expansion furnace	M12	In progress
13	Complete BPA leak rate dataset for material produced using pilot scale clean furnace	M18	Not started
14	Go/No-Go: Produce thin, low basis weight BPAs with leak failure rate due to inclusions of <5%.	M18	In Progress
15	Deliver the final design for a clean, full manufacturing scale expansion furnace	M21	-
16	Demonstrate full manufacturing scale flexible graphite production with improved process and materials	M24	-
17	Deliver flexible graphite for final BPA and short stack evaluation	M26	-
18	Complete detailed DFMA® BPA cost analysis and report on findings	M35	-
19	Complete leak rate dataset for final BPA production run	M20	-
20	Report performance of final BPAs in a short stack	M35	-
21	Complete ex-situ accelerated durability testing of BPAs	M35	-

*** Planned month of completion is shown for future milestones.**

Accomplishments and Progress – Task 1: Baseline Evaluations

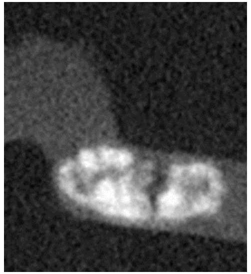
- Produced low basis weight (300-340 g/m^2) flexible graphite, first in sheet form then in continuous roll form. Milestones #1 and #2 complete.
- Evaluated baseline ash content, ash particle size distribution, and ash elemental composition of graphite rolls. Complete. Typical results:
  - Total ash content: 0.050 – 0.060 wt%
  - Ash content >200 µm: 6 – 22 ppm
  - Major elements: Fe, Si, Al, Ca, Mg, and O
- Ballard: Produced 683 leak-tight BPAs. Baseline leak failure rate due to inclusions was ~17%. Milestone #3 complete.

Flexible Graphite Sheets

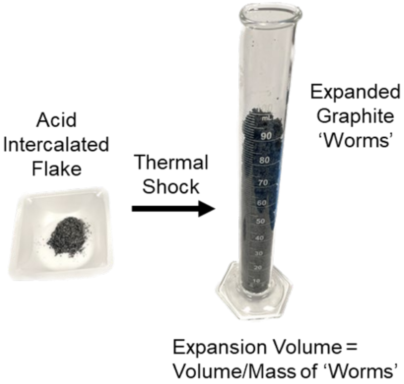
Flexible Graphite Roll

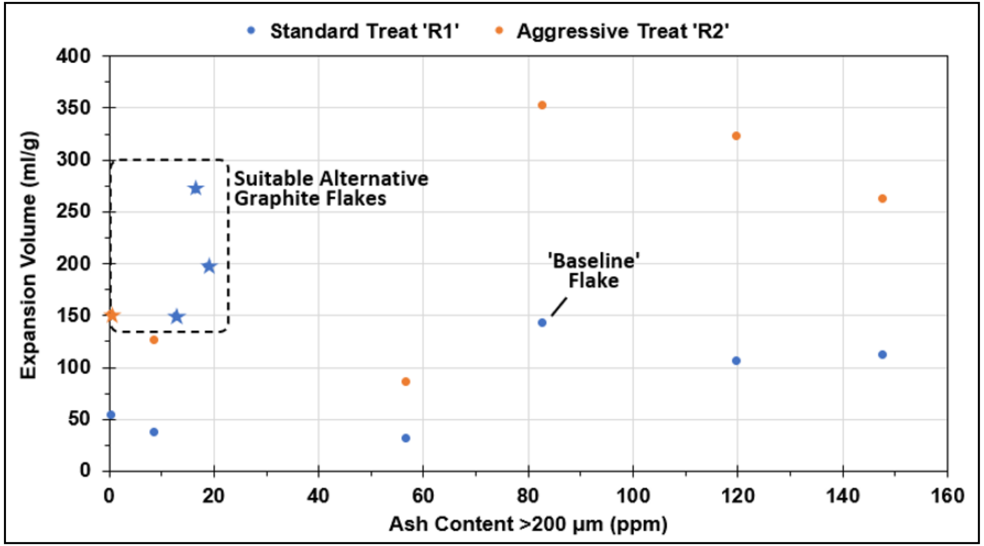
Suitable feedstock for continuous roll-to-roll embossing for high-throughput BPA formation

XCT Image of a leak-causing ash inclusion



Accomplishments and Progress – Task 2: Alternative Feedstocks





- Four suitable alternative graphite flake feedstocks were identified, having both notably lower content of ash particles >200 µm compared to the baseline flake, and sufficient expansion volume. Milestone #4 complete.
- Production-scale quantities of candidate flakes were ordered and will be made into flexible graphite and BPAs in later subtasks.

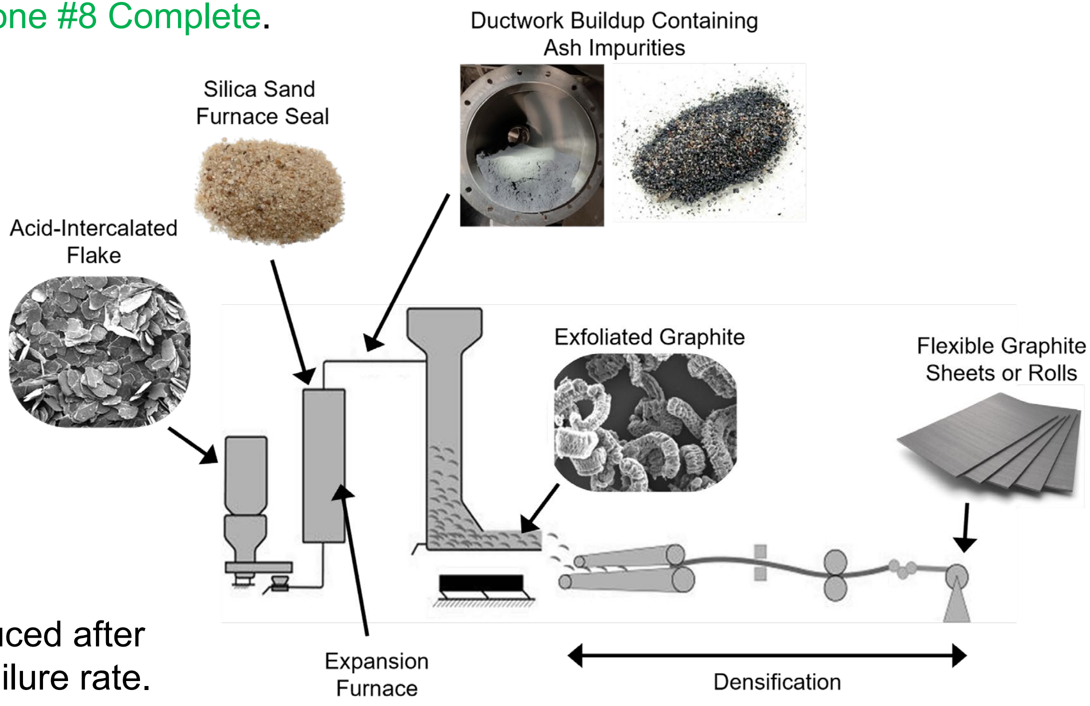
Accomplishments and Progress – Task 4: Process Improvements

4.1. Study the impact of furnace temperature on the degree of ash carryover in the product stream. Milestone #8 Complete.

4.2. Evaluate new separation processes to remove ash more effectively from the expanded graphite. **Progress**: Fabrication of improved ductwork designed to remove ash is underway.

4.3. Explore alternative furnace sealing materials to replace the current material (silica sand), which is a potential source of contamination. **Progress:** Plant trials using a more traceable sealing material, zirconia sand, are in progress.

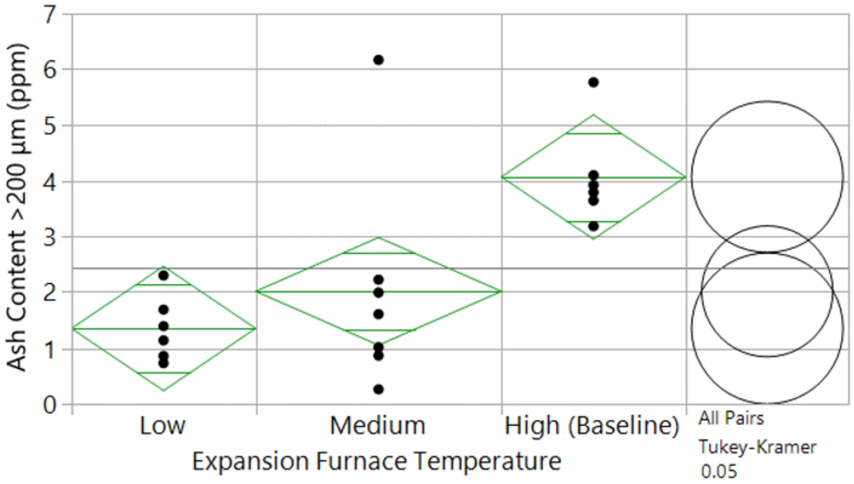
4.4. Form BPAs from flexible graphite produced after process improvements and evaluate leak failure rate.



Accomplishments and Progress – Task 4: Process Improvements

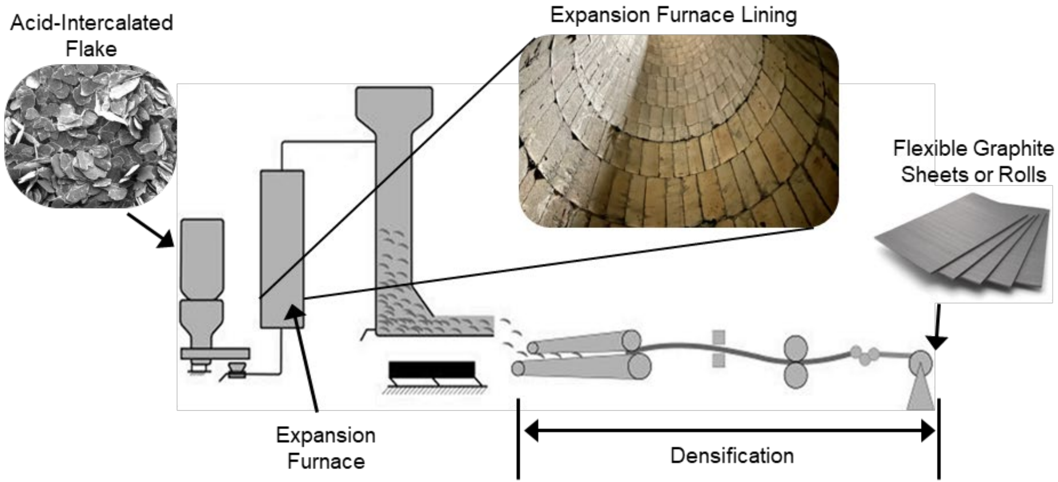
Outcome of Subtask 4.1 (Milestone #8): Potential impact of furnace temperature on the degree of ash carryover in the product stream.

- Little or no impact on total ash content.
- The ash content >200 µm was significantly reduced at low and medium furnace temperatures compared to baseline operation at high temperature.
- Low/medium temperature operation will be further investigated in later tasks to verify these promising results.



Accomplishments and Progress – Task 5: Clean Furnace Design

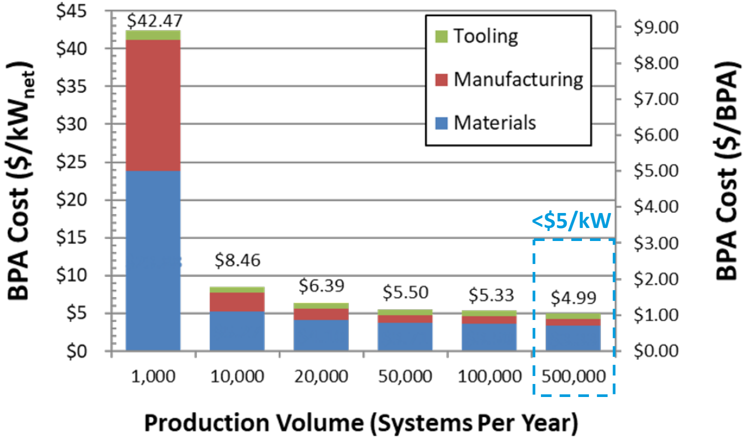
- **Challenge**: Common refractory bricks used in the expansion furnace lining are rich in alumina and silica and have poor abrasion resistance. Abraded particulate may contaminate the graphite product stream and cause leaks in the BPAs.
- A cleaner pilot-scale furnace designed around a quartz glass tube was originally proposed; however, lead times for suitable quartz glass tubes were found to be prohibitively long (i.e., 34-36 weeks).



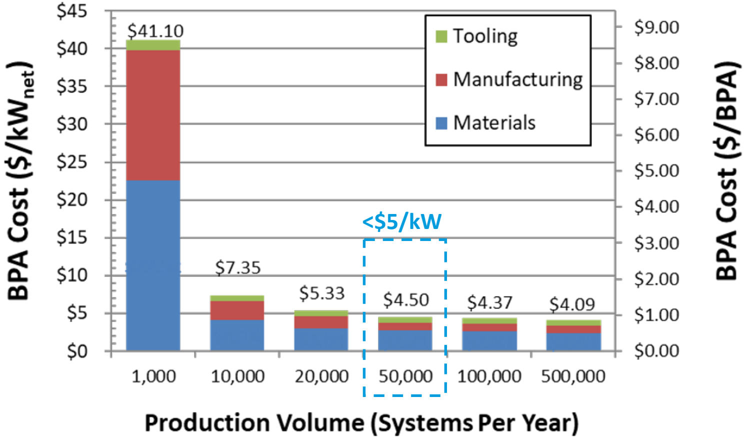
Progress:
- Identified three alternative refractory materials with enhanced strength and abrasion resistance compared to existing materials, as well as compatibility with the furnace environment.
- Refractory designs and pricing are being procured and reviewed before one material is selected.

Accomplishments and Progress – Task 3: Prelim. Cost Analysis

600 g/m² with 40% by mass resin content (Baseline Plate)



340 g/m² with 45% by mass resin content (Reduced Thickness Plate)



- Preliminary DFMA® cost analysis was conducted by Strategic Analysis, Inc. Milestone #7 Complete.
- Analysis shows the DOE cost target of <$5/kW is achievable at much lower production volumes for the reduced thickness BPAs compared to the baseline plate design.
- Modeling shows ~$1/kW BPA material cost reductions due to plate thickness and areal density reductions.

Response to Reviewer Comments

- This project was not reviewed last year.

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 Subtasks 1.1-1.3, 2.1, 4.1-4.3, and 5.1.
Ballard Power Systems	Industry, Sub	Lead BPA and short stack production, as well as leak failure rate and performance evaluations.	Completed Subtask 1.4, the formation of BPAs from baseline materials and evaluation of leakage rate due to inclusions.
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 completed work to date.
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 efforts will begin in Budget Period 2.

Remaining Challenges and Barriers

- The main technical challenge remaining is to reduce the BPA leak rate due to inclusions from the baseline of ~17% to less than 5% for the Go/No-Go decision point. Three specific developmental tasks are in progress to address this challenge.
  - Task 2: Find alternative graphite feedstocks with lower content of large ash particles.
  - Task 4: Implement graphite process improvements to reduce ash content in flexible graphite.
  - Task 5: Design a clean graphite expansion furnace to reduce potential contamination.
- Logistic challenges
  - Material lead times are longer than were anticipated during the initial project proposal.
  - NeoGraf is working with its network of local and global suppliers to keep on schedule; nonetheless, a no-cost time extension may be needed.

Proposed Future Work – FY 2023 Remainder

- Tasks include continuing to test alternative graphite flake feedstocks, optimize the graphite expansion process and material handling equipment to reduce ash/impurities, and develop a new graphite exfoliation process featuring clean furnace lining materials. BPAs will be formed using flexible graphite produced in these tasks and leak tested.
- Key milestones:
  - Produce flexible graphite from at least two alternative flake feedstocks.
  - Implement a new ash separation process and report on its efficacy.
  - Deploy a new furnace sealing material and evaluate the degree of contamination into the graphite product.
  - Produce BPAs from flexible graphite material with reduced content of ash particles larger than 200 μm and complete leak rate datasets.
  - Design, construct, and utilize a clean pilot scale expansion furnace.

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

Proposed Future Work – FY 2024

- The final month of Budget Period 1 falls in FY2024. This will mark the conclusion of Tasks 2 and 5 as well as the Go/No-Go decision point.
- Key milestones:
  - Complete leak rate datasets for BPAs produced from alternative graphite flake sources (Task 2) and using the cleaner graphite expansion process (Task 5).
  - Go/No-Go – Demonstrate <5% leak rate due to inclusions in thin, low basis weight BPAs.
  - Demonstrate full manufacturing scale flexible graphite production with optimized graphite flake feedstock, graphite expansion process conditions, and furnace design.
  - Form final BPAs using optimized flexible graphite and evaluate leak failure rate.
  - Complete detailed BPA manufacturing cost analysis and report on findings.

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

Summary

- Thin BPAs were produced from low basis weight flexible graphite and the baseline leak rate due to inclusions was determined to be ~17%.
- A multipronged approach is underway to reduce BPA leak rate due to inclusions to less than 5% for the Go/No-Go decision point.
  - Use alternative graphite feedstocks with lower content of large ash particles.
  - Implement graphite process improvements to reduce ash content in flexible graphite.
  - Design a clean graphite expansion furnace to reduce potential contamination.
- Preliminary cost analysis shows the DOE cost target of <$5/kW is achievable at much lower production volumes (~50,000 systems per year) for the reduced thickness BPAs compared to the baseline plate design (~500,000 systems per year).
- The expected outcome is to advance the state-of-the-art for flexible graphite BPAs towards meeting the performance, durability, and cost targets set by the DOE.