CLEAN RESOURCES FINAL REPORT PACKAGE

Project proponents are required to submit a Final Report Package, consisting of a Final Public Report and a Final Financial Report. These reports are to be provided under separate cover at the conclusion of projects for review and approval by Alberta Innovates (AI) Clean Resources Division. Proponents will use the two templates that follow to report key results and outcomes achieved during the project and financial details. The information requested in the templates should be considered the minimum necessary to meet AI reporting requirements; proponents are highly encouraged to include other information that may provide additional value, including more detailed appendices. Proponents must work with the AI Project Advisor during preparation of the Final Report Package to ensure submissions are of the highest possible quality and thus reduce the time and effort necessary to address issues that may emerge through the review and approval process.

Final Public Report

The Final Public Report shall outline what the project achieved and provide conclusions and recommendations for further research inquiry or technology development, together with an overview of the performance of the project in terms of process, output, outcomes and impact measures. The report must delineate all project knowledge and/or technology developed and must be in sufficient detail to permit readers to use or adapt the results for research and analysis purposes and to understand how conclusions were arrived at. It is incumbent upon the proponent to ensure that the Final Public Report **is free of any confidential information or intellectual property requiring protection**. The Final Public Report will be released by Alberta Innovates after the confidentiality period has expired as described in the Investment Agreement.

Final Financial Report

The Final Financial Report shall provide complete and accurate accounting of all project expenditures and contributions over the life of the project pertaining to Alberta Innovates, the proponent, and any project partners. The Final Financial Report will not be publicly released.

CLEAN RESOURCES FINAL PUBLIC REPORT TEMPLATE

1. PROJECT INFORMATION:

Project Title:	***Preparation and Characterization of Carbon Fibres from Alberta Bitumen Pitch***
Alberta Innovates Project Number:	G2020000152
Submission Date:	May18, 2022
Total Project Cost:	$486,435
Alberta Innovates Funding:	$65,000
AI Project Advisor:	Paolo Bomben

2. APPLICANT INFORMATION:

Applicant (Organization):	**Carbovate Development Corp.**
Address:	Sarnia- Lambton Research Park Bldg 1040, Suite 2300 1086 Modeland Road Sarnia, ON N7S 6L2
Applicant Representative Name:	Maike Luiken
Title:	Managing Director, R&D
Phone Number:	+ 1 519 381 2712
Email:	mluiken@carbovate.com

3. PROJECT PARTNERS

Please provide an acknowledgement statement for project partners, if appropriate.

RESPOND BELOW

Carbovate Development Corp. (Carbovate) wishes to acknowledge and thank the Bowman Centre for Sustainable Energy of Sarnia, ON, Toronto Zenith of Toronto, ON, Dr. Shahram Karimi and his team of Lambton College, Sarnia, ON, and Sharon Lackie of the Great Lakes Institute for Environmental Research at the University of Windsor, ON, and Surface to Surface Inc. of Petrolia, ON.

A. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

RESPOND BELOW

Project Description and Objective:

Pitch derived from thermally produced oil sands bitumen is more than an order of magnitude less costly than typical carbon fibre feedstocks, e.g., polyacrylonitrile (PAN). This cost difference provides an 'economic opportunity'.

This project aimed to investigate converting Alberta oil sands bitumen derived straight-run vacuum tower bottoms - residue - into a feedstock suitable for manufacturing general-purpose carbon fibre (GPCF). The focus was on determining whether and through which processes carbon fibre precursor material for GPCF manufacturing may be produced in a cost-effective manner from Alberta bitumen for high volume GPCF applications.

The intent was to create a new market for Alberta bitumen in the form of GPCF pre-cursor material and lower-cost, GPCF to be used for applications such as the automotive and concrete reinforcement industry sectors where the use of current carbon fibre is not feasible due to high cost. This opportunity may provide a path toward a new high tech, high value industry for Alberta.

The Key Goal of the Project:

Development of a thermal process to produce a precursor material suitable to manufacture GPCF from thermally processed Alberta bitumen.

Key Results & Learnings from the Project:

The project achieved partial success:

- *Green fibre was melt spun from developed pre-cursor material, and successfully oxidized. The fibres were found to be too brittle for further processing. Brittleness (Aldosari et al, 2020) [1] is a well-known challenge in the production of carbon fibres (CF).*
- *Modifications of the Carbovate treatment process will be required to produce precursor material that results in green fibre that is suitable for further processing into GPCF.*
- *Future process modification may include additional process steps, for example, filtering the pre-cursor material of any particles that may contribute to the brittleness.*

Benefits & Outcomes:

Successful further investigation and refinement of the Carbovate precursor process could potentially result in

- *Commercialization of new, Alberta bitumen-based, value-added products: GPCF precursor material and lower-cost GPCF.*
- *Development of a pathway for a new Alberta high-tech industry sector: cost-effectively manufacturing of GPCF precursors and GPCF. High-volume low-cost GPCF manufactured in Alberta could lead to a new Alberta industry sector with bitumen serving as the raw material.*
- *Opening of new markets for Alberta bitumen: production of GPCF precursor and carbon GPCF from Alberta bitumen would open new markets for that resource resulting in advanced materials including GPCF composites and offering high paying jobs.*

Please provide a narrative introducing the project using the following sub-headings.

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

RESPOND BELOW

[1] Aldosari, S. M., Khan, M. A. & Rahatekar S. S. (2020). Manufacturing carbon fibres from pitch and polyethylene blend precursors: a review. *Journal of Materials Research and Technology*}, 9 – 4, 7786-7806. https://doi.org/10.1016/j.jmrt.2020.05.037

Sector Introduction:

Carbon fibres are being used in many applications today with a trend for increasing demand – for high quality CF - for years to come. These include, but not limited to, green energy conversion and storage, aviation, automotive, sporting goods and computer components. New areas such as energy storage (battery technology requiring CF), additive manufacturing and replacing steel in concrete structures are accelerating the trend for increasing demand for CF. The global carbon fibre market size was valued at 2.25 billion USD in 2015 [2]and is projected to grow by more than 10.9% annually from 2017 to 2025 – for 'traditional applications' of CF. Currently, carbon fibres are most commonly produced from textiles such as polyacrylonitrile (PAN) fibres. PAN and other textiles are expensive and are a major contributor to high CF prices. This high feedstock cost inhibits broader and more extensive CF adoption into a variety of industries, applications, and sectors. Additionally, PAN as a CF precursor carries a very high carbon burden relative to thermally processed feed distilled from bitumen.

The CF market segment is being targeted because the potential to grow into a large 'mass' market for GPCF is high. Applications include reinforcement of concrete (replacement of steel reinforcement), reinforcing forestry manufactured wood products, and enhancement of concrete[3] (and potentially road asphalt) for longevity, and in green energy conversion and storage. These applications have been proven but conventionally produced CF are currently too costly for the mass market. A significant cost reduction is needed to increase the attractiveness of CF for these applications.

An example of a potentially very high volume low-cost GPCF application is the addition of GPCF to cement. Doing so would reduce the amount of cement required for high-volume structures and prolong the structures life span (no corrosion of re-enforcements). This could significantly lower the energy requirements as well as GHG emissions associated with the production, maintenance and replacement cost of concrete based infrastructures reinforced with GPCF.

Carbon fibre derived from bitumen could significantly reduce the costs because of the lower feedstock price compared to incumbent materials. Furthermore, the 2018 Bitumen Beyond Combustion (BBC) Phase 2 Report[4] prepared for Alberta Innovates by Stantec Consulting Ltd. states in its Summary Section (page vi) that:

> "CF markets globally are growing at a compound annual growth rate (CAGR) in excess of 10%, although from a small production base of less than 100,000 tons per annum (tpa), this is expected to grow to 250,000 tpa by 2030. Current high feedstock and manufacturing costs are limiting this growth.
>
> …
>
> CF production can be broken out into three main areas – precursor feedstock, fiber spinning and carbonization, and end-product manufacturing.

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[2] Grand View Research, August 2917, Market Research Report: Carbon Fiber Market Analysis By Raw Material (PAN, Pitch), By Tow Size, By Application (Automotive, Aerospace & Defense, Wind Turbines, Sport Equipment, Construction, Pressure Vessels), And Segment Forecasts, 2018 – 2025, May 7, 2022 <https://www.grandviewresearch.com/industry-analysis/carbon-fiber-market-analysis>

[3]Chung, D. D. L. Carbon Fiber Reinforced Concrete. Strategic Highway Research Program, 1992. CARBON FIBER REINFORCED CONCRETE (trb.org)

[4] Stantec Consulting Ltd., February 2018, Bitumen Beyond Combustion – Phase 2 Report, Stantec-Bitumen-Beyond-Combustion-Phase-2-Report.pdf (albertainnovates.ca), May 7, 2022

Considering the growth potential and relative early stage of development of the CF industry, there is a tremendous opportunity to work towards oil sands-based feedstocks becoming a major component in the evolving CF industry in the future. Additional aspects of CF production, such as spinning and end product manufacturing, could also present a major economic benefit for Alberta and Canada.*"*

And the latest Alberta Innovates Bitumen Beyond Combustion report, 2021[5], indicates that using the heavy fractions of bitumen for carbon fibre production raises the value of the bitumen barrel by an estimated $179. Since the value of the of the light fraction also becomes more valuable the total value per bitumen barrel increases from an estimated $30 to $213.

Knowledge and Technology Gaps:

CF is classified into three main categories: low, medium and high-performance materials or, alternatively, standard, intermediate, high and ultra-high modulus CF. Not all applications require high performance CF.

Carbovate is focused on producing a low-cost, low to medium performance, also referred to as general-purpose CF (GPCF).

CF production from PAN and other materials is well-known whereas CF production from Bitumen is developmental.

The CF production process involves the following high-level steps:

- *Precursor production starting with Alberta bitumen derived vacuum distillation residue*
- *Processing the precursor material into green fibres/filaments; that is, depending on the precursor material, melt-spinning, extruding or electro-spinning*
- *Stabilization of the green fibres through oxidation*
- *Carbonization*
- *Surface treatment of the resulting carbon fibres to achieve specific properties*

The critical knowledge gap investigated in this project is the process of how to prepare a suitable precursor for GPCF production from the thermally produced Alberta bitumen feedstock. The precursor properties, in particular the suitability of the precursor for successful melt-spinning and subsequent oxidation and carbonization of the spun filaments, are critical for the production of carbon fibre. Good carbon fibre cannot be made from a poor precursor material.

[5] Zhou, J., Bomben, P., Gray, M. & Helfenbaum, B. (2021). Bitumen Beyond Combustion. White Paper. *Alberta Innovates*, https://albertainnovates.ca/app/uploads/2022/04/AI-BBC-WHITE-PAPER_2022_WEB.pdf

B. PROJECT DESCRIPTION

Please provide a narrative describing the project using the following sub-headings.

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

RESPOND BELOW

Knowledge or Technology Description including Objectives:

The focus of this project was to develop technology and methods to produce a suitable precursor for manufacturing low-cost, GPCF. This GPCF precursor would be prepared from Alberta thermally produced oil sands bitumen, specifically, the bottoms product that is the residue from vacuum distillation of bitumen.

In summary, the objective was: development of a low-cost thermal process to produce a precursor material suitable to manufacture GPCF from thermally produced Alberta bitumen. If successful:

- *Determine the properties and performance characteristics of the treated pitch filaments and any derived GPCF.*
- *Establish whether the GPCF meet the performance requirements for GPCF – low to medium performance carbon fibre.*
- *Assess whether the processes identified to produce the GPCF precursor material are expected to lead to cost-effective production on a large scale.*

Updates to Project Objectives:

The original project objectives remain unchanged.

Performance Metrics:

The following project success metrics were set up at the outset of the project:

	Project Success Metrics		
C	**Metric**	**Project Target**	**Commercialization / Implementation Target**
1	*Outside Financing for Pilot or Demonstration Testing*		*$5 million - $10 million*
2	*CF produced by this project meets Commercial industry requirements*	*Produced CF has meets at least Standard or Intermediate Modulus. Project Tensile Strength: >= 2500 kPa; Modulus: >= 150 GPa*	
3	*New Product and Process*	*1 process - economical derivation of CF precursor and CF from Alberta Bitumen + 1 product - General Purpose Carbon Fibre*	
4	*Mesophase Content Analysis Achieved*	*mesophase analyses of multiple carbon fibre precursor material samples derived using different treatments*	
5	*Carbon Fibre produced*	*100 - 200 grams CF each from 6 to 8 trials*	
6	*Mapping of CF Properties to Material Treatments Achieved*	*determination of any correlation between CF pre-cursor treatment and CF properties*	
7	*Process Specifications*	*a cost-effective process to derive general purpose carbon fibre from SR-pitch from Alberta bitumen – established through bench-scale research and development*	
8	*Softening Point Achieved*	*220 °C*	*250-270 °C*
9	*Precursor Formulations Tested*	*6*	*15*
10	*Fate of Heteroatoms*	*Understanding/tracking heteroatoms through process*	*Reduction in content of heteroatoms to maximize performance*

Discussion:

The project success metrics were set up around measuring the specific project outcomes, such as raising the softening point of the residue through thermal treatment to a level that would permit spinning the produced pitch into green fibres and the expected number of precursor formulations to be investigated.

C. METHODOLOGY

Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.

RESPOND BELOW

The proposed process/technology was to de-oil the feedstock, Alberta Bitumen (Dilbit), through distillation followed by thermal treatment of the residue to produce pitch. The pitch would be a precursor for green fibres, which would be stabilized through oxidation and carbonization to produce GPCF.

These steps were followed during the Project:

- *Obtained Diluted SAGD Bitumen from two leases*
- *Deep vacuum distillation of feedstock to minimize vacuum gas oil content of residue. Each bitumen was distilled to temperatures where incipient thermal cracking was beginning to occur.*
- *Process residue to obtain pitch through thermal treatment of residue for 20 min to 24 hours in temperature ranges of 330 to 420 degrees C*
- *Testing of residue*
    - i. *Relative softening point determination*
- *Characterization of pitch samples*
    - i. *Penetration testing*
    - ii. *Quasi-softening point determination*
    - iii. *Qualitative assessment of fibre brittleness*
    - iv. *Raman Spectroscopy,*
    - v. *Optical microscopy*
    - vi. *Differential Scanning Calorimetry (DSC)*
    - vii. *ThermoGravimetric Analysis (TGA)*
    - viii. *Fourier Transform Infrared (FTIR)*
- *Melt spinning of pitch to produce green fibres under nitrogen*
    - i. *Die sizes, spinning temperatures and pressures were varied to obtain optimal filaments*
- *Oxidation of green fibres*
    - i. *Varied temperatures and residence times at different temperatures levels as well as oxygen concentration*

Facilities:

- *InnoTech, Edmonton, AB*
  Deep distillation of feedstock from two Alberta leases

- *Surface to Surface Inc., Petrolia, ON*
  Provided space and support for experimental set-up for thermal treatment of residue. Surface to Surface was open as an essential industry while local research institutions were not available due to COVID restrictions.

- *Lambton College, Nano-Electrochemistry Group, Sarnia, ON*
  Melt-spinning, penetration testing, softening point testing, optical microscopy, Raman spectroscopy, oxidation of green fibres, thermogravimetric analysis

- *University of Windsor – Great Lakes Institute for Environmental Research (GLIER), Windsor, ON*
  Analysis of the Raman spectra

D. PROJECT RESULTS

Please provide a narrative describing the key results using the project's milestones as sub-headings.

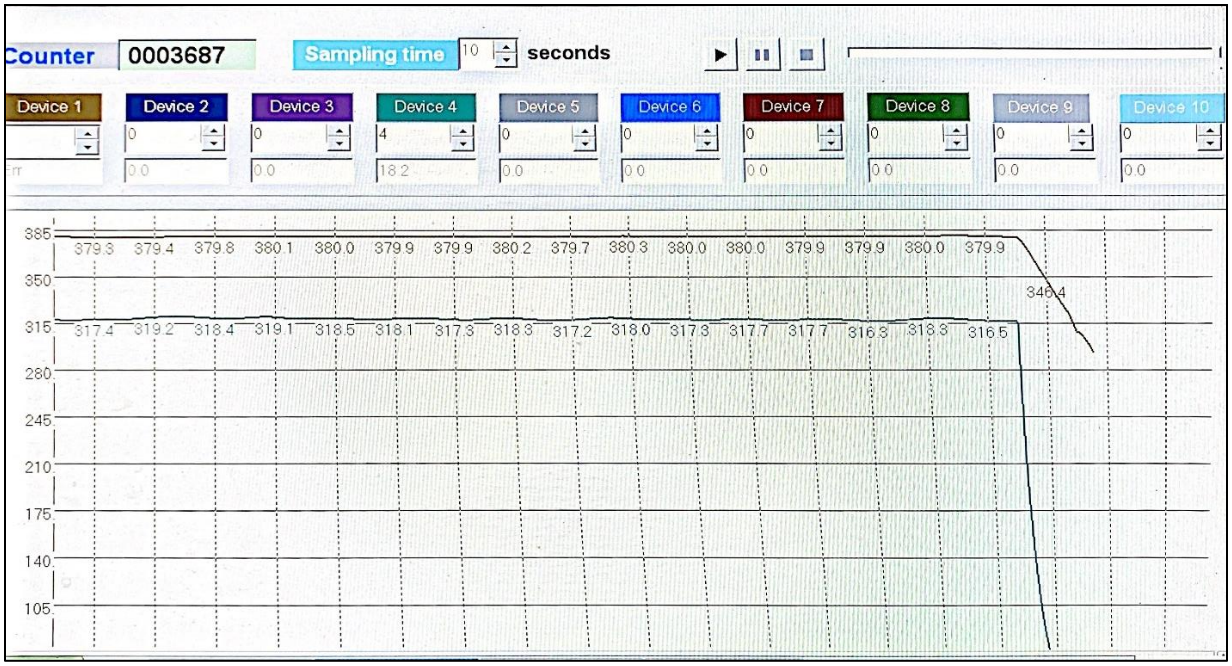
- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

RESPOND BELOW

Key Results:

The following results were obtained during the course of this project:

- *De-oiling of the feedstock – thermally produced Alberta bitumen was obtained by high temperature distillation of different bitumen samples accordingly to the methodology described above. Two separate batches of bitumen samples were obtained.*
- *Sixteen thermally treated samples were prepared from the two batches of distilled bitumen. Tight temperature control was achieved during the thermal treatment process, thus avoiding target temperature overshoots.*

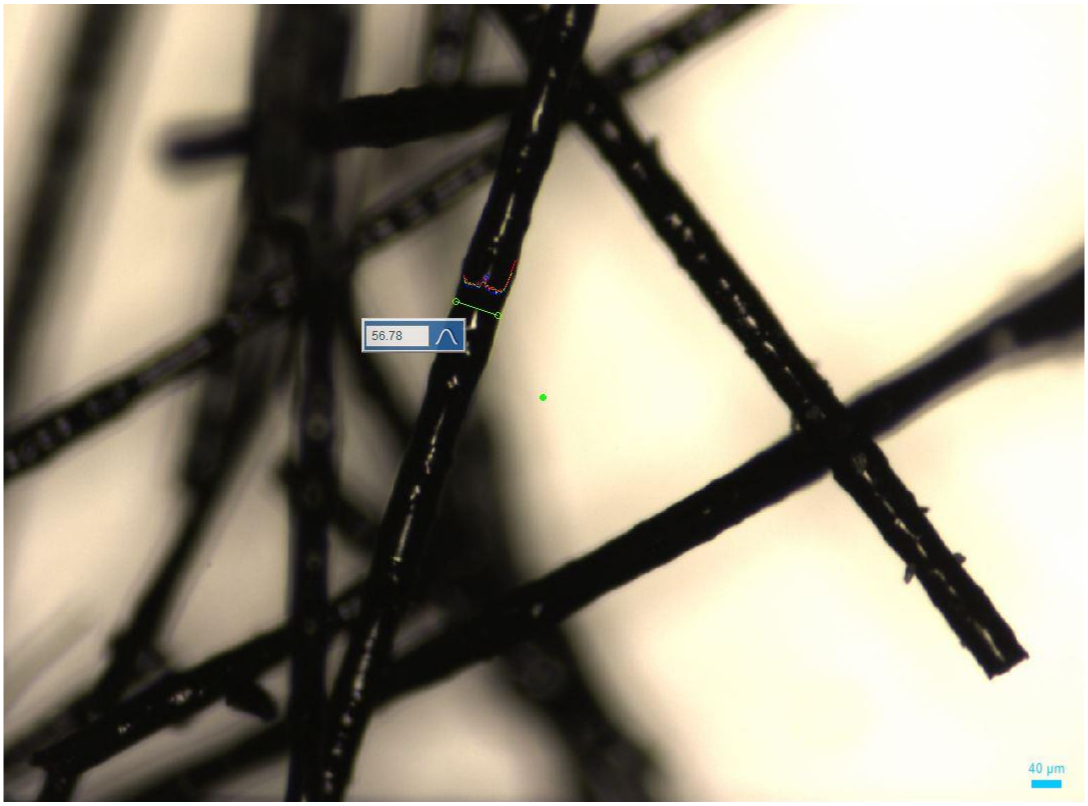


The image shows the internal reactor temperature (upper line) holding at 380^{0}C $\pm$ 0.7^{0}C until heater shut-off as well as the reactor wall temperature (lower line).

- *Softening point elevation was achieved to a sufficiently high level through the Carbovate thermal treatment process of the high temperature distillation derived residue to enable melt spinning and oxidation.*
- *The distilled bitumen residue softening points were found to be in the order of 50 – 60 degrees C. The thermal treatments at varying temperatures and residence times of the residue led to relative softening points of 200 degrees C and above and increase of over 150 degrees C bringing the softening point closer to the temperature range required for thermal oxidation of the fibre samples.*
- *Long strands of green fibre (1 meter plus) as output from the melt spinning process have been achieved (see image below). Numerous melt-spinning runs were carried out resulting in length of filaments varying from 10 cm to 1 m plus. However, the filaments are brittle.*

Green fibre output from the melt spinner – yielding filaments in excess of one meter long.

- *After spinning, oxidation of the filaments was carried out by varying the oxidation parameters with the result that the fibres can be oxidized but are too brittle to carbonize.*



Micrograph of one of the samples after oxidation. Filament diameter (micrometer) indicated.

- *Brittleness prevented further treatment beyond oxidation (i.e., carbonization).*
- *Additional treatment of the precursor or an entirely new treatment profile is required to reduce brittleness to allow for the carbonization process to proceed.*

Project Success Metrics Discussion:

C	Project Success Metrics Metric	Project Target	Commercialization / Implementation Target
1	*Outside Financing for Pilot or Demonstration Testing*		*$5 million - $10 million*
2	*CF produced by this project meets Commercial industry requirements*	*Produced CF has meets at least Standard or Intermediate Modulus. Project Tensile Strength: >= 2500 kPa; Modulus: >= 150 GPa*	
3	*New Product and Process*	*1 process - economical derivation of CF precursor and CF from SR Alberta Bitumen + 1 product - General Purpose Carbon Fibre*	
4	*Mesophase Content Analysis Achieved*	*mesophase analyses of multiple carbon fibre precursor material samples derived using different treatments*	
5	*Carbon Fibre produced*	*100 - 200 grams CF each from 6 to 8 trials*	
6	*Mapping of CF Properties to Material Treatments Achieved*	*determination of any correlation between CF pre-cursor treatment and CF properties*	
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8	*Softening Point Achieved*	*220 °C*	*250-270 °C*
9	*Precursor Formulations Tested*	*6*	*15*
10	*Fate of Heteroatoms*	*Understanding/tracking heteroatoms through process*	*Reduction in content of heteroatoms to maximize performance*

The proposed metrics were successfully achieved in part as detailed below. Whereas the produced precursor material is melt-spinnable and oxidizable, the spun green fibres exhibit a level of brittleness that prevents processing beyond oxidation into GPCF. Further work is required to refine the precursor production process such that it minimizes or avoids this brittleness in the resulting spun green fibres.

1. *n/a*
2. *CF production process is incomplete and inconclusive currently*
3. *Completion of the proposed new process requires further research*
4. *Mesophase content analysis is subject to further research*
5. *Green Fibres have been produced, GPCF production is still pending further research*

6. *Mapping of CF properties is subject to completion of successful GPCF production*
7. *Process specifications under development pending successful production of GPCF*
8. *Relative softening point elevation achieved to permit melt spinning and oxidation of the green fibres*
9. *Sixteen precursor formulations tested rather than six anticipated formulations*
10. *Due to the pandemic, the laboratory equipment required to determine the 'Fate of heteroatoms' was not available*

E. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

RESPOND BELOW

Key Learnings:

Heat treated residue derived from Alberta bitumen feedstock, pitch, and precursor samples with acceptable softening points were produced.

Green fibres (filaments) were successfully melt spun from this pitch. Some of the green fibres, those spun from pre-cursor formulations with the highest softening points, have been stabilized through oxidation.

A key challenge was to raise the softening point to a level that permitted melt-spinning and sub-sequent oxidation. Using sixteen different sets of parameters for thermal treatment of the bitumen residue, pitch was produced with varying softening points. These included softening points high enough to process the pitch into green fibres, 200 degrees C and above, and further oxidize the green fibres.

We discovered that although the pitch was spinnable into fibres longer than 1 meter, the green fibres were too brittle to process into GPCF. Parameters (e.g., feedstock, target temperature and residence time) in the thermal treatment process to obtain the pitch were varied to prevent brittleness in the filaments/green fibres. Further work is required to refine the process to increase melt-spun filament strength.

Further investigation is required to address the brittleness found in the green and oxidized fibres. There may be different causes for the brittleness, for example:

- *Composition of the feedstock*
- *Deep de-oiling distillation process used, such as highly controlled distillation using the patented Carbovate asphalt process as the first step.*
- *Composition of the residue after deep de-oiling through distillation*
- *Mesophase content levels of the precursor material - pitch*
- *Contamination of the precursor material – pitch – potentially due to coke fines formation during the thermal treatment process*

Additional thermal treatment options, e.g., residence time and temperature, as well as material filtering and further variation of the melt-spinning parameters should be explored along with more detailed analysis of the residue and precursor material samples.

F. OUTCOMES AND IMPACTS

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Resources Metrics:** Describe how the project outcomes impact the Clean Resources Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

RESPOND BELOW

Project Outcomes and Impacts:

It has been verified that Alberta Bitumen feedstock can be successfully processed into a precursor pitch that is melt-spinnable into green fibres. Some of these fibres have been treated using oxidation. The current precursor formulations do not lend themselves to be processed into GPCF due to brittleness found in the fibres produced by melt-spinning as well as in the fibres that were further processed through oxidation.

Hence, the currently obtained precursor samples are not suitable for GPCF production. Additional research is required to address the brittleness found in the obtained green fibres; please, see above.

Clean Resources Metrics:

A	Clean Resources Metrics Metric	Project Target	Commercialization / Implementation Target
1	*$ in Innovative Production and Distribution*	CAD 312,000 cash and in-kind contributions	A multi-billion-dollar sector
2	*TRL advancement*	TRL 1-3	TRL 4 -6
3	*# Clients selling goods or services internationally*	0	Multiple
4	*# field pilots/demonstrations*	0	1
5	*# of Publications*	0	
6	*# Students (Msc., PhD, Postdoc)*	6 or 7	no estimate, though student interns and Post Docs are expected to be part of the workforce during and after commercialization
7	*# projected new jobs created from future deployment*	0	potentially 100,000
8	*# Patents filed*	1-2 patents	
9	*Partnership agreements / MOUs?*	yes	multiple agreements across the supply chain
10	*# New products/services created*	general purpose CF precursor material and GPCF from Alberta Bitumen	GPCF from Alberta Bitumen and precursor for GPCF
11	*# New Spin-Off Companies created*	0	at least 1 Spin-off Company
12	*# actual GHG emissions reductions from project*	0	potential large-scale reduction in GHG emissions in the upstream applications such as concrete, steel and plastics

The clean resources metrics have been achieved in part as indicated below. In particular, technology development is incomplete and hence, a potential patent is not being pursued at this time.

1. *$443,123 in cash and in-kind contributions in innovative production and distribution: $131,123 more than the budgeted $312,000*
2. *Advanced to TRL 1-3*
3. *n/a*

4. *n/a*
5. *n/a*
6. *Recruitment was suspended due to the COVID19 pandemic. Over the course of the project, 2 students, 1 Post-Doctoral Fellow, and 4 lab techs (recent graduates) and one technical support person involved.*
7. *n/a*
8. *IP still under development, no patents currently applied for*
9. *Partnership agreements are pending further research outcomes*
10. *Creation of new products/services pending further research*
11. *n/a*
12. *n/a*

	Program Specific Metrics		
B	**Metric**	**Project Target**	**Commercialization / Implementation Target**
	Innovative Hydrocarbon Products Program Metrics		
1	*# of End Users participating*	1	new industry sector - could be 10's or 100's
2	*# commercial BBC products*	1 general purpose CF precursor	2 - 5 specific Carbon Fibre products
3	*$/bbl product uplift*	-	-
4	*Unique product/process*	yes	

The Program Specific Metrics have been achieved in part. In particular, the proposed process needs to be further researched and the proposed BBC product is pending the outcome of this research:

1. *One potential end-user is participating – from the construction sector and interested in reinforcing concrete with GPCF*
2. *No commercial BBC product is finalized*
3. *As stated in the Alberta Innovates White Paper[5] Bitumen Beyond Combustion:* "… the total value per bitumen barrel increases from an estimated $30 to $213*" – $ value based on the pricing at the time of white paper.*
4. *A unique process/product development is pending further research*

Project Outputs:

No reports have been issued.

G. BENEFITS

Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

RESPOND BELOW

Successful processing of Alberta Bitumen into GPCF would include the following potential benefits - after completion of further research.

Economic Benefits:

The potential economic benefits that could be realized are listed below.

- *Commercialization of new, Alberta bitumen-based, value-added products: GPCF precursor material and lower-cost GPCF;*
- *Development of a pathway for a new Alberta high-tech industry sector: cost-effectively manufacturing of GPCF precursors and GPCF.*
- *The global carbon fibre market size was valued at 2.25 billion USD in 2015 [6]and is projected to grow by more than 10.9% annually from 2017 to 2025 – for 'traditional applications' of CF.*
- *Opening of new markets for Alberta bitumen: production of GPCF precursor and GPCF from Alberta bitumen would open new markets for that resource resulting in advanced materials including GPCF composites and offering high paying jobs.*

Environmental:

There are a number of environmental benefits that can arise from generating carbon fibre from bitumen. These benefits arise from both the diversion of bitumen to a non-combustion product and the end use of carbon fibre by customers in their final implementation. These benefits are:

- *Avoided emissions by not refining and combusting bitumen. There will be emissions associated with manufacturing carbon fibre.*
- *Carbon fibre produced from Bitumen is estimated to have lower GHG impact than carbon fibre derived from other sources (Zhou et al, 2021[5]):*

  "Bitumen-derived BBC products can replace existing products with high emission intensities. For example, life-cycle analysis indicates that the GHG intensity of bitumen-derived carbon fibre may be 52 per cent lower than that of existing commercial polyacrylonitrile (PAN) carbon fibre".
- *Potential reduction of GHG emissions footprint for various applications such as concrete and construction materials resulting in reduction of required materials and added performance and longevity of infrastructure. The addition of GPCF to cement would reduce the amount of cement required for structures and prolong the structures life span (no corrosion of re- enforcements). This could significantly lower the energy requirements as well as GHG emissions associated with the production, maintenance, and replacement cost of concrete based infrastructures. These conclusions are supported by the following excerpt from Zhou et. al., 2021, Bitumen Beyond Combustion White Paper[5]:*

  "The use of carbon fibre increases the strength, rigidity and durability of wood panels, concrete and composite materials used in the built environment. Corrosion risk in concrete is reduced. Extending the life of the built environment will necessitate fewer repairs and reconstruction in the future, saving on emissions associated with manufacturing replacement building materials and the building process itself"
- *Another application is light weighting of vehicle parts (Zhou et. al. 2021[5]):*

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[6] Grand View Research, August 2917, Market Research Report: Carbon Fiber Market Analysis By Raw Material (PAN, Pitch), By Tow Size, By Application (Automotive, Aerospace & Defense, Wind Turbines, Sport Equipment, Construction, Pressure Vessels), And Segment Forecasts, 2018 – 2025, May 7, 2022 <https://www.grandviewresearch.com/industry-analysis/carbon-fiber-market-analysis>

"Carbon fibre composites in lightweight vehicles increase fuel efficiency and reduce GHG emissions by 22 to 36 per cent on a life-cycle basis as compared to a conventional vehicle".

- *Carbon fibre reinforced concrete, lumber and other building products will have greater strength and corrosion resistance leading to less material required and increased longevity.*
- *Emissions reductions of any kind will have a positive impact on health[7] and the global issue of climate change*

Social: we do not see any direct social benefits arising from this project. Any social benefits are secondary to the economic and environmental benefits described above.

Building Innovation Capacity:

- *Successful production of cost-effective GPCF from Bitumen would offer the opportunity for innovation and GPCF production capacity building for Alberta, thus realizing the potential economic benefits of this technology for a new supply-chain in Alberta.*
- *Innovation would not stop at the production of different types of GPCF: the true impact of the availability of such economical GPCF is in developing applications into different product lines from cement, wood, wind turbines, to all types of vehicles and so on. These applications are expected to result in longer life of the products and in lower GHG intensity.*

  In addition, these applications would be developed from the outset with 'sustainability by design' in mind, resulting in products whose parts could be repurposed and/or recycled and/or whose materials can be processed into new feedstocks at the end of life. Such products would support the circular economy and a Planet Positive future.

  Capturing the application and sustainability value chain in Alberta would build expertise in these areas, lead to company formation or re-location to the province, and grow the nascent composites and additives manufacturing sector. Collectively it would lead to significant growth in Alberta's innovation capacity in this economic area.

[7] CLEARING THE AIR: How Electric Vehicles and Cleaner Trucks Can Help Reduce Pollution, Improve Health and Save Lives in the Greater Toronto and Hamilton Area - Clearing The Air, May 7, 2022

H. RECOMMENDATIONS AND NEXT STEPS

Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

RESPOND BELOW

Next Steps: Refinement of the Carbovate Process to advance to GPCF.

Key to success of the GPCF from Alberta Bitumen research program is to overcome the observed brittleness of the melt-spun filaments in Phase 1.

Additional research is required to refine the Carbovate GPCF precursor production process such that the resulting precursor material lends itself to spinning into green fibre that exhibits less brittleness.

Refinements may include further variation of the thermal process parameters in terms of temperatures and residences times, filtering of the precursor material or the residue, addition of other materials to the residue or the pitch to name a few.

A phase 2 would have to grow the team in terms of expertise, laboratory facilities and staffing resources. Additional partnerships in industry and academia will be essential to provide additional resources to advance developments and learnings from this project.

I. KNOWLEDGE DISSEMINATION

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.

RESPOND BELOW

Due to the proprietary nature of this work, no knowledge dissemination has occurred at this point. We continue to look for strategic partnerships within industry to further develop this technology.

J. CONCLUSIONS

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

RESPOND BELOW

Project Objective:

The objective of the project was to develop a process to produce GPCF from thermally produced Alberta Bitumen.

Key Components:

Key components of the work include the treatment of the thermally produced bitumen such that it is melt spinnable into green fibres and suitable for further processing into GPCF.

Project Results, Learnings, Outcomes:

Current results and learnings show that the bitumen may be processed in a way that produces a pitch that may be melt-spun successfully, and the green fibres stabilized through oxidation. Further processing is inhibited by brittleness of the oxidized fibres.

Benefits:

Potential benefits are pending further investigation. Successful production of GPCF from Alberta Bitumen would open a path for a new economic sector in Alberta, that is the production of GPCF precursor materials, GPCF and derivatives. As the global economy pushes towards net-zero carbon emissions, these products would be in high demand and aid in pursuing this goal.

Next Steps:

Phase 2 will involve growing the team and further investigation and refinement of the Carbovate process to address the brittleness of the green fibre and produce GPCF with the required performance properties.