# Wet-Air Oxidative Regeneration Process for Regenerating Poisoned Catalysts

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VIRENT

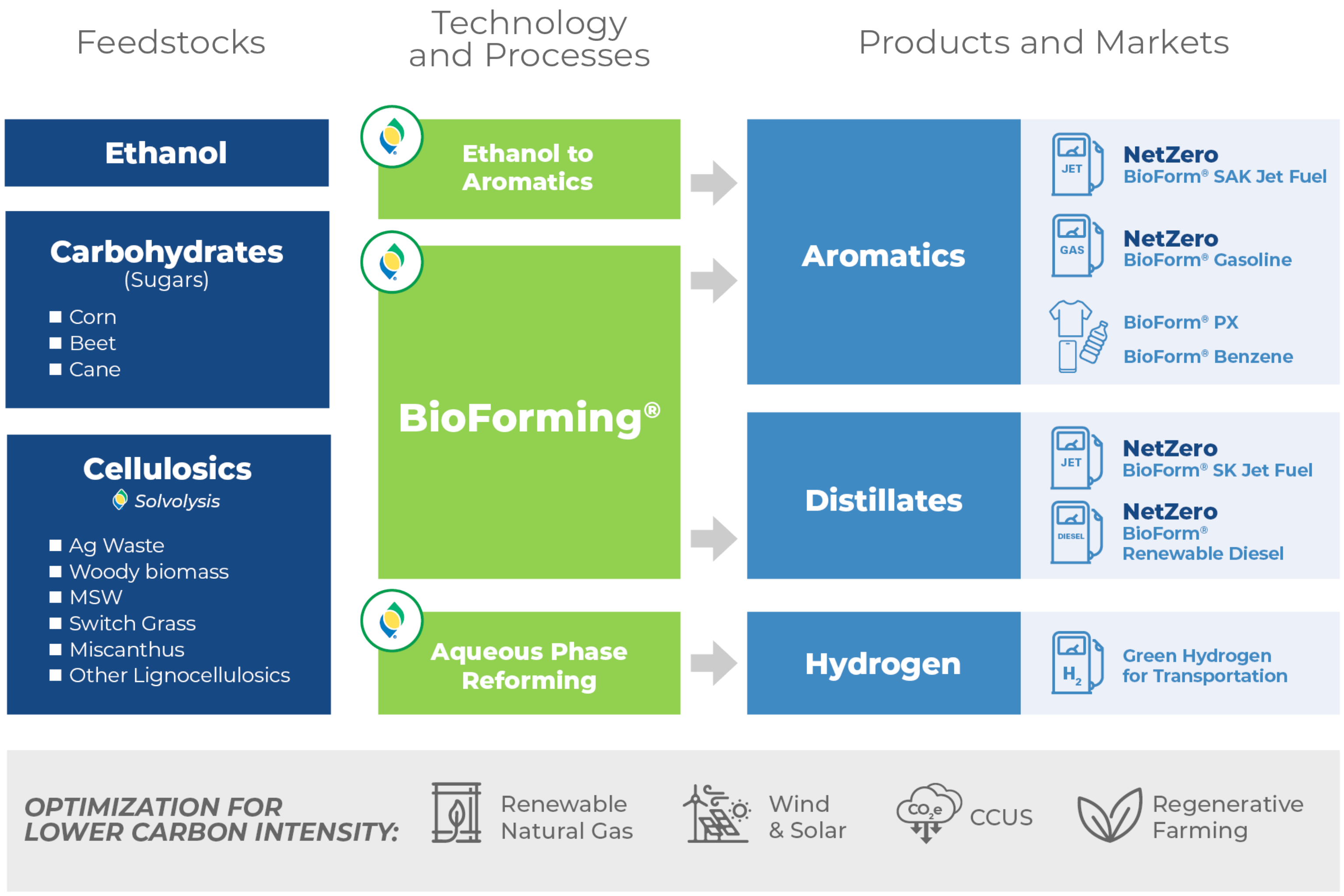
# Virent Forward Looking Statements

This Presentation includes forward-looking statements within the meaning of the Private Securities Litigation Reform Act of 1995. Such statements may relate to, among other things: our leadership in catalytic conversion; the future of compliance obligations in fuels; consumer preferences and demand in chemicals and fuels; our ability to implement our operational plans; branding effects, including “halo” effects; our ability to manage risks related to new technology, scale-up and regulatory incentives; feedstock prices and supply chain efficiencies; compliance costs and competition; our access to capital; and the contributions from and benefits to members of the Consortium, among others.

We have used words like “anticipate”, “believe”, “could”, “estimate”, “expect”, “intend”, “may”, “plan”, “predict”, “project”, “should”, “will” to identify forward-looking statements in this presentation. Although we believe the assumptions upon which these forward-looking statements are based are reasonable, any of these assumptions could prove to be inaccurate and the forward-looking statements based on these assumptions could be incorrect. Our operations and anticipated transactions involve risks and uncertainties, many of which are outside our control, and any one of which, or a combination of which, could materially affect our results of operations and whether the forward-looking statements ultimately prove to be correct. Actual results and trends in the future may differ materially from those suggested or implied by the forward-looking statements depending on a variety of factors which are described in greater detail in filings with the SEC by Marathon Petroleum Corp., of which Virent is a wholly-owned subsidiary. All future written and oral forward-looking statements attributable to us or persons acting on our behalf are expressly qualified in their entirety by the previous statements. We undertake no obligation to update any information contained herein or to publicly release the results of any revisions to any forward-looking statements that may be made to reflect events or circumstances that occur, or that we become aware of, after the date of this presentation.

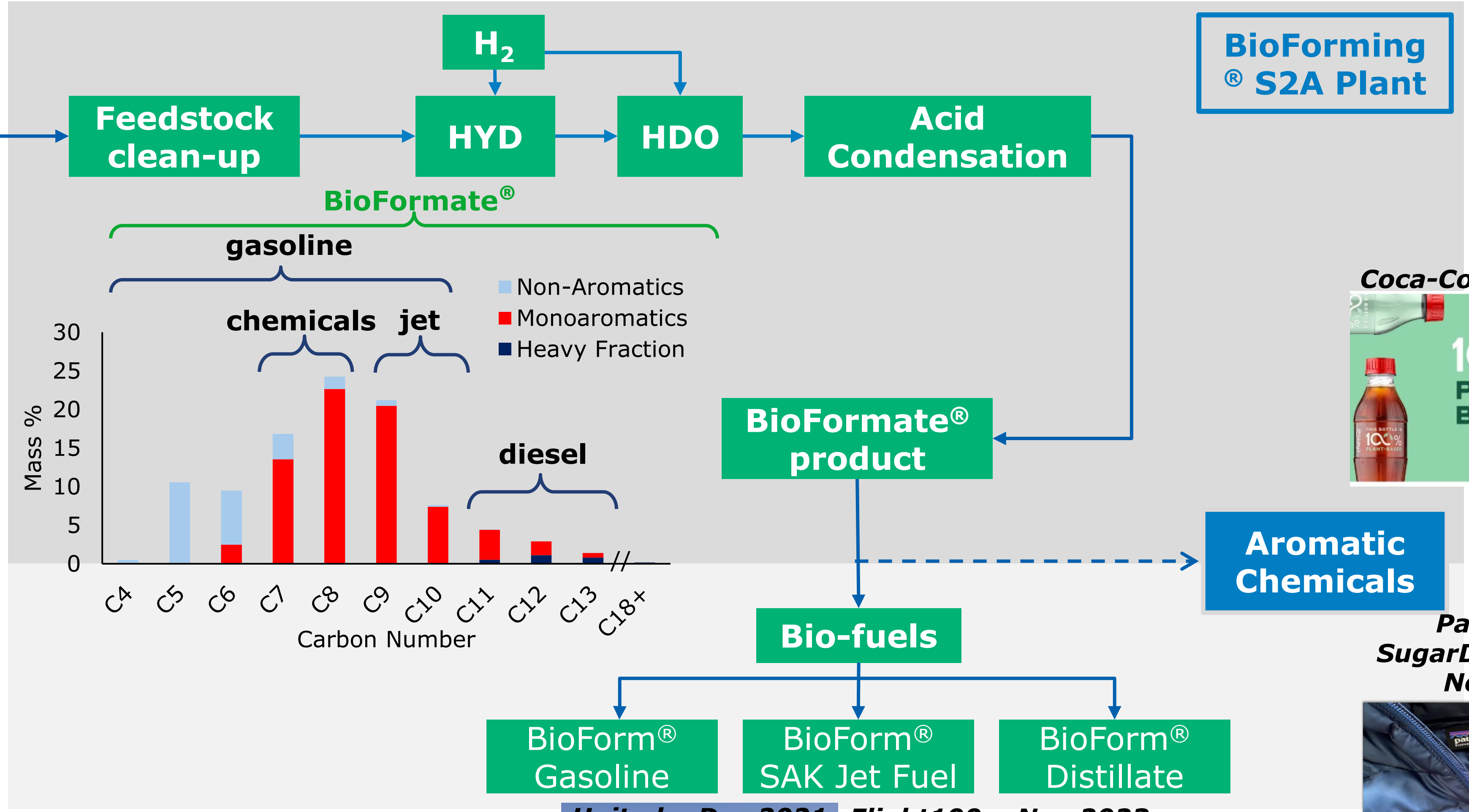
# Virent: Creating Opportunities for Renewable Markets

- **Headquartered in Madison, WI**
- **Founded in 2002**
- **A wholly-owned subsidiary of Marathon Petroleum Corporation**
- **Multiple pathways in development**
- **Commercial focus is on scale-up and first plant deployment**
  - Virent working with Johnson Matthey (JM) on commercial plant project to produce biofuels from sugars



# BioForming® Process – Sugars to Aromatics

## The S2A platform can work with a **range of sugar feedstocks** to produce **drop-in products** which can be blended with existing fuel product or refinery streams


***Coca-Cola – Nov 2021***

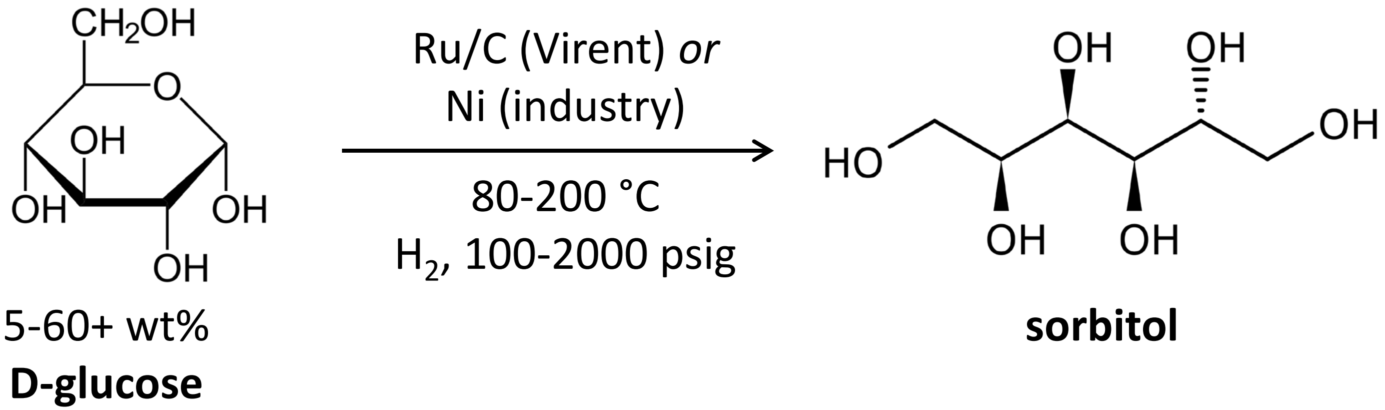

***Patagonia SugarDown Hoody Nov 2022***


***United – Dec 2021***


***Flight100 – Nov 2023***

# HYD - Sugar Hydrogenation

## Industrial Uses and Virent's Approach




- Virent hydrogenates sugars to sugar alcohols to increase thermal stability in HDO step
- Industrially, a semi-batch process with Ni catalysts is used to produce sorbitol[1]
- Continuous studies with Ru catalysts show higher performance than Ni catalysts
- Virent's tests with corn sugars showed catalyst deactivation

[1] Schiweck, *et al.* "Sugar Alcohols" *Ullmann's Encyclopedia of Industrial Chemistry*, **2012.**

# Sulfur Poisoning of Ru-catalyzed Hydrogenations

## Literature review suggested sulfur may be causing deactivation

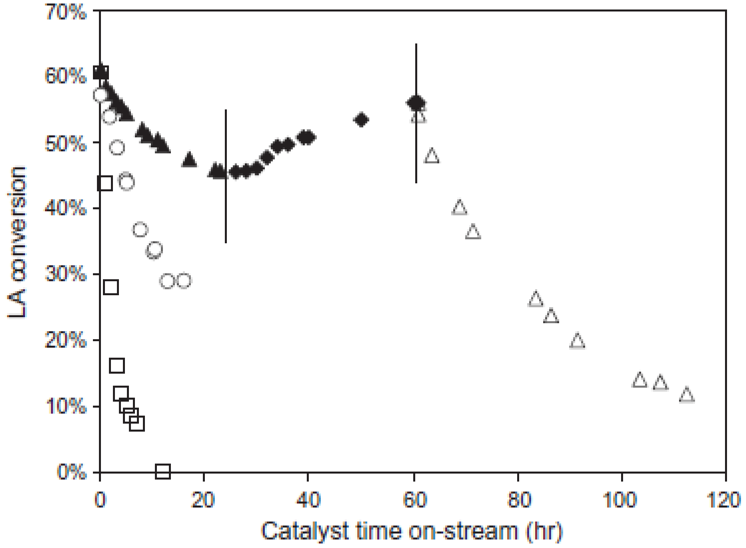



Fig. 8. Effect of cysteine and methionine addition on LA conversion at base-case conditions (Table 2): ▲, 50 ppm cysteine; □, 1000 ppm cysteine; ♦, refined LA; ○, 130 ppm methionine; Δ, 100 ppm cysteine. Vertical bars at 24 and 60 h denote change in feedstock composition.

Zhang et al. *Bioresource Technol.* **2008**, *99*, 5873-5880.

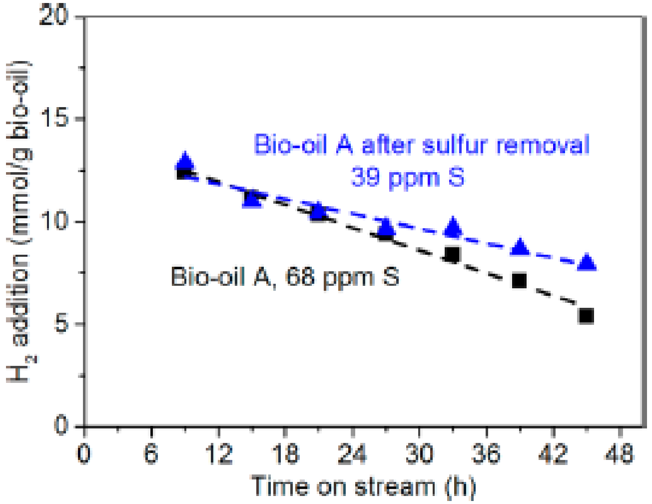



**Figure 10.** Effect of sulfur in bio-oil A in their hydrogenation performance. The hydrogen consumption, hydrogen-to-carbon ratio, and carbonyl contents of two hydrogenation tests using bio-oil A feed with different sulfur content. Reaction conditions: 160 °C, 1500 psig, 0.40 L bio-oil/L catalyst h, 2500 L hydrogen/L bio-oil.

Wang et al. *ACS Sust. Chem. Eng.* **2016**, *4*, 553-5545.

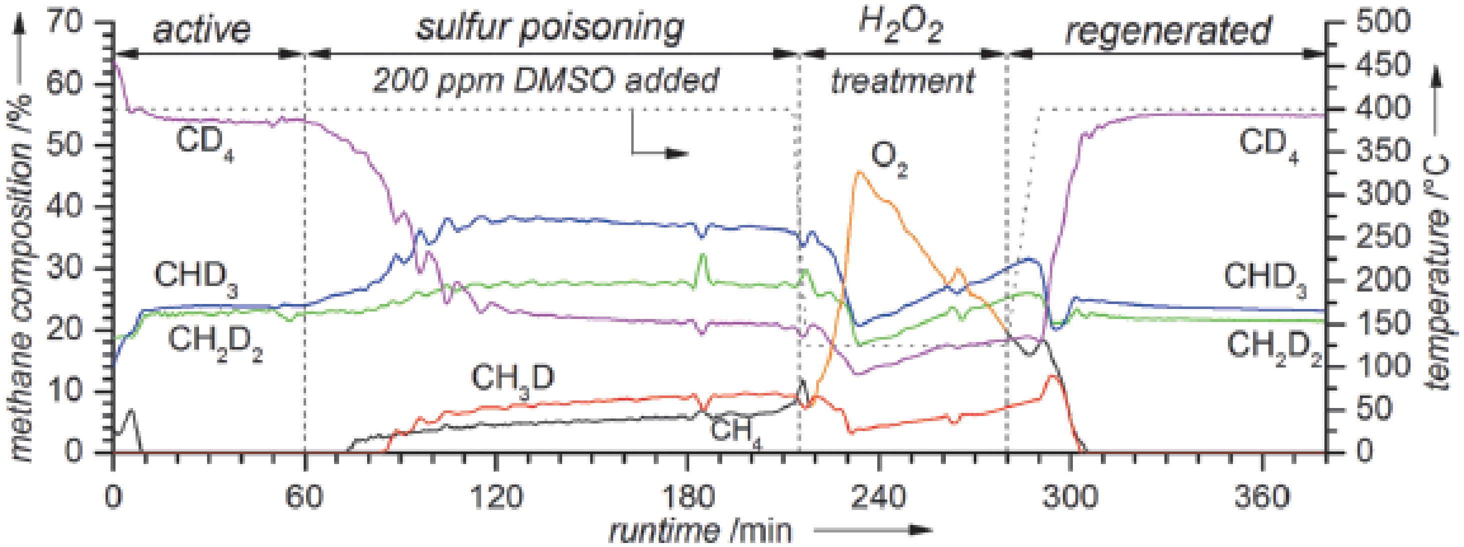
Sulfur frequently identified as a poison (typically through doping studies), but no catalyst regeneration procedures indicated

<u>Other references</u>:

- Glucose hydrogenation (Arena, *Appl. Catal. A: General*, **1992**, *87*, 219-229 and Elliott et al. *Appl. Biochem. Biotech.* **2004**, *113-116*, 807)
- Levulinic acid hydrogenation (Genuino *et al. ACS Sustainable Chem. Eng.* **2020**, *8*, 5903)
- Furfural hydrogenation (Li *et al. Energy Fuels* **2017**, *31*, 9585)

# $H_2O_2$-Based Regeneration of S-Poisoned Ru

## Mild oxidative treatment effective at recovering activity




- S poisoning in gasification of EtOH with Ru/C
- Regeneration of catalyst with $H_2O_2$ at ~100 °C recovers activity and selectivity
- Prolonged contact with $H_2O_2$ leads to cracking of support and loss of mesopore surface area

Dreher, M. Steib, M.; Nachtegaal, M.; Wambach, J.; Vogel, F. *ChemCatChem*, **2014**, *6*, 626-633.

Comparison of Methods for Regeneration of Raney Ni-Catalyst

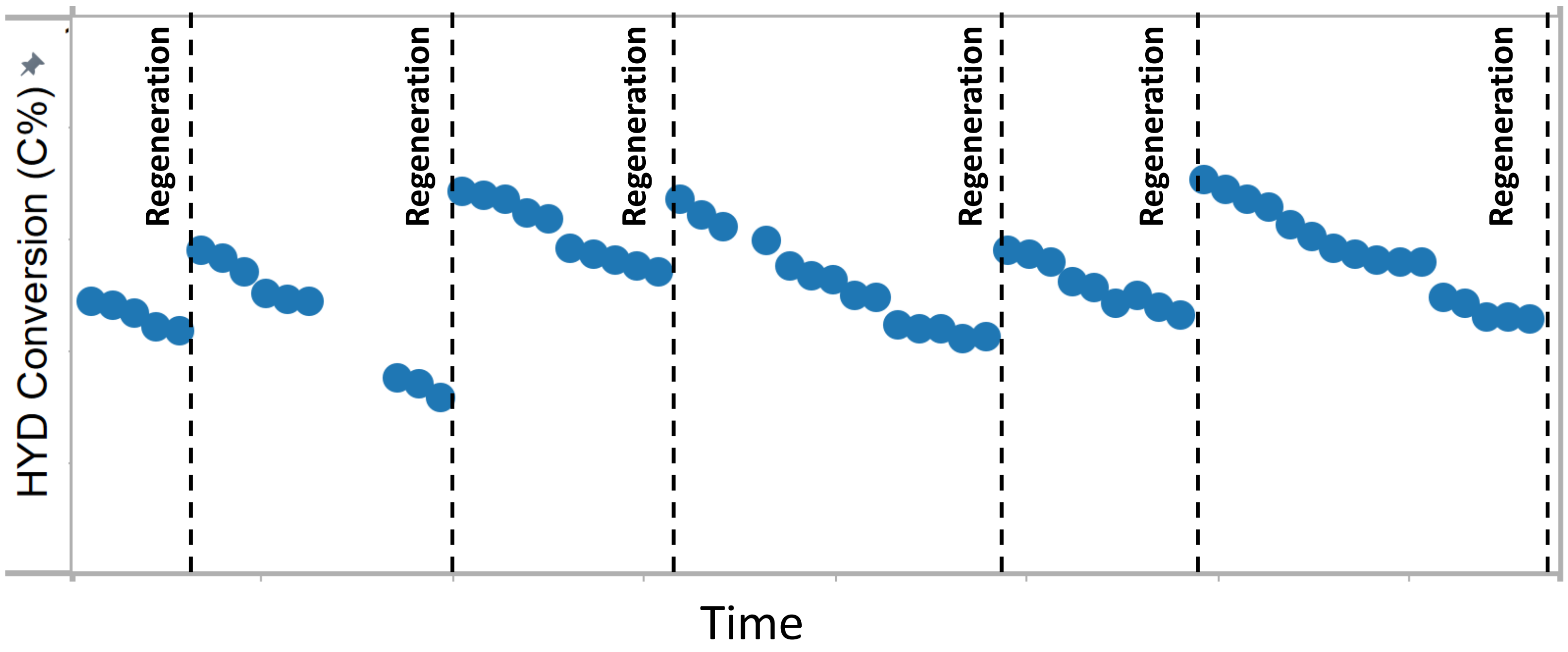
| Treatment | $H_2$ Pressure | Catalyst Activity Recovery (%) | Liquid Hourly Space Velocity (LHSV) | Time (hr.) |
|---|---|---|---|---|
| 70° C. wash | No | <10% | 1 | 14-24 hr |
| Bleach wash | No | 0% | 1 | 6-12 hr |
| 170° C. wash | 1200 psi | 80% | 1 | 4-10 hr |
| $H_2O_2$ wash | No | 90-95% | 1 | 6-24 hr |
| Feedtock: | 30% DS, 10% DP, 7 ppm of sulfur. | | | |
| Reaction condition: | Catalyst reduced under 1200 psi $H_2$, for 4-24 hrs, at 140° C. and 200° C., LHSV = 1 | | | |

- Ni- and Ru-catalyzed hydrogenation of sugars
- Regeneration with $H_2O_2$ recovers significant catalyst activity

Ma, C. "Regeneration of Catalyst for Hydrogenation of Sugars." US Patent 9,687,839. June 27,2017.

# Virent's Implementation of $H_2O_2$-Based Regenerations

## Regens conducted at moderate conditions with low [$H_2O_2$]

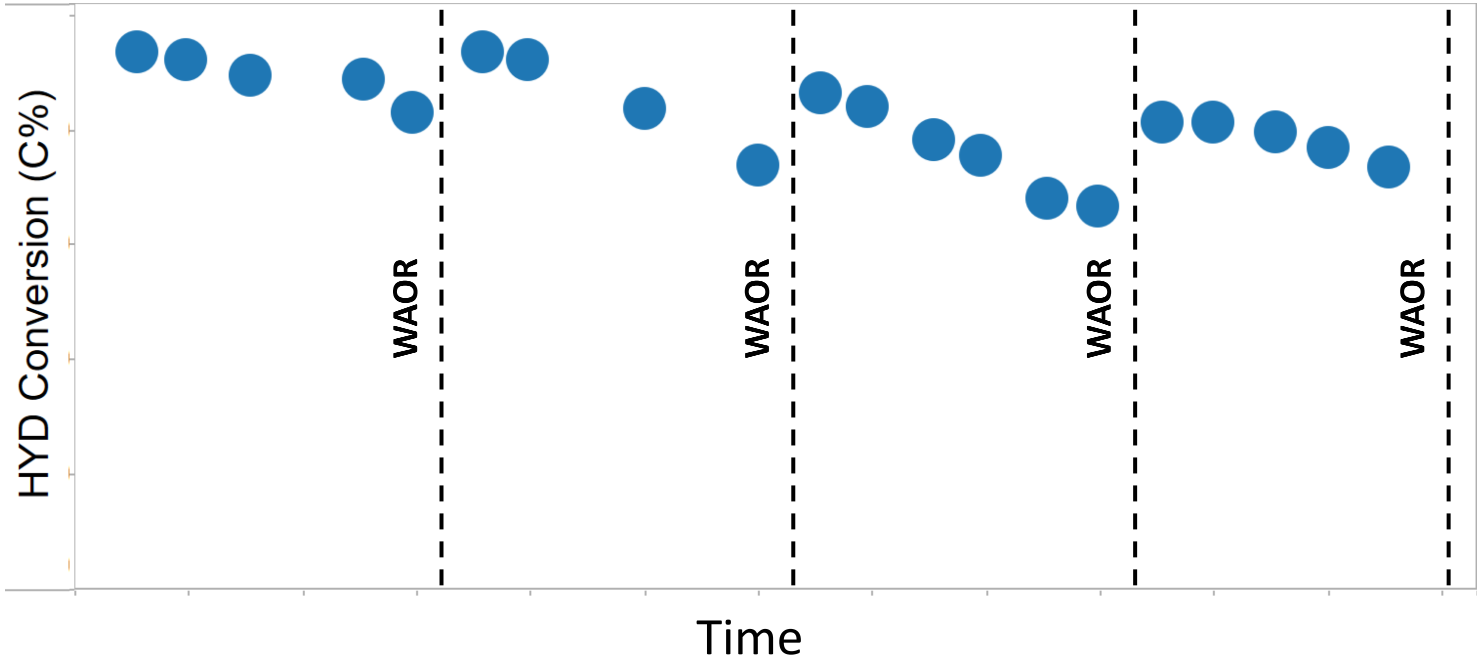



- Extended run showing positive impact of $H_2O_2$-based regenerations
  - Sulfur detected in effluent by ICP
- Upon emptying reactor, large amount of catalyst fines and weakened extrudates from carbon support
  - Damage presumably caused by $H_2O_2$ (as observed by Vogel et al)

# Developing Milder Regeneration

## Wet Air Oxidative Regeneration (WAOR)

- Virent hypothesized that using $O_2$ and water may provide a milder regeneration method
- Limit catalyst degradation and no need for $H_2O_2$ storage




- Proof of Concept: 4 successful regenerations using 1% $O_2$ with no observed catalyst damage

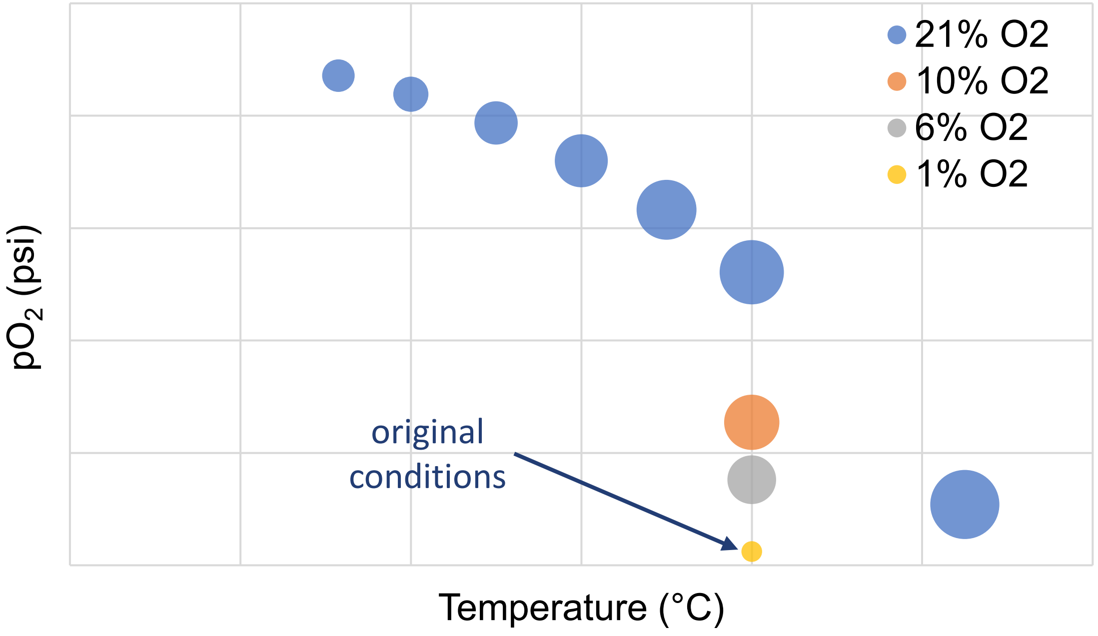


Blommel, B.; Anson, C.; van Straten, M.; Steenwinkel, E.; Holland, C.; Gearing, R.; Ferguson, C.; Wild, R.; Campbell, I. Systems and Methods for Wet Air Oxidative Regeneration of Catalysts. US 2023/0072588 A1. Published Mar. 9, 2023.

# Improving Commercial Viability

## High $N_2$ usage hurts economics of regeneration procedure

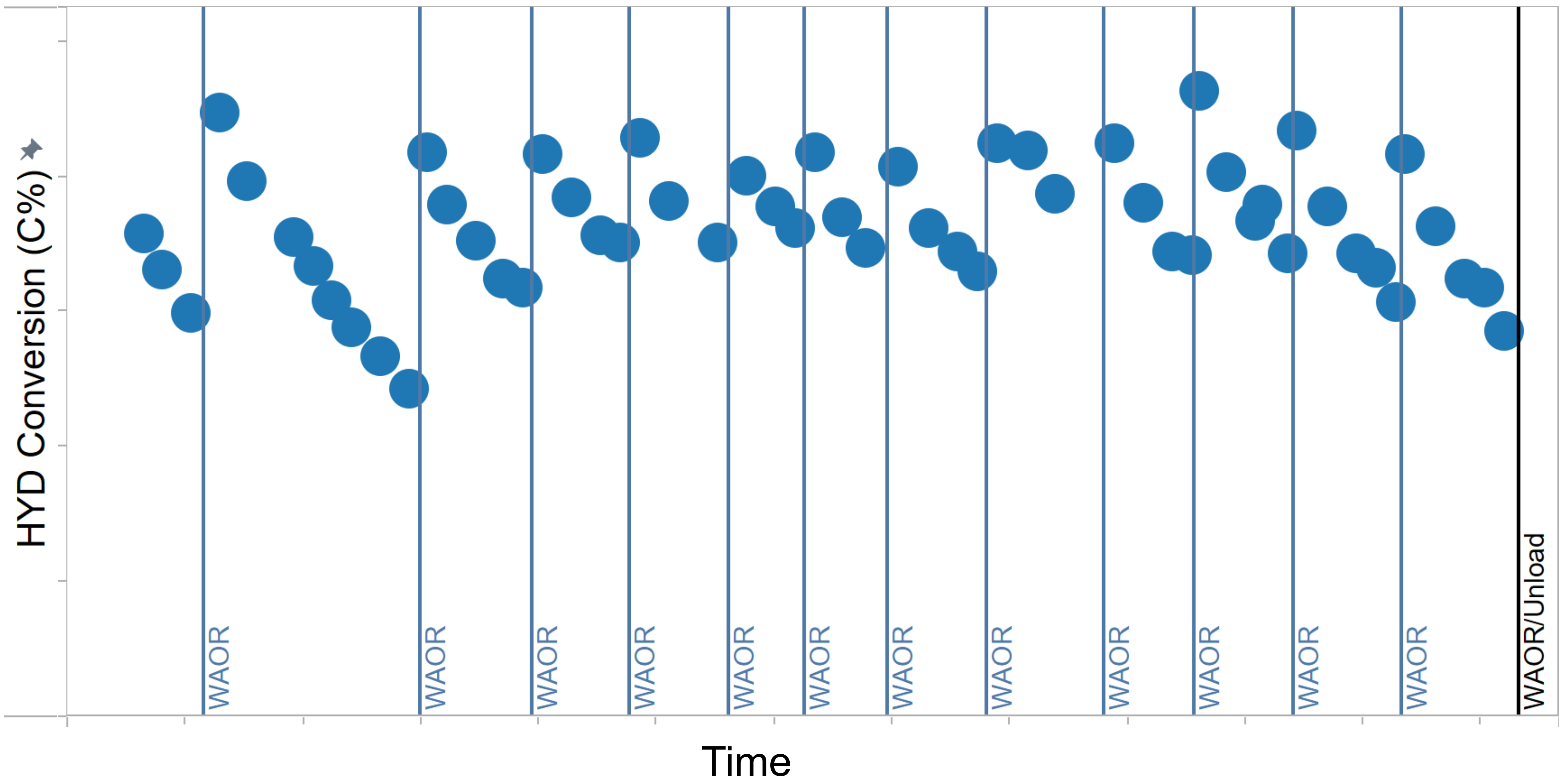
- While WAOR conditions are mild, can still cause support degradation
- To understand the impact of temperature and $O_2$ partial pressure, performed regenerations on "clean" catalysts




- Size of circles correlates with rate of $CO_2$ formation
- $pO_2$ calculated from $O_2$ composition, $H_2O$ vapor pressure, and reactor pressure at given temperatures

# Extended Catalyst Stability

## Regenerations using pure air and mild conditions

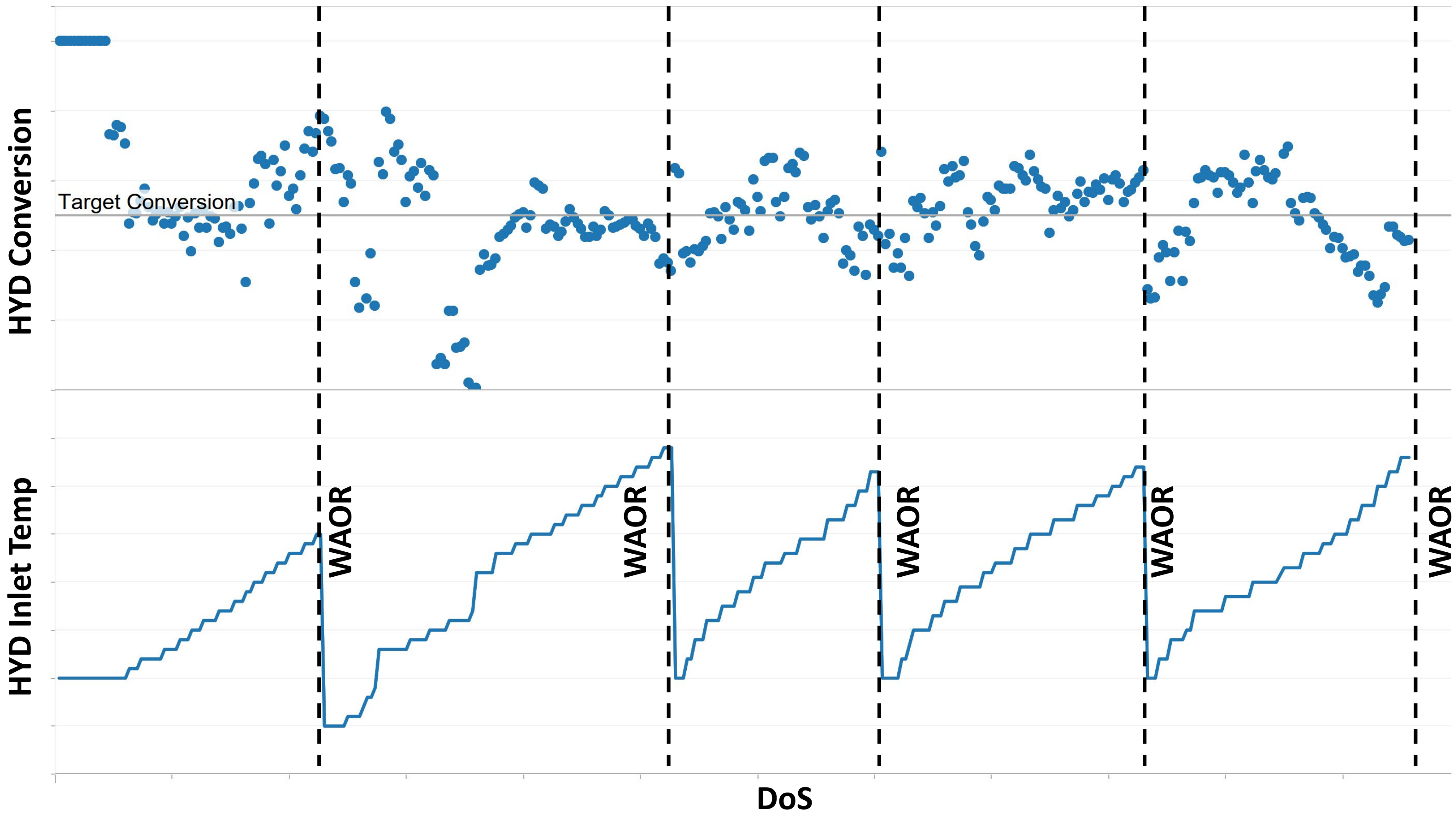



- Extended stability run over 13 regenerations shows good recovery of catalyst activity
- Unloaded catalyst did not show cracks in structure and maintained good mechanical strength


Blommel, B.; Anson, C.; van Straten, M.; Steenwinkel, E.; Holland, C.; Gearing, R.; Ferguson, C.; Wild, R.; Campbell, I. Systems and Methods for Wet Air Oxidative Regeneration of Catalysts. US 2023/0072588 A1. Published Mar. 9, 2023.

# Deploying WAOR on Demonstration Scale

## "Full Air" WAORs on Virent's Production Unit




Virent Demonstration Plant

- Production Unit controlled to hit a target HYD conversion to feed forward, so temperature used to control process
- High temperature leads to caramelization + fouling, requiring periodic regenerations
- System successfully completed >5 WAORs, further development on-going

# Thank you!

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