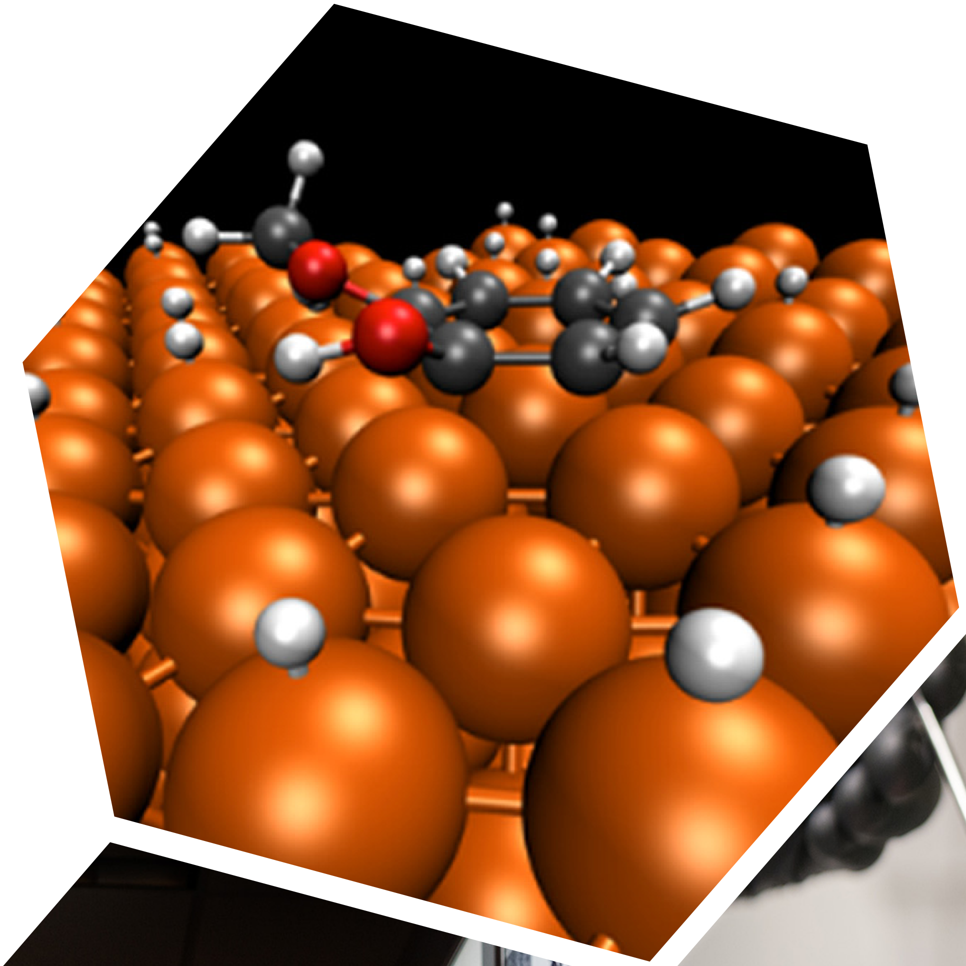
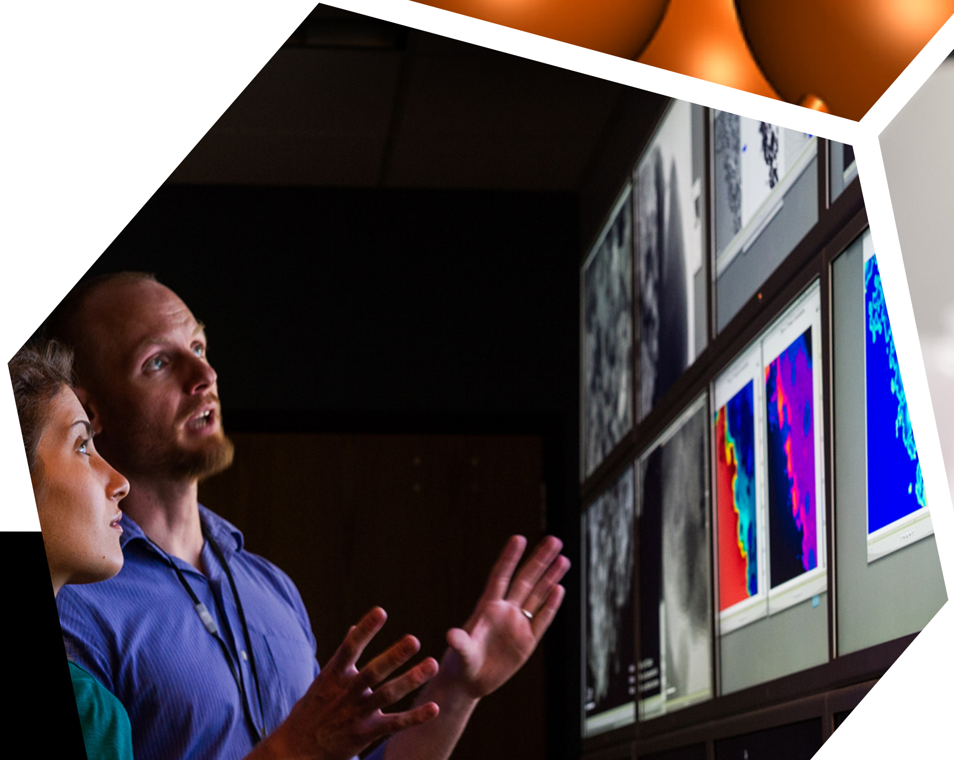
ChemCatBio
Chemical Catalysis for Bioenergy

Pacific Northwest
NATIONAL LABORATORY

DOE Bioenergy Technologies Office (BETO)
2021 Project Peer Review

2.5.4.501
Catalyst Deactivation Mitigation for Biomass Conversion





March 10, 2021
Catalytic Upgrading

Huamin Wang
Pacific Northwest National Laboratory

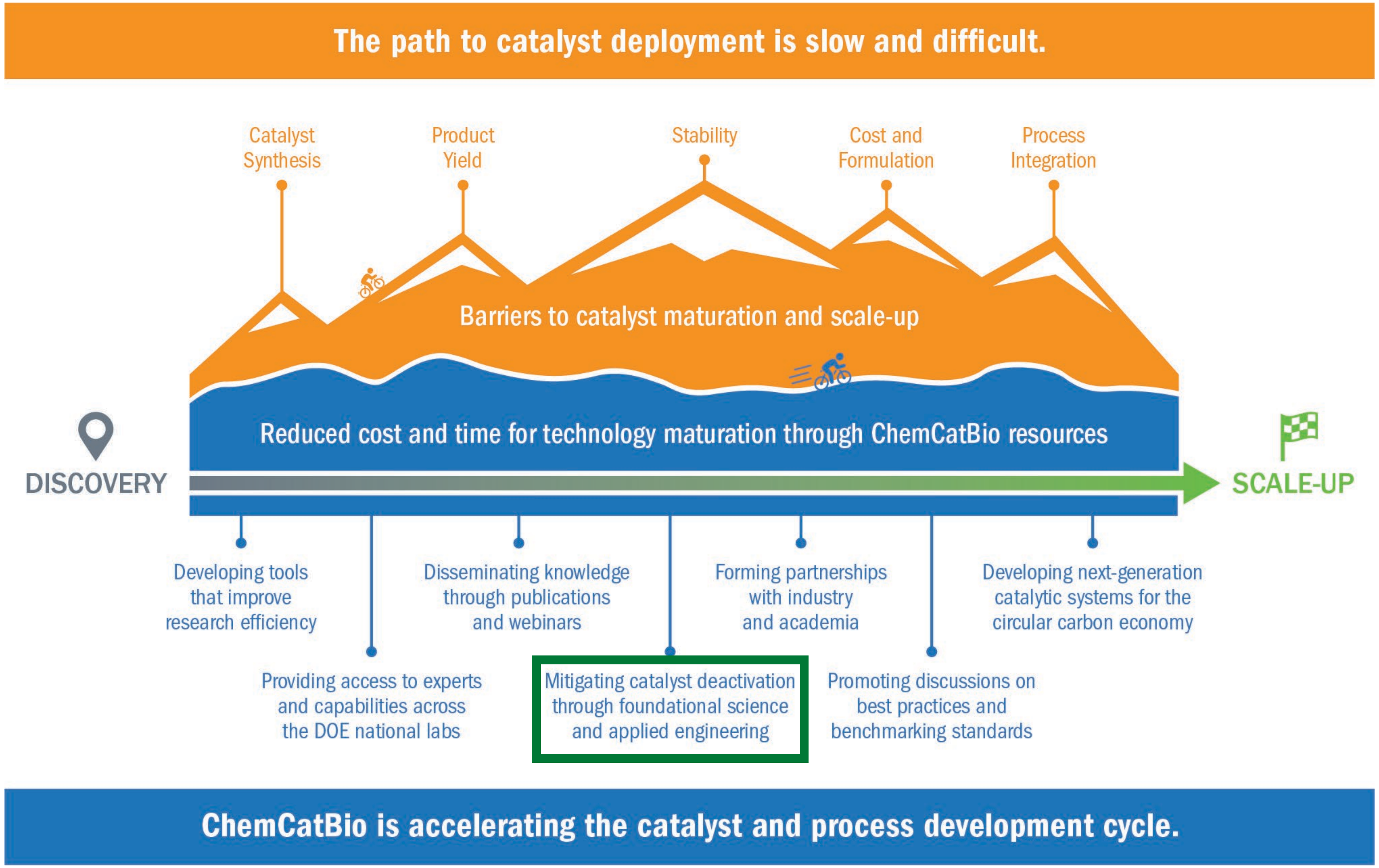
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
BIOENERGY TECHNOLOGIES OFFICE

Project Overview - **Our Goal is to Address Catalyst Deactivation Challenge**

Project Goal: Provide fundamental insight and actionable recommendations for ***extending catalyst lifetime*** in biomass catalytic conversion by a collective and collaborative effort within *ChemCatBio.*

Outcome: Accelerated catalyst and process development with:

- ***Knowledge on*** overarching catalyst deactivation issues;
- ***Catalyst with extended lifetime;***
- ***Tool/method*** to understand deactivation and faster evaluate stability.

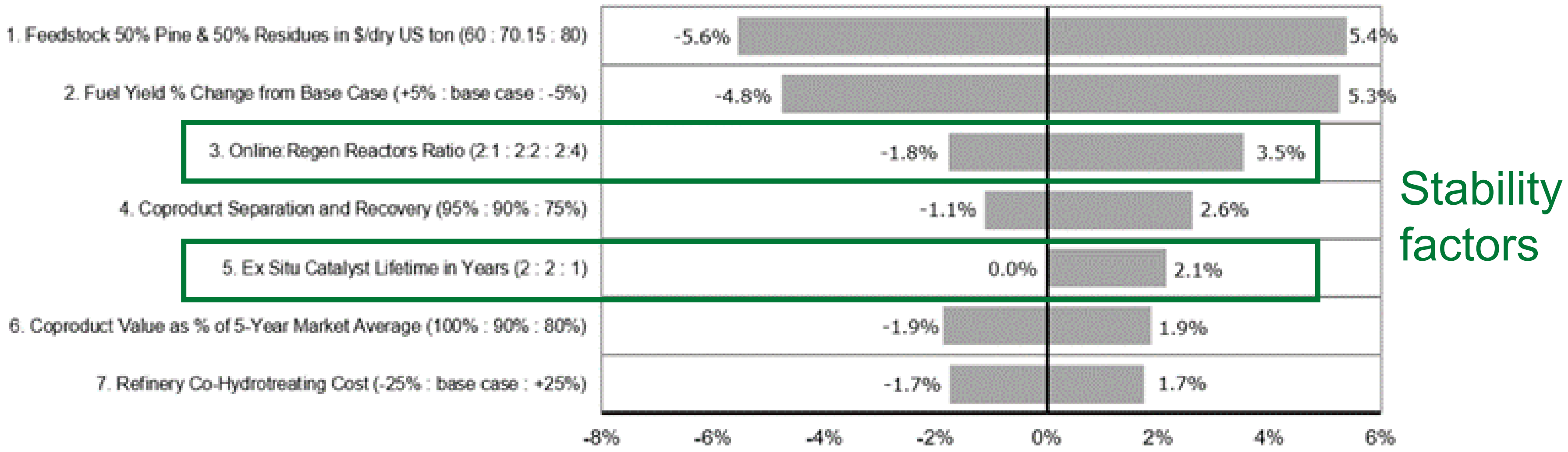


Relevance:

- Enable **cost and risk reductions** of catalysis processes for BETO conversion technologies
- Fulfill the need of emphasis on the catalyst stability in catalysis and biomass conversion R&D

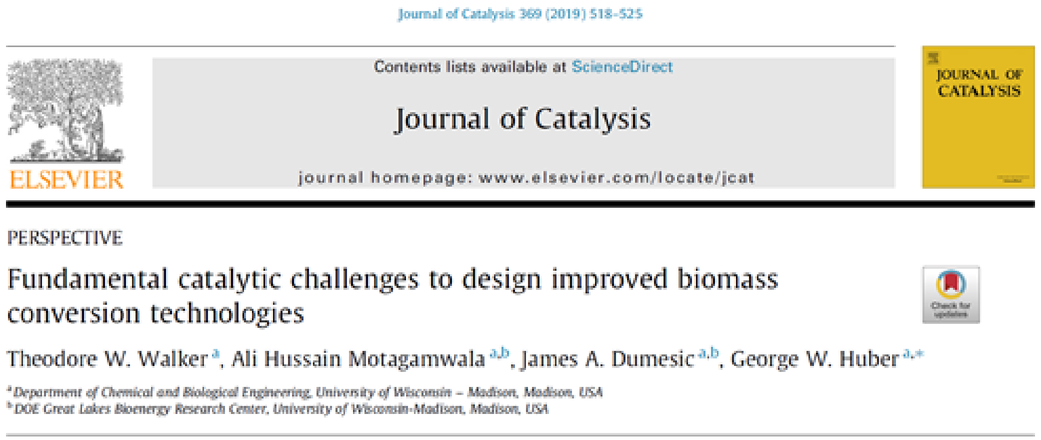
Project Overview - **Catalyst Stability is Key to Commercial Viability**

- Catalyst stability/lifetime plays a critical role in **process economics.**
- **A systemic need** within ChemCatBio to address catalyst deactivation issues.
- Our catalysis R&D communities are **calling for a focus** on catalyst stability.



% Change to MFSP from the *ex situ* CFP base case ($3.09/GGE)

CFP: catalytic fast pyrolysis; MFSP: minimum fuel selling price; GGE: Gasoline gallon equivalent



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PERSPECTIVE

Fundamental catalytic challenges to design improved biomass conversion technologies

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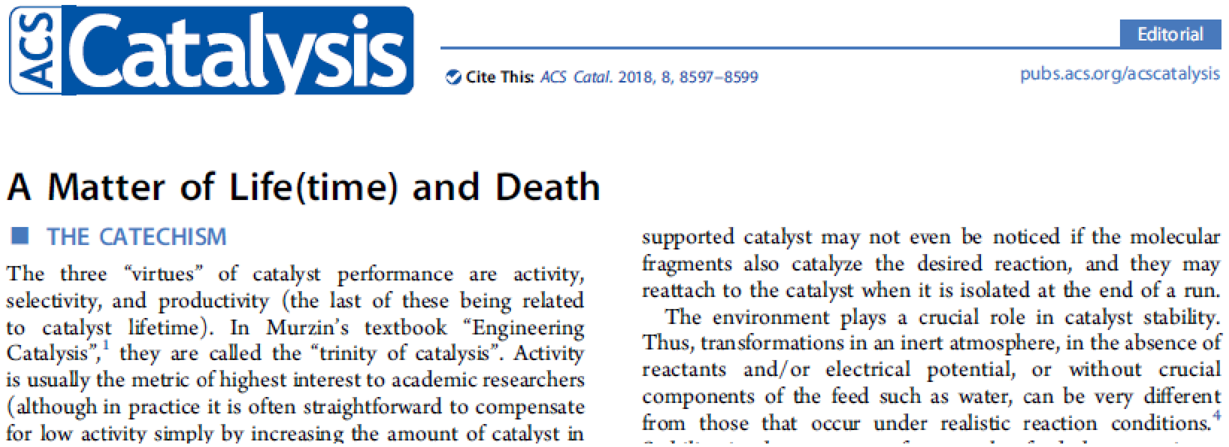
J. Catal. 2019, 369, 518



ACS Catalysis

Editorial

Cite This: ACS Catal. 2018, 8, 8597–8599

pubs.acs.org/acscatalysis

A Matter of Life(time) and Death

THE CATECHISM

The three "virtues" of catalyst performance are activity, selectivity, and productivity (the last of these being related to catalyst lifetime). In Murzin's textbook "Engineering Catalysis",[1] they are called the "trinity of catalysis". Activity is usually the metric of highest interest to academic researchers (although in practice it is often straightforward to compensate for low activity simply by increasing the amount of catalyst in

supported catalyst may not even be noticed if the molecular fragments also catalyze the desired reaction, and they may reattach to the catalyst when it is isolated at the end of a run.

The environment plays a crucial role in catalyst stability. Thus, transformations in an inert atmosphere, in the absence of reactants and/or electrical potential, or without crucial components of the feed such as water, can be very different from those that occur under realistic reaction conditions.[4]

ACS Catal. 2018, 8, 8597

Biomass derived feedstocks bring new challenges to catalyst longevity.

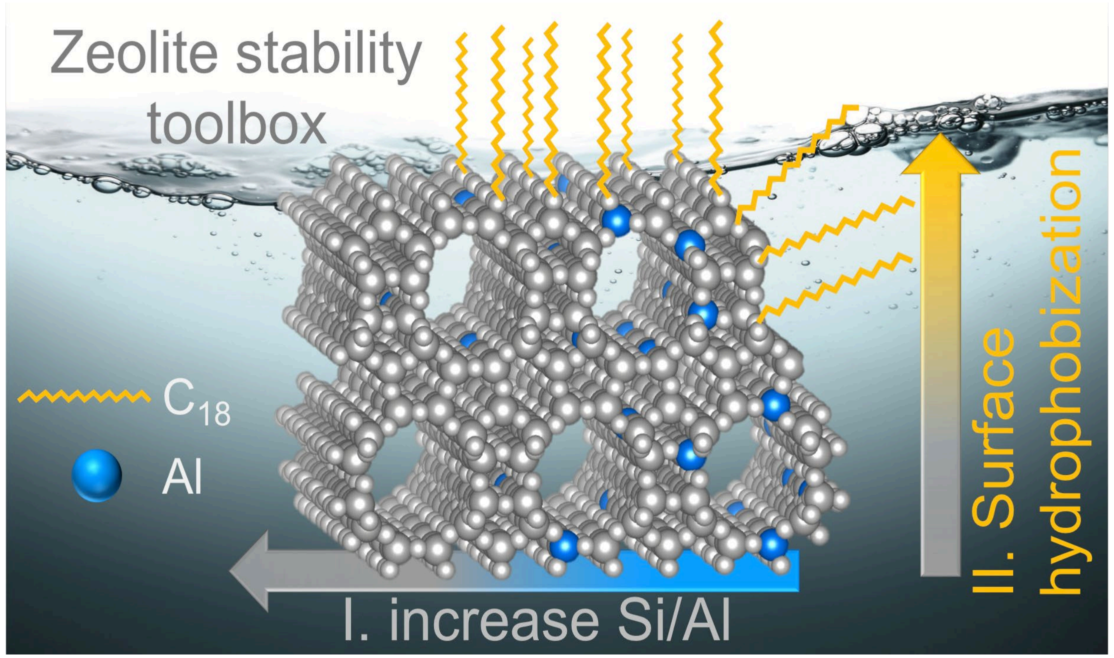
Project Overview - **We Leverage our Previous Success**

Extensive catalyst stability improvement for fast pyrolysis bio-oil upgrading

- Bio-oil Hydrotreating
  - Prevent plugging and extend operation time from *~90 to >1400 hours*
- Bio-oil stabilization
  - Develop regeneration and extend operation time from *~150 to >800 hours*

Biomass and Bioenergy, 2019; ACS Sustainable Chem. Eng. 2016; Topics in Catalysis 2016; Energy & Fuels, 2015

A toolbox for stabilizing zeolites in hot liquid water



J. Am. Chem. Soc. 2016; Chem. Mater. 2017; Appl. Catal. B, 2018

Previously encountered challenges and successful outcomes identified a need for a more collective and collaborative effort within ChemCatBio for a systematic study of catalyst deactivation.

1 - Management – ChemCatBio Foundation – FY21

Catalytic Technologies

Catalytic Upgrading of Biochemical Intermediates (CUBI)
(NREL, PNNL, ORNL, LANL)

Upgrading of C1 Building Blocks
(NREL)

Upgrading of C2 Intermediates
(PNNL, ORNL)

Catalytic Fast Pyrolysis (CFP)
(NREL, PNNL)

Electrocatalytic CO_2 Utilization
(NREL)

Enabling Capabilities

Advanced Catalyst Synthesis and Characterization (ACSC)
(NREL, ANL, ORNL)

Consortium for Computational Physics and Chemistry (CCPC)
(ORNL, NREL, PNNL, ANL, NETL)

Catalyst Deactivation Mitigation for Biomass Conversion (CDM)
(PNNL)

Industry Partnerships (Phase II Directed Funding)

Opus12 (NREL)

Visolis (PNNL)

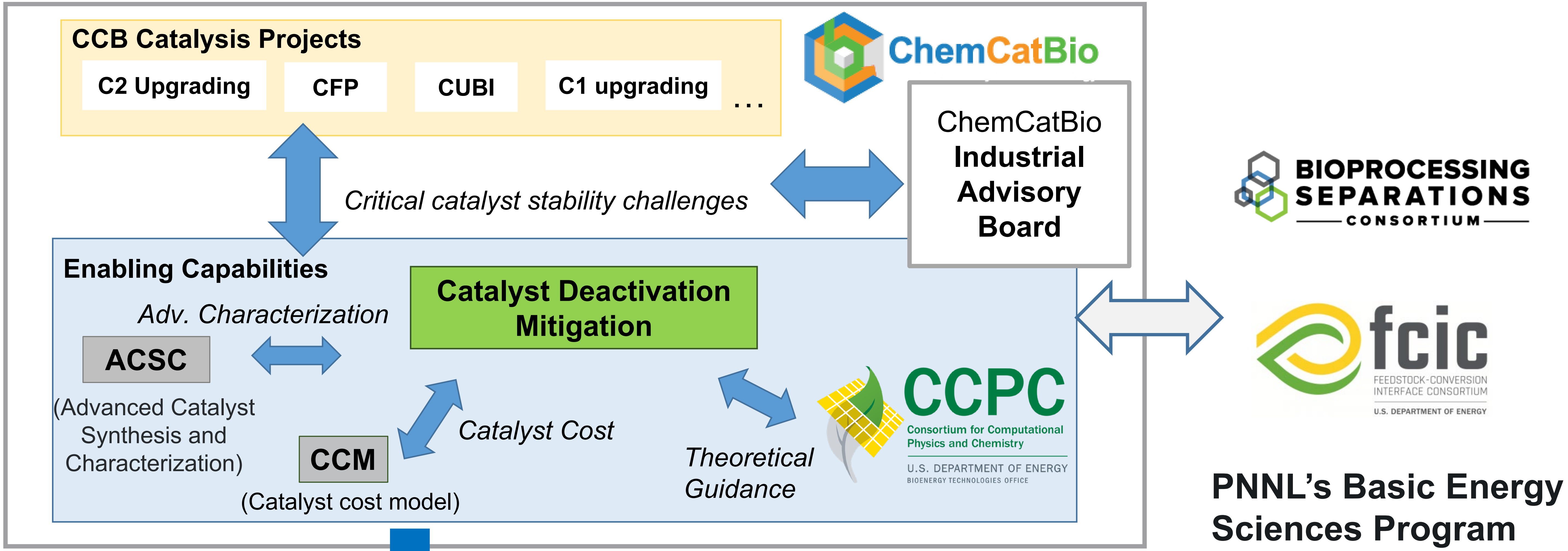
Sironix (LANL)

Cross-Cutting Support

ChemCatBio Lead Team Support (NREL)

ChemCatBio DataHUB (NREL)

1 - *Management* - CDM is an Enabling Capability



Collaborative Outcomes

Catalyst Lifetime Improvement	Cost Reduction and Risk Reduction	Relevant Knowledge for Broader Audiences

Integrated and collaborative portfolio of enabling technologies to help tackle critical catalyst deactivation challenges.

CUBI: Catalytic Upgrading of Biochemical Intermediates; CFP: Catalytic Fast Pyrolysis; C2 upgrading: Upgrading of C2 Intermediates; C1 upgrading: Upgrading of C1 Building Blocks

1 - *Management* - Close Communication with ChemCatBio Catalysis Team

Inputs

BETO quarterly and weekly meetings

BETO Peer review

ChemCatBio Industry Advisor Board

ChemCatBio Steering Committee

ChemCatBio Catalysis Project teams

Literature reviews

Project Structure

Outreach and Communication

Deactivation Mechanism Identification

Deactivation Mitigation Development

Project Management

- Joint milestones
- Go/No-Go decision
- Frequent task meeting with related projects
- Frequent update to ChemCatBio Steering Committee
- Annual ChemCatBio all hands meeting
- Webinars to public or with Industry Advisory Board

Risk Mitigation and Success Factor:

Ensure being relevant and valuable to catalysis technology developers.

2 - Approach – Targeting the Most Impactful Challenges and Supporting ChemCatBio

- **Identifying** deactivation problems
  - *catalysis project, CDM*
- **Determine** deactivation mechanism
  - *CDM, catalysis project, ACSC, CCPC*
- **Develop** mitigation approach
  - *CDM, catalysis project*
- **Verify** performance improvements
  - *catalysis project*

Improve catalyst lifetime for specific technologies

- *$Ag/ZrO_2/SiO_2$ for ethanol to butenes (with C2 upgrading project)*
- *Pt/TiO_2 for CFP (with CFP project)*
- Removing barriers and extending catalyst lifetime
- Cost/risk reduction

Address grand catalyst stability challenges

- *Impact of inorganics*
- *Impact of water (steam and overheated liquid)*
- *Fast coke formation*
- Overarching issues with broad impact
- Based on a survey within ChemCatBio on grand catalyst deactivation challenges

Risk Mitigation and Success Factor:

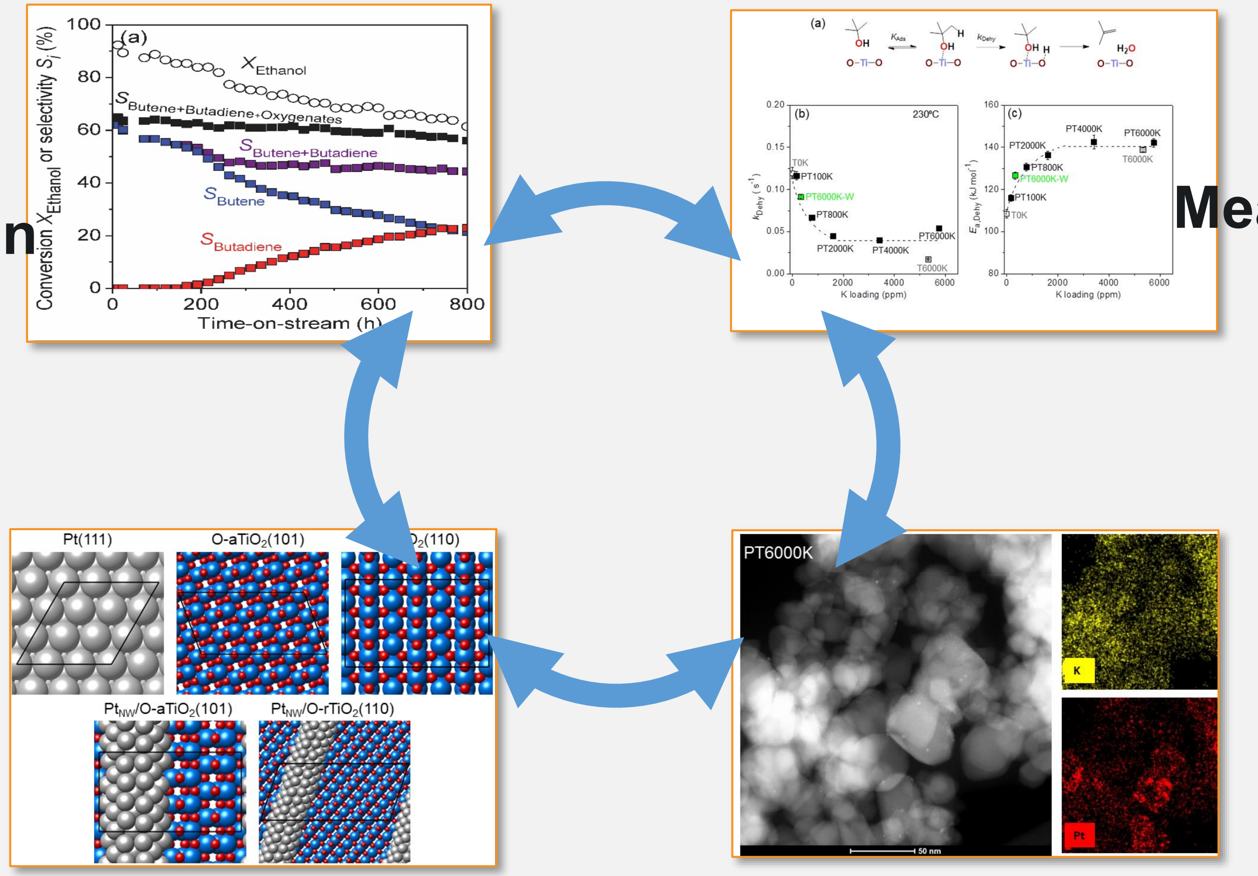
Tackle the most impactful catalyst stability challenges and balance overarching challenges with specific needs of catalysis projects.

2 - *Approach* - **Combing Multiple Technologies and Unique Capabilities**

- **Identifying** deactivation problems
  - *catalysis project, CDM*
- **Determine** deactivation mechanism
  - *CDM, catalysis project, ACSC, CCPC*
- **Develop** mitigation approach
  - *CDM, catalysis project*
- **Verify** performance improvements
  - *catalysis project*

Stability Evaluation

Kinetic Measurement



Computational Modeling

Advanced Characterization

- Hypothesis-driven deactivation mechanism identification
- Atomic level description of spent catalyst change
- Structure-performance correlation on catalyst deactivation

Risk Mitigation and Success Factor:

Multiple technologies to ensure rigorous deactivation mechanism determination.

2 - *Approach* - **Providing Mitigation Strategies**

- **Identifying** deactivation problems
  - *catalysis project, CDM*
- **Determine** deactivation mechanism
  - *CDM, catalysis project, ACSC, CCPC*
- **Develop** mitigation approach
  - *CDM, catalysis project*
- **Verify** performance improvements
  - *catalysis project*

Catalyst lifetime improvement toolbox

✓ Catalyst Regeneration
- Oxidation/reduction
- Solvent cleaning (*e.g. K removal for Pt/TiO_2 for CFP*)

✓ Catalyst Improvement
- More robust components (*e.g. next generation catalyst to replace Ag/TiO_2/SiO_2 for ethanol upgrading*)

✓ Process Improvement
- Feedstock pretreatment (Coordinate with FCIC (feedstock) and Separation Consortium (separation))
- Guard bed

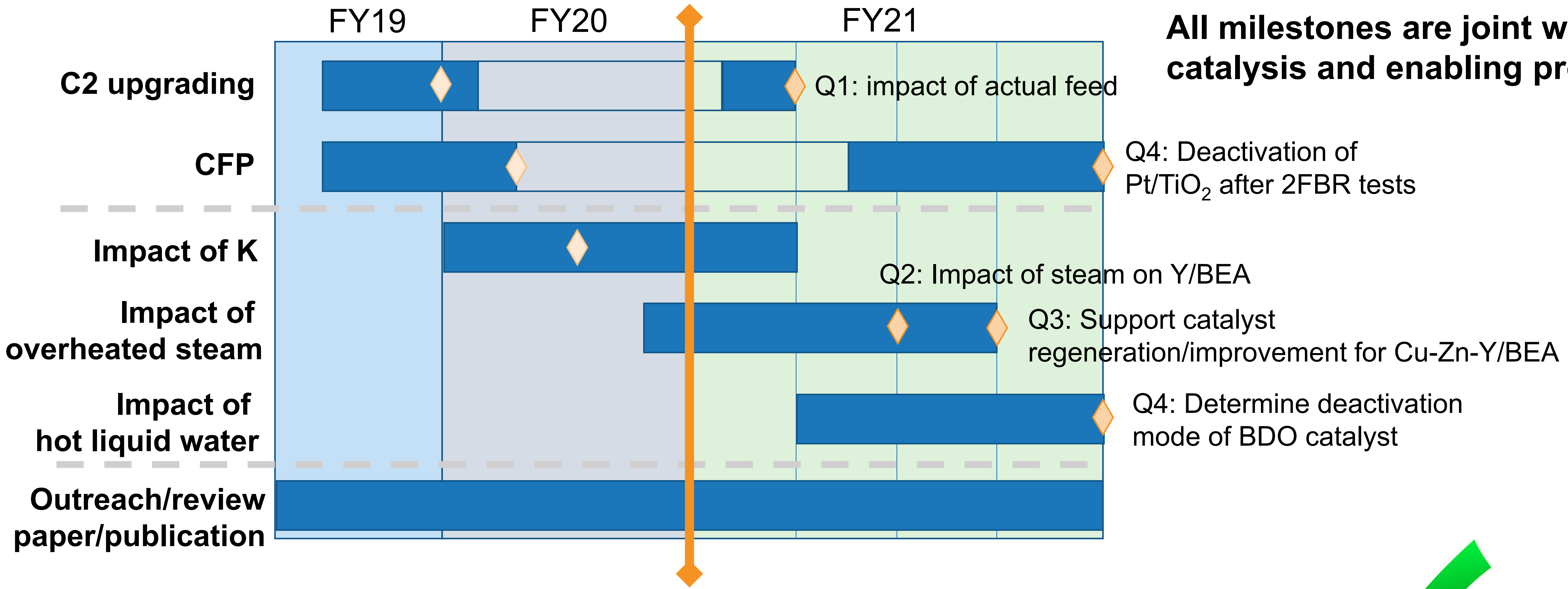
- Provide actionable recommendations.
- Performance verified by catalysis projects.
- Guided by economic assessment.

Risk Mitigation and Success Factor:

A coordinated approach to mitigate deactivation with economic assessment guidance.

2 - *Approach* - **Major Deliverables Scheduled**

All milestones are joint with catalysis and enabling projects.



Completed Go/No-Go:

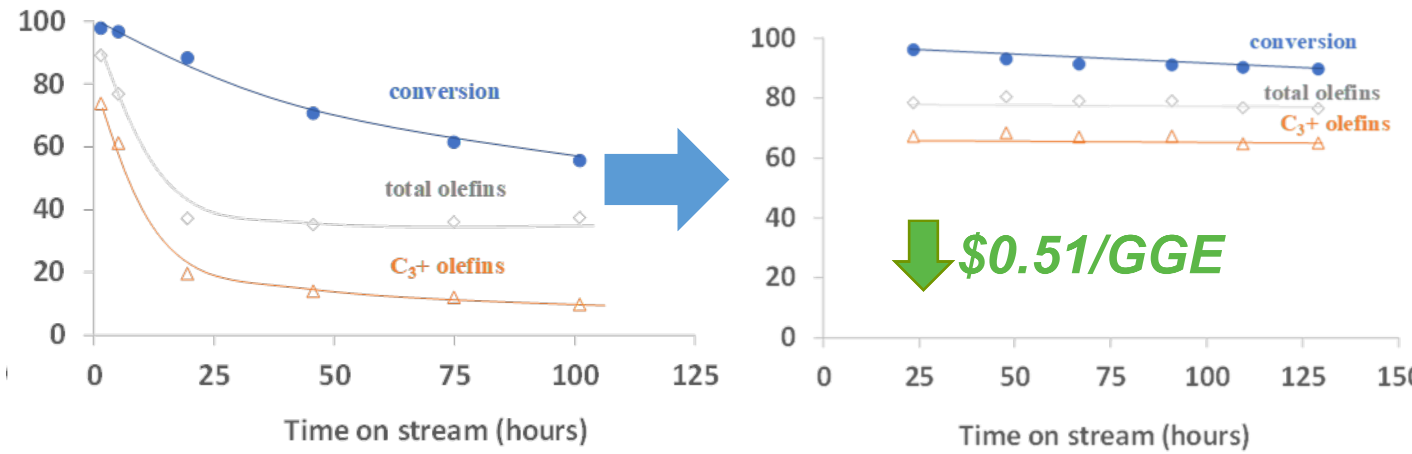
Elucidated that this project provided value with two examples, demonstrating:

- Enhanced understanding of catalyst deactivation mechanism and developed mitigation approach, leading to
- **Quantitative catalyst stability improvement** (>15% reduction of deactivation rate or >80% activity recovery by regeneration). (See more details in slide 27)

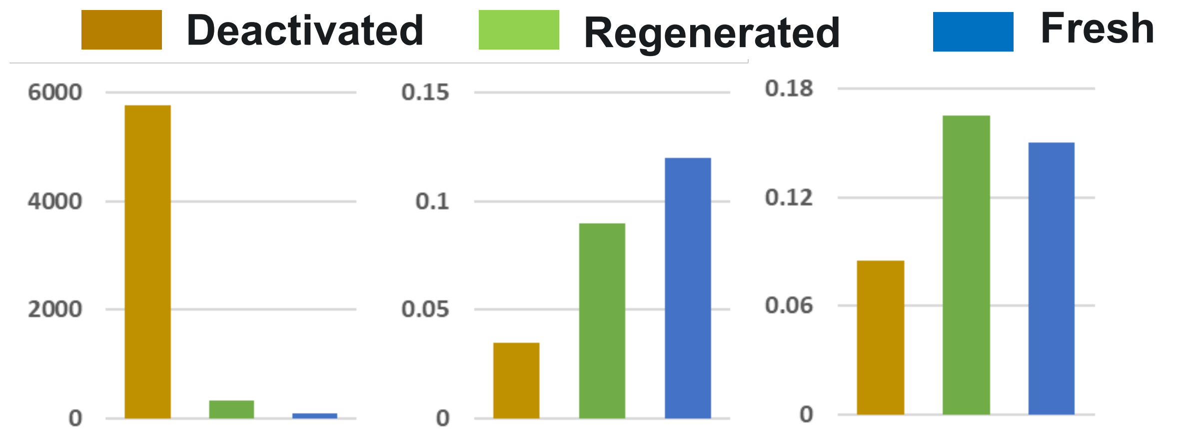
3 - Impact – Significant Catalyst Lifetime Improvement

- **Enhance the ChemCatBio portfolio**
  - "Catalyst deactivation is one of the major challenges and its mitigation is one critical component for ChemCatBio" – according to the *ChemCatBio Industrial Advisory Board*
  - **De-risking the technology and reducing of cost for the conversion.**

Baseline (< FY19) **Improved (FY20)**



***C2 upgrading:** next generation catalyst with much-improved stability and reduced cost*



>90% K removal **>75% dehydration activity recovery** **>95% HDO activity recovery**

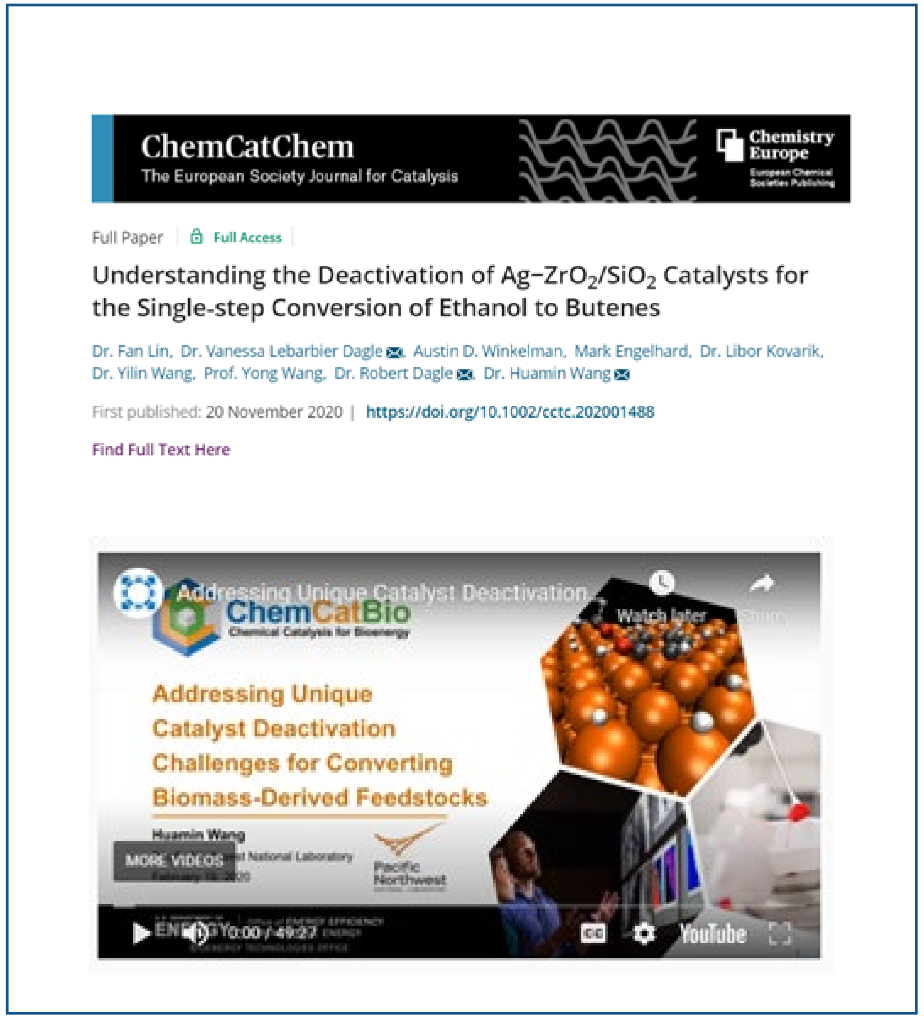
***CFP**: catalyst regeneration for K removal to recover activity*

- **Leverage** existing applied and fundamental research efforts and industrial supports.
- **Support BETO** to address barriers and achieve targets (Ct-E. Improving Catalyst Lifetime).

3 - *Impact* - **Provides Demanding Information on Catalysis**

- Provide **knowledge to industry and catalysis R&D communities** for rational design of more stable catalysts via:
  - A BETO webinar
  - A review document drafted
  - Publications (*three published and two in preparation*) and presentations (*four presentations*)
  - Input to ChemCatBio DataHub

- **A focus on catalyst stability** within ChemCatBio
  - Most of projects involve catalyst stability milestone(s)
  - Task teams to address grand catalyst stability challenges with extensive collaboration among enabling capabilities



> "Since such studies *(catalyst deactivation)* are currently under-presented in the catalysis literature, our science will advance, and our community will benefit from increased emphasis on the productivity *(catalyst stability)* metric." *Susannah L. Scott, Associate Editor, ACS Catalysis*
>
> *ACS Catal. 2018, 8, 8597*

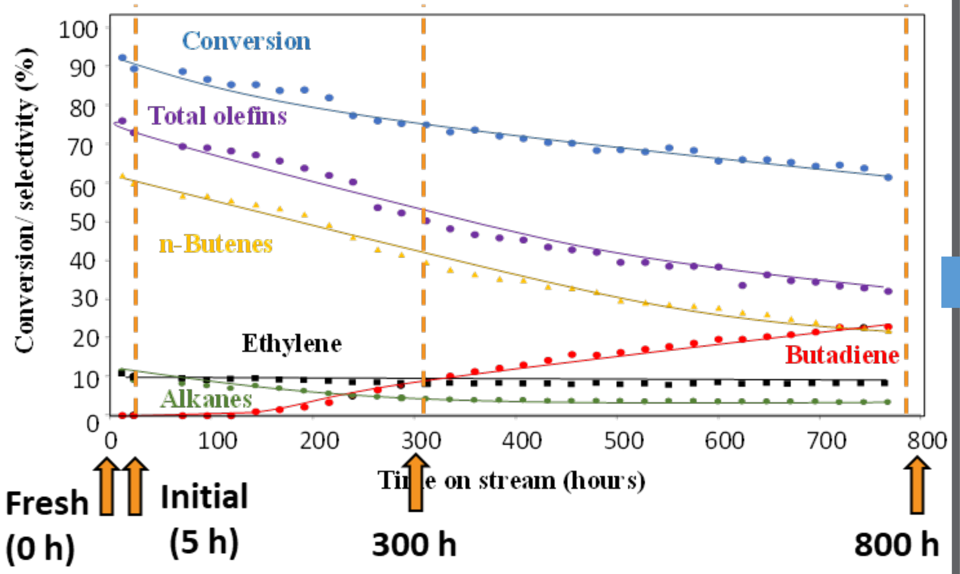
Addressing Grand Challenges and Supporting ChemCatBio Projects

Progress	Outcomes
Improve Catalyst Lifetime for Specific Technologies	
Enhanced **understanding of the deactivation of the $Ag\text{-}ZrO_2/SiO_2$** catalyst for ethanol-to-butene conversion. • Characterization along 800 hours' TOS testing • Identified three major causes of deactivation • Identified the impact of actual feed	• Based in large part on the deactivation mechanisms, the C2 Upgrading team successfully developed **a next-generation catalyst that has much-improved stability and process economy.**
Enhanced understanding of **the deactivation of the Pt/TiO_2** catalyst for CFP. • Identified three major deactivation modes	• Further action suggested to study the three deactivation modes and explore mitigation approach.
Address Grand Challenge	
Determined the **impact of inorganics (K)** on different type of active sites and developed regeneration method for K removal.	• The most completed understanding of the impact K to be **leveraged by other technologies** to improve their catalyst/process stability. • **Regeneration method to remove >90% K.**

Supporting ChemCatBio Projects - C2 Upgrading

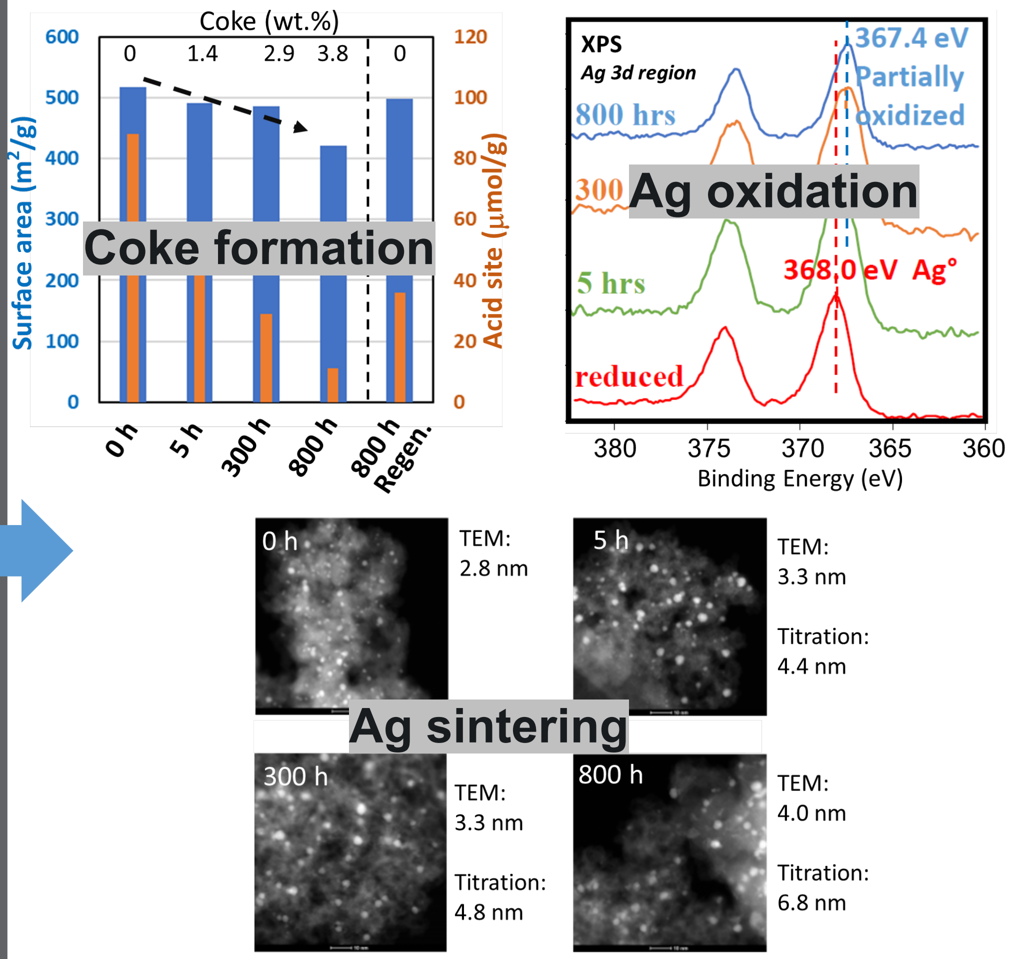
Objective: Mitigate the deactivation of ethanol upgrading catalyst

Deactivation Identification

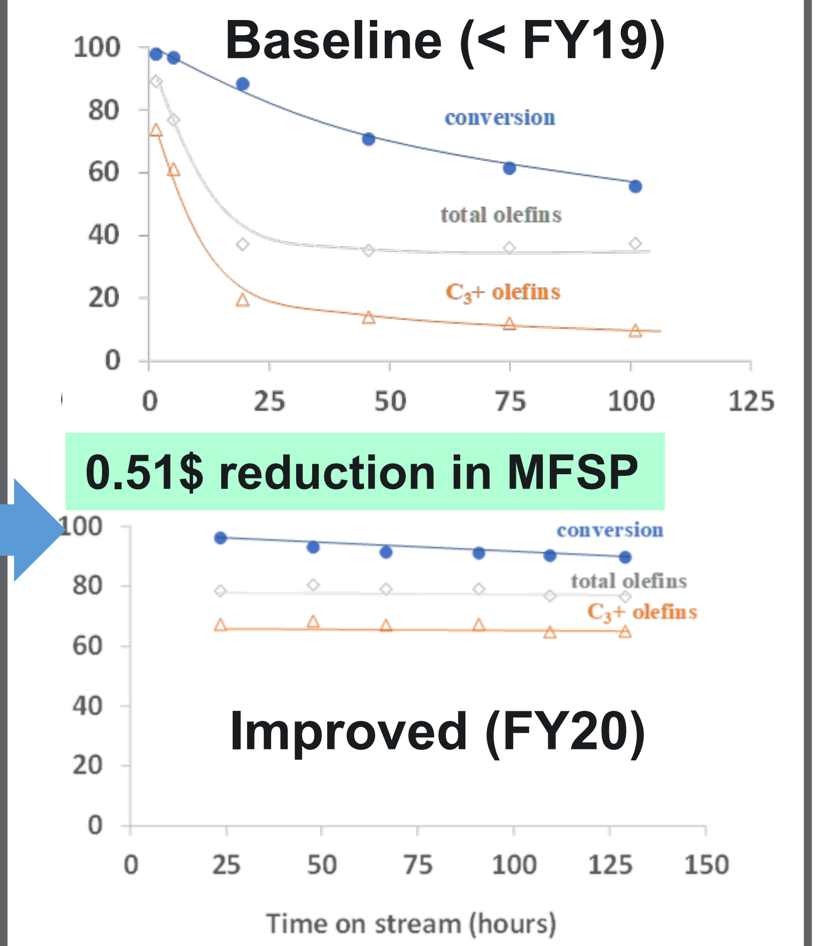


Change of conversion and selectivity along 800 h TOS

Deactivation mode determination



Catalyst improvement



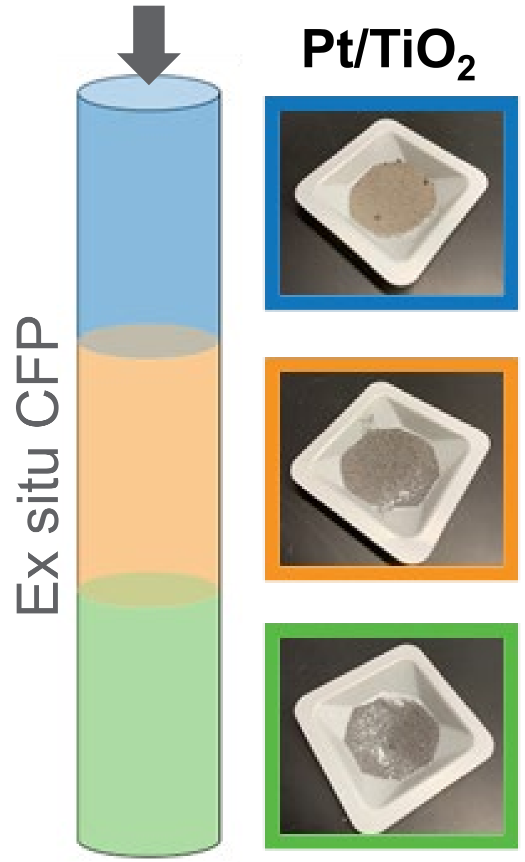
- Identified additional deactivation with actual fermentation derived feed.

Outcome: Deactivation mechanism identified and the guided catalyst modification leading to stability improvement.

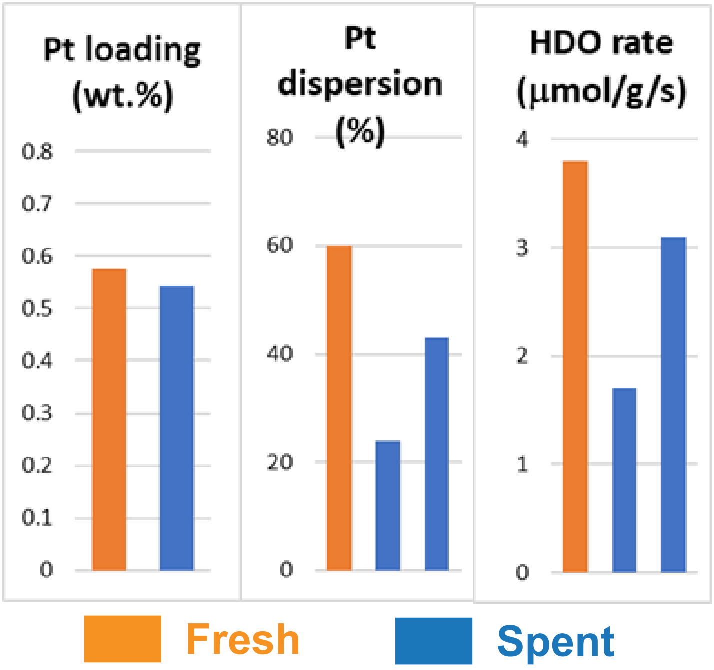
In collaboration with C2 upgrading project (2.3.1.304)

ChemCatChem, 2020, doi.org/10.1002/cctc.202001488

Objective: Determine potential deactivation of CFP catalyst in long-term operation



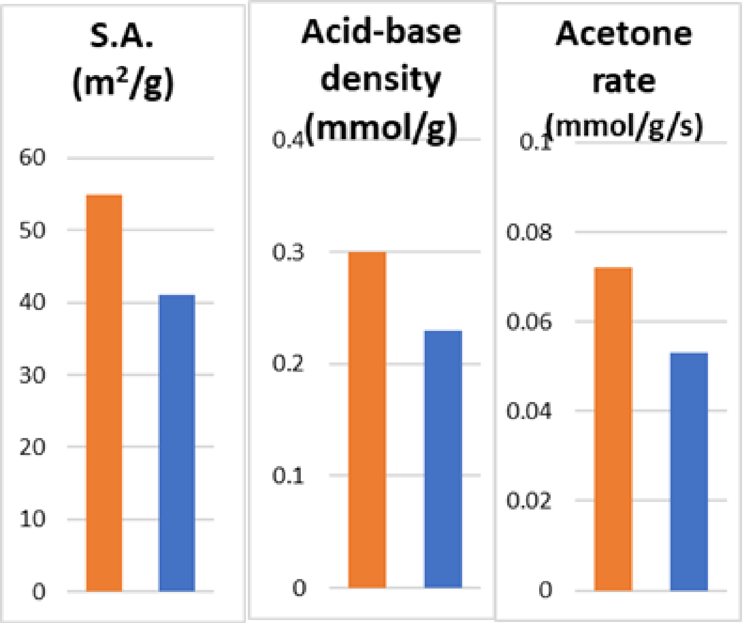
Dynamic Pt particles



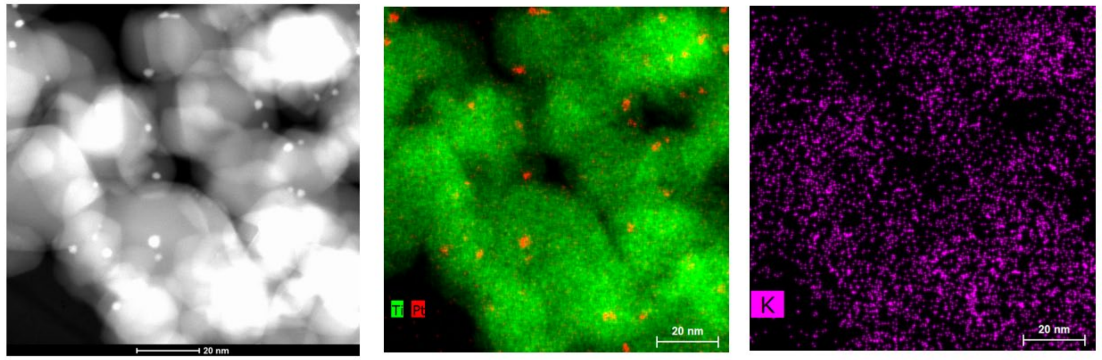
Active sites and activity largely maintained, and sulfur not found

Loss of surface area and acid base sites

Fresh
Spent



Uniform distribution of K across catalyst surface with higher content on the leading edge



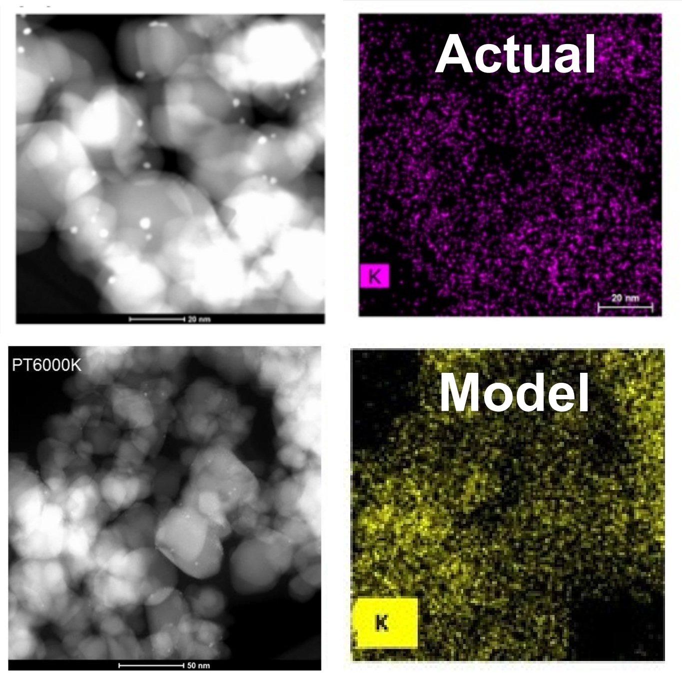
Outcome: Deactivation mode identified, and further actions suggested to understand the deactivation and improve the catalyst.

In collaboration with CFP project (2.3.1.314) and ACSC (2.5.4.303/304/305)

Addressing Grand Challenges - Inorganic Contamination

Objective: How to distinguish impact of K on individual active sites of multifunction catalyst?

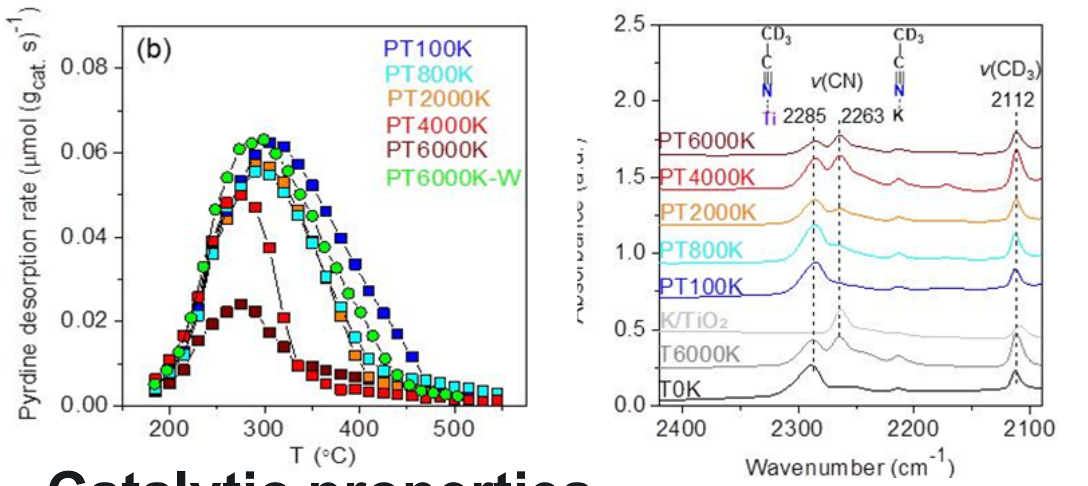
K distribution



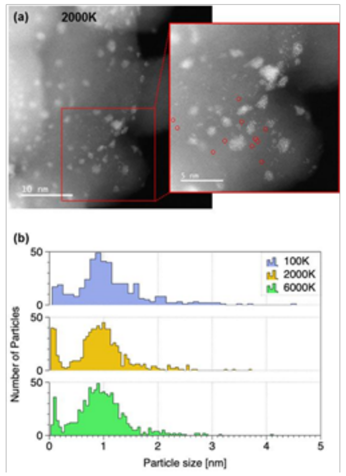
Model catalysts mimic real spent ones with better controlled uniformity

Physical and chemical properties

Change of acid sites



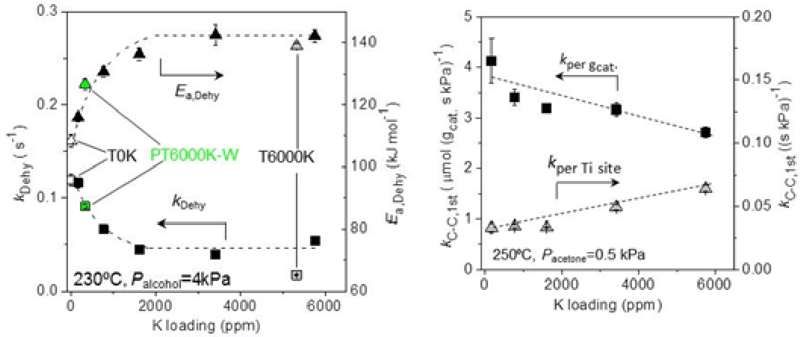
Change of metal sites



Change of acid-base and metallic sites along increased K coverage

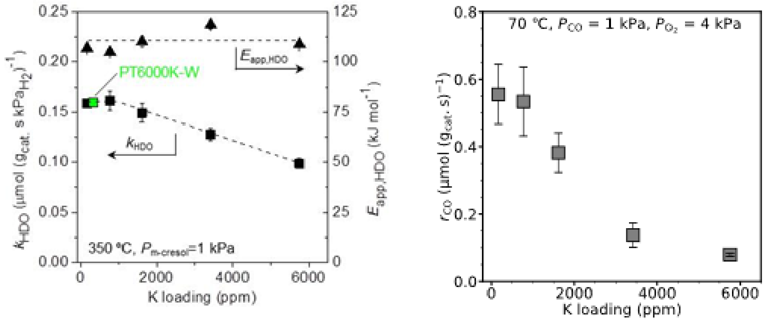
Catalytic properties

Dehydration and C-C coupling to probe acid-base sites

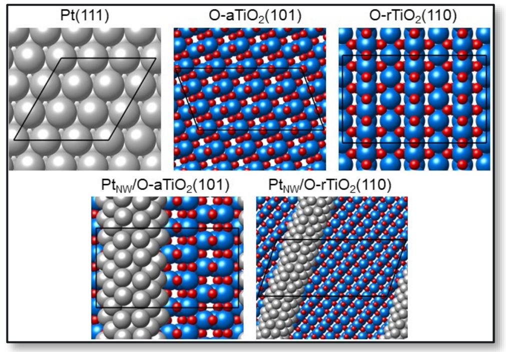


Kinetically distinguish different active sites at increased K coverage

HDO and CO oxidation to probe metal sites

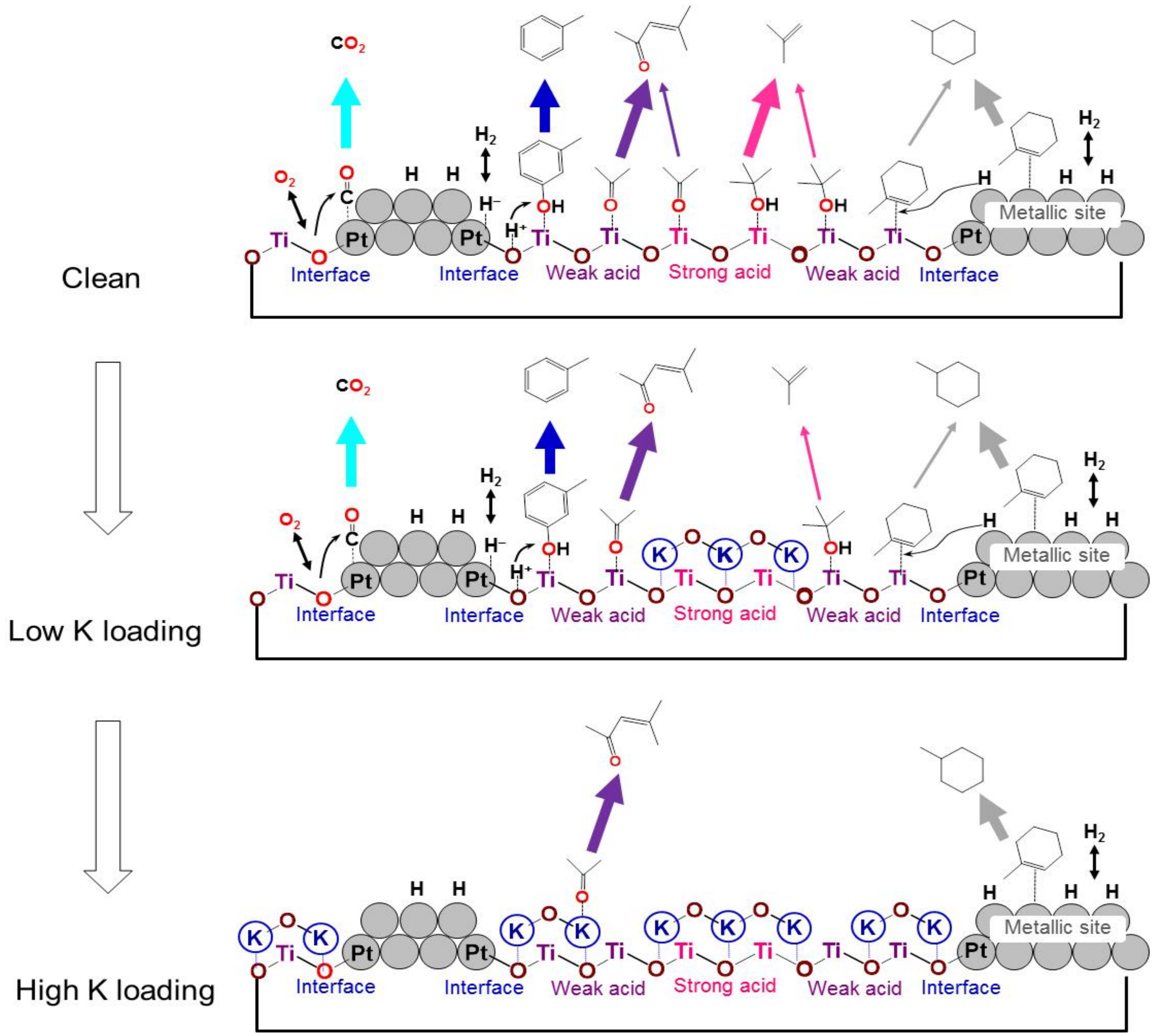


Theory



Outcome: Established structure-performance correlation and precise description of the atomic level interaction of K with each active site of the catalyst.

Addressing Grand Challenges - Inorganic Contamination



Objective: Understand the deactivation mechanism by K deposition

- K first titrates strong Lewis acid sites, then weak acid sites and Pt-TiO_2 interfacial sites
- K does not poison metal surface but can induce redispersion to single atom (negligible in Pt/TiO_2 case)
- K could generate (strong) base sites
- K could titrate Bronsted acid site by ion exchange (literature)

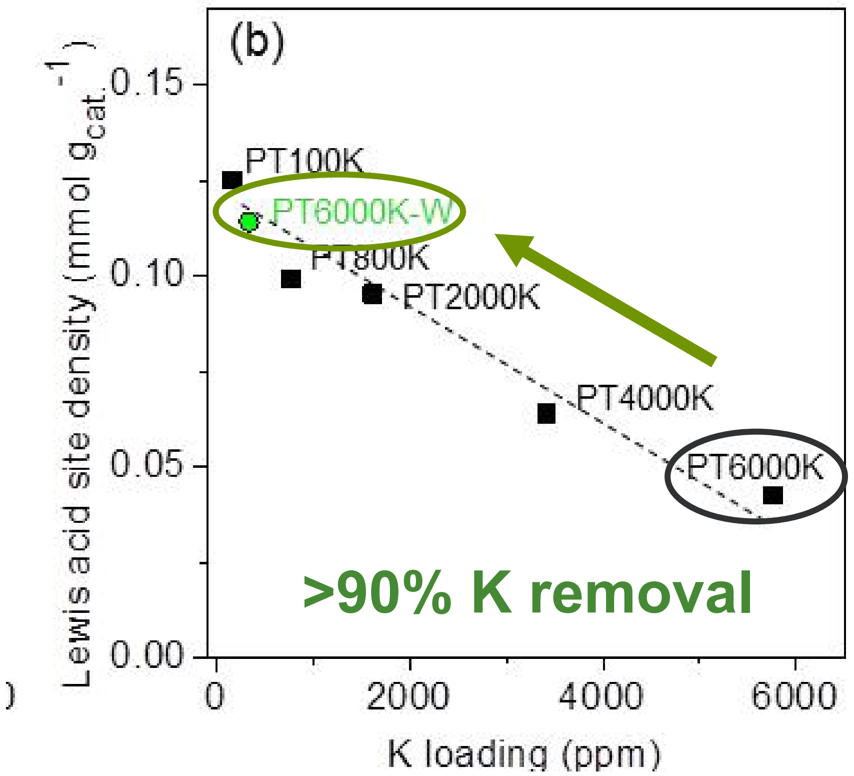
- **Predict impact of K at a longer time on stream**
- **Can be expanded to similar catalyst systems**

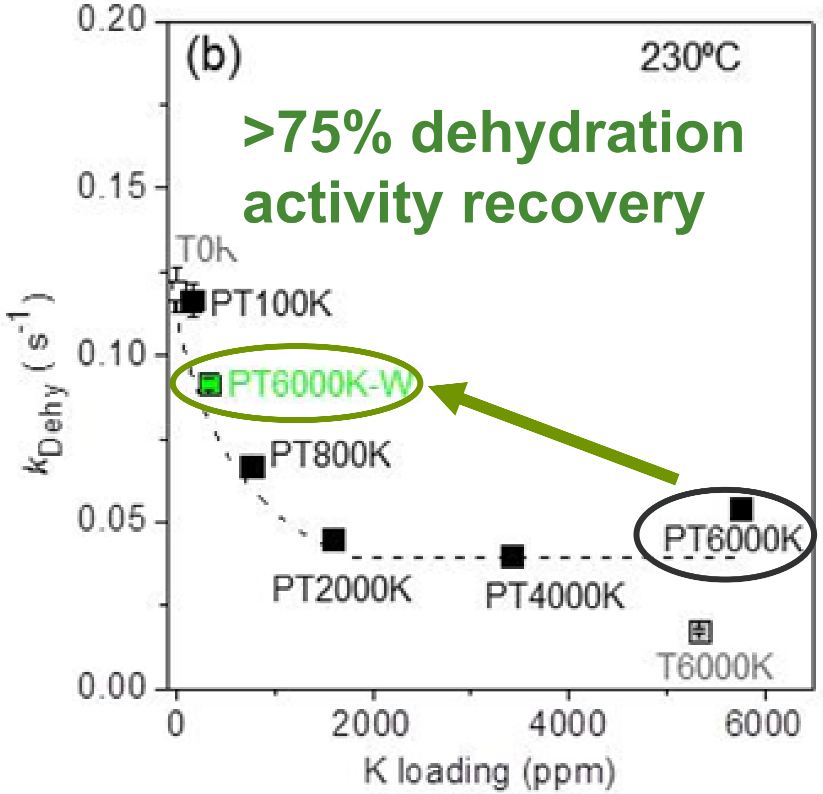
Outcome: A completed understanding of the impact K to be leveraged by other catalyst systems.

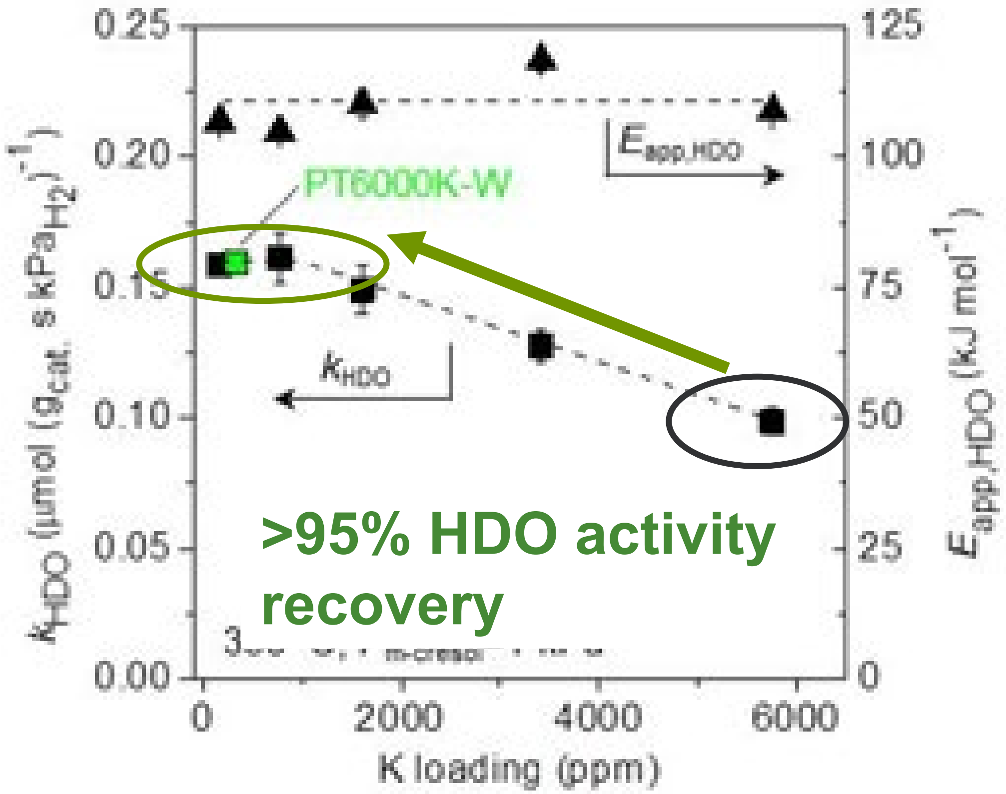
Addressing Grand Challenges - Inorganic Contamination

Objective: Mitigate the deactivation from K deposition

- Solvent washing method identified, and impact of solvent studied
- Simple method for straightforward practical implementation

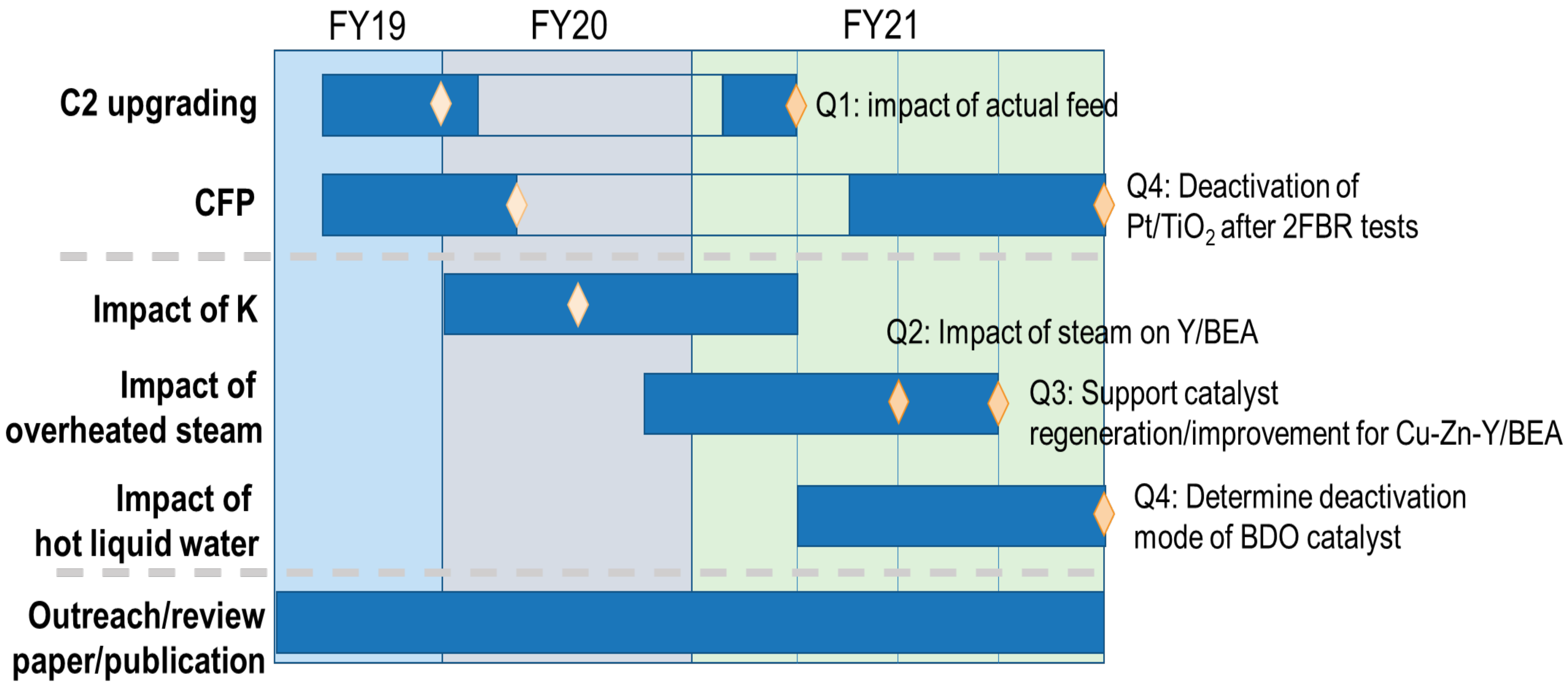






Outcome: Regeneration method to remove >90% K and extend catalyst lifetime.

4 – Progress and Outcomes Lead to Future Works – Continue Addressing Grand Challenges and Supporting ChemCatBio Projects



FY21-22

- Continue addressing the grand challenges
  - Extend to **other inorganics**
  - **Impact of water** (overheated steam and hot liquid water; in collaboration with C2 upgrading, CUBI, ACSC, and CCPC)
- Continue supporting ChemCatBio projects
- Develop a **database** on catalyst deactivation as part of central hub of knowledge

Beyond FY21-22

- Develop **accelerated testing** for faster catalyst stability evaluation and more rational catalyst lifetime prediction.
- More rigorously understanding deactivation by **probing deactivation *in situ*** by combing transient kinetics and operando spectroscopy.

Summary –
Our Goal is to Address Catalyst Deactivation Challenge

Management	• Close **communication** with ChemCatBio catalysis team • Targeting the most impactful challenges and supporting ChemCatBio – Addressing **grand catalyst deactivation challenges** (inorganics and water) – **Improve catalyst lifetime** for specific technologies (C2 upgrading and CFP projects)
Approach	• Integrated and collaborative effort within ChemCatBio • **Combing multiple technologies** to understand deactivation mechanism • Providing actionable recommendations and developing regeneration method to **address deactivation**
Impact	• **Catalyst lifetime improvement** - Cost and risk reductions of conversion technologies • **Provide demanding knowledge** for rational design of more stable catalysts
Progress and Outcomes	• Addressing **grand catalyst deactivation challenge** – Determined the **impact of inorganics** (K) on different type of active sites – Developed regeneration method for **K removal** • **Improve catalyst lifetime** for ChemCatBio projects – Understand deactivation of **Pt/TiO_2 for Catalytic fast pyrolysis** – Understand deactivation of **$Ag/ZrO_2/SiO_2$ for ethanol upgrading**, leading to **improved catalysts**
Future	• Addressing grand catalyst deactivation challenge – **water (overheated steam and hot liquid water)** • Improve catalyst lifetime for ChemCatBio projects • Knowledge and tools

Quad Chart Overview

Timeline
- Project start date: 10/1/2019
- Project end date: 9/30/2022

	FY20	Active Project
DOE Funding	$300,000	$900,000 (FY20-22)

Barriers Addressed

Ct-E. Improving Catalyst Lifetime

- Understanding causes of catalyst deactivation
- Develop improved catalyst regeneration

Ct-G. Decreasing the Time and Cost to Develop Novel Industrially Relevant Catalysts

Project Goal
Address the catalyst deactivation challenges in catalytic processes for biomass conversion to enable catalyst lifetime improvement for cost and technology uncertainty reduction of biomass conversion technologies and to enable accelerated catalyst and process development.

End of Project Milestone
Assist at least two CCB catalytic process to understand their catalyst deactivation mechanism and develop/propose mitigation approach (such as catalyst regeneration) which leads to reduction of deactivation rate and/or prediction of long-term stability and/or recovery of catalyst activity.

Funding Mechanism
ChemCatBio Merit Review AOP for FY20-22

Acknowledgement

- **PNNL**: Fan Lin, Yilin Wang, Robert Dagle, Vanessa Dagle, Austin Winkelman, Mark Engelhard, Libor Kovarik, Yong Wang, Karthi Ramasamy, Yubing Lu, Asanga Padmaperuma
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- **ORNL**: Zhenglong Li, Junyan Zhang
- **BETO**: Andrea Bailey, Trevor Smith, Nichole Fitzgerald, Sonia Hammache

Thank you!

ChemCatBio
Chemical Catalysis for Bioenergy

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Additional Slides

ChemCatBio
Chemical Catalysis for Bioenergy

Acronyms and abbreviations

ACSC	Advanced Catalyst Synthesis and Characterization project
BETO	Bioenergy Technologies Office
C2 upgrading	Catalytic Upgrading of C2 Intermediates project
ChemCatBio	Chemical Catalysis for Bioenergy Consortium; ChemCatBio consortium
CCM	Catalyst Cost Model project
CCPC	Consortium for Computational Physics and Chemistry project
CDM	Catalyst Deactivation Mitigation for Biomass Conversion project
CFP	Catalytic Fast Pyrolysis project
CUBI	Catalytic Upgrading of Biochemical Intermediates project
FCIC	Feedstock-Conversion Interface Consortium
HDO	Hydrodeoxygenation
IAB	Industrial Advisory Board
PNNL	Pacific Northwest National Laboratory
TOS	Time on stream

Responses to Previous Reviewers' Comments

Comments: This overarching project, along with the theory program, can be a broad but impactful component of ChemCatBio. This project has the potential of becoming an entire center of excellence focused on deactivation of catalysts in bioenergy applications. This is an important project that aims to address catalyst stability in a variety of biomassupgrading technologies. The goal of the project—to improve catalyst stability (lifetime) for ChemCatBio catalysis projects through understanding catalyst deactivation and developing mitigation approaches—is surely relevant for the core work of the consortium

Response: We thank the reviewers for their support of this project. This support enables the overall ChemCatBio program and mission to increase the fundamental understanding of catalyst deactivation mitigation for the scientific community. We agree with the importance of dealing with the deactivation "head on" in a systematic, rigorous, and comprehensive fashion, which is what this project attempts to do.

Comments: It would be helpful to see more specifics about the important modes of deactivation in a specific technology, how they will be investigated, how they will be mitigated, etc. It would be interesting to see more solid and articulated ideas on how to provide stability on the more complicated systems being studied in this consortium, such as the multifunctional systems. It would have benefited from a better discussion of the hypothesis involving catalyst deactivation being studied and the approaches.

Response: We have provided specifics about the hypothesis for modes of deactivation, the approach to investigate and mitigate them, and the clear targets in this presentation. As presented here, we combine various approaches to develop a rigorous deactivation mechanism for the complicated catalyst systems actionable recommendation and regeneration methods to enhance catalyst stability.

Comments: It seemed like more homework could have been done by the authors of the proposed work to identify the needs of the consortium, instead of making one of the tasks to find out what the needs are. Building on and augmenting prior studies is key and something that should be monitored carefully to make sure these deactivation studies do not "reinvent the wheel".

Response: We are working closely with ChemCatBio catalysis teams to make sure we are meeting their target and relevant to their research needs. We identified specific technologies to support and extend their catalyst lifetime. All the technologies are unique and require deactivation mitigation to reduce cost and remove barriers. This project is also tackling overarching challenges to benefit research communities with greater impact.

FY2020 Go/No Go

Go/No-Go Description and Criteria

Elucidate that this project provided value to the core catalysis projects. The outcome of the go/no-go decision will identify areas for improvement and/or tasks that should be integrated with or removed from the project.

The value of this project will be evaluated based on one of the following criteria: 1) demonstrating the **enhanced understanding of catalyst deactivation** for a catalytic process that leads to proposing mitigation strategies that **can reduce the deactivation rate by 15%** and/or prediction of long-term stability of the catalyst used; or 2) developing a **mitigation approach** that could **recover at least 80% of catalyst activity** by regeneration or could **increase the catalyst lifetime by at least 20%.**

Accomplishment

In working with the C2 Upgrading project, we enhanced understanding of the deactivation of the incumbent catalyst system developed at PNNL for one-step ethanol-to-butene conversion. Based in large part on the deactivation mechanisms identified in this work, the C2 Upgrading experimental team successfully improved the catalyst formulation and developed a next-generation catalyst that has much-improved stability. The newly developed catalyst showed a much slower deactivation (~6% decrease in ethanol conversion over ~80 hours' time-on-stream) than Ag-ZrO_2/SBA-16 (~25% decrease in ethanol conversion over ~80 hours' time-on-stream).

Working with NREL's CFP Project, we provided enhanced understanding of deactivation of the Pt/TiO_2 catalyst, especially related to the impact of potassium (K) accumulation on Pt/TiO_2. We developed a regeneration method to remove K and demonstrate significant active recovery over a model system (>90% K removal, >95% recovery of hydrodeoxygenation activity for its metallic function and >75% recovery of dehydration activity for its acidic function).

Based on the accomplishments listed above, we conclude that this CDM project is providing significant value to the core catalysis project of the ChemCatBio consortium, and our recommendation is to proceed with current tasks and scopes as described in the AOP.

Publications and Presentations

Peer Reviewed Journal Article and Book Chapter

- F Lin, V.L. Dagle, A.D. Winkelman, M. Engelhard, L. Kovarik, Y. Wang, Y. Wang, R. Dagle, H. Wang, **Understanding the Deactivation of Ag-ZrO_2/SiO_2 Catalysts for the Single-Step Conversion of Ethanol to Butenes**, *ChemCatChem*, 2020, doi.org/10.1002/cctc.202001488
- F. A. Agblevor, H. Wang, S. Beis, K. Christian, A. Slade, O. Hietsoi, and D. M. Santosa, **Reformulated Red Mud: a Robust Catalyst for In Situ Catalytic Pyrolysis of Biomass**, *Energy Fuels*, 2020, 34, 3, 3272–3283
- H. Shi, K. Ramasamy, R. Ma, H. Wang, **Nanoporous Catalysts for Biomass Conversion**, in "Nanoporous Materials for Molecule Separation and Conversion", edited by Jian Liu and Frank Ding, Elsevier, Chapter 12, 2020.
- F. Lin, Y. Lu, K. Unocic, S. Habas, M. Griffin, J. Schaidle, Y. Wang, H. Wang, **Deactivation by Potassium Accumulation of Pt/TiO_2 Bifunctional Catalyst for Biomass Catalytic Fast Pyrolysis**, in preparation for ACS Catalysis.
- F. Lin, M. Xu, K. Ramasamy, Z. Li, J. Schaidle, H. Wang, **Catalyst Deactivation and its Mitigation during Catalytic Conversions of Biomass**, in preparation for Chemical Society Reviews.

Presentation

- H. Wang, **Catalyst Deactivation Mitigation in Biomass Conversion: Connections and Zeolite Stability in Water**, 2019, ACS Spring Meeting, Orlando, invited oral presentation.
- F. Lin, H. Wang, **Deactivation of Pt/TiO_2 Catalyst for Biomass ex situ Catalytic Fast Pyrolysis by Potassium Accumulation**, 2020, accepted for presentation at ICC-2020
- F. Lin, H. Wang, **Deactivation of Pt/TiO_2 Catalyst for Biomass ex situ Catalytic Fast Pyrolysis by Potassium Accumulation**, 2020, Oral presentation at TCS-2020 virtual meeting.
- H. Wang, **Addressing Unique Catalyst Deactivation Challenges for Converting Biomass-Derived Feedstocks**, 2020, ChemCatBio Webinar