Designing Internal Surfaces of Porous Electrodes in Solid Oxide Electrolysis Cells for Highly Efficient and Durable Hydrogen Production

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DOE Award – FE-0032112
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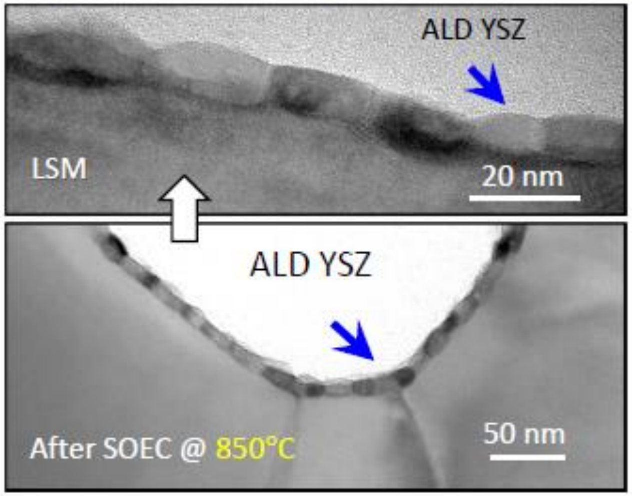
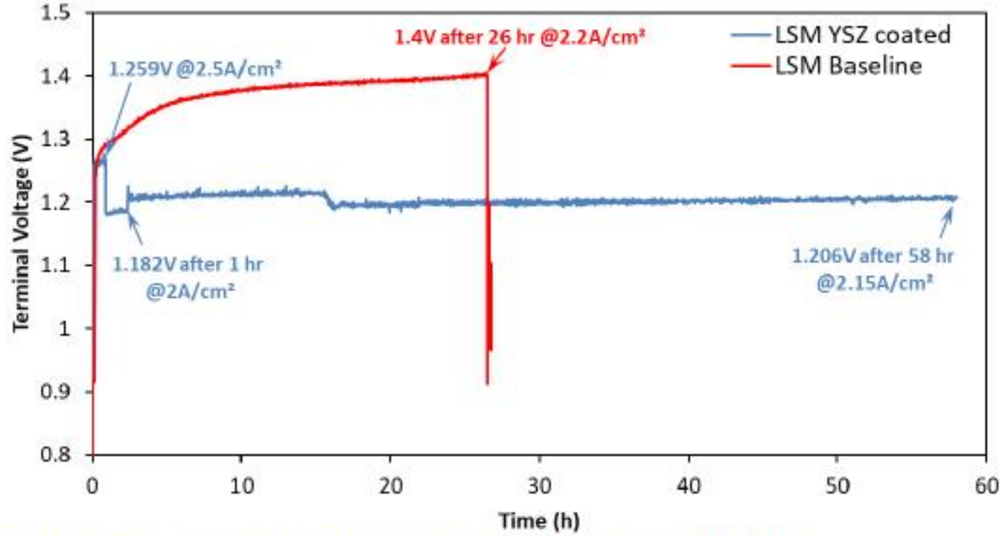
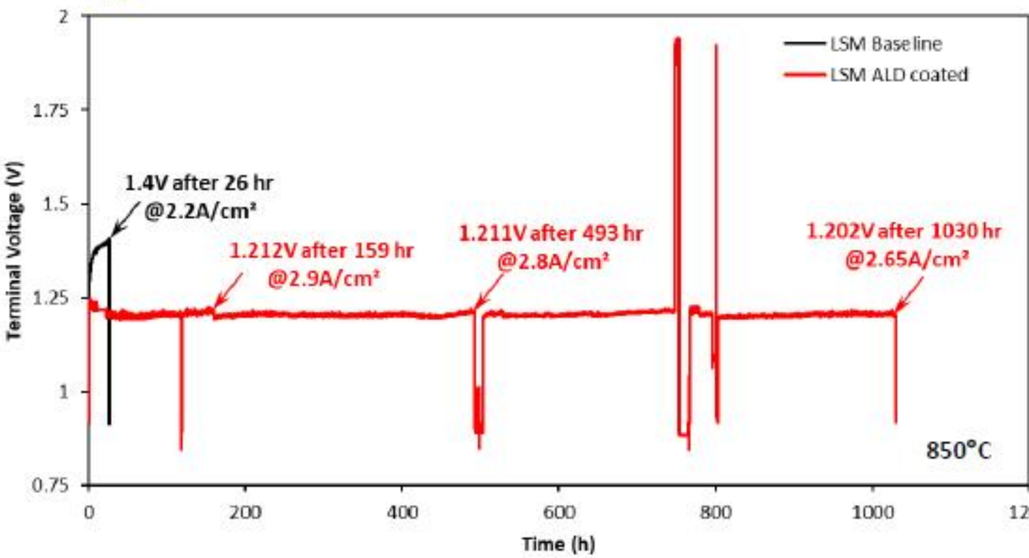
HIGHLIGHTS

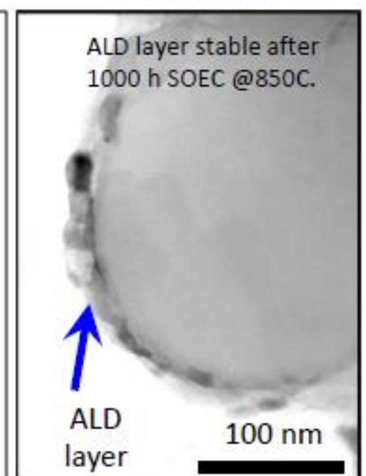
- Exceptional Stability of Nano ALD Layer in SOEC Operated @ 850°C.

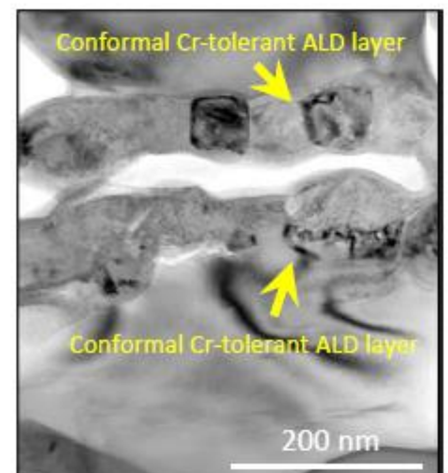




- ALD coated cell: H_2 Production @>2.5A/cm^2; 1.2V, superior stability for the first 1000 h;
  H_2 Production @ >~2.5A/cm^2 exceed DOE 2025 electrolysis goal of 1.5A/cm^2.







- Conformal ALD layer is Cr tolerant mixed conductor, further increasing the SOEC durability.

OVERVIEW

Project Background & Challenges

Solid Oxide Electrolysis Cells (SOEC) and Degradation

- Fuel electrode: Ni migration
- Oxygen electrode: LSCF/SDC decomposition, Sr surface segregation, Cr contamination
- Oxygen electrode: LSM/YSZ delamination, Cr contamination

Project Scope & Activities

- Project Objective
- Technical Approach
- Project Structure & Success Criteria

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On-Demand Design of ALD Layer Structure & Chemistry for Inherently Functional Commercial Cells

- Commercial cells with LSCF/SDC: ALD Coating LSCF/SDC Induced High Current Density
- Commercial cells with LSM/YSZ: Designing Internal Surface of LSM/YSZ by ALD Coating
  - ALD Layer of Conformal YSZ Nanoionics: Exceptional Stability in SOEC Operated @ 850°C
  - ALD Layer of Mixed Conductor:
    - ✓ SOFC: Increase of cell peak power density up to 250%
    - ✓ SOEC: High H_2 production rate @ >2.5A/cm^2 850°C, superior stability >1000h
    - ✓ Cr tolerant ALD layer is tunable from discrete particles to conformal layer
- Direct Impact of High Hydrogen Production Rate on SOEC Commercialization.

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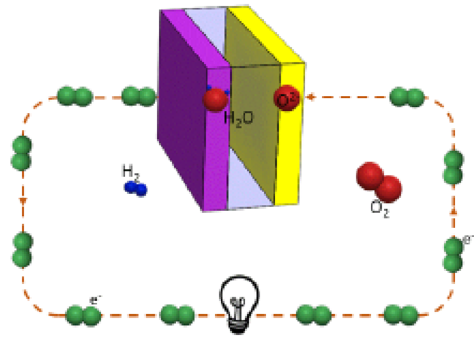
Solid Oxide Cells, SOEC Electrolyzing water to produce hydrogen

Solid Oxide Fuel Cells-SOFC:

- Oxidizing a fuel to produce electricity.
- High efficiency, fuel flexibility, low emissions.



Oxygen Electrode in SOFC

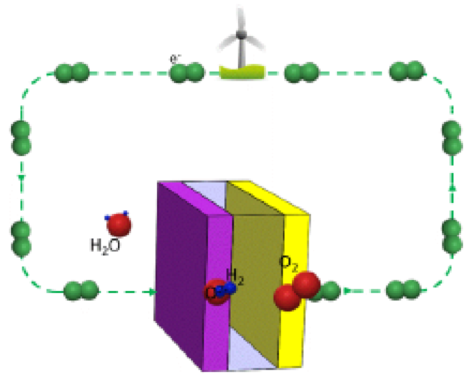
$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$$

Fuel Electrode in SOEC

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

Solid Oxide Electrolysis Cells- SOEC:

- Electrolyzing water to produce hydrogen and oxygen gases.
- Produce pure green hydrogen.



Oxygen Electrode in SOEC

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$$

Fuel Electrode in SOEC

$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

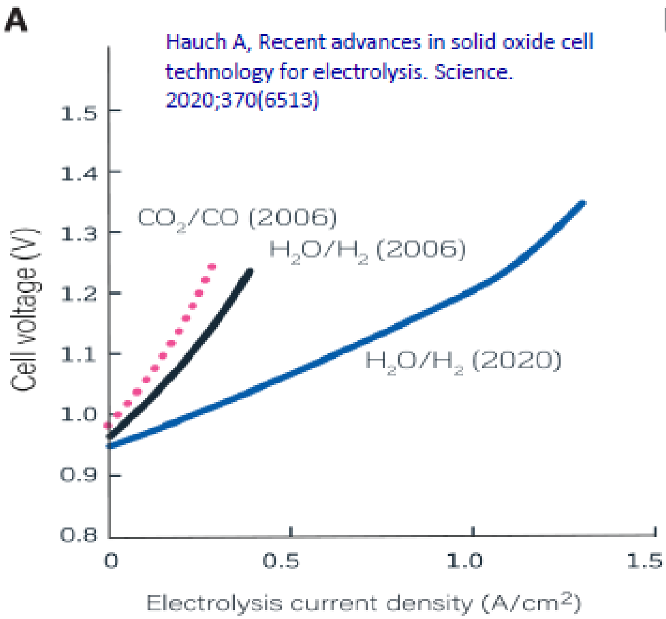
SOEC systems are practically adapting the well-developed SOFC systems to shorten the development of SOEC devices.

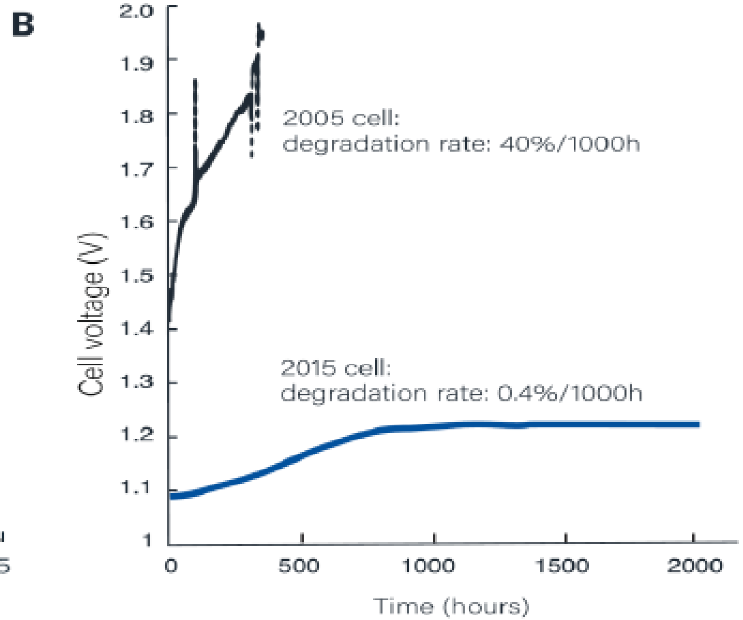
https://solydera.com/

Operation of the SOEC stacks at higher current densities over 0.75A/cm^2 and a low degradation rate could enable cost-competitive production of synthetic hydrocarbon and hydrogen.

Ebbesen SD, Jensen SH, Hauch A, Mogensen MB. High temperature electrolysis in alkaline cells, solid proton conducting cells, and solid oxide cells. Chemical reviews. 2014; 114 (21): 10697-734.

Increasing hydrogen productivity >0.75A/cm² being pursued in Europe





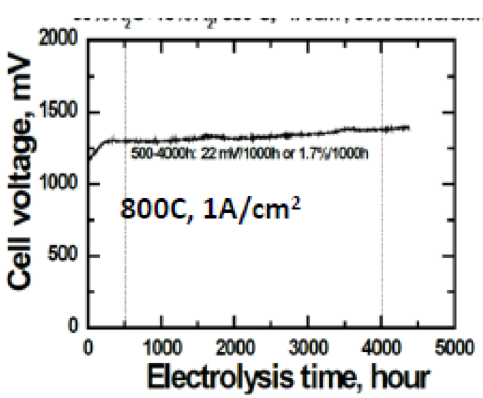
Electricity consumption < 40 kWh/kg

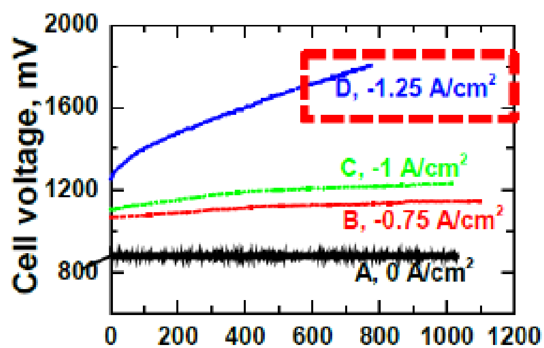
Production loss rate < 1.9%/1000h

Availability >95%
Reversible FC efficiency 54%

Current density 1.25A/cm2
Steam conversion rate > 85%

Cell-level. (A) Current-voltage curves for cells fabricated in 2006 and 2020 with data from at 750°C, measured in H2O/H2 = 1 or CO2/CO = 1. (B) Durability test of H2O electrolysis at 1 A/cm2 on a cell fabricated in 2005 measured at 850°C and a cell fabricated in 2015 measured at 800°C. All cells were supported by a Ni-YSZ electrode and had an active area of 16 cm².





- Hagen A, Frandsen HL. Recent Highlights of Solid Oxide Fuel Cell and Electrolysis Research at DTU Energy. Ecs Transactions. 2021;103(1):327.
- Atanasiu M, Tsimis D, Aguilo-Rullan A, Lymperopoulos N, Dirmiki D, editors. (Plenary), The Status of SOFC and SOEC R&D in the European Fuel Cell and Hydrogen Joint Undertaking Programme. ECS Meeting Abstracts; 2021: IOP Publishing.
- Chen M, Tong X, Ovtar S. Lessons Learned from Operating a Solid Oxide Electrolysis Cell at 1.25 a/cm2 for One Year. Ecs Transactions. 2021;103(1):475.

- **Extensive (> 9000 hours) long term SOEC testing has been performed in Europe.**
- **Significant degradation during initial operation (first ~ 500 hours), regardless of temperature and cells.**
- **Degradation is severe especially at the higher production rate with the current density > 1A/cm²**

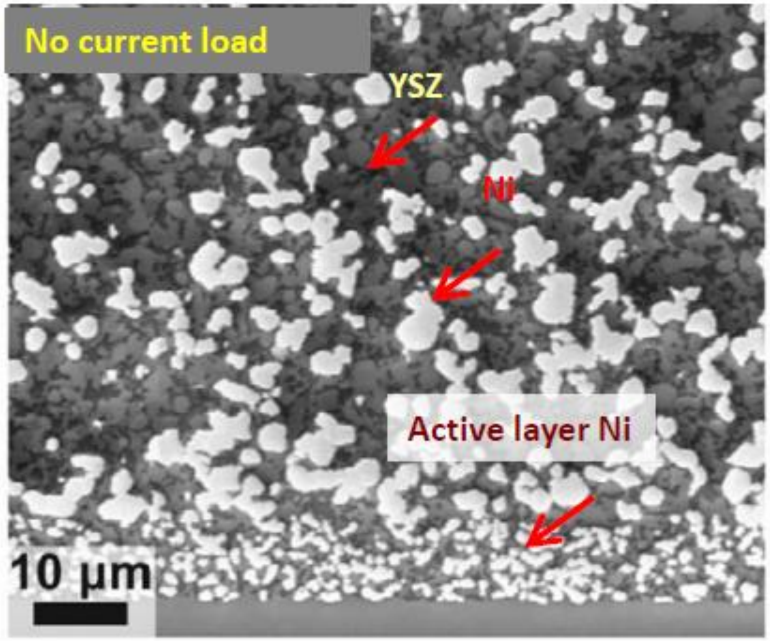
SOEC usually presents more severe degradation than SOFC

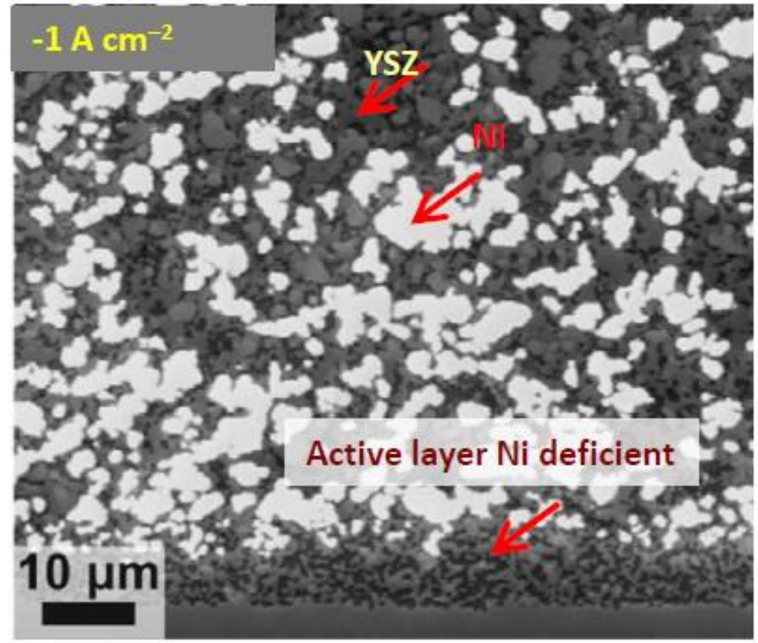
SOEC Degradation of is strictly dependent on the electrolysis operating conditions.

SOEC degradation is rooted in electrolyte, both fuel and oxygen electrodes.

SOEC degradation varies based on the chemistry of the electrodes.

- Ni/YSZ fuel electrode is the primary source of degradation for most long-term SOEC tests.





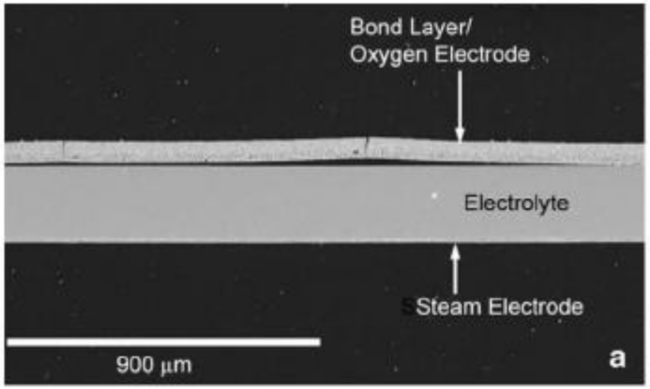
Significant Ni migration upon current load, operation for 9000 hours, 800C.

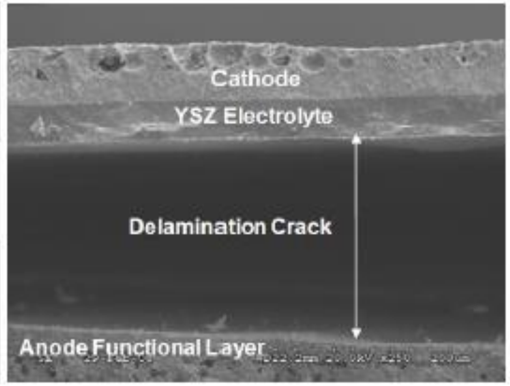
Mogensen MB, et al. Relation between Ni particle shape change and Ni migration in Ni–YSZ electrodes–a hypothesis. Fuel cells. 2017;17(4):434-41.

Alternative Ni-free ceramic oxide-based hydrogen electrodes generally have low electrical conductivity which can cause a significant increase in the resistance of the cell. Accordingly, the well-developed Ni/YSZ currently is still the best-performing fuel electrode for SOEC.

SOECs present more severe degradation than SOFCs, Oxygen electrode

LSM/YSZ Oxygen electrode, severe delamination at the electrolyte and electrode interface

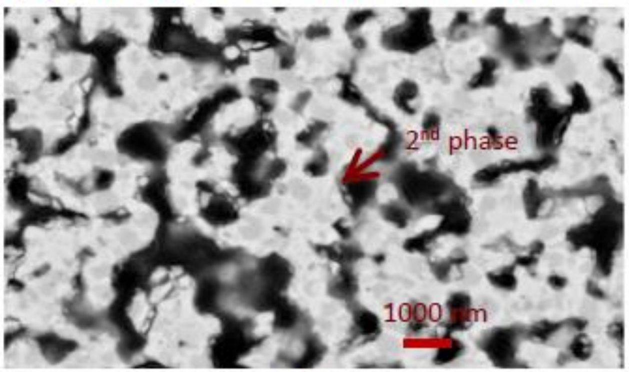


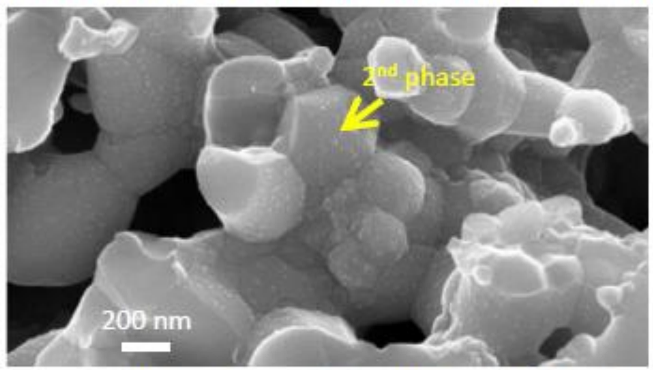


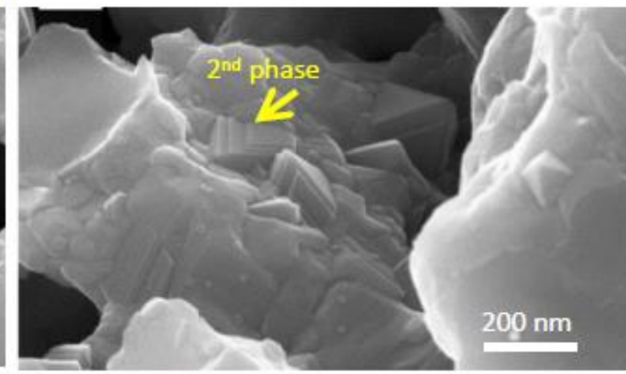
- Delamination, <u>due to lack of ionic conductivity in LSM</u>, could happen ~48 hours after SOEC operation.
- Cr contamination also cause the degradation.

Mawdsley JR,. <u>Post-test evaluation of oxygen electrodes from solid oxide electrolysis stacks</u>. international journal of hydrogen energy. 2009;34(9):4198-207. Virkar AV, Lim H-T, Tao G. <u>Failure of solid oxide fuel cells by electrochemically induced pressure</u>. Procedia IUTAM. 2014;10:328-37.

LSCF/SDC oxygen electrode, (1). LSCF decomposition, loss of the electrocatalytic activity, Sr surface segregation. (2). Cr vapor contamination from the interconnect, and their reaction with Sr.







Tietz F, Sebold D, Brisse A, Schefold J. <u>Degradation phenomena in a solid oxide electrolysis cell after **9000 h** of operation</u>. Journal of Power Sources. 2013;223(0):129-35.

SOEC degradation is taking place on both the fuel and oxygen electrodes.

– **Ni/YSZ, LSM/YSZ, LSCF/SDC degradation due to different nanostructure/chemistry reasons.**

This project:

✓ **Improving of SOEC performance through modifying internal surface of porous electrodes.**

✓ **Atomic layer deposition of porous Ni/YSZ, LSM/YSZ, LSCF/SDC (separately) of commercial SOCs.**

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  - Fuel electrode: Ni migration
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  - Oxygen electrode: LSM/YSZ delamination, Cr contamination

- **Project Scope & Activities**
  - **Project Objective**
  - **Technical Approach**
  - **Project Structure & Success Criteria**

- **Current Results**

  On-Demand Design of ALD Layer Structure & Chemistry for Inherently Functional Commercial Cells
  - Commercial cells with LSCF/SDC: ALD Coating LSCF/SDC Induced High Current Density
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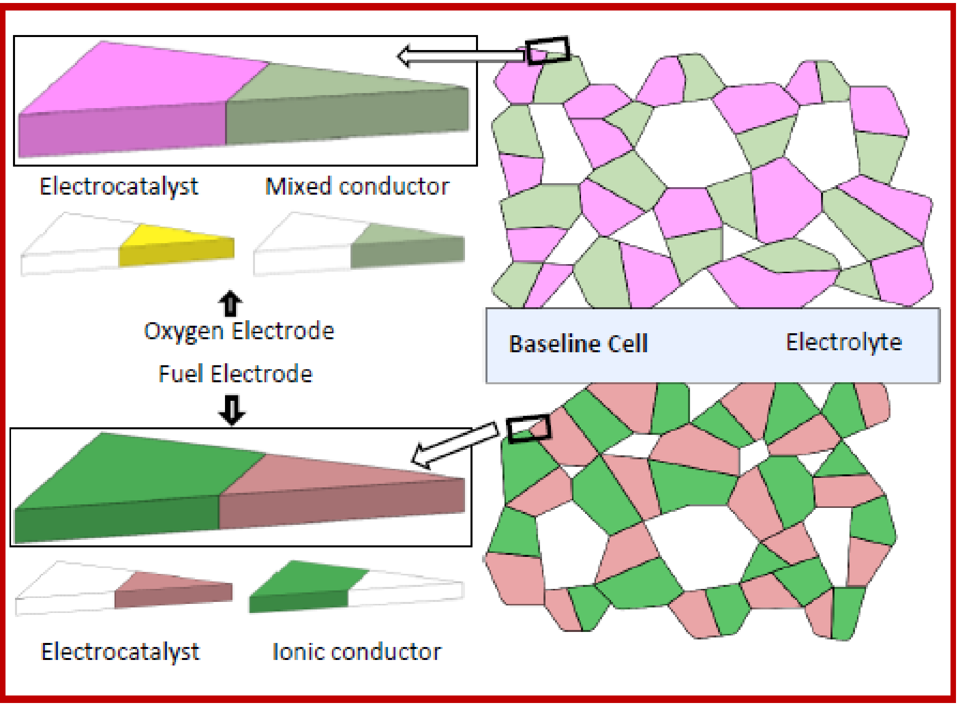
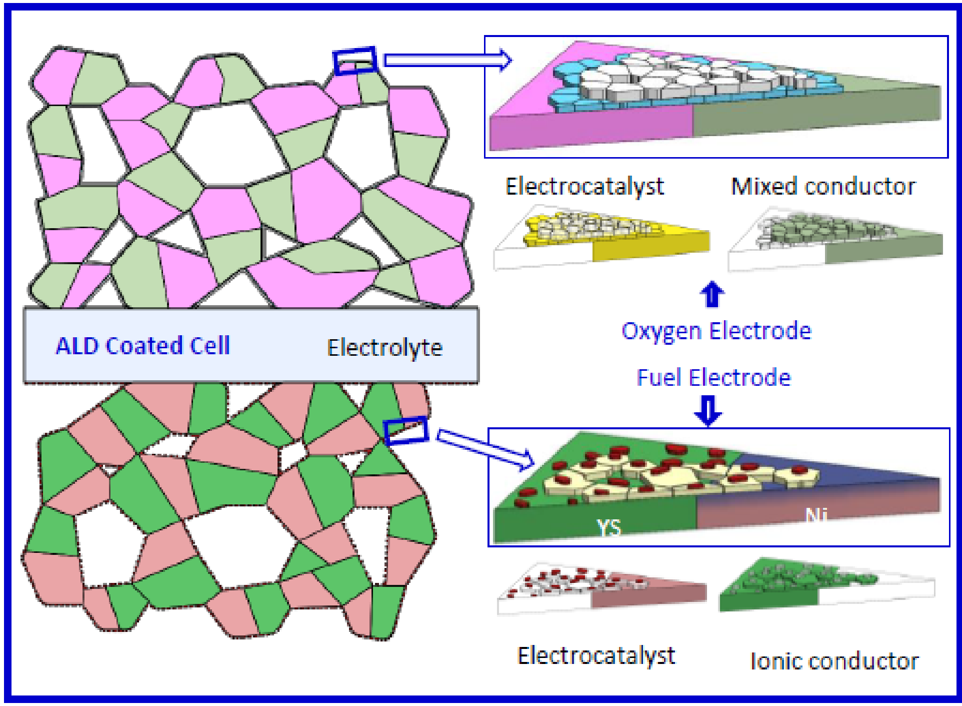
Project Objective

Objective of this research is to achieve highly efficient and durable hydrogen production.

Approach: Decrease electrode resistance, increase hydrogen production rate, increase durability, by ALD coating.

- The commercial cells adapted for this study consist of the Ni/YSZ fuel electrode and $La_xSr_{1-x}Mn_yO_3$-(LSM)/YSZ and $La_xSr_{1-x}Co_yFe_{1-y}O_3$ (LSCF)/Sm_2O_3 doped CeO_2 (SDC) oxygen electrodes.
- Highly active and robust nano-scale coating layers will be developed using the ALD and implanted to the internal surface of the porous electrode of as-fabricated commercial cells.
- For both the fuel and oxygen electrodes, innovative conformal surface consisting of nanocrystalline ionic conducting materials will be incorporated into the ALD coating layer to provide structure protection for increased durability towards both the intrinsic and extrinsic degradation.





Project Structure & Success Criteria

SCOPE OF WORK & common approaches for tasks.

Commercial Cells: We will work on **state-of-the-art commercial cells** provided by different manufacturers that are being developed and matured worldwide during the past two decades.

- **ALD processing:** ALD coating using a commercial ALD system: Computer-controlled automatic switching of the precursor with a one-step processing. The ALD processing procedure will be developed to control the chemistry and the thickness of the ALD layer.
- **SOEC hydrogen production evaluation:** Lab-scale cell testing of the commercial button and planar cells: The cell testing will be performed on baseline and surface-modified cells. The cells will be tested using the state-of-the-art test stations at the PI's lab. Testing conditions such as operation temperature, operation current density, operation voltage and durability, will be adjusted at the industrially relevant operating conditions.
- **Nanostructure evaluation:** ALD layer nanostructure evaluation of as-deposited cells and ALD layer nanostructure evaluation of cells after electrochemical testing.

Success Criteria.

The proposed work will accomplish the validation of concepts at a laboratory scale by direct comparison of the electrolysis performance of the as-received commercial baseline cells and the commercial cells subjected to subsequent to ALD coating developed through this project.

All lab-scale cell testing will be performed at the industry-relevant operation conditions as detailed below:

- Cells for testing will be **state-of-the-art commercial cells (SOFCs), with excellent performance repeatability**.
- Long-term stability tests will be carried out **over 500 hours** of continuous operations. The desired operation current density is over **$0.75 A/cm^2$**.

Very challenging to achieve for the commercial cells.

For instance, baseline cells with LSM/YSZ experience delamination under high current even **after ~50 hours operation**.

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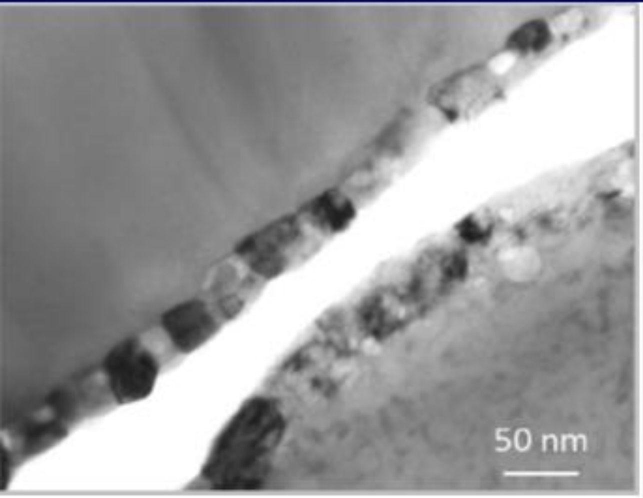
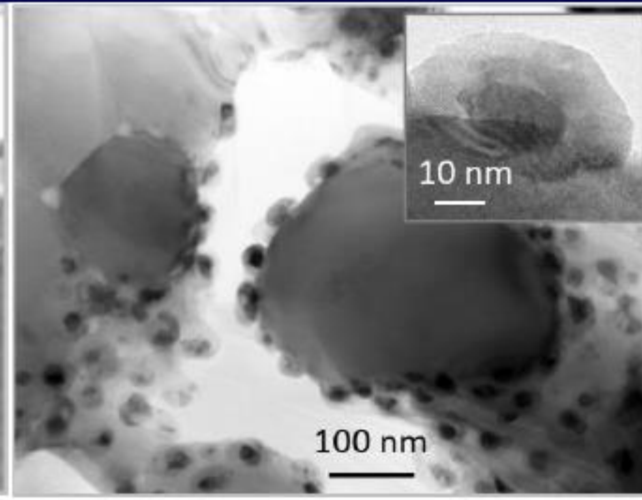
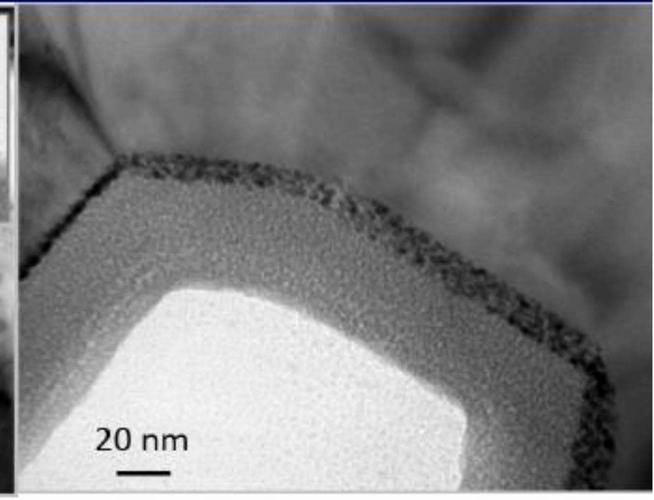
On-Demand Design of Nanostructure & Function of ALD Layer



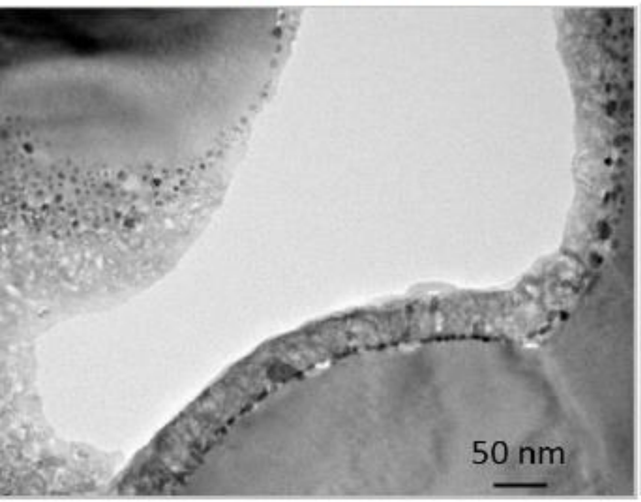
Single layered nanoionics



Discrete core-shelled catalysts



Multilayered nano-composite



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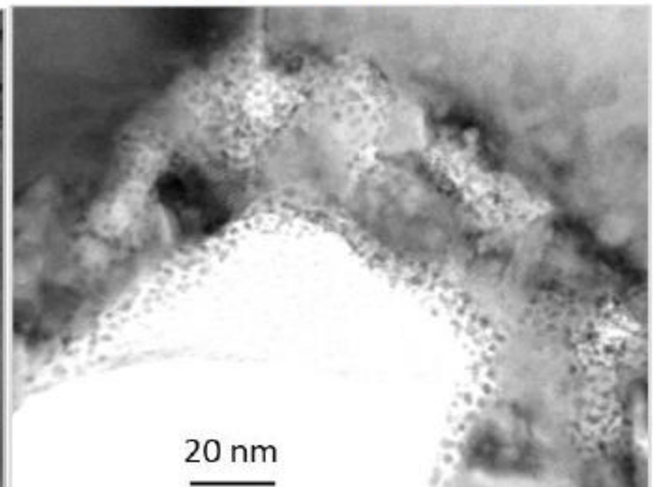
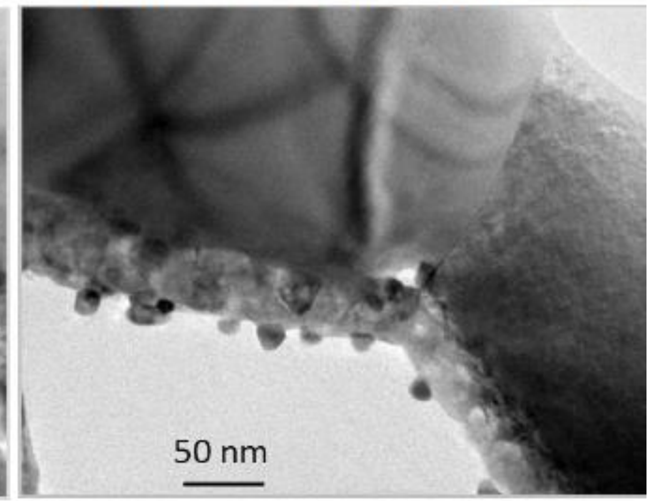


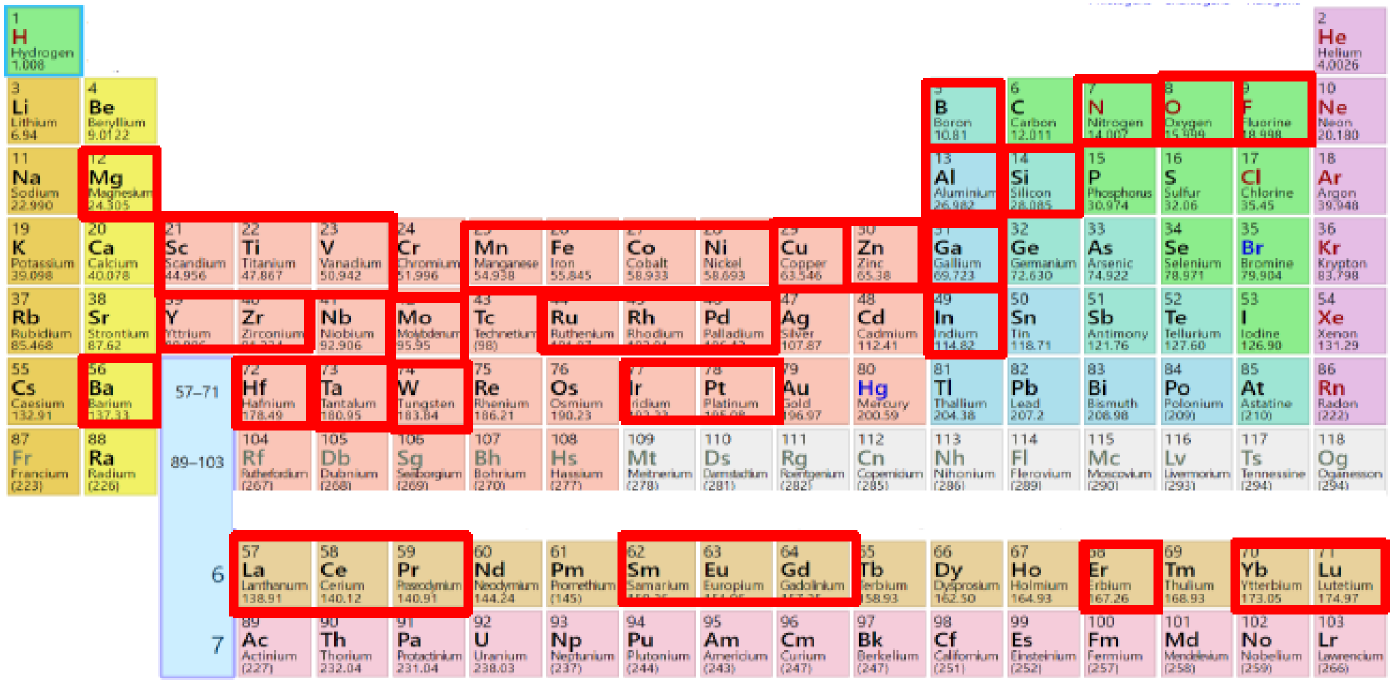


Porous composite having pores filled with nano catalyst

- ALD layer could be single layered, either conformal continuous layer or discrete particles.
- ALD layer could be heterogenous composite, layered or porous filled with nano catalysts.

Scientific Reports 6, 32997, 2016 *J Power Sources, 405, 45-50, 2018.* *ACS Catalysis, 9(8), 6664-6671, 2019* *Nano Letters, 19(12), 8767-8773, 2019*

ALD Coating of Elements We Work On



- ALD layer nanostructure and chemistry could be designed on demand, based on the electrode backbone structure & chemistry.
- ALD coating as-made inherently functional fuel cells, (1). increase cell power density to 300%, (2). mitigate intrinsic degradation caused by cation segregation, (3). mitigate the Cr contamination.

Beneq

The most recognized provider of ALD equipment for R&D & Industry.

Air Liquide

Air Liquide Advanced Materials

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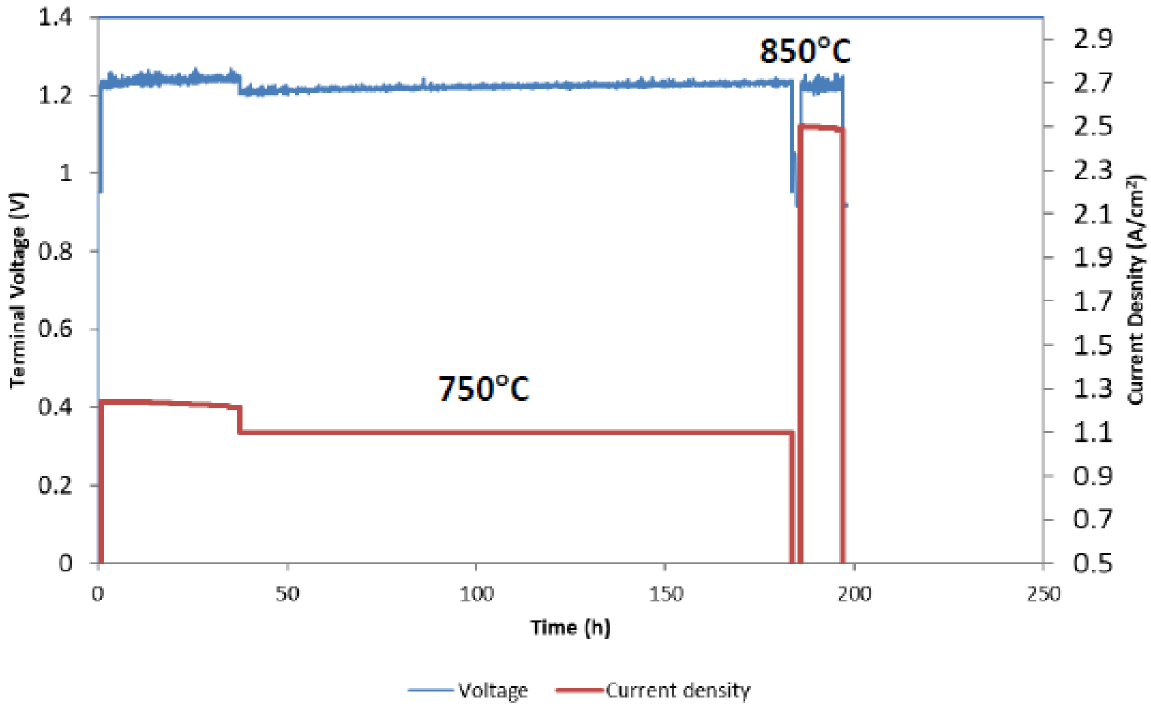
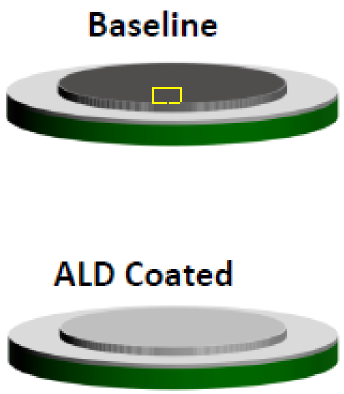
SOEC: ALD Coating LSCF/SDC of Commercial Cell Resulted in Hydrogen Production Rate > 1A/cm²





Experimental Conditions:

- Commercial Cell with LSCF/SDC oxygen electrode and Ni/YSZ fuel electrode.
- Ni/YSZ electrode is not ALD coated.
- ALD Coating on the LSCF/SDC electrode only.

❖ **ALD coating on LSCF/SDC resulted in high current density of >1.1A/cm²; @ 750°C; 2.5A/cm²; @ 850°C.**

❖ **ALD coating of LSM/YSZ of commercial cells resulted in better SOEC performance than that of ALD-coated LSCF/SDC cells.**

❖ **ALD coating of LSM/YSZ of commercial cell, mitigate the electrode delamination, achieved >2.5A/cm² after > 1000 hours SOEC.**

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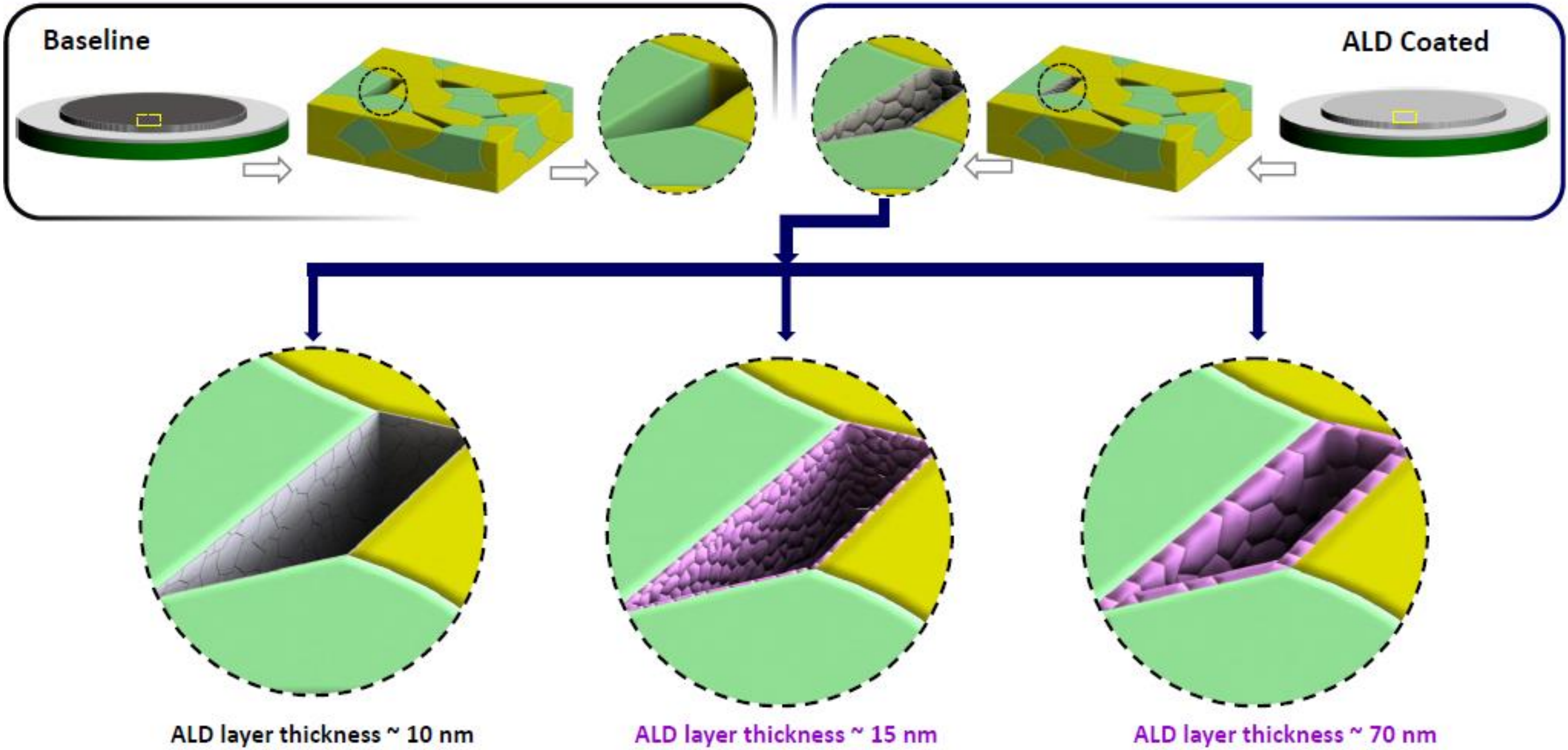

ALD YSZ ionic conductor

ALD Cr Tolerant Mixed Conducting Oxide

- Internal surface of porous electrode of as fabricated commercial SOC offers the design space for further tuning the chemistry & structure of the electrode.
- ALD layer creating new sites for facilitating the electrochemical reactions for increasing SOEC hydrogen production rate, and cell durability.
- ALD layer protective coating for increasing cell tolerance of contaminants such as Cr.

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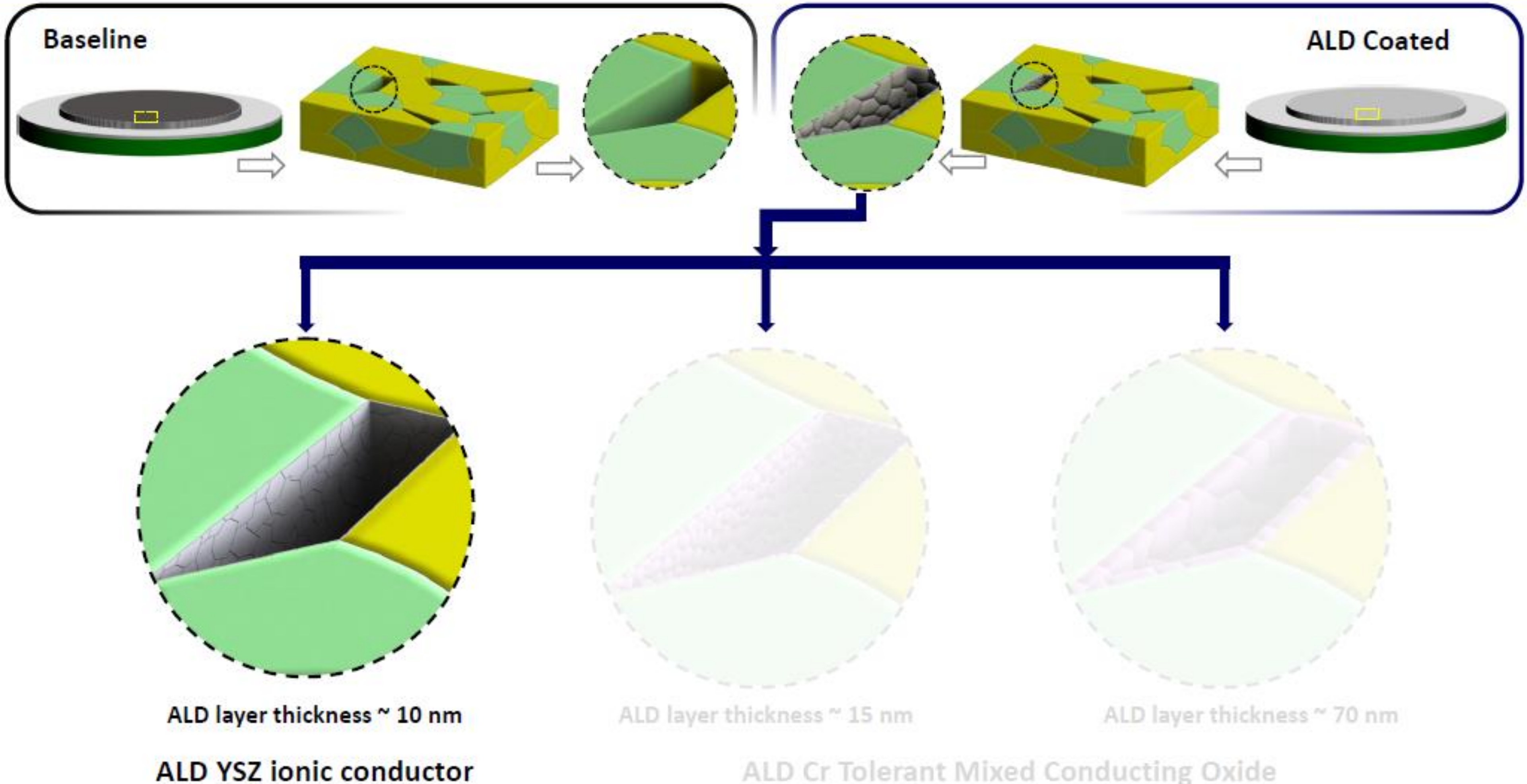

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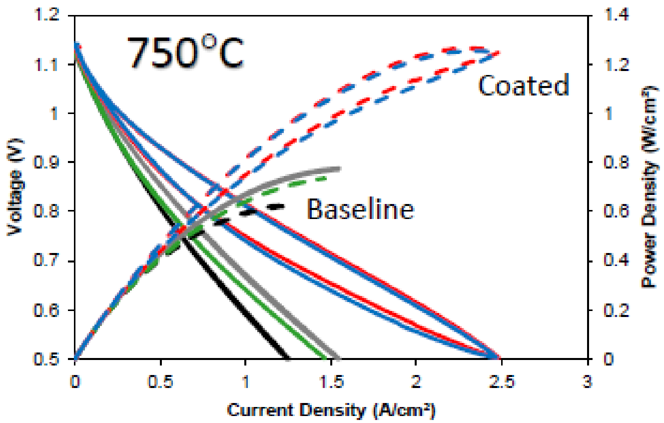
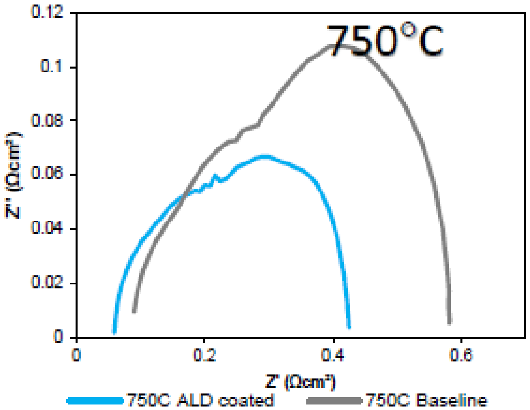
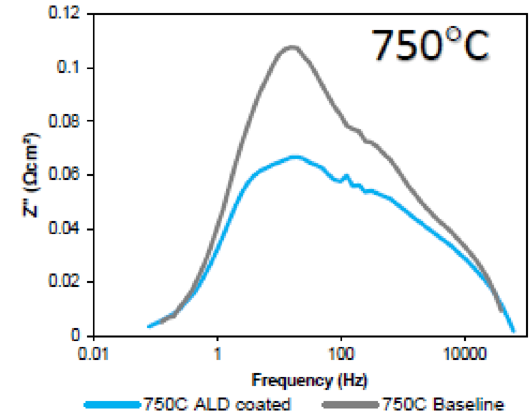
- ALD layer protective coating for increasing cell tolerance of contaminants such as Cr.

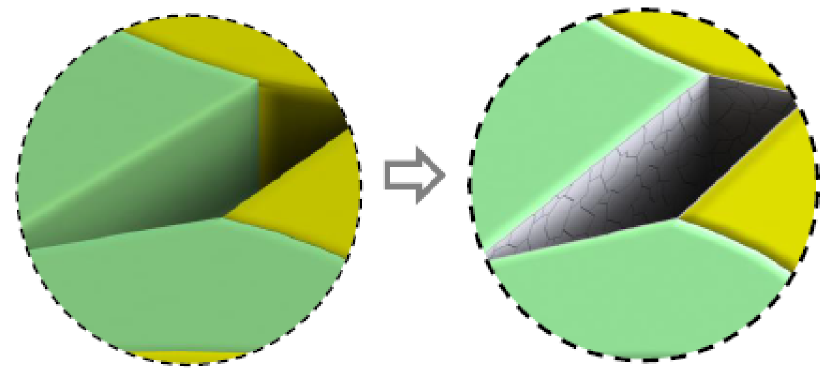
SOFC: ALD Coating YSZ Nanoionics (~ 10 nm thick)







ALD coated cell		Baseline cell		Enhancement
Operation	Peak W/cm²	Operation	Peak W/cm²	
0 hr **750°C**	0.734	0 hr **750°C**	0.627	**117%**
24 hr **750°C**	1.264	0 hr **750°C**	0.714	**163%**



Baseline

ALD Coated

ALD of ionic conductor YSZ
ALD layer thickness ~ 10 nm

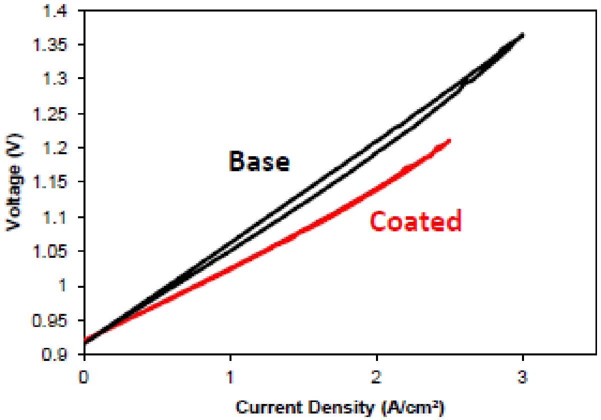
Experimental Conditions:

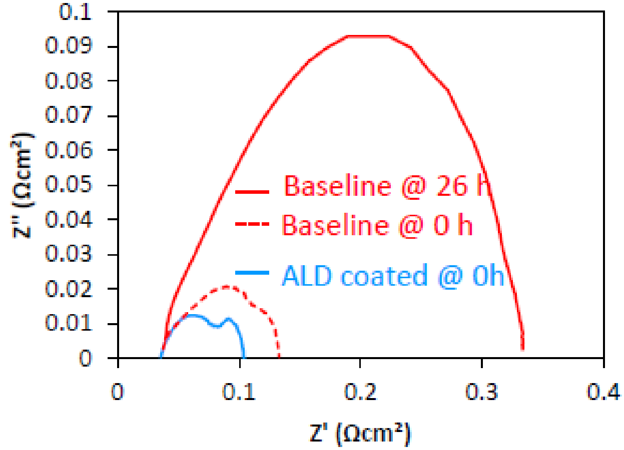
- Commercial Cell with LSM/YSZ and Ni/YSZ.
- Ni/YSZ electrode is not ALD coated.
- ALD Coating on the LSM/YSZ electrode only.

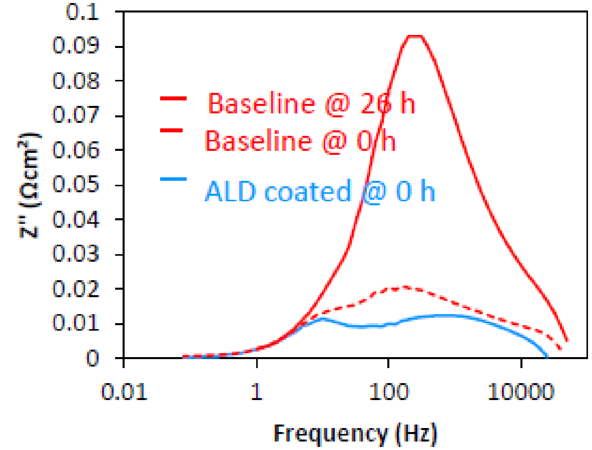
ALD YSZ nanoionics on LSM/YSZ of commercial SOFC

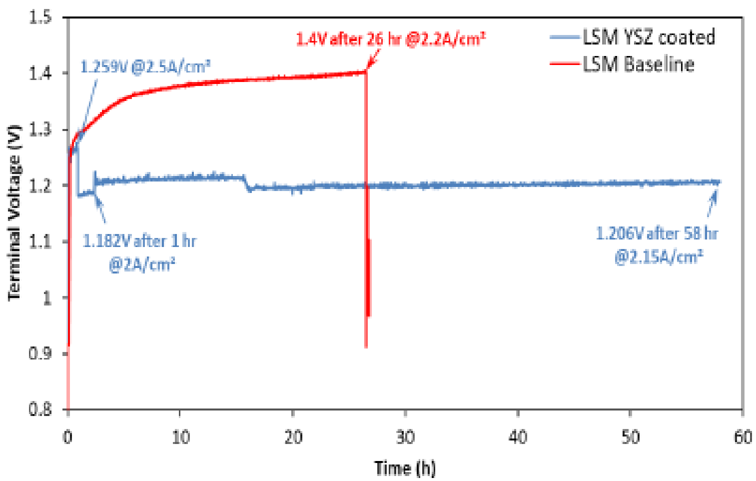
- **ALD coating achieves a 163 % peak powder increase at 750°C**
- **ALD coated reduced both the ohmic and polarization resistance of the entire cell.**

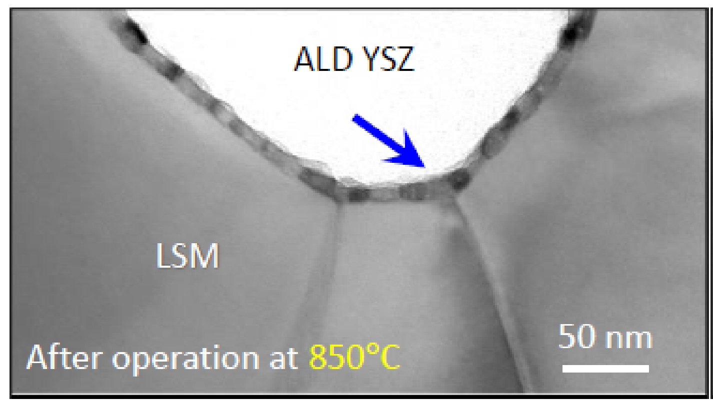
SOEC: ALD Coating YSZ Nanoionics (~ 10 nm thick)

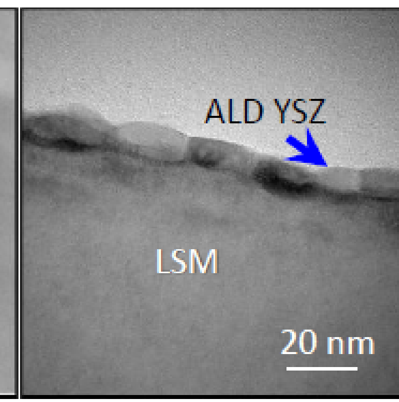












Baseline SOEC with LSM/YSZ fast degradation after 26 hours at 850°C

SOEC at 850°C, ALD coating of LSM/YSZ resulted in:

- ✓ **Reduced the cell resistance. Lower the SOEC operation voltage. High SOEC current of >2A/cm²**
- ✓ **Mitigate the cell delamination, increase the cell durability.**
- ✓ **ALD nano-YSZ, Exceptional stability. After 850 ° C for 150 hours, ALD nano-YSZ layer remains to be conformal ~ 10 nm in thickness without any agglomeration.**

OVERVIEW

- **Project Background & Challenges**

  Solid Oxide Electrolysis Cells (SOEC) and Degradation

  - Fuel electrode: Ni migration
  - Oxygen electrode: LSCF/SDC decomposition, Sr surface segregation, Cr contamination
  - Oxygen electrode: LSM/YSZ delamination, Cr contamination

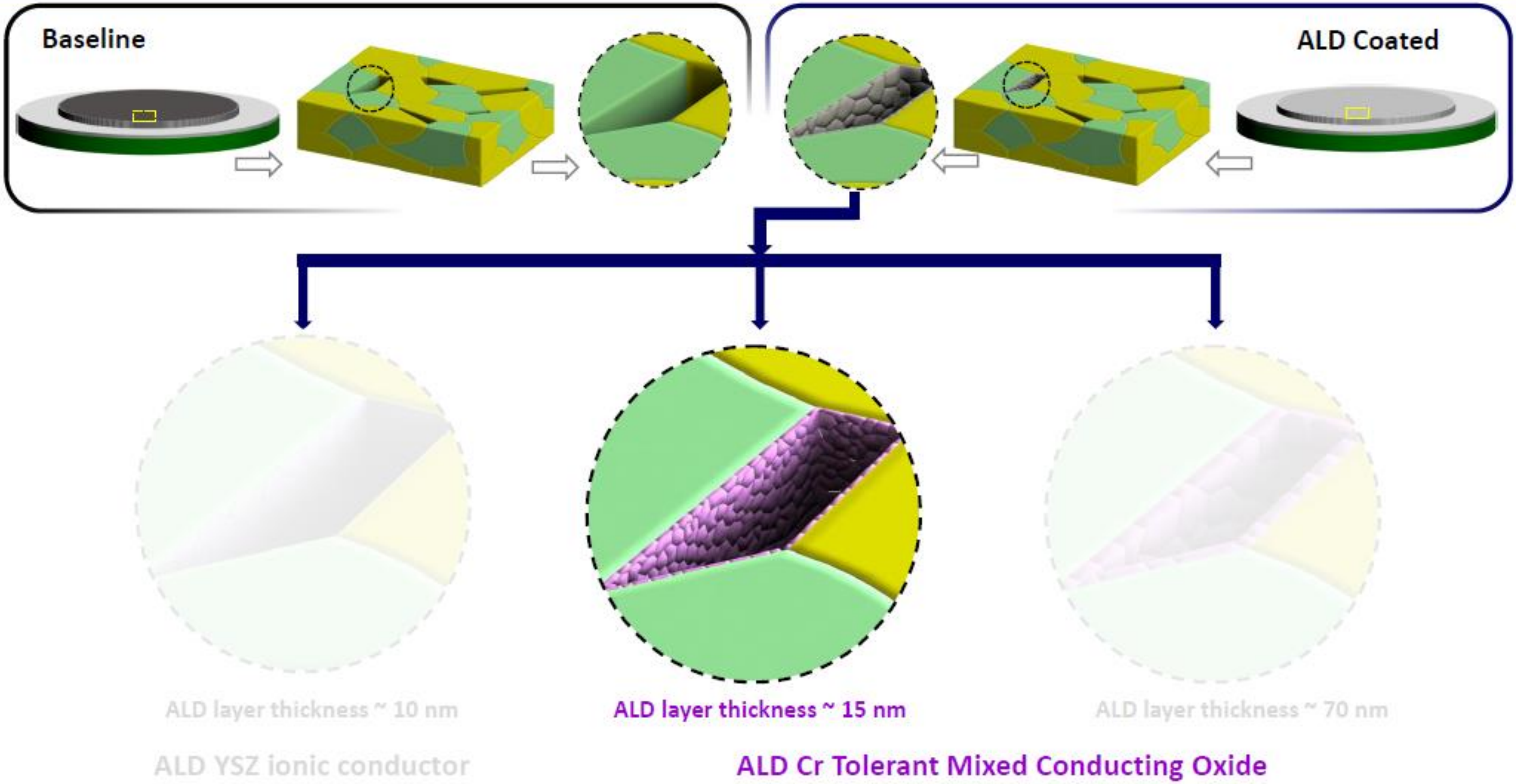
- **Project Scope & Activities**
  - Project Objective
  - Technical Approach
  - Project Structure & Success Criteria

- **Current Results**

  On-Demand Design of ALD Layer Structure & Chemistry for Inherently Functional Commercial Cells

  - Commercial cells with LSCF/SDC: ALD Coating LSCF/SDC Induced High Current Density
  - Commercial cells with LSM/YSZ: Designing Internal Surface of LSM/YSZ by ALD Coating
    - ALD Layer of Conformal YSZ Nanoionics: Exceptional Stability in SOEC Operated @ 850°C
    - ALD Layer of Mixed Conductor:
      - ✓ SOFC: Increase of cell peak power density up to 250%
      - ✓ SOEC: High H_2 production rate @ >2.5A/cm^2 850°C, superior stability >1000h
      - ✓ Cr tolerant ALD layer is tunable from discrete particles to conformal layer
  - Direct Impact of High Hydrogen Production Rate on SOEC Commercialization.

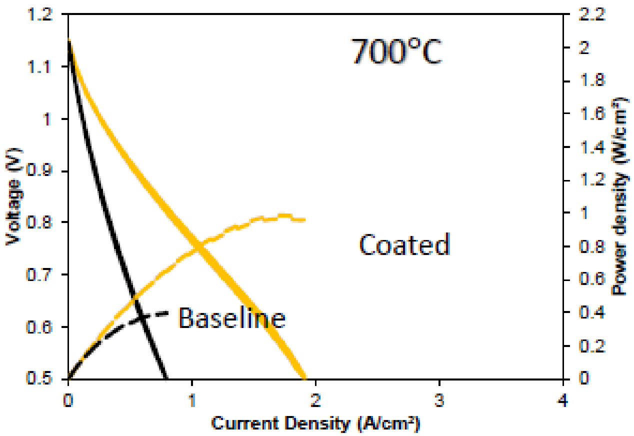
Designing Internal Surfaces of Porous LSM/YSZ Electrode

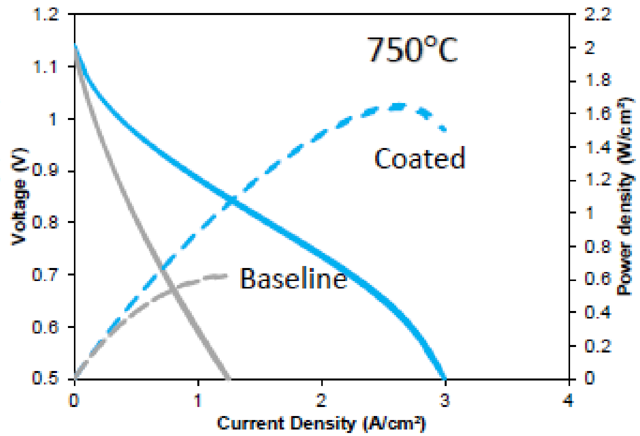


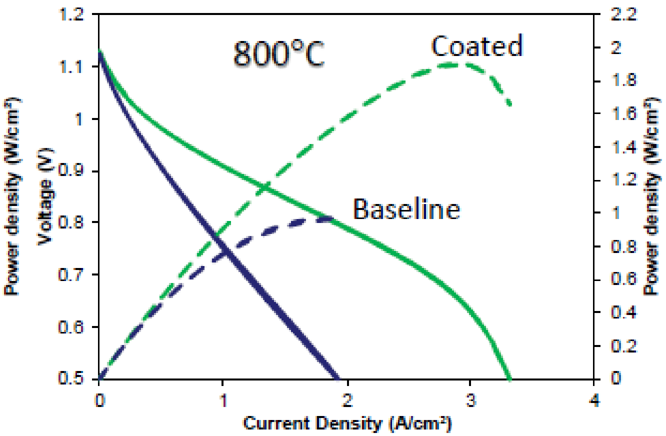
- Internal surface of porous electrode of as fabricated commercial SOC offers the design space for further tuning the chemistry & structure of the electrode.
- ALD layer creating new sites for facilitating the electrochemical reactions increasing increase SOEC hydrogen production rate, and cell durability.
- ALD layer protective coating for increasing cell tolerance of contaminants such as Cr.

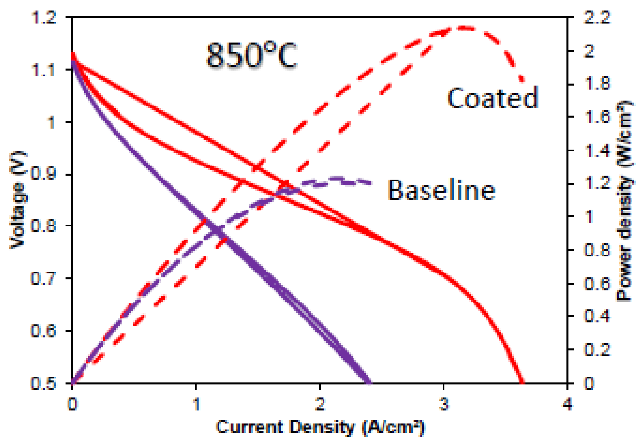
ALD layer: Cr-Tolerant Mixed Conductor Oxide

SOFC: Coating LSM/YSZ, Increase Cell Peak Power Density Up To >250%







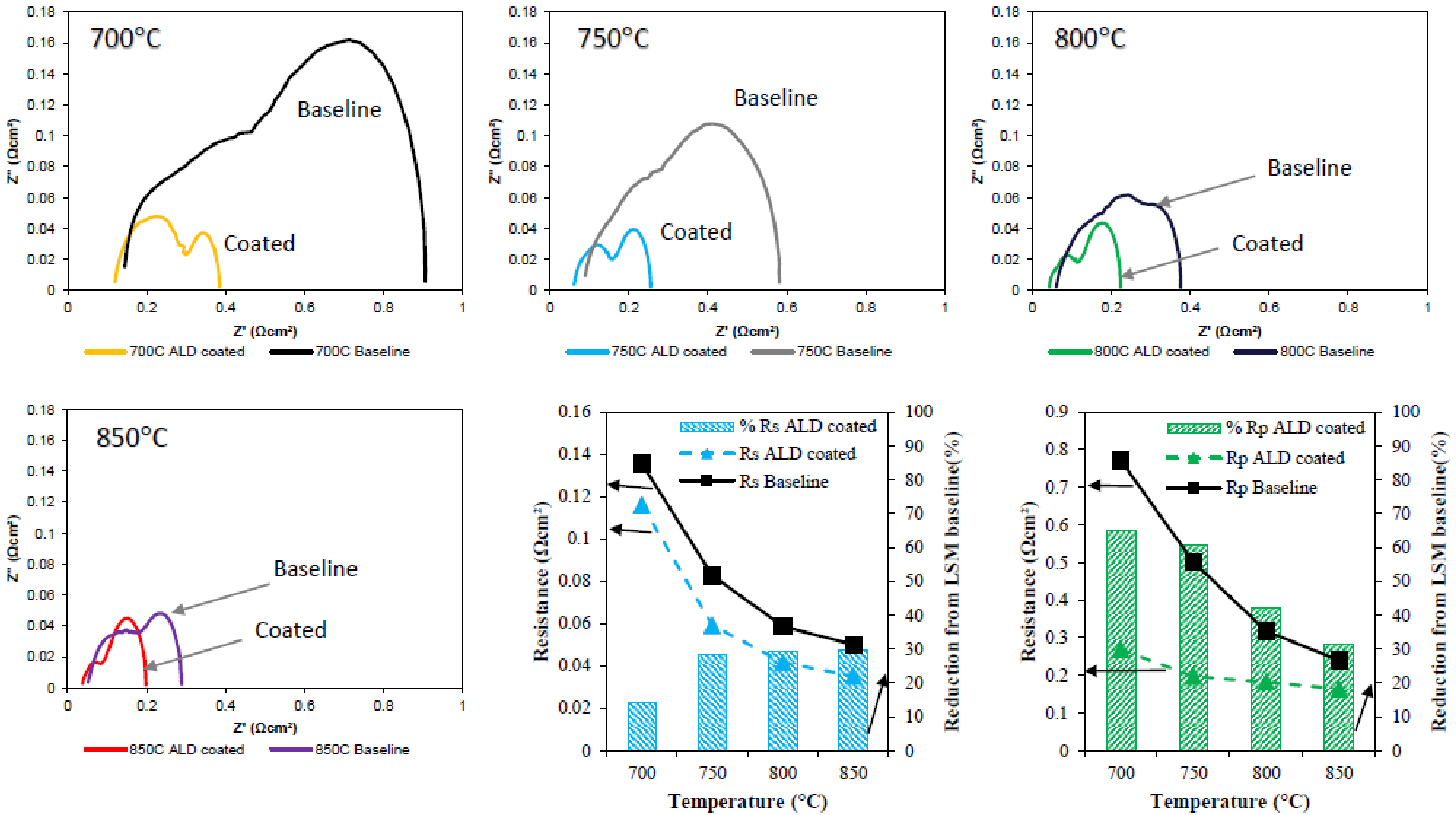


ALD coated cell		Baseline cell		Enhancement
Operation	Peak W/cm²	Operation	Peak W/cm²	
0 hr **700°C**	0.99	7 hr **700°C**	0.40	**248%**
0 hr **750°C**	1.65	0 hr **750°C**	0.63	**264%**
0 hr **800°C**	1.90	0 hr **800°C**	0.97	**196%**
0 hr **850°C**	2.14	1 hr **850°C**	1.23	**174%**

<u>With same power output requirement, ALD-coated cell could operate at much lower temperature</u> (100° lower):

- ALD coating impact is more significant at lower temperate: 248% at 700°C, remains 174% at 850°C.
- ALD coated cell at 700°C outperforms baseline at 800°C.
- ALD coated cell operated at 750°C outperforms baseline at 850°C.

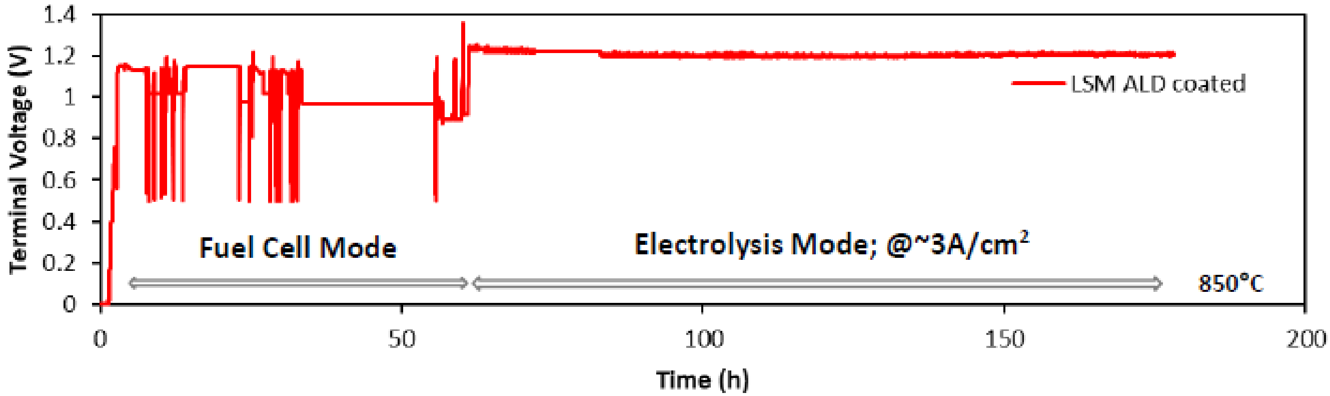
SOFC: Large Reduction of Resistance Induced by ALD Coating



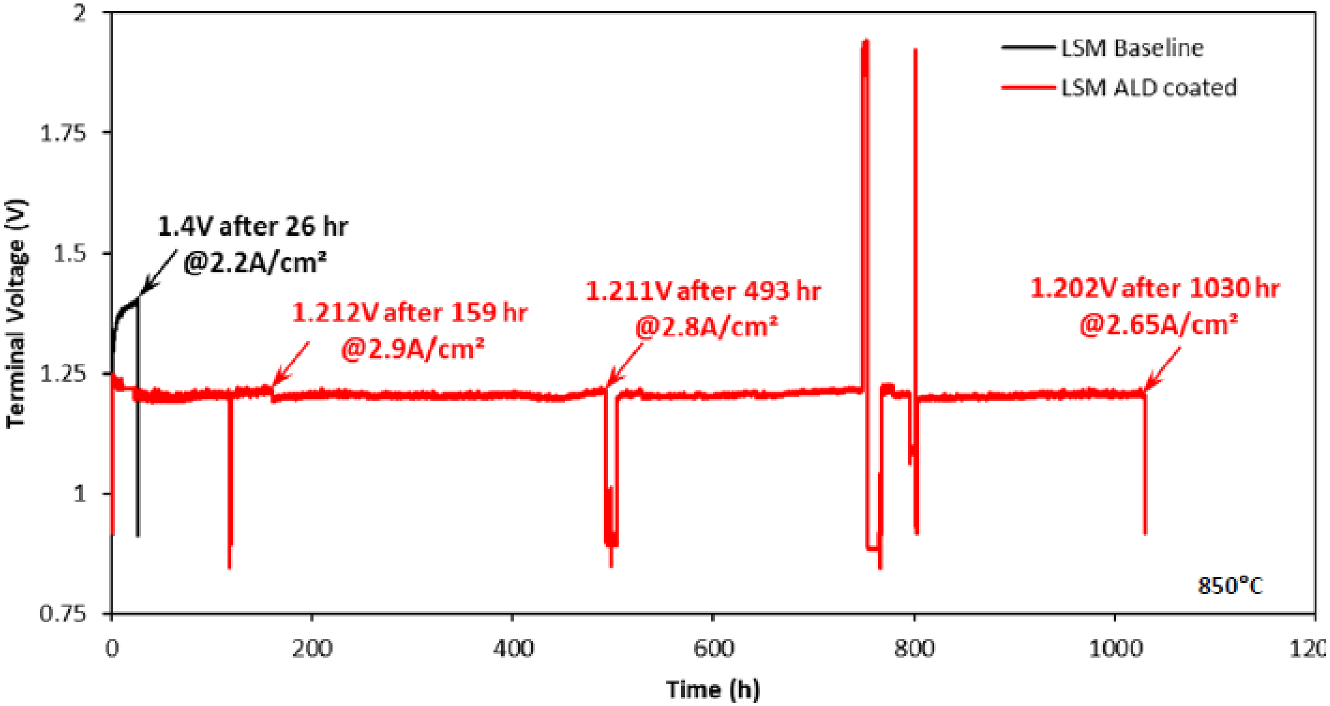
Both ohmic resistance and polarization resistance decreased at temperature of 700-850C.

- Rs: 14%, 28%, 29%, and 30% reduction on the Rs values for the ALD coated cell for the temperature range of 700-850 °C, with a Rs value of 0.0351 Ωcm^2 at 850°C compared to 0.0499 Ωcm^2 for the LSM baseline.
- Rp: 65%, 61%, 42%, and 32% reduction on the Rp values for the ALD coated cell for the temperature range of 700-850 °C, with a Rp value of 0.1637 Ωcm^2 at 850°C compared to 0.2390 Ωcm^2 for the LSM baseline. While more notorious reduction of 0.2686 Ωcm^2 at 70°C compared to 0.7711 Ωcm^2 for the LSM baseline

SOEC: ALD coating induced higher current, lower voltage

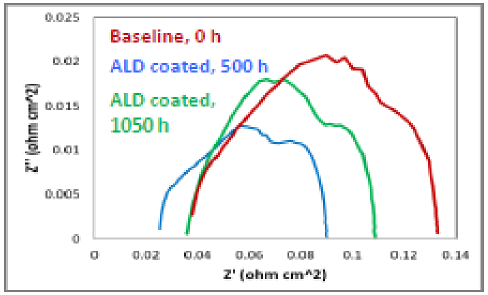


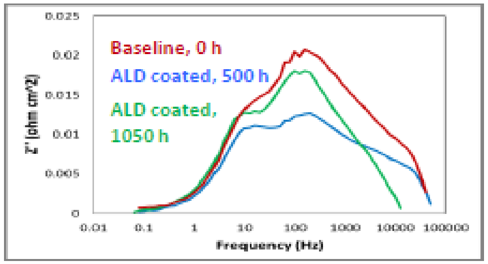
Ni/YSZ-YSZ-LSM/SSZ cell, commercial button cell, **direct switch from SOFC to SOEC.**



Baseline delaminated after 26 hours operation, ALD coated cell appears stable for the first 1000 hours.

ALD coated cell: a high current density of >2.5 A/cm^2, with low voltage of 1.2V after 1000 hours operation.



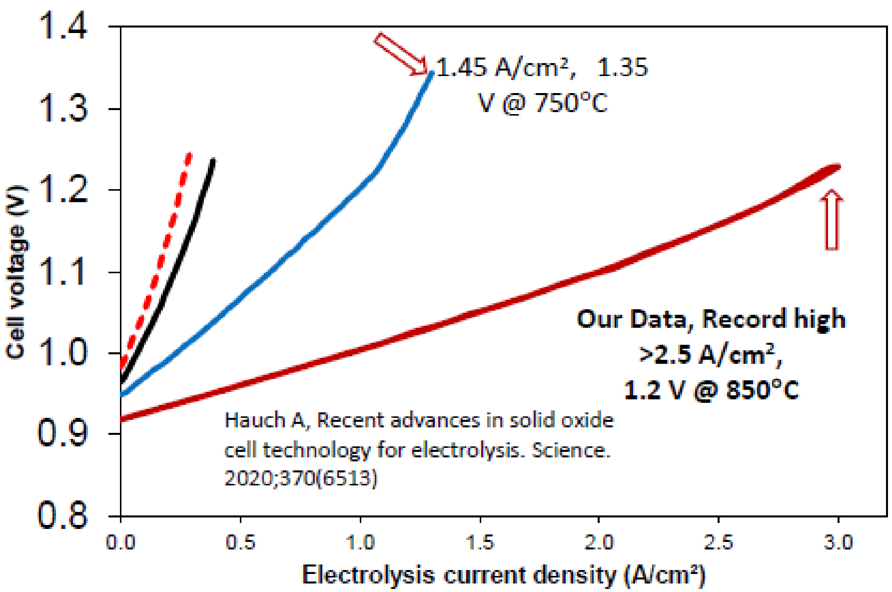


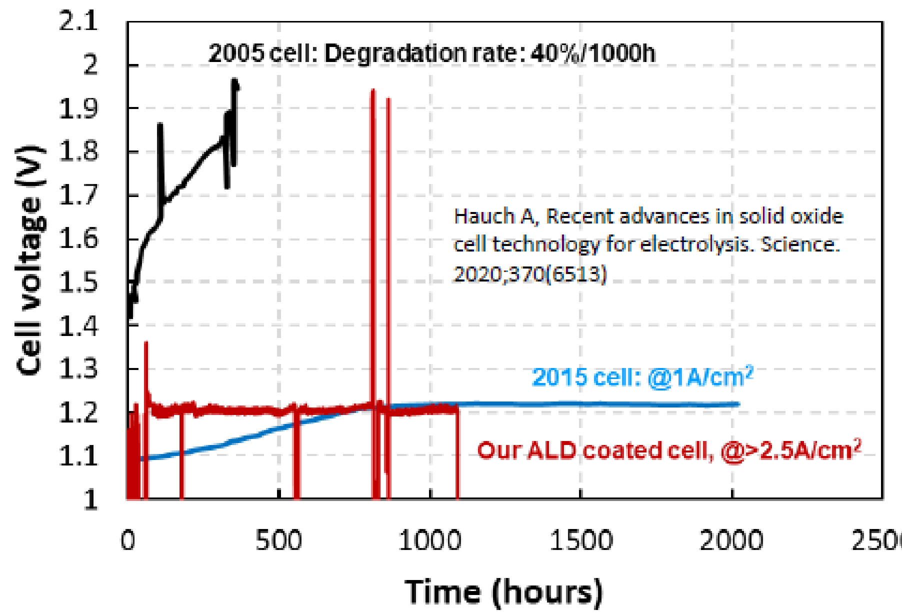
Operation	Rs (Ω cm2)	Rt (Ω cm2)	Rp (Ω cm2)
500 h, Coated	0.0247	0.0901	0.0654
1050 h, Coated	0.0354	0.1087	0.0733
0 h Baseline	0.0359	0.1332	0.0972

- **ALD coated cell process significant lower resistance than that of the baseline after 1000 hours operation.**
- **ALD coated cell increase in resistance, especially Rs, probably due to degradation from electrolyte and Ni/YSZ.**
- **ALD coating of LSM/YSZ alone mitigate the electrode delamination, resulted high current and superior stability for the first 1000 hours SOEC operation.**

SOEC: Record high SOEC performance achieved by ALD coating

- High hydrogen production rate over 2.5A/cm², Highest reported water electrolysis performance to date for SOEC with LSM or LSCF-based electrodes.
- Low electricity consumption, operational voltage of ~ 1.2 V at 850°C.
- Superior stability for the first 1000 hours SOEC with no sign of delamination.





Electrolyzer Stack Goals by 2025		
	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm²	98% at 1.5 A/cm²
Lifetime	80,000 hr	60,000 hr

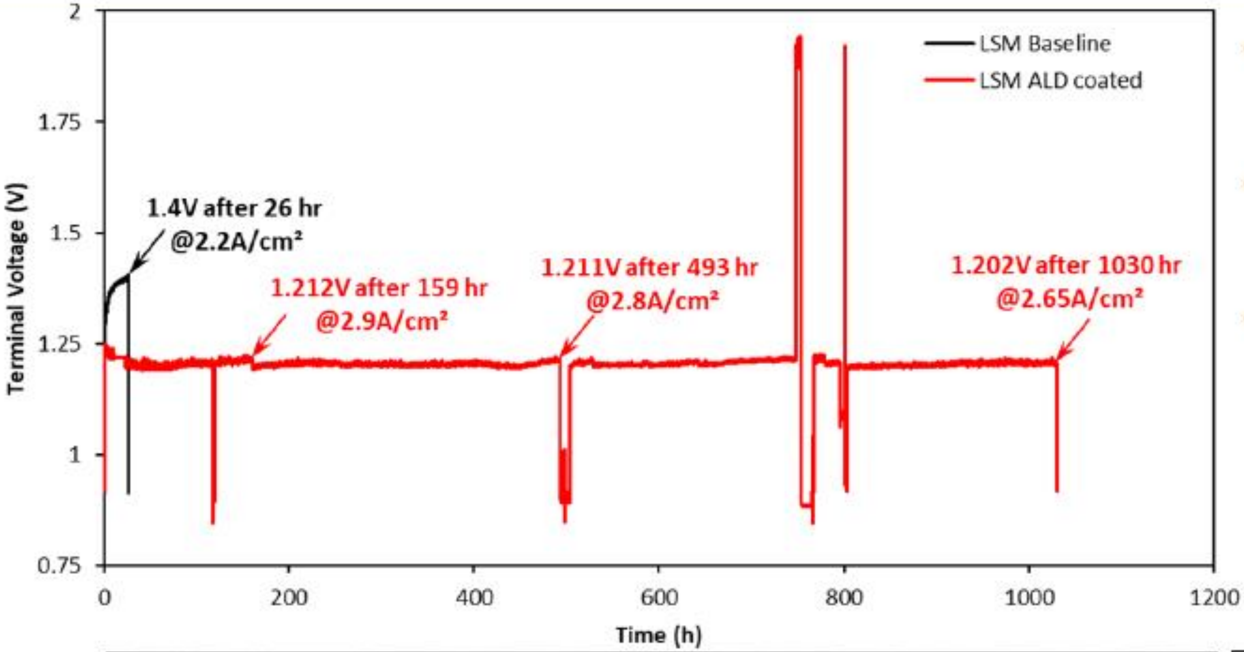
H_2 production from Present ALD coated cells **at 2.5 A/cm² @ 1.2V, exceed DOE 2025 program goal of 1.5A/cm²**

In terms of Hydrogen production, DOE 2025 program goal for HTE stack is 1.5A/cm²

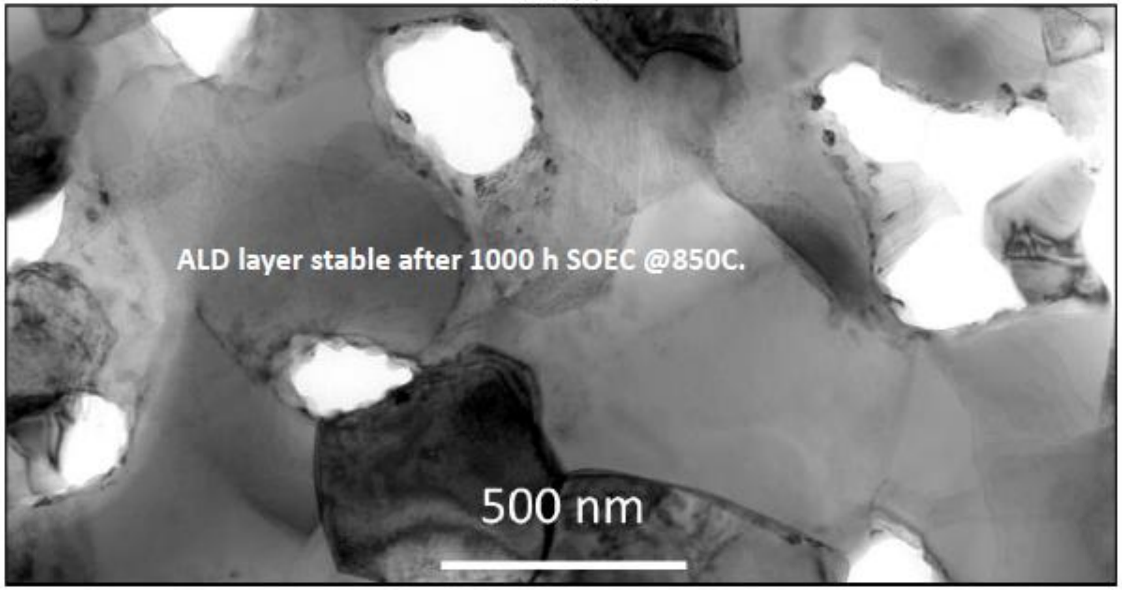
Dr. Sunita Satyapal, Director, U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, **2021 AMR Plenary Session.**

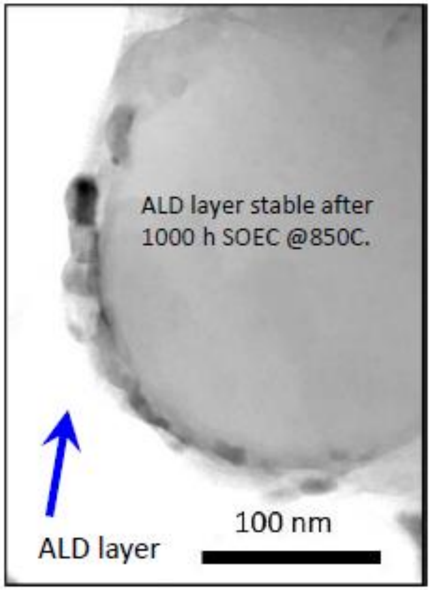
ALD layer: Cr-Tolerant Mixed Conductor Oxide

SOEC: Highh H_2 Production Rate, Exceptional Stability



- Stable SOEC operation for the first 1000 hours.
- Exceptional Stability of nanostructure of ALD layer:
- ALD layer nano-grains, remained to be ~ 20 nm after 1000 hours SOEC @ 850C.





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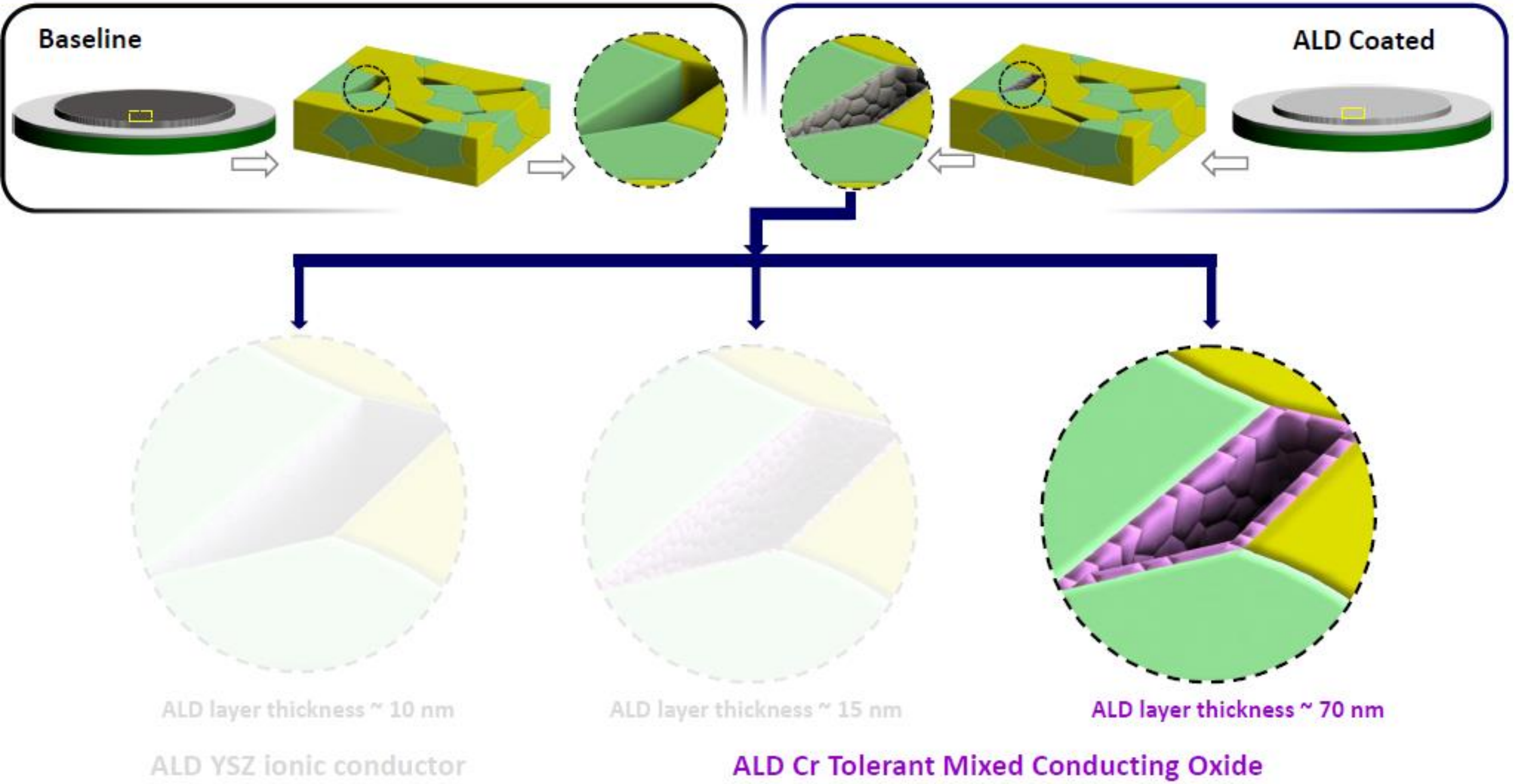
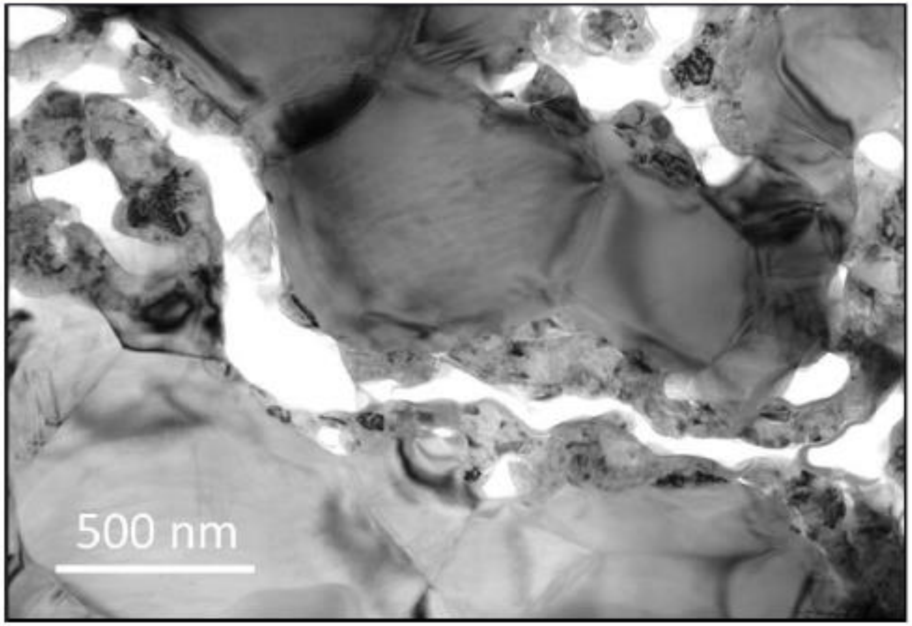
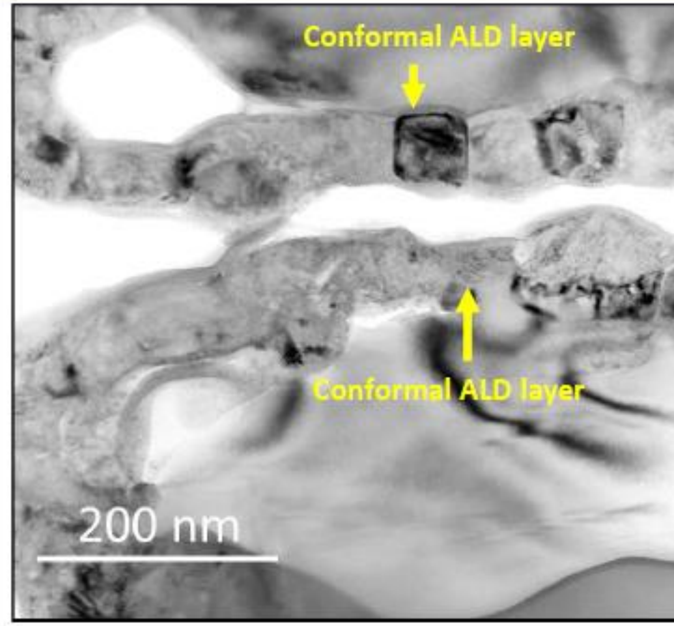
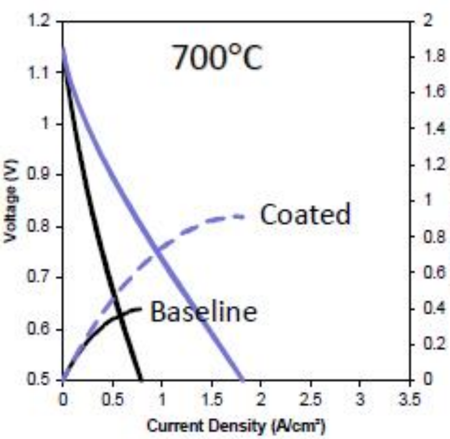


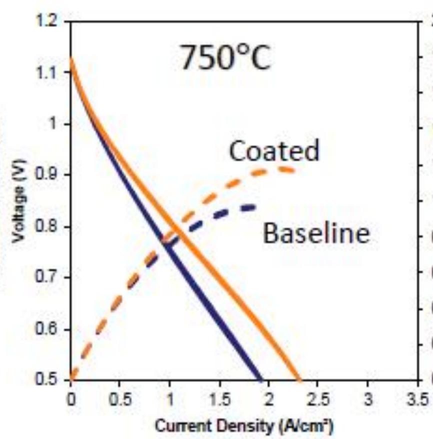
- Internal surface of porous electrode of as fabricated commercial SOC offers the design space for further tuning the chemistry & structure of the electrode.
- ALD layer creating new sites for facilitating the electrochemical reactions increasing increase SOEC hydrogen production rate, and cell durability.
- ALD layer protective coating for increasing cell tolerance of contaminants such as Cr.

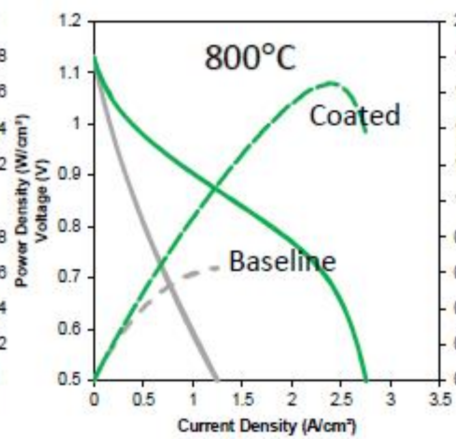
Cr Tolerant ALD layer Tuned to Be Conformal Layer

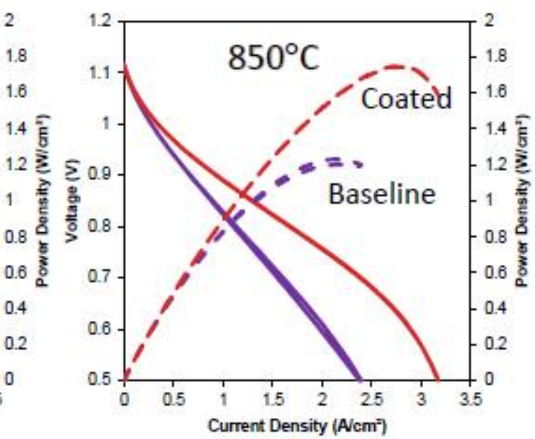












ALD coated cell		Baseline cell		Enhancement
Operation	Peak W/cm²	Operation	Peak W/cm²	
0 hr **700°C**	0.913	0 hr **700°C**	0.349	**262%**
0 hr **750°C**	1.18	0 hr **750°C**	0.627	**188%**

ALD coated cell		Baseline cell		Enhancement
Operation	Peak W/cm²	Operation	Peak W/cm²	
0 hr **800°C**	1.652	0 hr **800°C**	0.969	**170%**
0 hr **850°C**	1.749	1 hr **850°C**	1.184	**148%**

Overview

- **Project Background & Challenges**

  Solid Oxide Electrolysis Cells (SOEC) and Degradation
  - Fuel electrode: Ni migration
  - Oxygen electrode: LSCF/SDC decomposition, Sr surface segregation, Cr contamination
  - Oxygen electrode: LSM/YSZ delamination, Cr contamination

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  - Commercial cells with LSM/YSZ: Designing Internal Surface of LSM/YSZ by ALD Coating
    - ALD Layer of Conformal YSZ Nanoionics: Exceptional Stability in SOEC Operated @ 850°C
    - ALD Layer of Mixed Conductor:
      - ✓ SOFC: Increase of cell peak power density up to 250%
      - ✓ SOEC: High H_2 production rate @ >2.5A/cm^2 850°C, superior stability >1000h
      - ✓ Cr tolerant ALD layer is tunable from discrete particles to conformal layer
  - **Direct Impact of High Hydrogen Production Rate on SOEC Commercialization.**

Impact of High Hydrogen Production Rate on Commercialization.

- **Commercial and state-of-the-art cells** from different manufactures is **~1 A/cm^2 at ~1.3V**
- ALD coated commercial cells (with LSM/YSZ electrode), achieved:
  - **~2.5A/cm^2 & ~ 1.2V** is **2 times** the Hydrogen Production Rate
  - **~2.5A/cm^2 & ~ 1.2V** could achieve an estimated **two-fold reduction** in SOEC stack and Balance of Plant (BOP) cost and footprint.

Brief technoeconomic analysis

For a state-of-the-art commercial SOFC system and **a stack (or portion of a stack)** able to generate **1.5 kW** of electricity in **SOFC mode**), when operated reversely in the electrolysis mode:

- If the electrolysis current density is **2.5A/cm^2**, the 1.5 kW stack is estimated to generate ~15 kg of green hydrogen per day (or ~5,200 kg per year).
- If the hydrogen market price is ~$5/kg, this **1.5 kW SOFC stack** is estimated to generate revenue on the order of **~$25,000/yr** when operated in electrolysis mode to produce green hydrogen.

https://solydera.com/

Expected & Ultimate Cost-Benefit Resulting from ALD Coating






ALD coating porous electrode increase hydrogen production rate and cell durability:

- Double or even triple the hydrogen production rate (Kg/h) from that of the baseline cell by decreasing cell resistance & increasing current density,
- Increase SOEC durability and significantly decrease cell degradation.

Scale-up ready:
The Beneq P1500 for large scale industry processing

- Can <u>**accommodate**</u> parts up to 1300 × 2400 mm (**1.3 m x 2.4 m**) in size,
- Enables the deposition of high-quality, functional optical coatings on wide area mirrors or lenses; Possible substrates include: Generation display glass; Photovoltaic glass sheets; Astronomical mirrors, Semiconductor chamber lids, liners & showerheads; Printed circuit boards
- **The commercial ALD systems are ready for processing multiple SOC stacks simultaneously.**

SUMMARY

- ALD coating of LSCF/SDC electrode of commercial cell result in SOEC of high current of 1.1A-2.5A @ 750°C.
- As-fabricated commercial SOFC with LSM/YSZ air electrode experienced degradation within first 50 hours.
- ALD coating of the LSM/YSZ oxygen electrode mitigate the cell degradation, lower the SOEC operation voltage and increase the hydrogen production rate.
  - ALD Coating of YSZ ionic conductor
    - ✓ Significantly increase SOFC peak power density to 160%, reduction both Rs and Rp.
    - ✓ Increase of SOEC current density for higher hydrogen production rate.
    - ✓ Increase SOEC durability. Extraordinary structure stability ALD nano-YSZ after SOEC @850°C.
  - ALD coating mixed conducting metal oxide, discrete nano-grains of 15 nm
    - ✓ ALD coating significantly increase the SOFC peak power density by up to 250%.
    - ✓ ALD coated SOEC is with high current density of >2.5A/cm2, low voltage of 1.2V.
    - ✓ ALD coated SOEC is with superior stability, for the first 1000 hours.
  - ALD coating mixed conducting metal oxide, conformal coating, ~ 70 nm thick.
    - ✓ ALD coating significantly increase the SOFC peak power density by up to 260%.
    - ✓ Conformal ALD coating layer is Cr-resistant, could further increase cell durability.

ALD coating of as-fabricated commercial SOFC for their SOEC application:

- Achieved the record high performance of >2.5A/cm^2, stable SOEC for the first 1000 hours.
- **ALD coated cell is with high hydrogen production rate 2.5A/cm^2, exceed the DOE 2025 target of 1.5A/cm^2.**
- ALD coating of commercial cells: **Two granted patens, Four pending patents.**

ACKNOWLEDGEMENTS

DOE-SOFC Program

National Energy Technology Laboratory

Program Manager: Dr. Debalina Dasgupta

Technology Manager: Dr. Shailesh Vora

beneq

The most recognized provider of ALD equipment for R&D services & industry.

Air Liquide

Air Liquide Advanced Materials