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:	**Fabrication and application of short carbon fibers using asphaltene-based carbon precursors**
Alberta Innovates Project Number:	G2019000513 (AI 2519)
Submission Date:	August 30, 2021
Total Project Cost:	$660,000
Alberta Innovates Funding:	$400,000
AI Project Advisor:	Dr. Paolo Bomben

2. APPLICANT INFORMATION:

Applicant (Organization):	**University of Alberta**
Address:	85 Ave & 116 St Edmonton AB T6G 2R3
Applicant Representative Name:	Dr. Weixing Chen
Title:	Professor
Phone Number:	(780) 492-7706
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3. PROJECT PARTNERS

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

RESPOND BELOW

The principal investigation would like to CNOOC International Limited for financial support and Mr. Milan Todorovic and Dr. Nestor Zerpa of CNOOC for project management and valuable discussions.

A. EXECUTIVE SUMMARY

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

RESPOND BELOW

This proposal was aimed at developing cost-effective methods of fabricating short carbon fibers (CFs) using Alberta asphaltenes as carbon precursors for the following two categories of applications:

1. Short CFs for making reinforced composite materials with either concrete-, plastic-, ceramic- or metal-matrices. Efforts will be focused on improving the mechanical properties of the short CFs and hence their composites. For these applications, it is targeted to achieve a tensile strength and tensile modulus of 2000 MPa and 250 GPa, respectively.

2. Short CFs for making electrode materials for supercapacitors. Efforts will be focused on achieving high supercapacitor performance with a capacitance target over 300 F/g at 1 mA/cm^2.

All the above indicated performance targets have been achieved or exceeded. These performances were achieved using a fiber fabrication facility with batch loading. Based on extensive investigations performed, the performances in all categories can be further improved if asphaltenes-based feedstocks are further modified and a continuous precursor feeding spinner rather than a batch-loading spinner is to be used to fabricate asphaltene fibers.

It is believed that technology being developed during this project can be used by existing Carbon Fibre manufacturers and oil sands companies to engage a pilot trial to manufacture carbon fibres from Alberta oil sands asphaltenes.

B. INTRODUCTION

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

Sector Introduction

This project is aimed at developing cost-effective methods of fabricating short carbon fibers (CFs) using Alberta asphaltenes as carbon precursors. The PI's research group has successfully fabricated long carbon fibers using asphaltene carbon precursors in August 2018 in an on-going project jointly sponsored by Alberta Innovates and Nexen Energy (now CNOOC International). Long CFs are usually superior in terms of mechanical properties, but they are expensive, and their applications are limited by available methods of making CF reinforced composites. Short fibres are much more versatile from the point of view of processability. For example, they can be sprayed with thermosetting resins or fabricated by extrusion and moulding processes, by pressing and injection. These manufacturing processes cause degradation of long fibres.

So far, CFs for either mechanical or electrochemical applications are primarily fabricated from expensive polyacrylonitrile (PAN)-based precursors. The impurities in raw asphaltenes that are a concern for some applications are, in fact, highly desirable when present in short CFs used for fabricating electrodes for supercapacitors. Asphaltenes have much higher carbon content but much lower oxygen content, which would increase the yield of CFs because of significantly reduced CO_2 conversion during thermal treatment. Therefore, it is expected that short CFs fabricated using asphaltenes either for supercapacitors or for structural composites can be achieved at competitive cost and with good performance.

Knowledge or Technology Gaps:

The project is aimed to bridge the following three key technology gaps:

1) Fabrication of short carbon fibers using asphaltene as carbon fiber precursors
2) A technology for achieving desirable mechanical properties of short carbon fibers made using asphaltene as carbon fiber precursors.
3) A technology for achieving improved supercapacitor performance using asphaltene-derived carbon fibers as active materials for supercapacitor electrode.

C. 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:

The technologies pursued in this project are a manufacturing process for short carbon fibres, and development of supercapacitors from the short carbon fibres. Objectives for this project are:

1) For the technology of fabricating short carbon fibers, it was initially proposed to fabricate short asphaltene fibers by a method involving extrusion of solvent-asphaltene drops through a nozzle hole to form discrete filaments or fibers.
2) For the fabrication of carbon fibers with targeted mechanical properties, the attention will be paid to the treatment of asphaltene precursors, dimension control of asphaltene precursor fibers, and post precursor fiber treatments.
3) For the use of asphaltene-derived carbon fibers as active materials for supercapacitors, efforts are made in processing carbon fibers with increased surface areas and decorating them with oxides to achieve pseudo capacitive effects.

Updates to Project Objectives

There are no changes to the original project objectives.

This proposal is aimed at developing cost-effective methods of fabricating short carbon fibers (CFs) using Alberta asphaltenes as carbon precursors for the following two categories of applications:

1) Short CFs for making reinforced composite materials with either concrete-, plastic-, ceramic- or metal-matrices. Efforts will be focused on improving the mechanical properties of the short CFs and hence their composites. Specifically, it is targeted to achieve tensile strength up to 2.0 GPa, tensile modulus above 250 GPa, and a strain of about 1%.

2) Short CFs for making electrode materials for supercapacitors. Efforts will be focused on achieving high supercapacitor performance. Specifically, it is aimed to reach a capacitance larger than 300 F/g at 1 mA/cm^2 in 6 M KOH.

It is believed that both the above targets have been reached. The project has enabled training of high qualified personnel, two MSc students were either gradated or transferred to PhD program at end of the project. The project has yielded 9 journal publications, 4 of them were published, the remaining are currently under review.

D. 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

Carbon Fibre

The fabrication of asphaltenes-derived carbon fibers was achieved following the following steps:

- Pre-treatment of as received asphaltenes was done to increase their softening points and spinnability.

- Melt spinning is the method of forming fibers through the rapid cooling of a melt. Asphaltene-based carbon precursors were tested to determine the proper temperature at which fibers can be extruded under pressurized nitrogen gas environments. The fibers obtained were characterized for their diameter as a function of winding speed.

- Oxidation is used to cross-link the molecules to the point where the fibers do not melt or fuse together. This step is extremely important because it produces fibers that are stable at the high temperatures of carbonization and graphitization. Without cross-linking, the fibers would fail in these process steps.

- Carbonization is achieved by heating the fibers to high temperatures (above 1000 °C) in an environment without oxygen. This step removes most of the impurities (e.g., hydrogen, oxygen, nitrogen) from the fibers, leaving mainly crystalline carbon in mostly hexagonal rings.

- Graphitization is the process of treating the fibers at high temperatures in order to improve the alignment and orientation of the crystalline regions along the main fiber axes. Having the crystalline regions aligned, stacked, and oriented along the main fiber axis increases the overall strength and stiffness of the carbon fibers. Graphitization was not performed in this project because of temperature capacity of existing furnace.

- Field-emission scanning electron microscopy (ZEISS Sigma 300 VP-FESEM) was used to measure the diameters of the fibers and to investigate the surface morphology and composition of the CF. The mass change of the green fibers after each oxidation treatment was measured using a Mettler Toledo Balance XS105 with a resolution of 0.01 mg. A Mettler Toledo Thermogravimetric Analyzer / Differential Scanning Calorimeter (TGA/DSC1) system, equipped with a large 1100 furnace, a sample robot, and an MX5 internal microbalance, was used to further measure the mass change under simulated oxidation conditions. FTIR-i50 spectroscopy (Nicolet Instrument Corporation) was utilized to characterize the evolution of chemical bonds in fibers fabricated from the two different asphaltene precursors. A fully automatic Thermo Flash 200 Elemental Analyzer was employed to analyze the carbon, hydrogen, nitrogen, and sulfur (CHNS) content of asphaltene precursors and resulting fibers after oxidation and carbonization. Specific surface area and pore volume of the prepared carbon fibers were measured through N_2 adsorption at 77 K with an Autosorb Quantachrome 1 MP system. Specific surface areas were determined in the relative pressure range of 0.05 – 0.2 applying Brunauer-Emmett-Teller (BET) theory. Pore volume was calculated at 0.95 relative pressure (p/p_0). X-ray photoelectron spectroscopy (XPS) was done using a PHI VersaProbe III scanning XPS Microprobe with a monochromatic Al X-ray source operated at 210 W and a pass energy of 20 eV. The spectra were calibrated using the C1s binding energy of 284.6 eV. Crystal structure was characterized using x-ray diffraction (XRD, Rigaku Ultima IV) operating at 38 kV and 38 mA with a Co radiation source. The scanning range was 5 – 90 ° 2θ with a scanning speed of 2 °/min. Individual carbon fibers after carbonization were used to prepare tensile samples with a gauge length of 12.7 mm. These samples were tested with an INSTRON 5565 machine to determine their tensile properties. At least 20 single fibers were prepared for a given treatment. The fiber strength was calculated based on the average diameter of the 20 fibers.

Capacitors

- Preparation and Characterization of Carbon Fibers and Activated Carbon Fibers: Asphaltenes-derived carbon fibers were mixed with dry KOH with different mass ratios; i.e., *R* = (mass of KOH)/(mass of fibers) from 1 to 3 and then activated at temperatures 800 ^{o}C for 2 hours. CF and activated carbonized fibers (ACF) with different R values (ACF-R) were washed with 35 wt% HCl and deionized water multiple times using a vacuum filtration system. The final samples were dried in a vacuum oven at 100 °C for at least 12 h.

- Preparation of Electrodes: Electrodes were prepared by mixing 90 wt% of the CF or ACF-R samples, 5 wt% of polytetrafluoroethylene (PTFE, suspension), and 5 wt% of acetylene black at 80 °C in an agate mortar to form a homogeneous paste. After drying the paste in a vacuum oven at 100 °C for 12 h, electrode films were obtained. Disks, 1.92 cm^2 in area, were sectioned from the films to be used as the electrodes. The mass of the electrodes was 15–25 mg, whereas the thickness was 100–150 µm.

- Preparation of Supercapacitor Cells: Coin cells were prepared using two electrodes with the same mass and thickness pressed onto stainless steel current collectors with a conductive adhesive paint and a separator between them. 100 µL of electrolyte was added to the set-up before sealing; 6 M KOH and 1-ethyl-3-methylimidazolium tetrafluoroborate ($EMIMBF_4$) were used as the aqueous and ionic liquid electrolytes, respectively.

- Electrochemical Measurements: Electrochemical tests were conducted to evaluate the capacitive performance, using a VSP potentiostat (Biologic). The tests included cyclic voltammetry (CV, scan rate from 10 to 100 mV s^{-1}), galvanostatic charge/discharge with potential limitation (GCPL, specific currents from 40 mA g^{-1} to 4 A g^{-1}), and electrochemical impedance spectroscopy (EIS, frequency from 50 mHz to 500 kHz).

E. 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

The following is a summary of key results:

Carbon Fibre

1. Initial attempts to produce short carbon fibres using solvent-asphaltene drops was unsuccessful. The project pivoted to generating short carbon fibres from continuous fibre.
2. Spinnability: The asphaltene-based carbon precursors could be processed to reach a spinning speed as high 900 m/minute. Commercial production of carbon fibers usually requires a spinning speed larger than 500 m/minute. High winding speed was achieved through pre-treatment of asphaltene feedstocks.
3. Chemical treatment of as-spun asphaltene-fibres was needed to avoid fusing of as-spun asphaltene-fibers during heating to the temperature for oxidation. This step is needed because asphaltene carbon precursors are featured with molecular components with varied melting points and oxidation that could cross-link the molecules to the point where the fibers do not melt, or fuse together takes place at temperatures higher than the melt points of some molecular constituents.
4. Oxidation treatment can be optimized to complete within 3 hours that is critical in terms of reduction of energy consumption.
5. Carbonization was performed at temperatures up to 1500^{o}C under various heating rates and carbonization times. Carbonization conditions have been optimized to achieve higher tensile properties of resulting carbon fibers.
6. The highest yield of carbon fibers derived from asphaltenes-based carbon precursors reached 53%. Higher yields of carbon fibers were often accompanied with higher tensile properties. Typical images of resulting carbon fibers are shown in Figure 1.

Capacitors

7. Carbon fibers (CF) derived from asphaltene were chemically activated to prepare activated carbon fibers (ACF), which have achieved a specific surface area as high as 2290 $m^2\ g^{-1}$ and total porosity of 1.27 $cm^3\ g^{-1}$ that included 0.88 $cm^3\ g^{-1}$ of micropores (pore width < 2 nm) and 0.29 $cm^3\ g^{-1}$ of mesopores (2 nm < pore width < 50 nm).
8. The maximum specific capacitance (C_s) reached was 311 F g^{-1} at a specific current (I_s) of 0.04 A g^{-1} that dropped to 248 F g^{-1} at 1 A g^{-1} (in 6 M KOH) (see Figure 2); capacitance retention was 91% after 10,000 cycles. This material was later used in an EDLC device with an ionic liquid electrolyte

(EMIMBF$_4$, 1-ethyl-3-methylimidazolium tetrafluoroborate); specific energy (E_s) and power (P_s) values of 35.7 Wh kg^{-1} at a P_s of 525.4 W kg^{-1}, respectively, were achieved. These were comparable to energy and power values delivered by some batteries.

9. A method involving dip asphaltene-based carbon fibers to form V_2O_5-coating on carbon fiber has been developed. The materials were applied as supercapacitor using 1 M Li_2SO_4 showing specific capacitances of up to 125 F g^{-1} with a discharge current of 0.25 A g^{-1} for the highest annealing temperature. The supercapacitor cells retain 89% of their initial performance after 10,000 charge-discharge cycles.

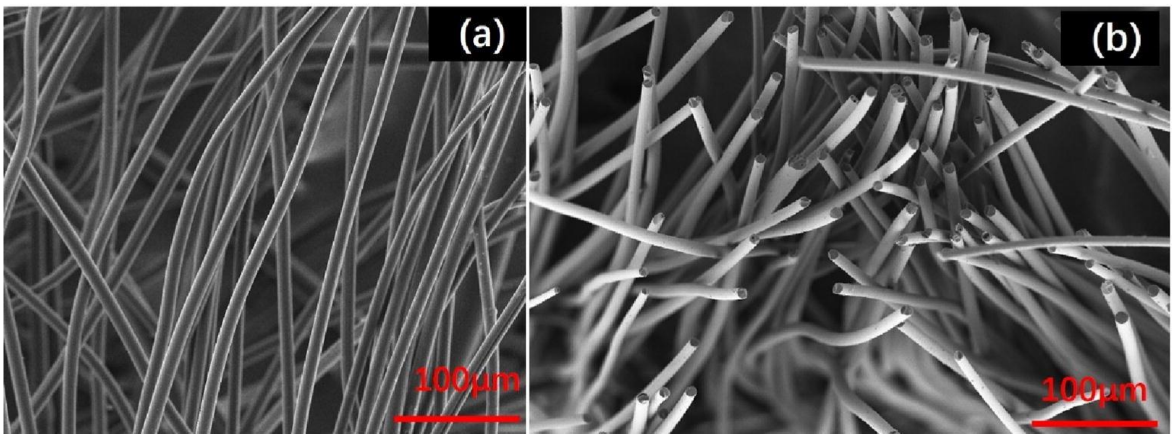

Figure 1 Physical appearance of asphaltenes-derived carbon fibers: a) length view of carbon fibers, b) cross-sectional view of carbon fibers.

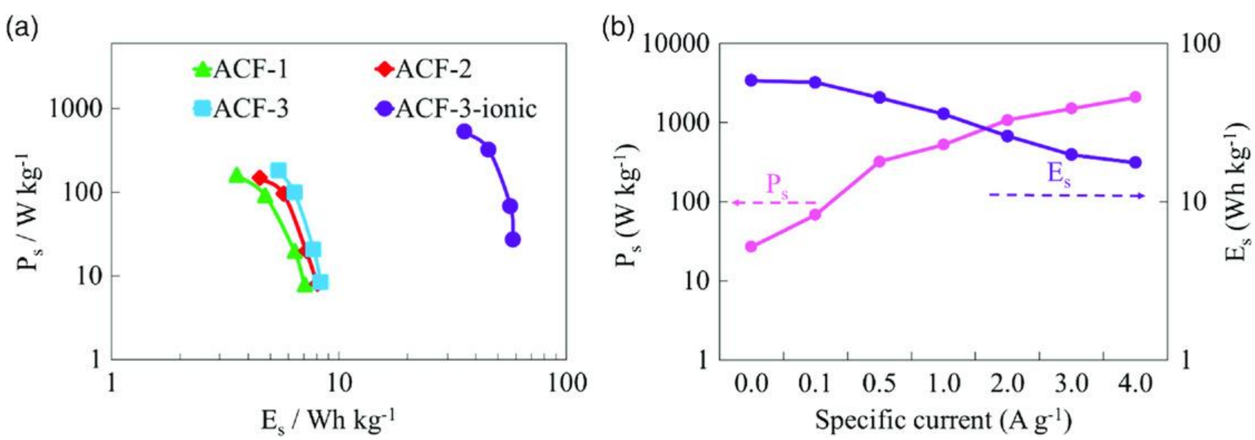

Figure 2 a) Ragone plot for all EDLS cells studied. b) E_s and P_s for ACF-3-ionic at different specific currents.

Project Specific Metrics

Project Success Metrics (Metrics identified by Applicant)		
Metric		Project Target
To develop a proof-of-concept technology for the synthesis of short carbon fibers using asphaltenes as precursors, for both mechanical and electrochemical applications.	A scalable facility that can be used to make short carbon fibers directly from asphaltenes	Design and construction of the facility within 4 months from start of the project (**Achieved**)
		Facility capable of fabricating short carbon fibers at up to 20 g/h (**Achieved**)
	Tensile properties for structural application	Tensile strength up to 2.0 GPa, tensile modulus above 250 GPa, and a strain of about 1%. (**Achieved**)
	Capacitance for supercapacitor applications	> 300 F/g at 1 mA/cm^2 in 6 M KOH (**Achieved**)
To explore the feasibility of incorporating chemical additives into short CFs to improve the performance of carbon fiber supercapacitors. These chemicals are added as active materials to enhance pseudocapacitive performance.	Maximum wt% of chemical ingredients to be added without sacrificing the ability of fabricating raw CFs	Up to 30% (not tried in this project)
To maximize the benefits of impurities present in the raw asphaltene feedstock for improved electrochemical performance.	The amount of impurities including S, O, N, V, Ni and Fe in asphaltene feed stock to be removed	0% (not tried in this project)
To design pilot processes for pre-commercialization of short-carbon fibers using asphaltenes as carbon precursors.	Yield efficiency	70 % (A yield of 53 % was achieved)

The project achieved some but not all of the metrics above. Desired tensile properties were met for carbon fibres with diameter lower than 5 micrometers. Capacitance for supercapacitor applications was achieved. Yield efficiency is 30-50%, much lower than initially projected. Further research is required to understand the pathways to achieve yields as high as 70%. Given the challenges in achieving the performance of carbon fibre desired, a fulsome analysis of benefits of impurities in the fibres was not undertaken but should be performed in the future.

F. 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

1. Key learnings on further improving mechanical properties of asphaltenes-derived carbon fibers

- On pre-treatment of asphaltene feedstocks: The asphaltene feedstocks obtained from straight de-asphalting process have low spinning temperatures which are prone to fiber fusing during oxidation and poor spinnability in terms of low winding speed, large variation in green fiber diameter and short time window for spinning. These shortcomings could be resolved by pre-treatment of the asphaltene feedstocks.

- On the spinnability of asphaltene-based carbon precursors: The asphaltene-based carbon precursors were spun on a spinner with a batch loading of precursor, which was extruded under a given pressure of nitrogen gas. The batch loaded asphaltene-based carbon precursors were heated to the spinning temperature at the same time. The amounts of green fibers obtained from each batch process varied from less 1 gram to as high as 15 grams for a batch loading of 20 g of precursor, and the winding speed from as low as 100 m/min to as high as 900 m/minute. These variations indicate different spinnability of asphaltenes-derived carbon precursors, probably because their different rheological behavior, which should be further studied.

- On the oxidation/stabilization of green fibers: Many efforts have been made in optimizing the oxidation/stabilization conditions to reach an improved mechanical properties of resulting carbon fibers, and shortening the time required for oxidation/stabilization. However, the oxidation conditions being determined from this investigation may bear little connection to an industrial process of oxidation/stabilization of green fibers because of a relatively large variation of green fiber diameters and much efficient heating furnace used in industrial production. The oxidation of green fibers involves in the diffusion of oxygen into green fibers, and the time of diffusion required to achieve a desirable level of oxygen varies with square of fiber radius.

2. Key learnings on further improving the performance of carbon fiber-based supercapacitors

- Optimization of the ratio between the capacitance of carbon fibers and the pseudocapacitive species, which is coated on the fibers. Using carbon fibers with smaller diameters would lead to smaller fiber particles and, therefore, a lower resistance of the electrode. This would also yield higher total amount of V_2O_5, or shorter diffusion path because of potentially thinner V_2O_5 layer. Both could enhance pseudocapacitive behavior.

- Carbon fiber-based Li^+ ion battery: A composite of Li^+ intercalating V_2O_5 with conductive carbon fibers could be a promising alternative to the conventional Li-ion electrode materials, especially considering the low costs of asphaltene-based carbon fibers.

G. 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 Energy 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

The work on the project advanced the understanding of how to make carbon fibres with desired properties from asphaltenes. More work needs to be done to achieve the desired performance metrics and fully close the technology gap.

Supercapacitor performance was successfully demonstrated. Optimization is required to fully close the technology gap.

Clean Resources Metrics

This project began before the Clean Resources metrics were developed. Thus, the metrics below are based on the original proposal.

Metric	Project Target
TRL advancement	TRL 4 to 6
# of Publications	*6*
# Students (MSc., PhD, Postdoc)	5 (2 MSc and 3 Postdoc)
# projected new jobs created from future deployment	5
# Patents filed	1
# New products/services created	1

TRL advancement, publications, number of students trained, and new product/services met the expected target. A patent is expected to be filed in the future. And future R&D should create the estimated jobs in the table above. The project has demonstrated the feasibility of making high performance carbon fibers from abundant resources of asphaltenes in Alberta. The project has also enabled training of high qualified personnel including two postdoctoral fellows and two MSc students. The latter two either graduated or transferred to a PhD program by the end of the project. The project has also yielded 9 journal publications (5 of them were published, the remaining are currently under review or in preparation) and 3 conference presentations.

Project Outputs

Journal publications and submissions

1. Zahra Abedi, Desirée Leistenschneider, Weixing Chen, and Douglas G. Ivey, Superior Performance of Electrochemical Double Layer Supercapacitor Made with Asphaltene Derived Activated Carbon Fibers, Energy Technol. 2020, 8, 200058 (11 pages), Impact factor: 3.175
2. Peiyuan Zuo, Desirée Leistenschneider, Yuna Kim, Zahra Abedi, Douglas G. Ivey, Xuehua Zhang, Weixing Chen, Asphaltene thermal treatment and optimization of oxidation conditions of low-cost

asphaltene-derived carbon fibers, Journal of Industrial and Engineering Chemistry, Available online 29 August 2021

3. Desirée Leistenschneider, Peiyuan Zuo, Yuna Kim, Zahra Abedi, Douglas G.Ivey, Arno, de Klerk, Xuehua Zhang, Weixing Chen, A mechanism study of acid-assisted oxidative stabilization of asphaltene-derived carbon fibers, Carbon Trends, Volume 5, October 2021, 100090
4. Zuo P., Leistenschneider D., Kim Y., Ivey D.G., Chen W., The effect of thermal pretreatment temperature on the diameters and mechanical properties of asphaltene-derived carbon fibers, Journal of Materials Science, Volume 56, Issue 27, Pages 14964 – 14977, September 2021.
5. Kim, Yuna; Leistenschneider, Desirée; de Klerk, Arno; Chen, Weixing, Rigorous Deasphalting, Autoxidation, and Bromination Pretreatment Methods for Oilsands Bitumen Derived Asphaltenes to Improve Carbon Fiber Production, Energy & Fuels, 2021, 35, 17463-17478..
6. Desirée Leistenschneider, Zahra Abedi, Douglas G. Ivey, and Weixing Chen, Facile dip coating of asphaltenes-based carbon fibers with V2O5 for supercapacitor application, ChemSusChem, submitted, September 2021
7. Zahra Abedi, Desirée Leistenschneider, Weixing Chen, Douglas G. Ivey, Spinel Type Mn-Co Oxide Coated Carbon Fibers as Efficient Bifunctional Electrocatalysts for Zinc-air Batteries, Batteries & Supercaps, submitted, August 2021
8. Zahra Abedi; Douglas Ivey; Weixing Chen; Desiree Leistenschneider, Charge storage mechanism of asphaltene derived activated carbon fibers and birnessite type MnO2 composite electrodes, J of Materials Science, submitted, July 2021
9. Desirée Leistenschneider, Peiyuan Zuo, Calvin Phan, Yuna Kim, Zahra Abedi, Douglas G. Ivey Weixing Chen, Fabrication of carbon fibers from solvent de-asphalting asphaltenes – Investigation of oxidation, carbonization, yield and mechanical properties, in preparation.

Conference presentations:

1. Desirée Leistenschneider, Peiyuan Zuo, Zahra Abedi, Yuna Kim, Weixing Chen, Fabrication of V2O5 decorated carbon fibers using asphaltene from solvent-de-asphalting for energy storage application, ACS Spring 2021, April 12, 2021.
2. Yuna Kim, Dr. Arno de Klerk, Dr. Weixing Chen, Pretreatment of Asphaltenes as Precursors for Carbon Fiber Production, ACS Spring 2021, April 12, 2021.
3. Zahra Abedi, Desiree Leistenschneider, Weixing Chen and Douglas G. Ivey, Carbon Fibers for Energy Storage Devices: Electrochemical Double Layer Supercapacitors, Pseudocapacitors and Zn-Air Batteries, Virtual MRS Meetings – Spring 2021, April 19, 2021, Abstract ID: 3561189

H. 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

Economic

The project is developing carbon fibre from asphaltenes. If commercially successful, this technology would attract new investment to build manufacturing facilities. This would lead to new employment and generate additional end uses for bitumen. Carbon fibres are an exportable product generating revenue streams for Alberta businesses.

Environmental and Social

The project will create the following environmental and social benefits if successful:

- Climate adaptation: CF-reinforced composites would allow the use of less material or lighter structures without compromising the mechanical integrity, which can yield a lower consumption of energy.
- Land disturbance and management: With an increase of partial up-grading, the amount of asphaltene by-product can be huge, approximately 60 Mton of asphaltene by-product per day. CF production would be an end use for asphaltene by-product.
- Contaminant reduction: It has been determined that asphaltene by-product usually contains about 0.5 wt.% metal contaminants, which would create a huge environmental impact if they were released to the soil and water systems from the landfill.

Building Innovation Capacity

The project has also enabled training of high qualified personnel including three postdoctoral fellows and two MSc students. The latter two either graduated or transferred to a PhD program by the end of the project. One of the HQPs being trained has already been employed by a company who is currently in commercializing asphaltene-derived carbon fibers. The team built capacity at the University of Alberta for spinning carbon fibre.

I. 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

Recommended next steps:

1) Replace batch fabrication process with a continuous extruding process to avoid alteration of feedstock in batch process, especially when batch loading is large.
2) Continue R&D on feedstock modification and optimization to improve spinnability and fiber consistency.

J. 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

The results being published will help other researchers who are engaged in developing carbon fibers from the same or similar hydrocarbon feedstocks. One of the HQPs being trained has already been employed by a company who is currently in commercializing asphaltene-derived carbon fibers.

K. 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

The project has demonstrated the feasibility of making high performance carbon fibers from abundant resources of asphaltenes in Alberta and using them to achieve desired performance in capacitors. Key performance targets for carbon fibre and capacitors have been reached. This project showed the importance of pre-treatment on asphaltene feedstocks, need for good spinnability and challenges to optimize oxidation/stabilization of fibres. Overall, this project moved the idea of asphaltene to carbon fibre forward towards commercialization. The project has also enabled training of high qualified personnel including two postdoctoral fellows and two MSc students. The project has yielded 9 journal publications and 3 conference presentations. It is recommended that pilot trial of fabrication of asphaltene-based carbon fibers through a continuous extruding process to avoid alteration of feedstock in batch process, and continuous R&D on feedstock modification and optimization to improve spinnability and fiber consistency.