Carbon Hub Webinar - Call for Proposals Fall 2021

Carbon Hub




Topic #1: Improve understanding of the catalysis and reaction mechanism in (thermocatalytic) pyrolysis to efficiently convert methane to VACS



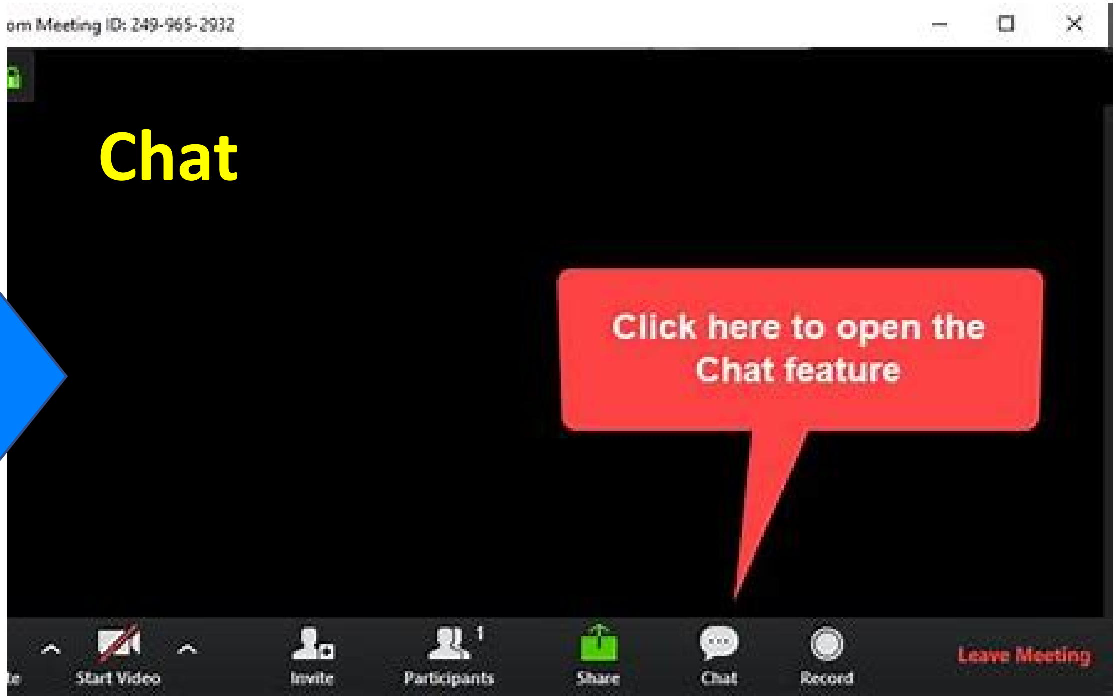



Carbon Hub Webinar - Agenda

Carbon Hub

General	❑ Introduction Carbon Hub ❑ Mission and Vision	10 min
What are we trying to solve?	❑ Topic Introduction ❑ Expert deeper dive ❑ Key deliverables ❑ What is out of scope – What are we NOT looking for ❑ Budget and timeline	30 min
Q&A	❑ Please ask us questions	15 min
Next Steps	❑ In summary – How to submit your proposal ❑ Call for Proposal Process and timeline - Some Terms & Conditions	5 min

Q&A – Please ask us any questions you might have

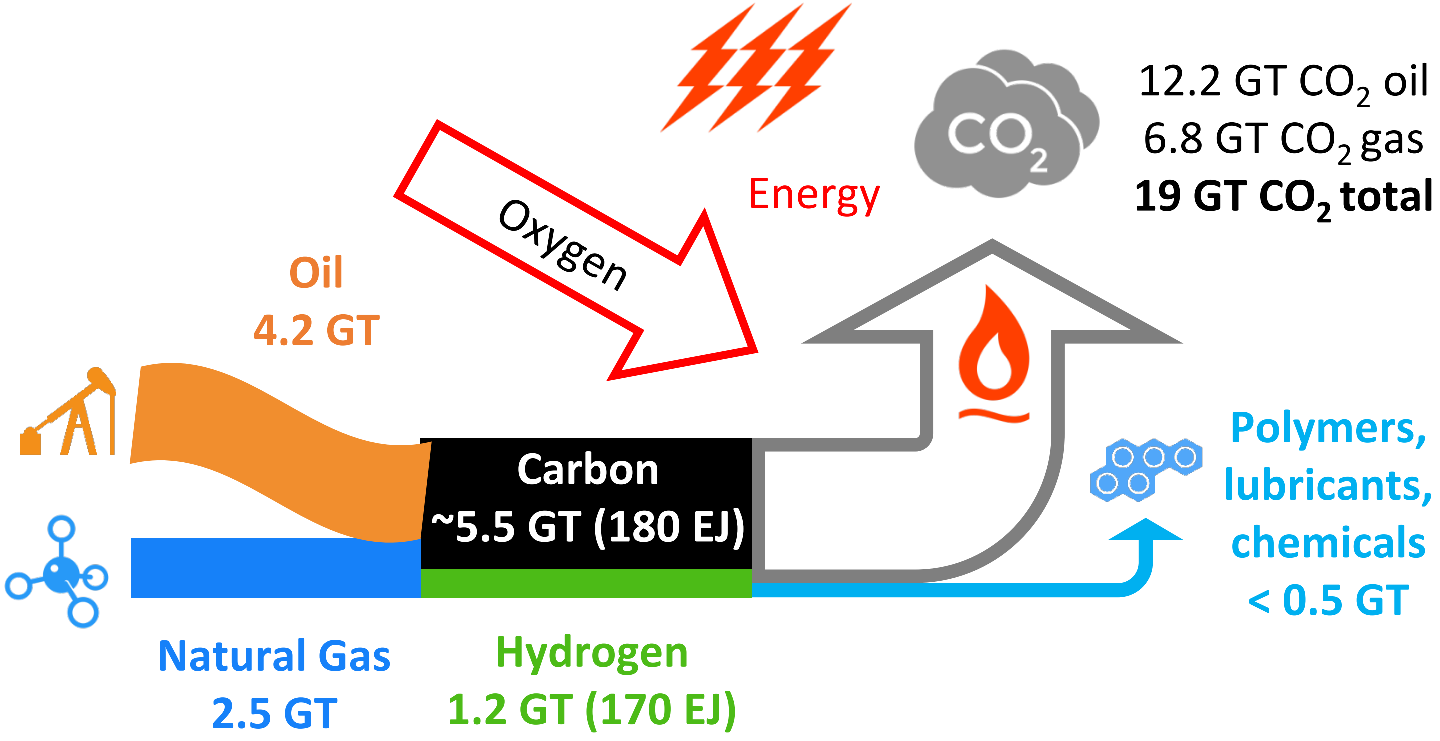


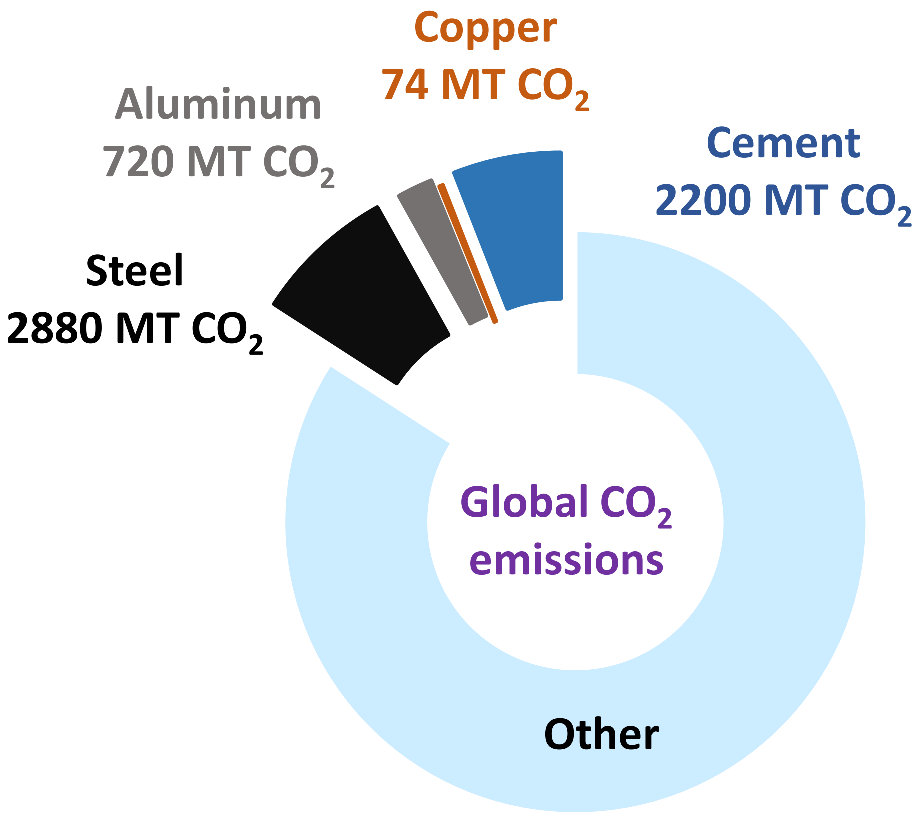
The Carbon and Material Challenge

Carbon Hub

85% of world energy comes from carbon combustion

12% of world energy is used for production of steel , aluminum and copper





19 GT CO_2 / yr

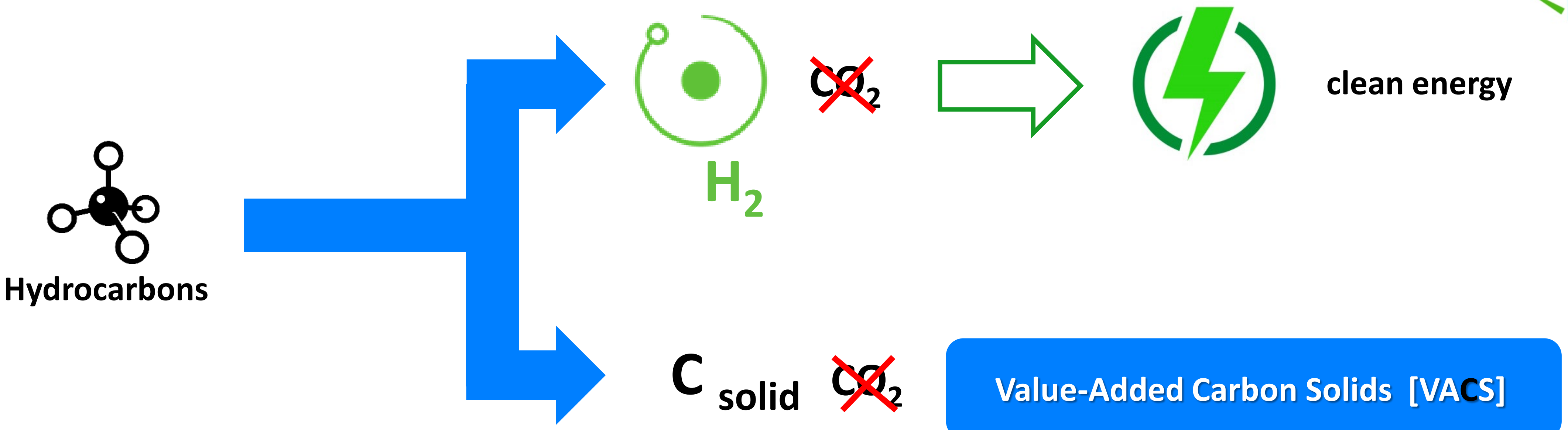
"indicative numbers" 2017 data

5.9 GT CO_2 / yr

"indicative numbers"

The Carbon Hub aims to alter the Energy – Materials Nexus

Carbon Hub



C solid
e.g. Soil amendment

GHG emission reduction
Enhance the soil microbial environment

Might reduce energy intensive fertilizer manufacturing

Improve soil drainage and water quality

Structured C solid
Displacing metals & building materials

CO_2 emission reduction
Lower need for metals, less metal oxide reduction

Energy & CO_2 reduction
Metal production is energy intensive

Avoid metal mining & processing

New materials

CO_2 emission reduction
New light weight materials for transportation in the distribution chain

The carbon materials are recyclable

Value-Added Carbon Solids – Our definition

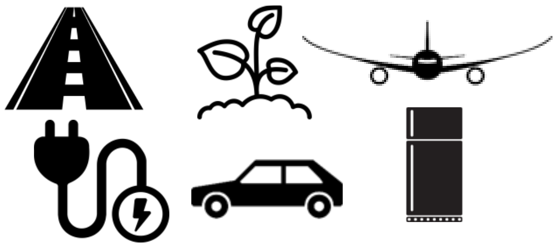
NG
Natural Gas
Light HC

→

H_2 ~~CO_2~~
C solid

→

Application in end-products



VACS

A solid carbon material produced by splitting efficiently (e.g., by pyrolysis) methane and light hydrocarbons with concurrent production of hydrogen and no carbon dioxide emissions.

Being used pervasively (>1 MM Tons/year)

Displacing metals, traditional construction ceramics, fertilizers and other materials with high CO_2 footprints.

excluded

- Carbon black, amorphous carbons, graphite
- Polymers
- Solid carbon whose only value is a CO_2 emission avoidance or that will be oxidized in other processes (e.g., metallurgical coke)

included

- Carbon materials that have macroscale structural integrity and properties that overlap with widespread materials
- Carbon powders that have potential use as additives in very large-scale systems, e.g., in soil or concrete

Examples of Value-Added Carbon Solids – Carbon Nanotubes (CNTs)

Carbon Hub

Opportunities

- CNTs can be synthesized in one process step from methane or light hydrocarbons
- CNTs can be converted into macroscopic materials;
- based on properties, a subclass of CNT macro-materials could replace metals or other construction material

Challenges

- CNT synthesis is still an early-stage, **low-volume** endeavor;
- synthesis **efficiency is low** and must be increased by orders of magnitude to attain competitiveness with incumbent materials;
- the **knowledge base** for increasing the efficiency and scale of CNT synthesis must be developed

VACS

Application in end-products

scale value

Examples of Value-Added Carbon Solids – Soil Amendment

Opportunities

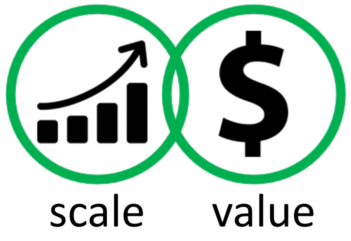
- ❑ forms of carbon (e.g., biochar) may improve the fertility and viability of soils while simultaneously reducing fertilizer usage and the agricultural carbon footprint.

Challenges

- ❑ current carbon soil additives are **too expensive** for large-scale deployment
- ❑ and are **not made from methane** and light hydrocarbons;
- ❑ the **knowledge base** for efficiently synthesizing soil additives from methane and light hydrocarbons must be developed

VACS

Application in end-products



The Carbon Hub aims to alter the Energy – Materials Nexus

Carbon Hub

Hydrocarbons → topic 1 → H_2 ~~CO_2~~ → clean energy

Hydrocarbons → topic 1 → C solid ~~CO_2~~

Carbon Hub Fall 2021 Call for Proposals Themes

C solid (topic 4)

e.g. Soil amendment

GHG emission reduction
Enhance the soil microbial environment

Might reduce energy intensive fertilizer manufacturing

Improve soil drainage and water quality

Structured C solid (topic 2)

Displacing metals & building materials

CO_2 emission reduction
Lower need for metals, less metal oxide reduction

Energy & CO_2 reduction (topic 3)
Metal production is energy intensive

Avoid metal mining & processing (topic 5)

New materials

CO_2 emission reduction
New light weight materials for transportation in the distribution chain

The carbon materials are recyclable

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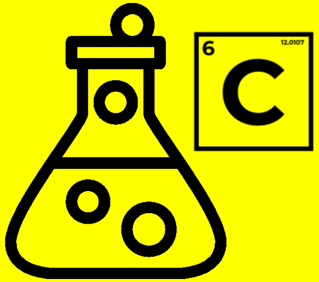
Overview Fall 2021 - Call for Proposal Topics

Carbon Hub

1

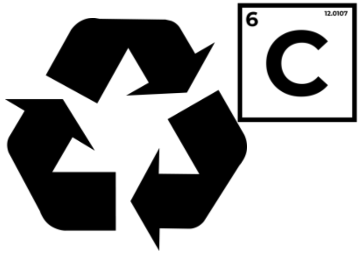
Improve understanding of the catalysis and reaction mechanism in (thermocatalytic) pyrolysis to efficiently convert methane to VACS.



2

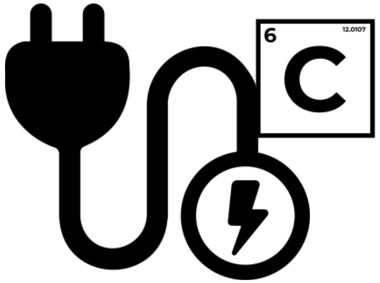
Improve Carbon nanotube [CNT] and VACS standardization and environmental impact understanding.

- CNT material standardization (terminology, testing)
- LCA and End-of-Life use mapped for CNT or other VACS



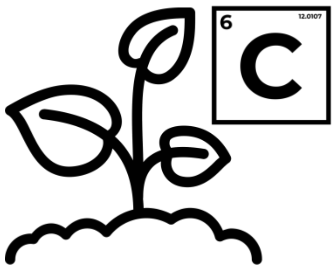
3

Demonstrate the value of a Carbon nanotube [CNT] fiber-based power cable prototype.



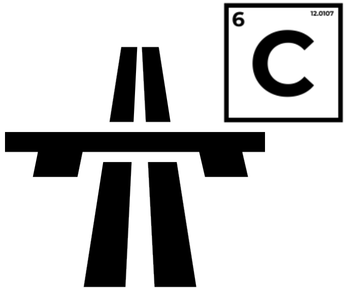
4

Demonstrate and explain efficacy of a VACS as a soil amendment.

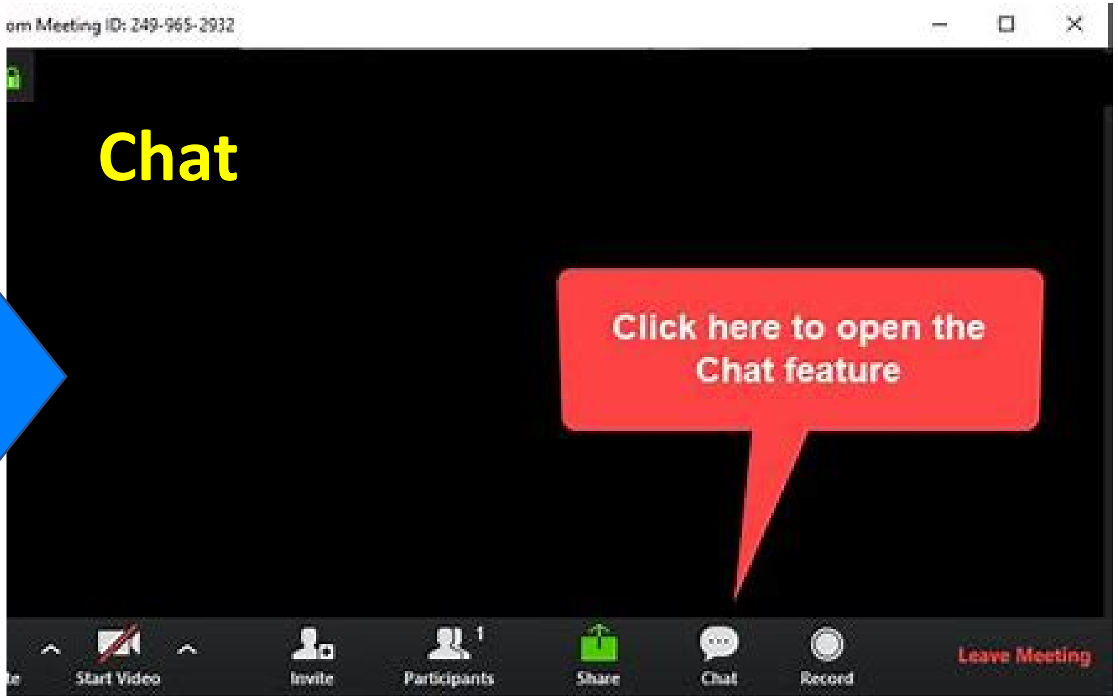


5

Demonstrate the value of CNT or other VACS, in structural applications, including non-critical ones.



Q&A – Please ask us any questions you might have



Topic #1 Introduction – Key Research Challenge Summary

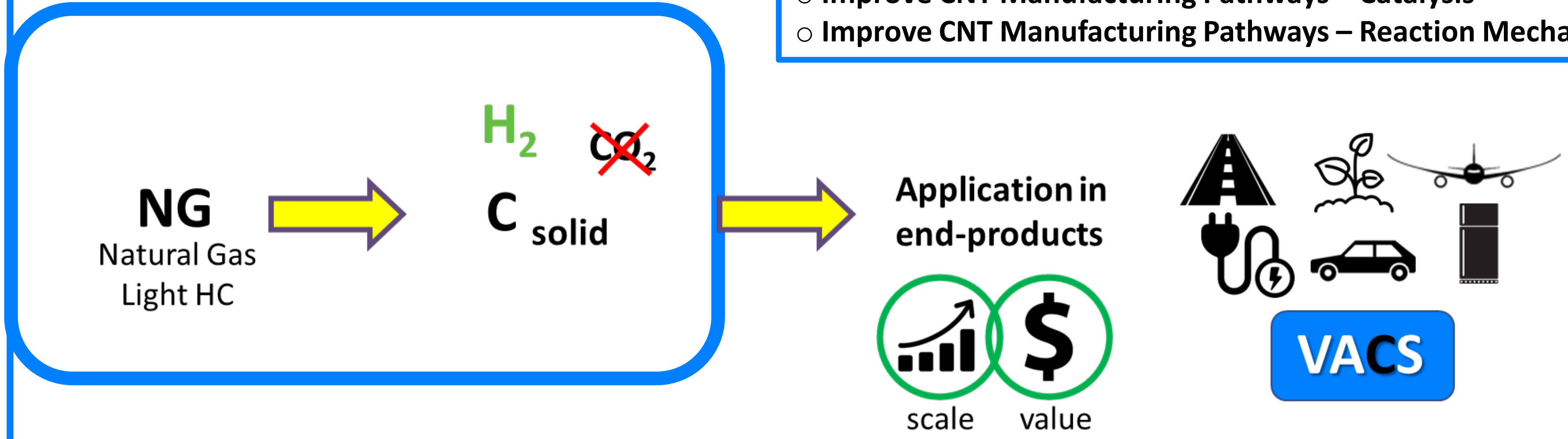
Carbon Hub

We seek breakthrough understanding to unlock high yields and selectivity for the production of VACS materials using (thermocatalytic) pyrolysis, with an emphasis on methane.

Improve understanding of the catalysis and reaction mechanism in (thermocatalytic) pyrolysis to efficiently convert methane to VACS.

This topic is derived from the Feb 14, 2020 Technical Workshop

- **Improve CNT Manufacturing Pathways – Catalysis**
- **Improve CNT Manufacturing Pathways – Reaction Mechanisms**



A solid carbon material produced by splitting efficiently (e.g., by pyrolysis) methane and light hydrocarbons with concurrent production of hydrogen and no carbon dioxide emissions.

Being used pervasively (>1 MM Tons/year)

Displacing metals, traditional construction ceramics, fertilizers and other materials with high CO_2 footprints.

Key research questions to consider:

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- Do we need to tear apart the existing hypothesis for synthetic pathways and start fresh?
- How can we probe the reaction mechanism better (in-situ?)?
- How do we identify and exploit the barriers to efficiency? What fundamental knowledge must be generated to support the reaction and reactor design?
- How do we design/manufacture the correct catalyst (diameter, composition, durability) to selectively control product morphology and achieve high conversions of feedstock?
- Can we improve product performance and selectivity with additives to the workhorse Fe catalyst? Or are there improved catalyst compositions that can be used?
- What roles can improved Reaction Engineering and Novel Reactor concepts play in improving efficiency?

First Project Awarded in Topic #1 – 2020 Cycle

- ***A modular and hierarchical kinetic framework for the thermo-catalytic pyrolysis of methane for VACS production: an application to carbon-nanotubes (CNT).***

Dr. Matteo Maestri
Professor in Dipartimento di Energia

SHAPE

erc European Research Council

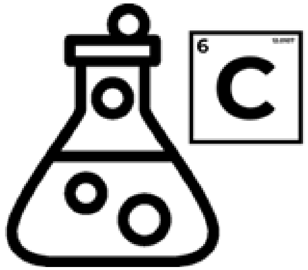
POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

Structure dependent microkinetic modeling of **H**eterogeneous c**A**talytic **P**roc**E**sses

Carbon Hub 2020 CFP Cycle Awardee in Topic #1

Milan Polytechnic's Matteo Maestri and Matteo Pelucchi aim to pave the way for optimized co-production of hydrogen and carbon nanotubes by developing descriptive frameworks for competing catalytic reactions. The information would allow process engineers to minimize production of unwanted soot in large-scale reactors for nanotube production.

TOPIC #1: Improve understanding of the catalysis and reaction mechanism in (thermocatalytic) pyrolysis to efficiently convert methane and light hydrocarbons to VACS.



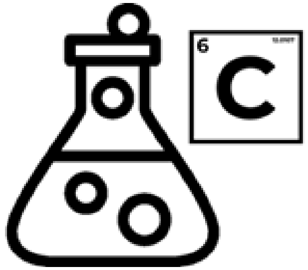
We seek breakthrough understanding to unlock high yields and selectivity for the production of VACS materials using thermocatalytic pyrolysis, with an emphasis on methane.

First Project Awarded in Topic #1 – 2020 Cycle

Dr. Adam Boies
Head of Energy Group Department of Engineering, University of Cambridge
Carbon Hub 2020 CFP Cycle Awardee in Topic #3

Cambridge's Adam Boies, Simone Hochgreb, James Elliot and Matthew Juniper will investigate the fundamental kinetics of catalytic reactions that produce carbon nanotubes from methane. The research aims to gather necessary information for the design and scaleup of reactors for high-yield production.

TOPIC #1: **Improve understanding of the catalysis and reaction mechanism in (thermocatalytic) pyrolysis to efficiently convert methane and light hydrocarbons to VACS.**



We seek breakthrough understanding to unlock high yields and selectivity for the production of VACS materials using thermocatalytic pyrolysis, with an emphasis on methane.

What are our Equipment Options to Scale?

Carbon Hub

TOKYO ELECTRON

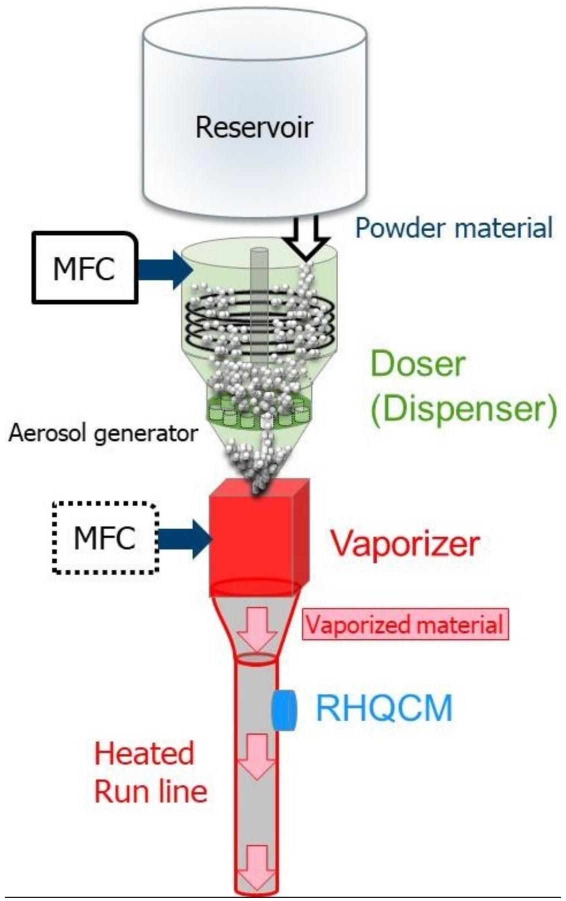
APPLIED MATERIALS®

HALDOR TOPSØE

GEA engineering for a better world

- In chemical/industrial markets, there are key equipment vendors that supply to manufacturers, innovate on the equipment
- VACS/CNT do not have an equipment vendor/developer ecosystem yet – how does this technical community converge on key equipment and suppliers – FCCVD has unique needs with catalyst delivery and other reactor setups will have their specific needs/equipment designs; since we are dealing with the same feedstock (e.g. CH_4), we may all be facing a similar, governing phenoma
- Potential to scan other industries to find equipment that may fit needs – STeXS OLED System is one potential for ferrocene delivery
- As we build all of these new insights, how will we make them actionable in the reactor/system design? How will we CONTROL the underlying phenomena we uncover?

Production Equipment for Organic and Organometallic Small Molecule Vapor Deposition - OLED Display Technology



Source: https://apeva.de/technology/stexs

Carbon Nanotubes went Mainstream in 2020 – Major Acquisition

Carbon Hub

- Following MWCNTs increasing adoption into Li-ion batteries as conductive materials, Cabot (a US publicly traded company) acquired SUSN, discussed as the 2nd largest MWCNT manufacturer globally
- Industry coverage by BNEF started in 2021
- Market size is approaching $1B by 2025 for Li-ion conductive additives
- SWCNT, few wall CNTs are following fast in the adoption/replacement cycle – cost and purity are key drivers

Batteries

Cabot Corporation Completes Acquisition of Shenzhen Sanshun Nano New Materials Co., Ltd (SUSN)

Apr 01, 2020 04:30 pm

BOSTON -- Cabot Corporation announced that it has completed its previously announced acquisition of Shenzhen Sanshun Nano New Materials Co., Ltd (SUSN) for approximately $115 million. The business will be integrated into Cabot's Performance Chemicals Segment.

SUSN is a leading carbon nanotube (CNT) producer in China. The acquisition significantly strengthens Cabot's market position and formulation capabilities in the high-growth batteries market, particularly in China, which is the largest and fastest growing electric vehicle market in the world. With this acquisition, Cabot becomes the only carbon additive supplier with commercially proven carbon black, CNT, carbon nanostructure and dispersion capabilities.

"We are pleased to complete this acquisition and officially welcome our new colleagues from SUSN to Cabot. We look forward to collaborating with them to strengthen our global leadership position in carbon additives," said Jeff Zhu, senior vice president and president, Performance Additives business. "The addition of SUSN's CNT technology complements our already strong portfolio of conductive carbon products, and creates significant opportunity to deliver new innovative formulated solutions for improved battery performance for the rapidly growing energy-storage market."

SUSN's 2019 revenue was $28 million and the combination of Cabot's energy materials portfolio and SUSN will create a business with approximately $50 million in revenue. Revenue is expected to grow at a rate of 20-25% over the next five years from continued growth in electric vehicles and other lithium-ion battery storage applications, making this a meaningful part of Cabot's portfolio of specialty chemicals businesses.

BloombergNEF

Advanced Materials Primer: Carbon Nanotubes
February 8, 2021

Contents

Advanced Materials Primer: Carbon Nanotubes

Carbon nanotubes, first discovered in 1991, are one of the most unique forms of pure carbon. Their adjustable electrical, mechanical, optical and thermal properties has garnered significant attention over the last three decades. Some envisioned applications such as using carbon nanotubes (CNT) to build a space elevator have yet to progress. However using CNTs to improve performance of batteries has already reached commercialization.

Cabot Corp (NYSE:CBT) Q2 2021 Earnings Call May 4, 2021, *8:00 a.m. ET*

And third, Cabot has a rich legacy of innovating in demanding technical applications. Our experience in the CMP market for semiconductors and inkjet has offered invaluable practices and protocols that will be critical for the battery market. In terms of financial performance, we believe that the battery application will become a material contributor to the Performance Chemicals segment over the next few years. The current conductive carbon additives market for lithium ion batteries which includes both CNTs and conductive carbon black is approximately $400 million in material value.

We expect this market will grow to approximately $1 billion in value by 2025. Our energy materials business is off to a strong start in fiscal 2021 with forecasted revenue of approximately $80 million for the fiscal year. Over the past five years, revenue has grown at a CAGR of roughly 50% which includes the acquisition of our CNT business in China. While we are making significant investments to drive qualification and further extend our technical capabilities EBITDA is forecasted to be between $15 million and $20 million in fiscal year 2021. We are excited about the promise of this emerging application and will continue to focus our efforts to support customers and realize the potential of energy storage.

Carbon Nanotubes …….Production differences

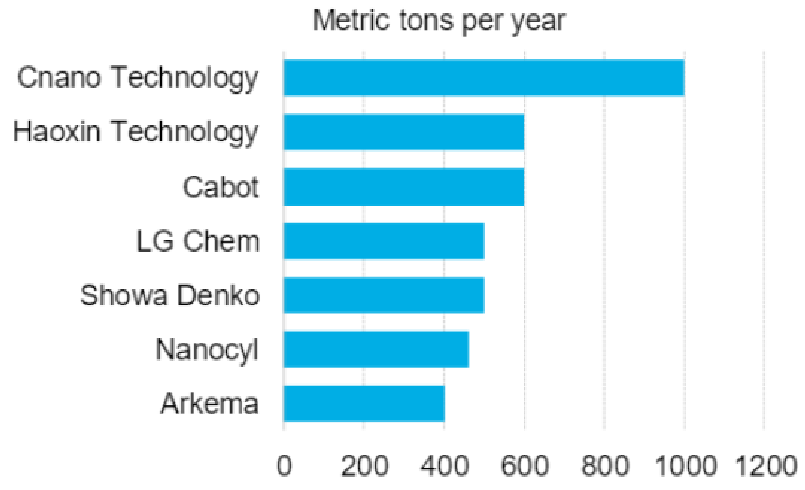
- MWCNT manufacturers have not been able to transfer technology/know-how to SWCNT/Few Wall CNT production and product control
-

Advanced Materials Primer: Carbon Nanotubes

February 8, 2021

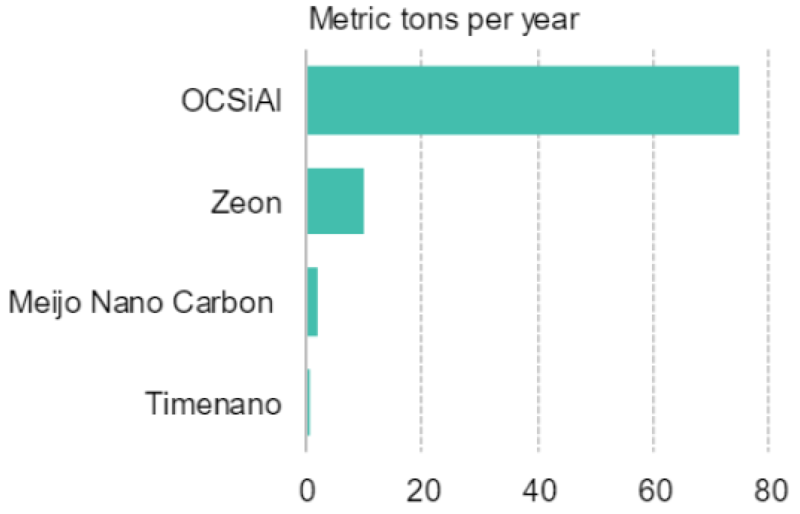
BNEF

Figure 6: MWCNT production capacity by company



Source: BloombergNEF, NEDO, Company websites. Note: Cabot acquired Shenzhen SUSN Sinotech New Materials this year.

Figure 7: SWCNT production capacity by company



Source: BloombergNEF, NEDO, Company websites.

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Short Review of Key Points

Topic #1 Introduction – Workshop Grounding

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1-CNT-1

Manufacturing @ Scale - CNT

Improve CNT Manufacturing pathways – Catalysis

Potential Key topics to be addressed: [Poster text]
Understand and control catalyst design/formation.
How to have efficient catalyst formation & delivery that is decoupled from the synthesis step?
How to enable high-volume manufacturing?
How to improve catalyst utilization?
In lower yield processes, is it possible to recycle catalyst?

1-CNT-2

Manufacturing @ Scale - CNT

Improve CNT Manufacturing pathways – Reaction Mechanisms

Potential Key topics to be addressed: [Poster text]
Improve understanding of the reaction mechanism and how to leverage in reactor design
Improve understanding of the reaction zones, to enable design of novel manufacturing approaches
Improve understanding of the coupling of the heat/mass transport and fluid mechanics in the reactor
Improve mechanism understanding of the three microscopic steps (carbon gets into the catalyst; carbon moves in the catalyst; carbon is "extruded" from the catalyst into a nanotube)
Multi scale modeling of reaction mechanisms
How to rapidly make progress on basis of 2-decades of research

Call for Proposal Recommendation by workshop participants
Linking of 4 critical areas:
1. Manufacturing methods: reactor design, kinetics, CFD
2. catalyst: kinetic, energy at catalyst NT interface: MW or SW : what is the goal, impact of sulfur
3. experimental mechanism understanding: gas (HC rad, soot, PAH), aerosol, CNT growth, sulfur, catalyst life
4. experimental methods: optically transparent reactors, in-situ/ex-situ characterization, XAS, aerosol (DMA, CPMA)

These two topics were merged, and expanded with the definition of VACS

TOPIC #1: Efficiency and Morphology . . .

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To achieve a VACS with commercial potential, we expect that particle design will be critical

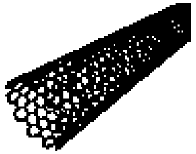
For many applications, ability to convert primary particles into hierarchical structures will be necessary

Potentially for powder based applications, particle design/morphology may be critical for efficacy in functional systems . . . . and to some degree, resultant higher order morphology

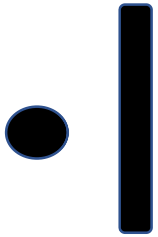
With an identified, useable morphology/particle design, the efficiency must have a path to and be explained – we're realists, we know it won't go straight to upper limits

What are controlling factors for particle design – process parameters, Catalyst Design – combinations?

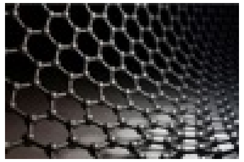
CNT



Particles To be Designed

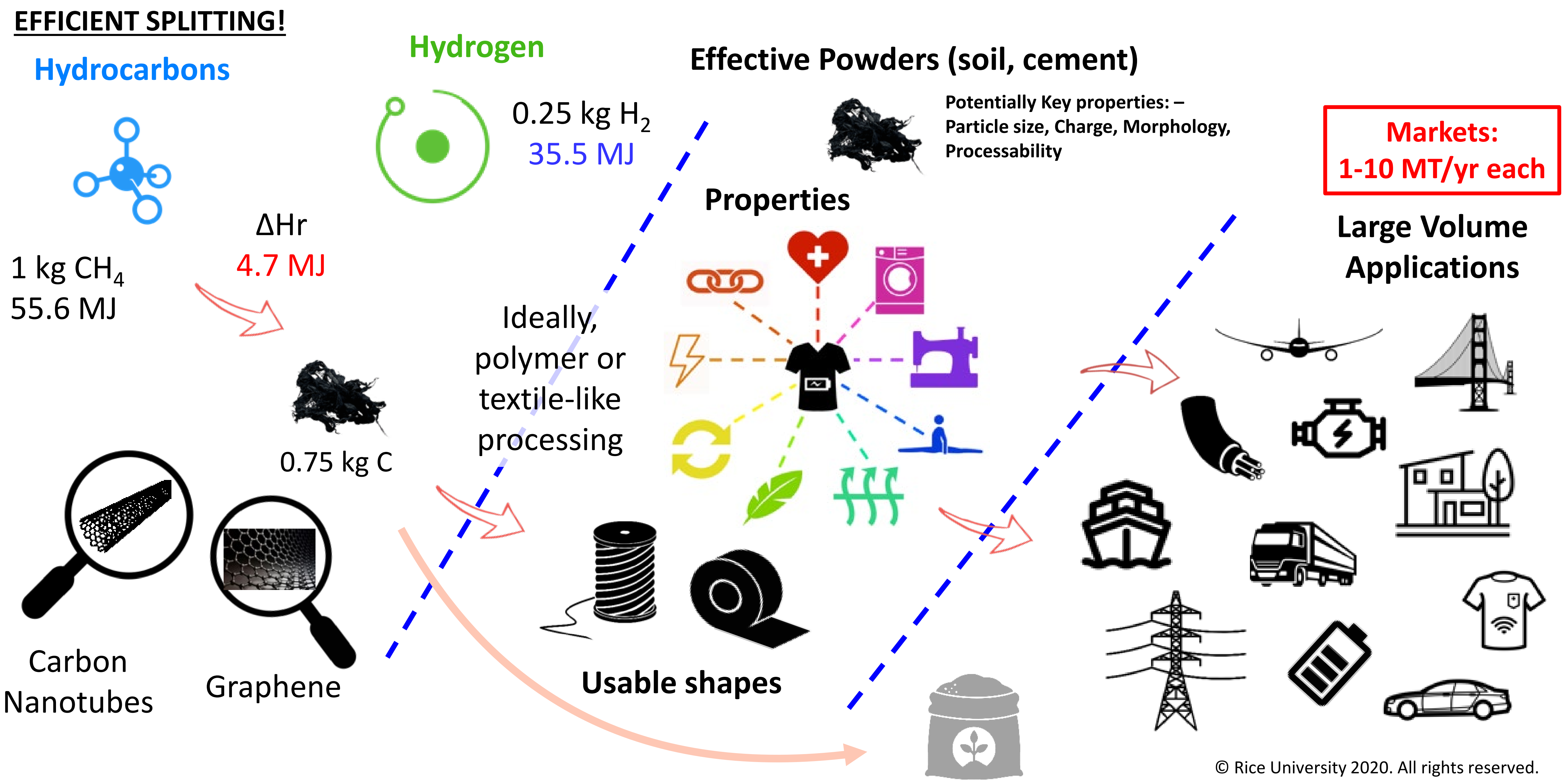


Graphene



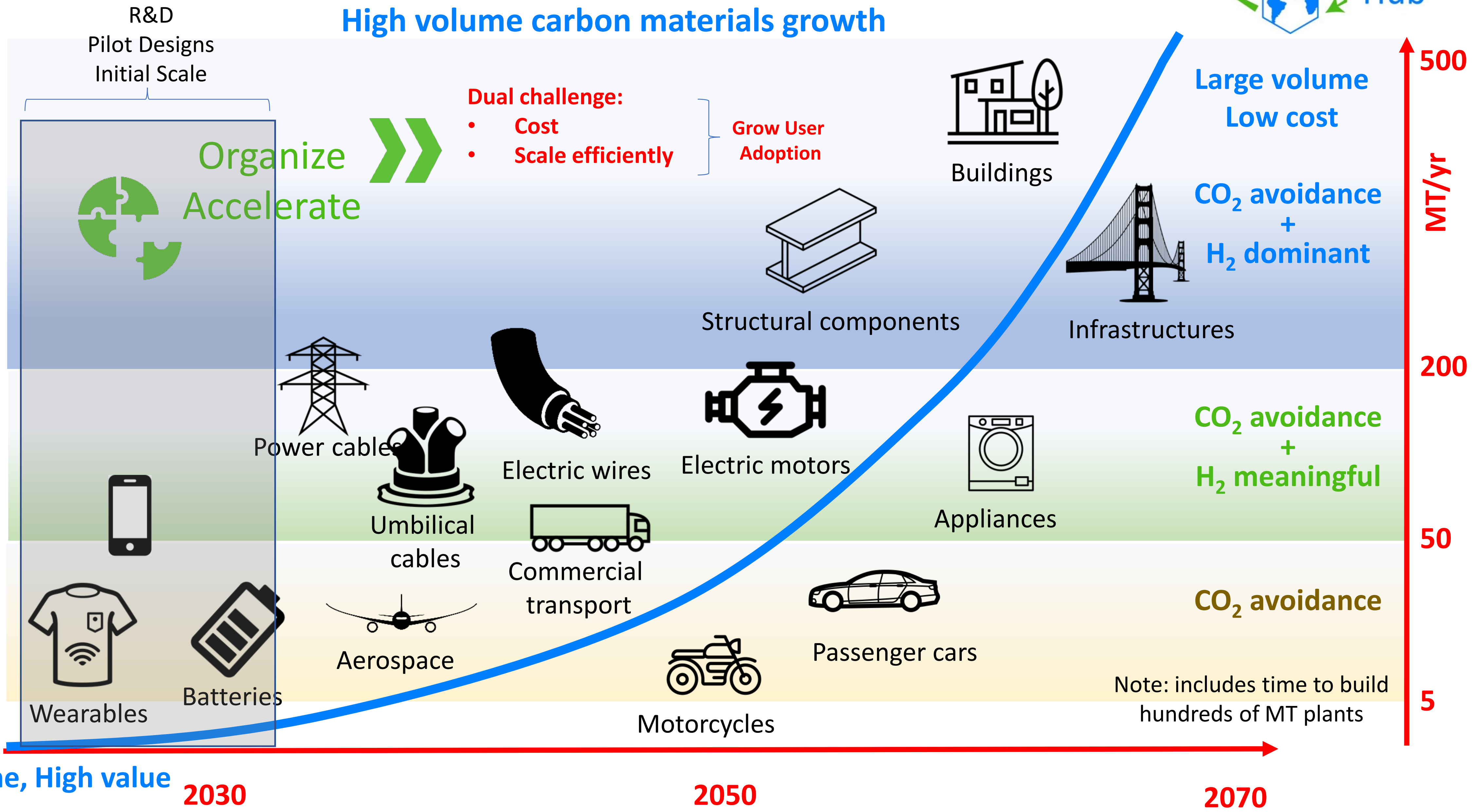
Properties

A NOVEL HYDROCARBON PATHWAY
Zero Emission Energy + VACS



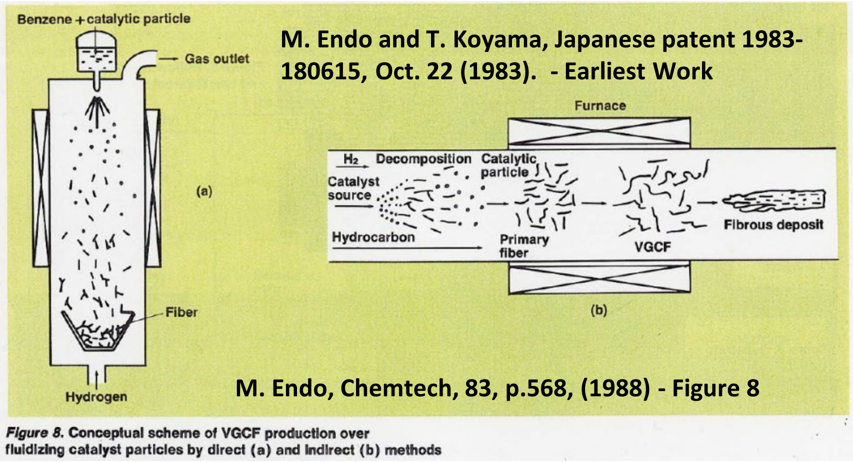
Deploying VACS into Commercial Markets

- Cost is established with lower volume, higher cost material opportunities
- Transparent Thin Film Conductors for mobile devices have market size @ 10 – 20 Metric Tons/yr
- In Parallel, applications development must occur
- Growth curve will depend on community size, Gov't Investment, Policy development, and technical successes



Catalytic Flow Reactors Technical Lineage 1983 – Present
Vapor Grown Carbon Fibers to Carbon Nanotubes

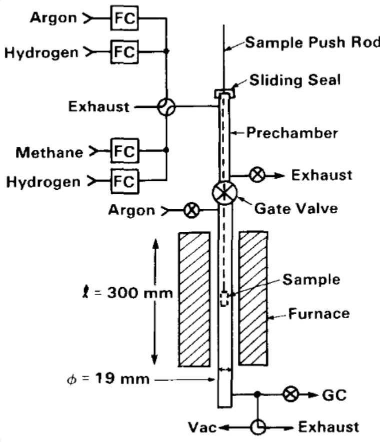
← VGCF | CNT →



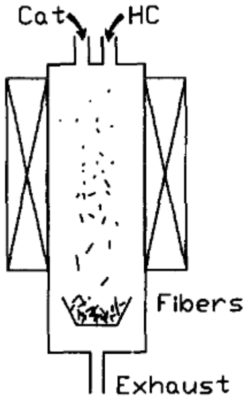
M. Endo and T. Koyama, Japanese patent 1983-180615, Oct. 22 (1983). - Earliest Work

M. Endo, Chemtech, 83, p.568, (1988) - Figure 8

Figure 8. Conceptual scheme of VGCF production over fluidizing catalyst particles by direct (a) and indirect (b) methods



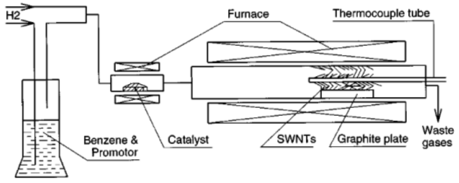
Journal of Crystal Growth 73 (1985) 431—438



Carbon Vol. 27. No. 5. pp. 745-747, 1989

M. Endo and G. Tibbets lead designs forPrecursor systems to the primary CNT Flow Reactor Design In mid-1980s – 1993 introduced the now familiar design with a metallocene Catalyst source

Appl. Phys. Lett. 72, 3282 (1998)



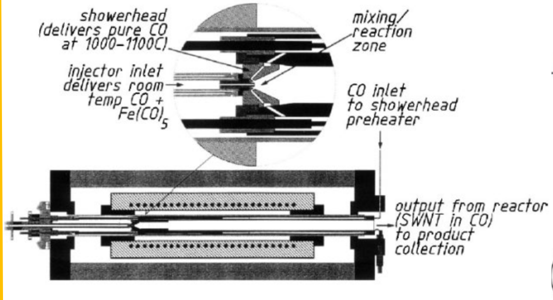
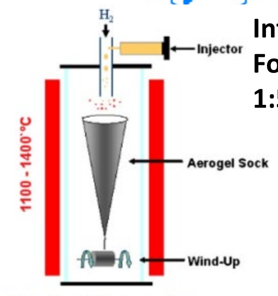


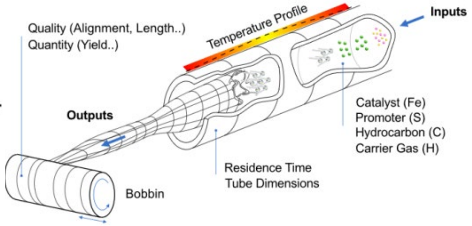
FIG. 1. HiPco reactor, with the mixing/reaction zone shown enlarged.

J. Vac. Sci. Technol. A 19.4., Aug 2001



1 Schematic of Cambridge set-up [21]

Int J Mater Form (2008) 1:59–62



Carbon, Volume 146, May 2019, p. 789-812

1980s.................................... 2020

- Major questions that were rarely addressed in the 1990s – Present:
  - Is the equipment appropriate to control the underlying phenomena:
    - How does the reactor geometry influence reaction?
    - Can catalyst be supplied appropriately – mean size, distribution, flux/concentrations – Most systems used sublimation units (poor scalability)
  - System design had little change or explanation from 1993 - present
- How is Heat Supplied for endothermic reaction?
- What is interplay between thermochemistry, transport phenomena, reactor and reaction design?

Rice lab overcomes supply issue in nanotube commercialization

JADE BOYD – FEBRUARY 6, 2003

POSTED IN: CURRENT NEWS

Like 0 Tweet Share

Rice lab overcomes supply issue in nanotube commercialization

BY JADE BOYD
Rice News Staff

Following four years of arduous work, chemists in Rice University's Carbon Nanotechnology Laboratory (CNL) have created the first system that can continuously produce single-walled carbon nanotubes in bulk.

The refinement of the high-pressure carbon monoxide process, known as HiPco, is a watershed achievement in nanoscience because it eliminates the most significant bottleneck to nanotube commercialization: supply.

Postulated FCCVD Process Steps

We're interested in fundamental studies that clearly articulate mechanisms, remove roadblocks to efficiency (catalyst utilization), equipment improvements

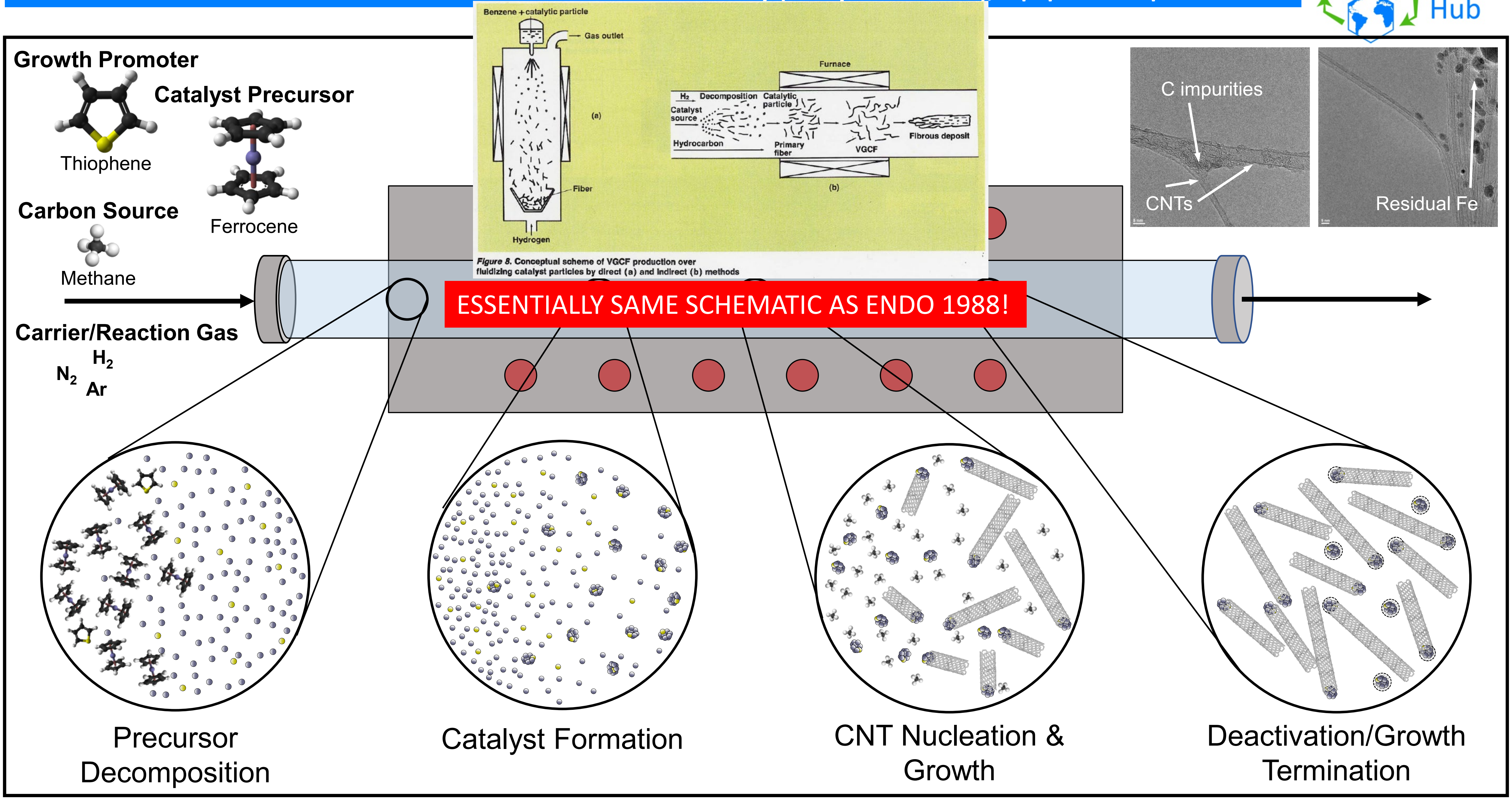


Figure 8. Conceptual scheme of VGCF production over fluidizing catalyst particles by direct (a) and indirect (b) methods

FCCVD Flow Reactors for CNT Synthesis: Literature Synopsis

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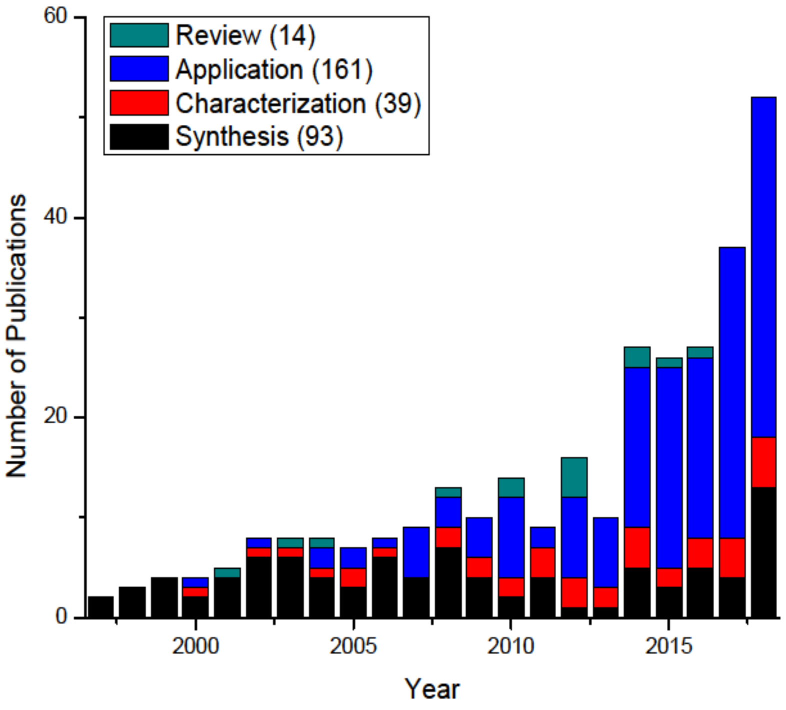
REACTOR PARAMETERS	%
Temperature Profile Inside Reactor	16
Pressure Inside Reactor	29
Injection Configuration	39
Reactor Dimensions/Geometry	46
Carbon Feedstock	100
Carbon Feedstock Flow Rate	84
Carrier Gas	91
Carrier Gas Flow Rate	79
Catalyst	100
Catalyst Mass Flow Rate (mass/time)	66
Catalyst Mean Particle Size	39
Growth Promoter	100
Growth Promoter Flow Rate (mass/time)	71
Reactor Tube Material	61
MATERIAL CHARACTERIZATION	**%**
CNT Selectivity and/or Catalyst Efficiency	13
Carbon Conversion	11
Raman (G/D and/or RBM)	62
Residual Catalyst Content	21
Production Rate (mass/time)	20
Average Wall Number	62
Average CNT Length	29
Average CNT Diameter	79

N = 85 papers which focused primarily on synthesis



Over 300 papers were reviewed to evaluate progress in research for FCCVD-grown CNTs

Our team at Rice completed a meta-analysis of FCCVD related publications and found limited attention paid to reactor and reaction design

Many works focused on CNT material properties "goals" and applications

Correlating reactor design and reaction almost non-existent

Floating Chemical Vapor Deposition for Scalable Carbon Nanotube Production: A Review
Emily Yedinak+, Clayton Kacica+, Arthur Sloan, Leonardo Spanu, Jonathan Bloom, Brendan Ni, Glen C. Irvin*, Matteo Pasquali

FCCVD Flow Reactors for CNT Synthesis – Multiple Reactions, Reaction Management

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$$CH_4 \rightarrow C_{solid} + 2H_2 \quad \Delta H_{298^oC} = +75.3 \frac{kJ}{mol_{CH_4}}$$

$$S_{CNT/Soot} = \frac{r_{CNT}}{r_{Soot}}$$

But, the reaction is much more complicated due to reactor Design and inability to control Selectivity:

A range of Competing Parallel and Competing Consecutive Reactions are occurring

$$CNT + C_n \rightarrow CNT - Amorphous\ Carbon$$

$$Fe_n + C_{monomer} \rightarrow Fe_n - Amorphous\ Carbon$$

$$CH_4 \rightarrow C_{soot} + 2H_2$$

Must manage fast dynamics of potential reactions with CH_4

What is competition between Homogeneous and Heterogeneous CH_4 decomposition?

How to manage competition between CNT and other amorphous carbons?

Homogeneous CH_4 decomposition Is RAPID

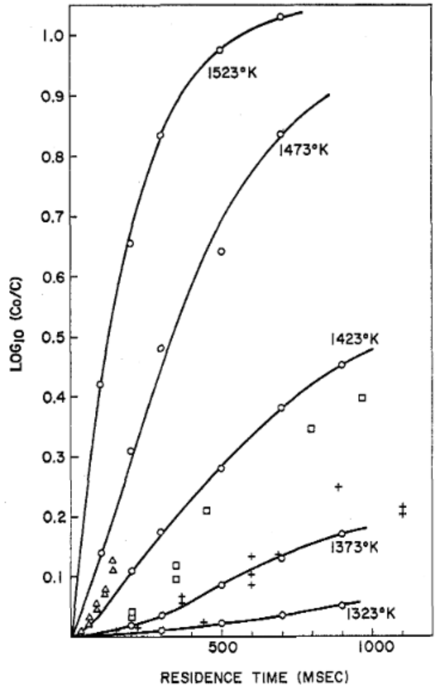


Figure 2. Kinetic results at five temperatures, at input concentrations close to 10 mole %. The results of Eisenberg and Bliss[7] are shown for comparison, as follows: crosses, 1371°K, 15–25 mole %; squares, 1409°K, 15 mole %; triangles, 1458°K, 15 mole %.

H. Palmer, J. Lahaye, K. Hou, Kinetics and mechanism of the thermal decomposition of methane in a flow system, Journal of Physical Chemistry 72 (1968) 348–353.

The Literature only demonstrates one Route to manage these reactions:

Addition of H_2

- Significantly reduces CH_4 decomposition
- Pushes reaction temperatures higher
- Reactive with Ferrocene

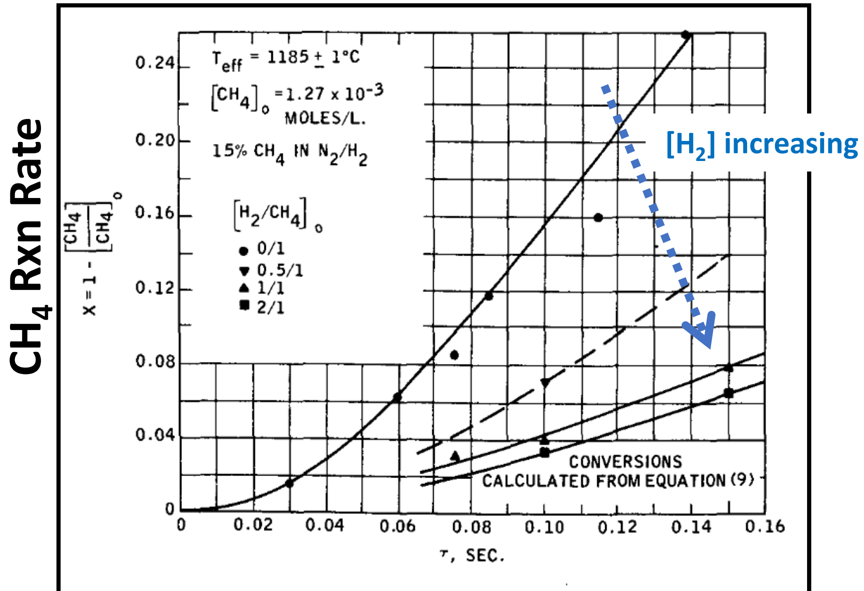


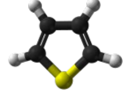
Fig. 8. Effect of hydrogen.

B. Eisenberg, H. Bliss, Kinetics of methane pyrolysis, Chemical Engineering Progress Symposium Series 63 (1967) 3–17.

FCCVD Flow Reactors for CNT Synthesis – Catalyst Design/Production, Reaction Complexity

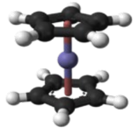
System originally designed to Manage multiple reactions simultaneously

Growth Promoter



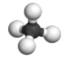
Thiophene —decomposition→ Sulfur ↓ S_n?

Catalyst Precursor



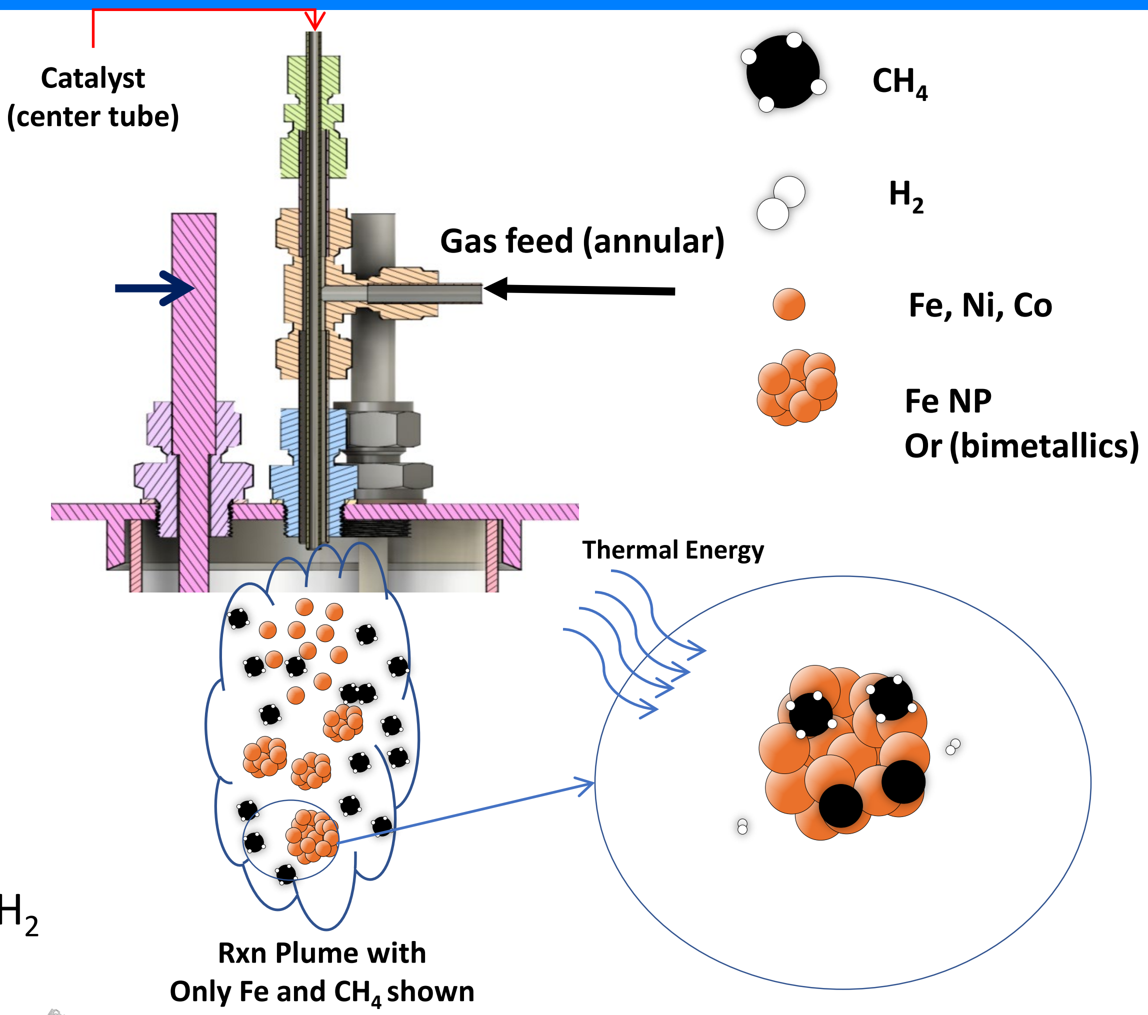
Ferrocene —decomposition→ Fe ↓ $(Fe)_n$

Carbon Source



Methane —decomposition→ $C_{atom} + H_2$

C_{atom} + $(Fe)_n$ —growth→



Spatio-Temporal Perfection is critical

- Catalyst/reaction promoters have been used with minimal understanding, no definitive mechanism
- Equipment for catalyst formation historically has had limited capability, limiting whole reaction system
- Catalyst has generally been formed within reaction environment, requiring multiple reactions to be managed simultaneously
- Controlling particles to desired 1 – 2 nm size has limited options; Empirical data says larger catalyst particles are functional
- Characterization of real-time reaction environment has generally been sporadic in literature; insight into these dynamics would be beneficial
- What are paths to Scale?

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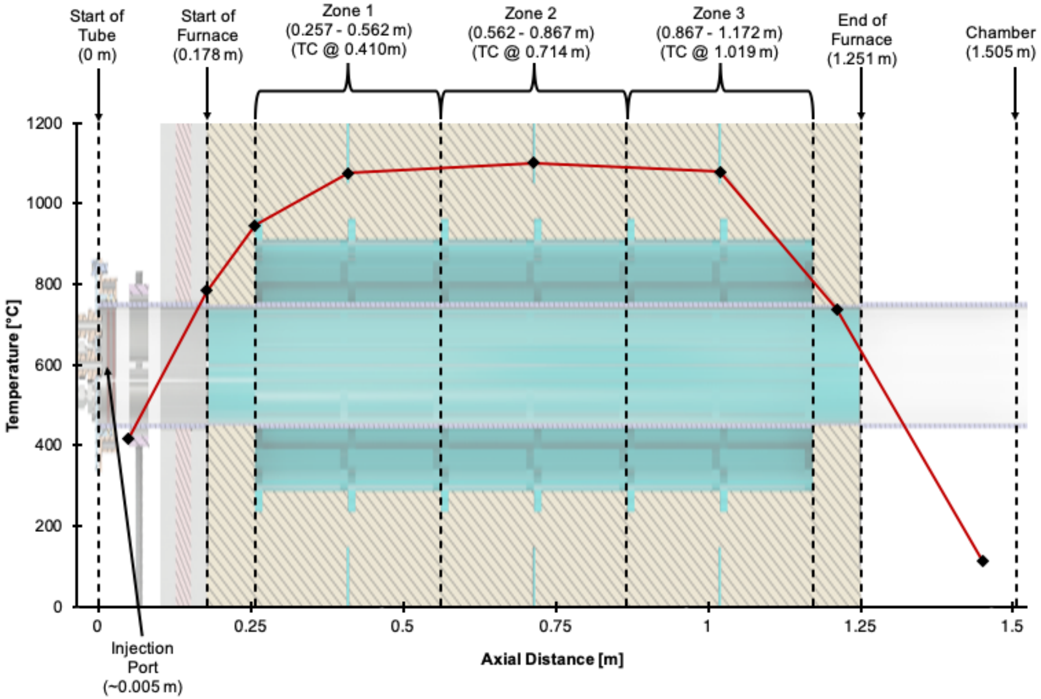
FCCVD Flow Reactors for CNT Synthesis – Thermal Profile/Heat Integration

$$CH_4 \rightarrow C_{solid} + 2H_2 \quad \Delta H_{298^oC} = +75.3 \frac{kJ}{mol_{CH_4}}$$

Supplying heat is not straightforward in this, low density Gas-phase reaction – Scaled solutions not clear

sensible heat + reaction enthalpy

$$Q_{rxn} = \dot{n}_{CH_4} c_{p,CH_4} M_{CH_4} \Delta T_{CH_4} + \chi \, \dot{n}_{CH_4} \Delta H_{Rxn}$$



Typical FCCVD flow reactors have non-uniform thermal profiles, Leading to non-uniformities in key reaction control factors:

- reaction rate
- reactive species/distribution
- transport – mass, thermal

How can Thermal Transport be improved – Reactor Design?

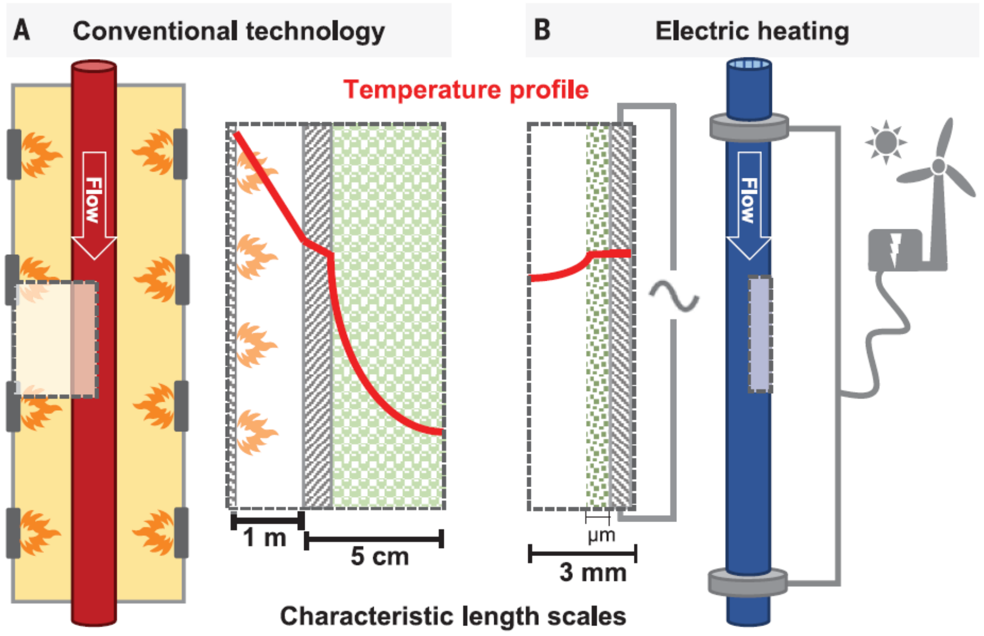


Fig. 1. Heating principles. (**A**) Conventional fired reactor. (**B**) Electric resistance–heated reactor. Characteristic radial length scales and temperature profiles are shown across the heat source, reactor wall (gray), and catalyst material (green). In (B), the heat source and reactor wall are one. Illustrations are not to scale.

Wismann et al., Science 364, 756–759 (2019)

A Reactor system that is reportedly making progress: OCSiAl

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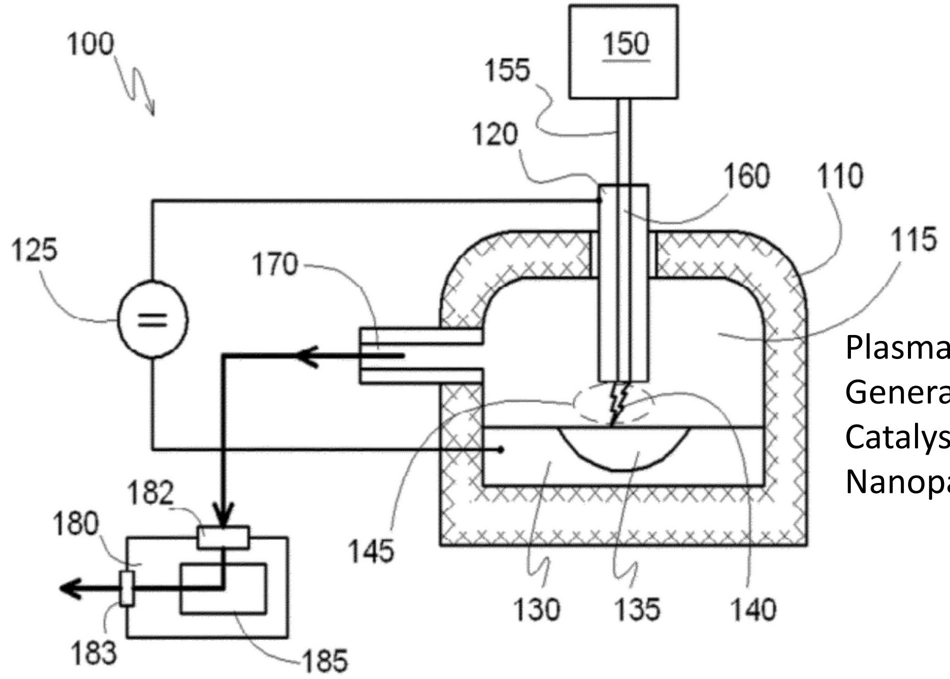
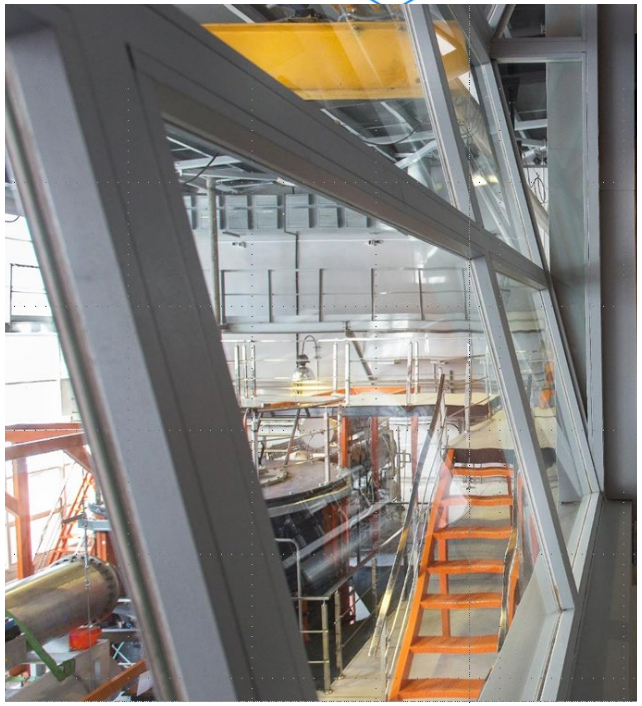
US Patent# 8137653 – “OCSiAl”



Plasma Generation of Catalyst Nanoparticles



Plasma torch can achieve very high Fe Saturation Ratios

Appears to be Flow Reactor setup based on Press and Images found

Unknown what is the efficiency, but data suggests it still is not Very high due to residual metals in products (Tuball)

The most obvious technology OCSiAl brought to table is Plasma Reactor technology for Catalyst nanoparticle formation

This Reactor, Grapheton 1.0 started with a nameplate capacity Of 1 Metric Ton/yr

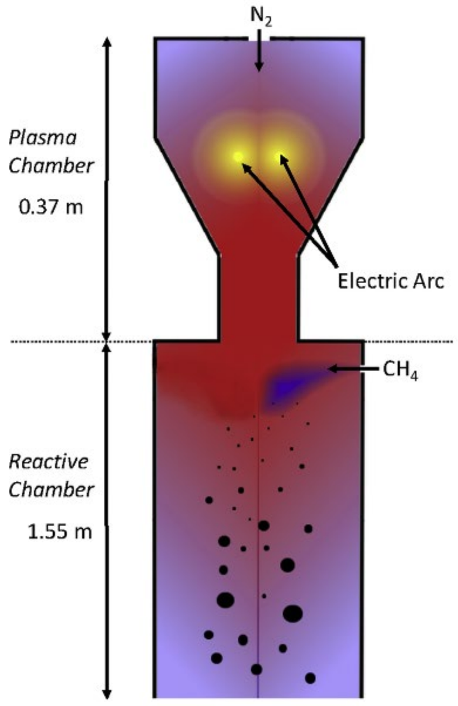
Over 4-5 years, reports indicate it grew to 10 Ton/yr and finally 17 Ton/yr

50 Ton Reactor reported to be designed and operational

At multiple Tons/yr scale, had to address Heat Integration

Other reactor approaches – Efficient Splitting in O_2 free environment

- Controlling morphology in these systems is important – what is controlling particle dimensions?
- Heat Integration techniques?
- Product separations, solids & gases
- How does mass transport influence growth & morphology development?
- What are paths to Scale?
- ***Is there a fundamental phenomena across the different reactor platforms that governs VACS growth via CH4 – that the community is missing currently?***

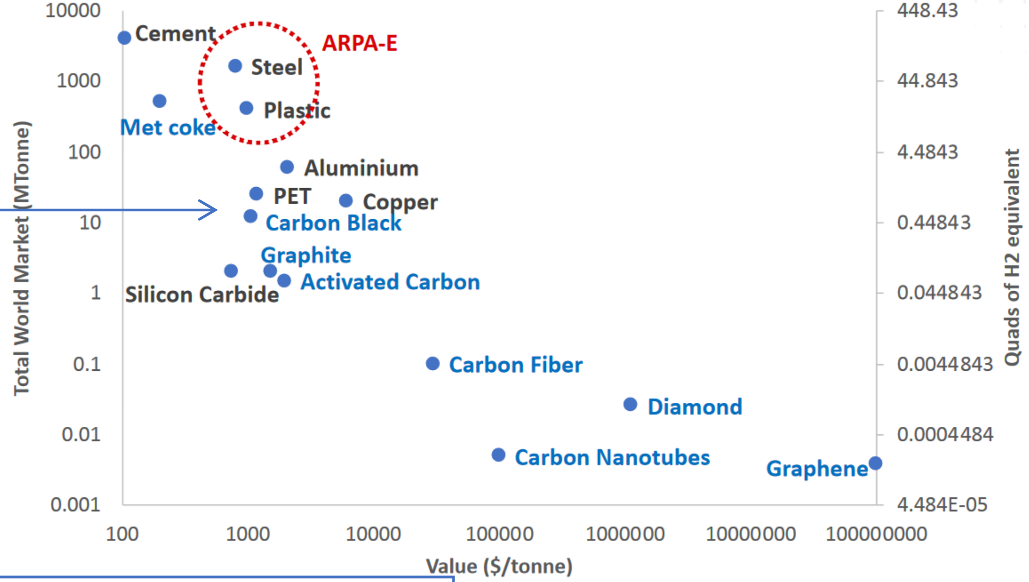


Courtesy Eric McFarland, ARPA-E Methane Pyrolysis Kick-off Dec 2019

Gautier M, et al., Direct decarbonization of methane by thermal plasma for the production ofhydrogen and high value-added carbon black, International Journal of Hydrogen Energy (2017),

What is OUT OF SCOPE – what are we NOT looking for

Slide courtesy of Marc von Keitz, ARPA-E/DOE Methane Pyrolysis Cohort Kickoff Houston, TX Dec. 9 & 10, 2019



- ❑ Any work related to Carbon Black
  - @ 12-16Mt/yr with 4% growth
  - Reaches ~40Mt/yr in 2050
- ❑ Projects not linked to Carbon Hub Vision
- ❑ Studies previously completed

New Insights are Critical – re-hashing previous investigations without clear advancement potential will not Move the goals forward

– new fundamental insights, that will remove roadblocks or generate new paths forward, are of interest, needed

- Must be VACS
- Path to Scale, efficiently (geometric similarity)
- Preferable to have multiple GHG, energy impacts

e.g. lightweighting in application and eliminates needs for metals production upstream

- Efficiently splitting Methane, without O_2

Roadmapping Synthesis . . . . December 2021?

Carbon Hub

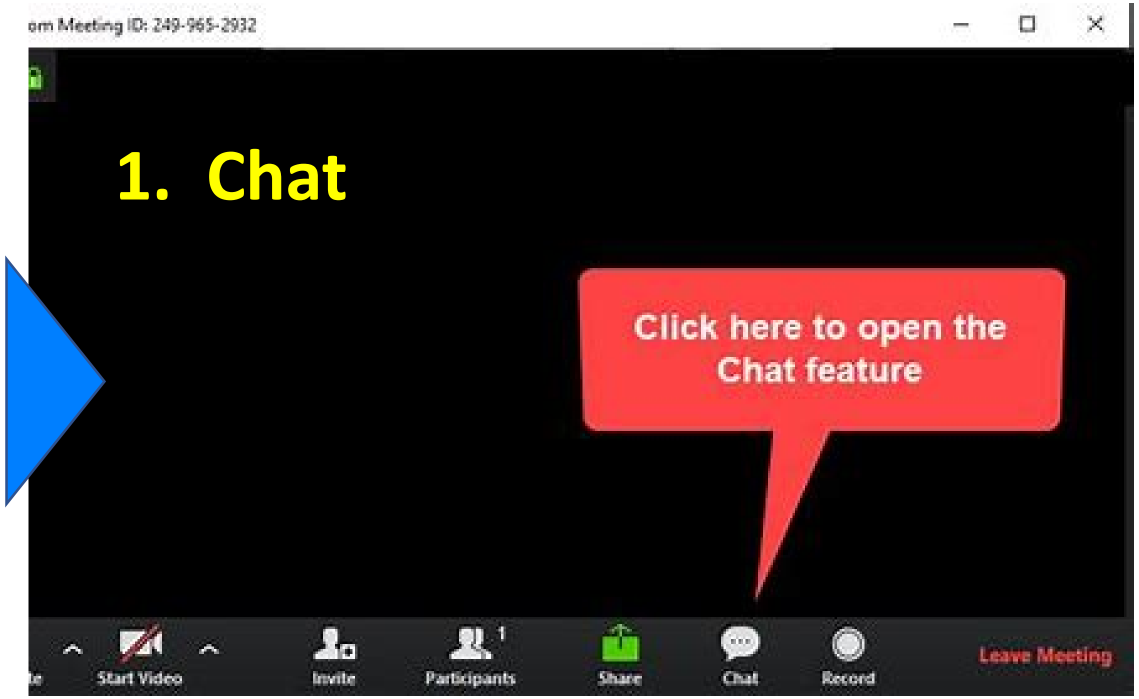
- ❑ How do we become more actively engaged?
- ❑ The Carbon Hub may have an in person event in December 2021
- ❑ We can use the time to further organize key efforts needed, State of the Art benchmarking, and establish some Goals to help direct the technical community

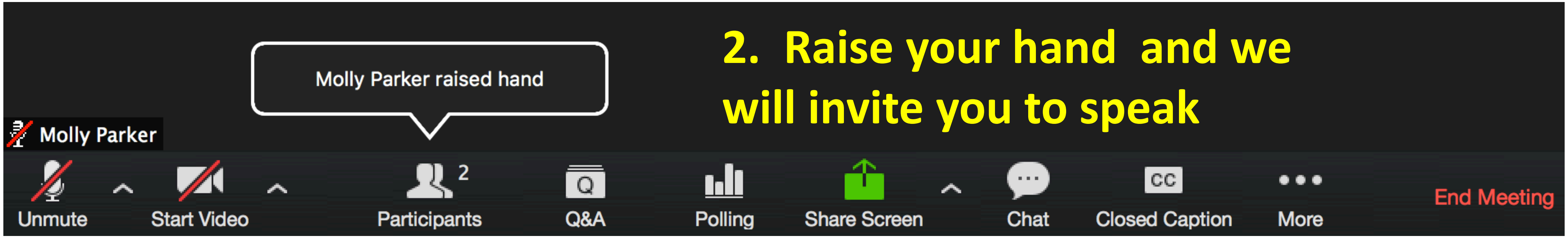
Carbon Hub Webinar - Agenda

Carbon Hub

General	❑ Introduction Carbon Hub ❑ Mission and Vision	10 min
What are we trying to solve?	❑ Topic Introduction ❑ Expert deeper dive ❑ Key deliverables ❑ What is out of scope – What are we NOT looking for ❑ Budget and timeline	30 min
Q&A	❑ Please ask us questions	15 min
Next Steps	❑ In summary – How to submit your proposal ❑ Call for Proposal Process and timeline - Some Terms & Conditions	5 min

Q&A – Please ask us any questions you might have





Carbon Hub Webinar - Agenda

Carbon Hub

General	❑ **Introduction Carbon Hub** ❑ **Mission and Vision**	10 min
What are we trying to solve?	❑ **Topic Introduction** ❑ **Expert deeper dive** ❑ **Key deliverables** ❑ **What is out of scope – What are we NOT looking for** ❑ **Budget and timeline**	30 min
Q&A	❑ **Please ask us questions**	15 min
Next Steps	❑ **In summary – How to submit your proposal** ❑ **Call for Proposal Process and timeline - Some Terms & Conditions**	5 min

Next Steps – How to submit

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carbonhub.rice.edu/CFPCollaborators

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Carbon Hub
Accelerating the Energy Transition Through Green Hydrocarbons

Menu

Carbon Hub - Call For Proposals 2021

On this page, you will find the Call for Proposals details that are restricted to our Collaborators only.

You may download the full Call for Proposals guidelines and instructions document in PDF form here.

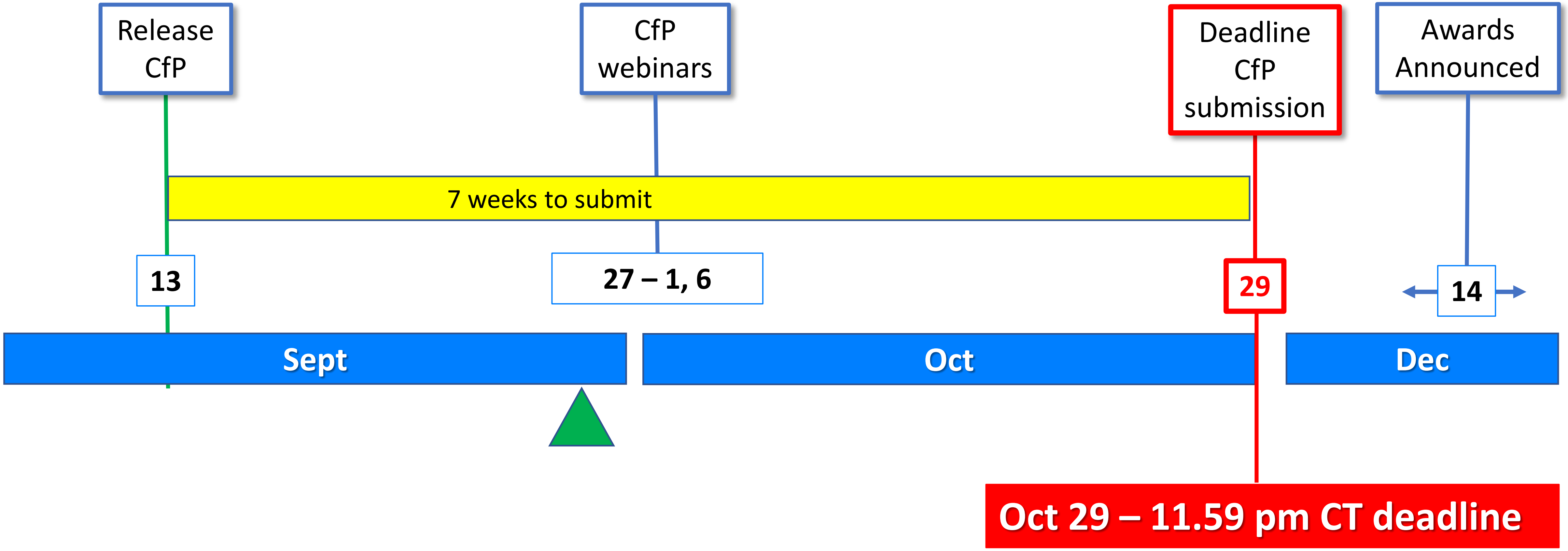
**UPDATE: The Budget guidelines are attached here and the referenced spreadsheet can also be found here.

Please note, all Rice Collaborators should contact us directly at carbonhub@rice.edu to obtain the internal Budget template. That template cannot be shared with external Collaborators.

Oct 29 – 11.59 pm CT deadline

Call for Proposal Timeline

Carbon Hub



A Summary of the aspects we'd like you to address in your proposal (1/2)

CURRENT PROPOSAL SECTION	SECTION CONTENTS	PAGE LIMITATIONS
Executive Summary	Research Team a) Name of Principal Investigator(s) b) Affiliation – institute c) Address, city, country Contact details: email and phone Topic # and Proposal Title Abstract	1
Innovation, Impact, and Linkage to Carbon Hub Vision	How are you addressing the Topic Challenge? Provide a concise description of why the proposed research will further the Carbon Hub Vision.	1
Proposed Work	What techniques & knowledge will you use? Provide a concise description of the equipment, technology and knowledge you will be using. Why is this an effective way to address the challenge? Provide a concise description why your approach is an effective and innovative way to create new insights and value. What are the key deliverables?	4

A Summary of the aspects we'd like you to address in your proposal (2/2)

Carbon Hub

CURRENT PROPOSAL SECTION	SECTION CONTENTS	PAGE LIMITATIONS
Team Organization and Capabilities	What is the team to address this challenge? Concise description of research team actively working on proposed effort: names, project roles. Why should we fund your team? What is the team's expertise and capabilities? Concise description of key expertise and capabilities as related to the project approach.	1
Budget	Breakdown by categories, including any cost share. (budget template will be provided by September 30, 2020)	1
References cited	Includes both literature references and references to earlier work by the proposing team.	2
Personnel Qualifications Summaries	NSF-style preferred	2 pages per person
Risks and Other Insights	What are the key risks in your approach? How are you managing the risks? What else might be important?	1

Some of the Terms & Conditions

Carbon Hub

- ❑ **The primary Principal Investigator (PI) must be a Carbon Hub Academic Collaborator** (https://carbonhub.rice.edu/collaborators) to be eligible to submit a proposal
- ❑ If you are not currently a Collaborator, please inquire at **carbonhub@rice.edu**

- ❑ **Fall 2021 : $1.5+ million budgeted for new and continuing awards**
- ❑ Anticipate~~s~~ granting 4 - 7 awards across the 5 Topic areas
- ❑ **Individual awards may vary between $50,000 and $250,000**
- ❑ For PIs who are not at Rice University, funding will start upon successful negotiation of a subcontract between Rice University and their home institution
- ❑ Funding agreements are expected to launch in Feb 2022, or once negotiations are complete

Results can be published – THEY ARE <u>NOT</u> CONFIDENTIAL
Results will be shared with Carbon Hub members

Further details on the Carbon Hub website and in the Call for Proposal documents

Carbon Hub Webinar - Call for Proposals Fall 2021

Carbon Hub