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2023

Scalable metamaterial thermally sprayed catalyst coatings for nuclear reactor high temperature solid oxide steam electrolysis

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What is H2?

- H2 is a gas. It is colorless, odourless, tasteless, non-toxic and highly combustible
- Its density – 0.08375 kg/m3 (comparison: air 1.18 kg/m3)
- The most abundant chemical element – contribute 75% of the mass of the universe
- But here is the problem – it is very scare as a gas, vast numbers of hydrogen atoms are contained in water, natural gas, plants etc.
- Hydrogen can be produced from a variety of resources such as natural gas, biomass and water

Why is H2?

- For many years, we used natural gas for heating home and businesses and generating electricity
- Currently, 85% of homes and 40% electricity relies on natural gas.
- Here is the problem:

  $CH_4 + 2\ O_2 \dashrightarrow CO_2 + H_2O$ (ΔH = - 891 kJ/mole) or 55.5 MJ/kg or 42 MJ/m3

  Burn 1 kg CH_4 and you produce 2.75 kg CO_2
- Possible Solution:

  $H_2 + 1/2\ O_2 \dashrightarrow H_2O$ (ΔH = - 286 kJ/mole) or 114.80 MJ/kg; 12.7 MJ/m3

  Burn 1 kg H_2 and you produce Zero CO_2

Uses of H2?

- Current use: refining petroleum, treating metal, producing fertiliser and processing foods.
- H2 fuel cells produces electricity via an electrochemical process wide uses such as powering mobile phone, laptop, supply electricity to electric power grids, supply backup or emergency power in buildings and off grid power supply
- Burning hydrogen for electricity generation – blending with natural gas
- Hydrogen use in vehicles – fuel cells can power vehicles – advantage longer range
- Burning hydrogen for domestic heating and cooking – blending with natural gas
- So what are the challenges – production, storage and transportation

How is hydrogen produced?

- **Steam – methane reforming – mature production process**
- **Three steps:**
  - Methane reacts with steam at 700-1000OC and 3-25 bar in presence of a catalyst (Nickel) to produce H2, CO
  - $CH_4 + H_2O$ + (Heat) -> $CO + 3\ H_2$
  - CO and steam are reacted in presence of a catalyst (Nickel) to produce

  CO_2 and more H_2

  $CO + H_2O$ - > $CO_2 + H_2$

  CO and other impurities are cleaned up to produce clean H_2

  Blue Hydrogen + Fuel cell vehicle -> 50% emission reduction and 90% reduction of petroleum uses

Green Hydrogen Production

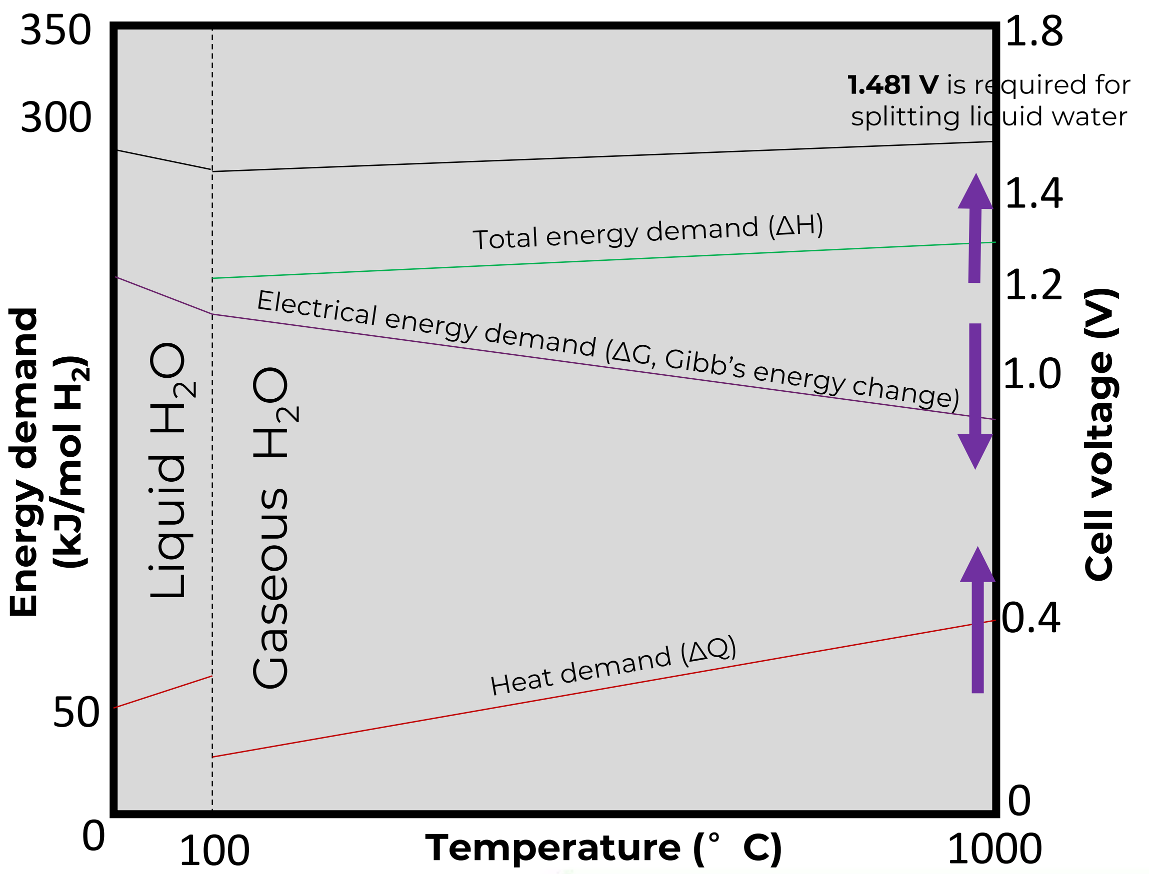
$$H_2O + \text{Heat} + \text{Electricity (+ Catalyst)} = H_2 + \tfrac{1}{2} O_2$$

Heat -> waste heat, solar or nuclear plant
Electricity -> Excess from Wind, Wave or Nuclear

Temperature, energy demand, cell voltage

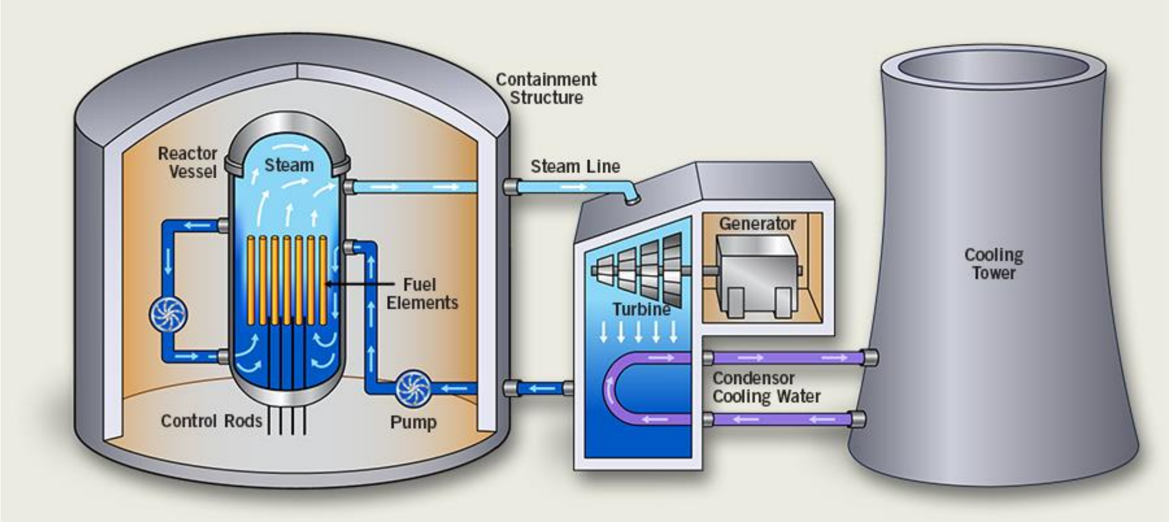
- The increase in **temperature can eliminate the need for expensive catalysts**, which may be required for some low temperature water electrolysers.
- High temperature systems operate **between 100 °C and 850 °C**.
- Above 850 °C, the capacity of standard **chromium steels to resist corrosion decreases**.
- At 2500 °C, electrical input is unnecessary because **water breaks down** to hydrogen and oxygen through thermolysis.
- With the increase in temperature (0–1000 ° C), the overall energy demand (ΔH) varies slightly (i.e., between 283.5 and 291.6 kJ/mol H_2).
- The **heat share (ΔQ) rises with temperature, reducing the minimum electrical energy demand (ΔG).** Beside improved kinetics, the high heat utilisation of internal losses is a major motivation of high-temperature electrolysis (e.g., 700-900 ° C).

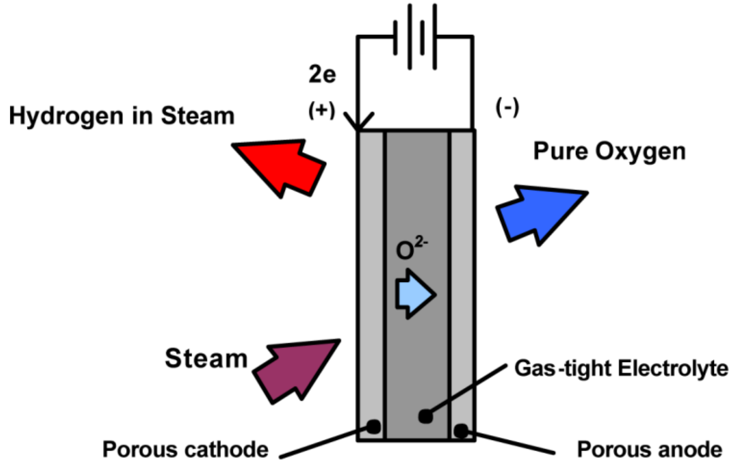
Energy demands for water electrolysis at high temperature



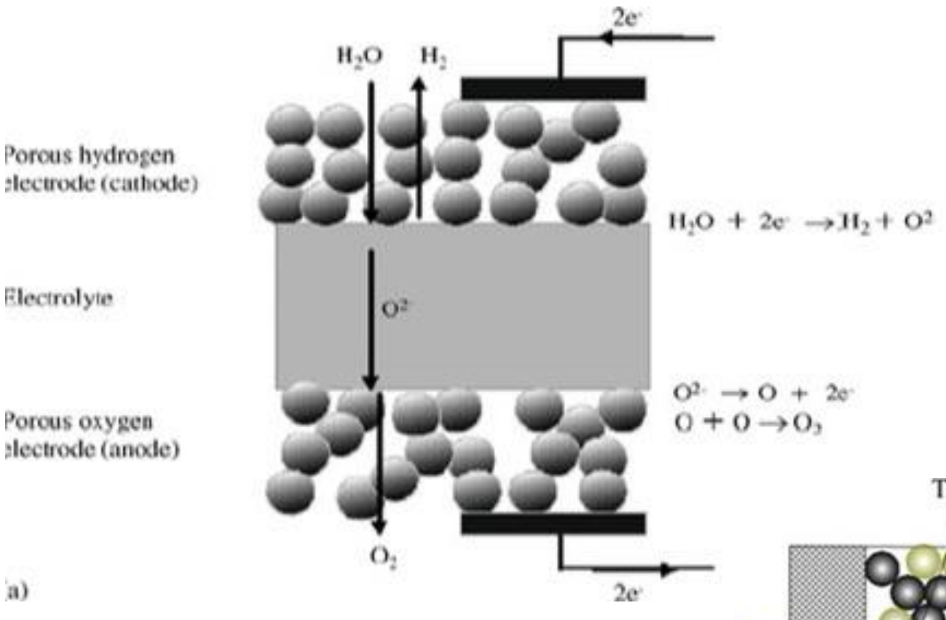
Plot schematically adapted (from Buttler and Spliethoff, 2018)

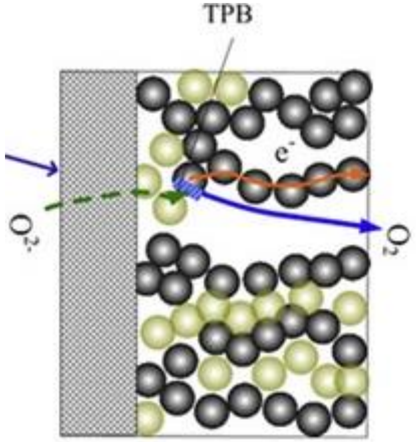
Excess heat and Electricity from Nuclear Reactor to Solid Oxide Electrolyser

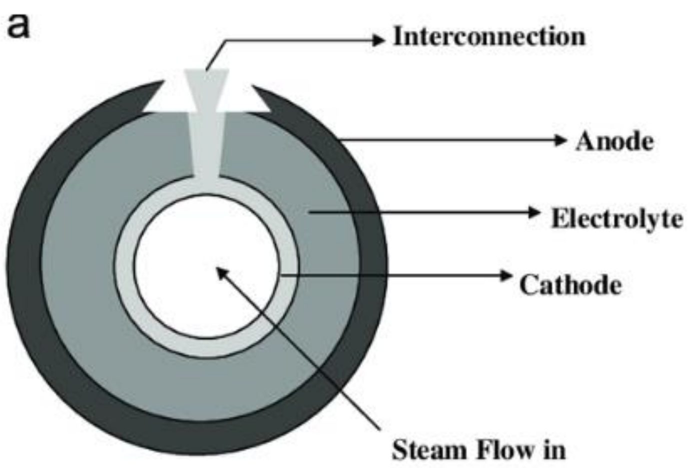


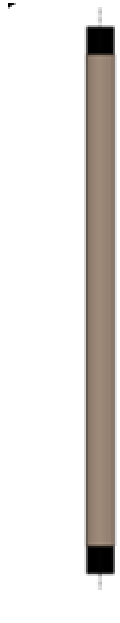


Solid Oxide Electrolyser Working Principle







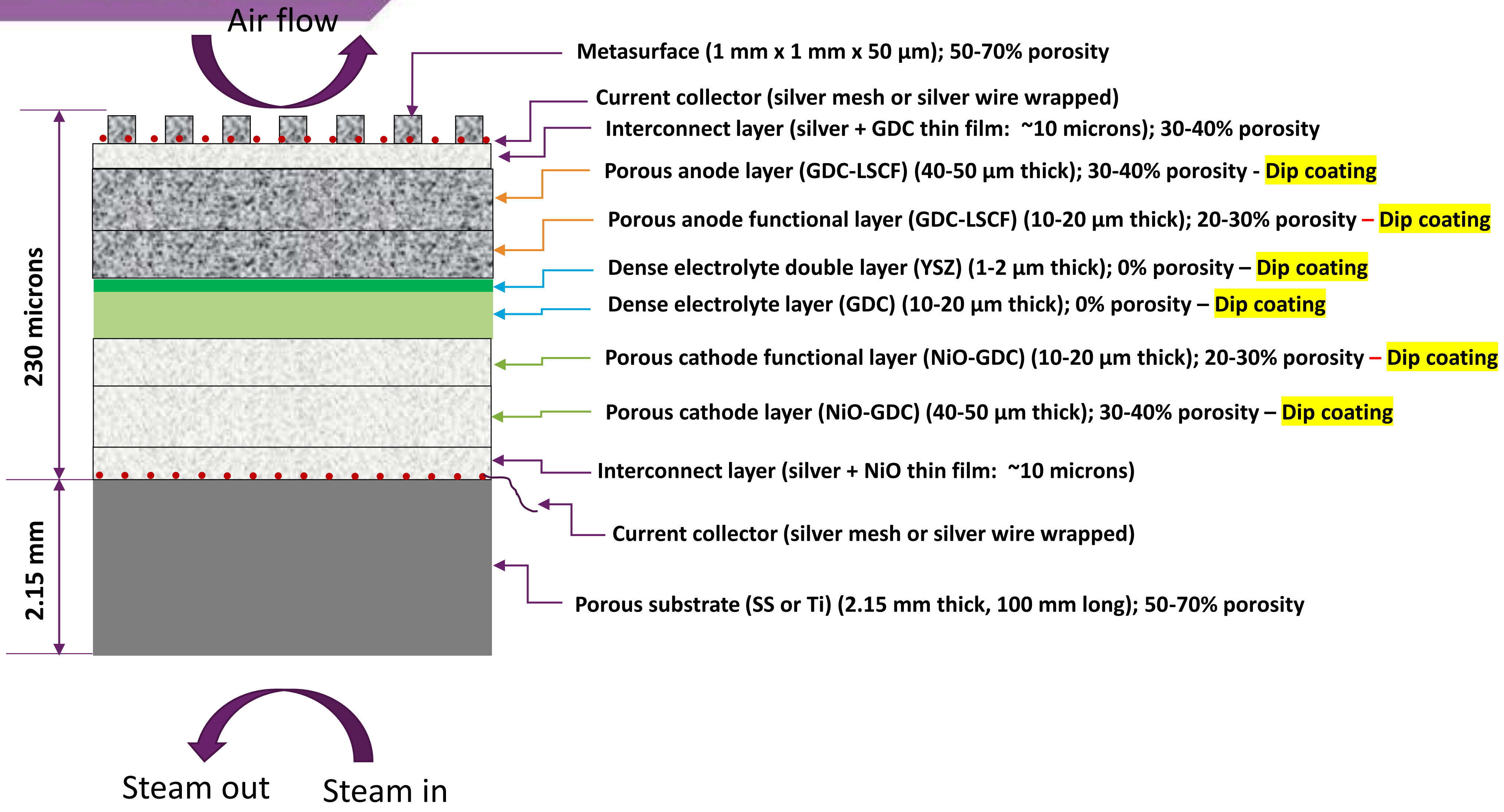


Single tube

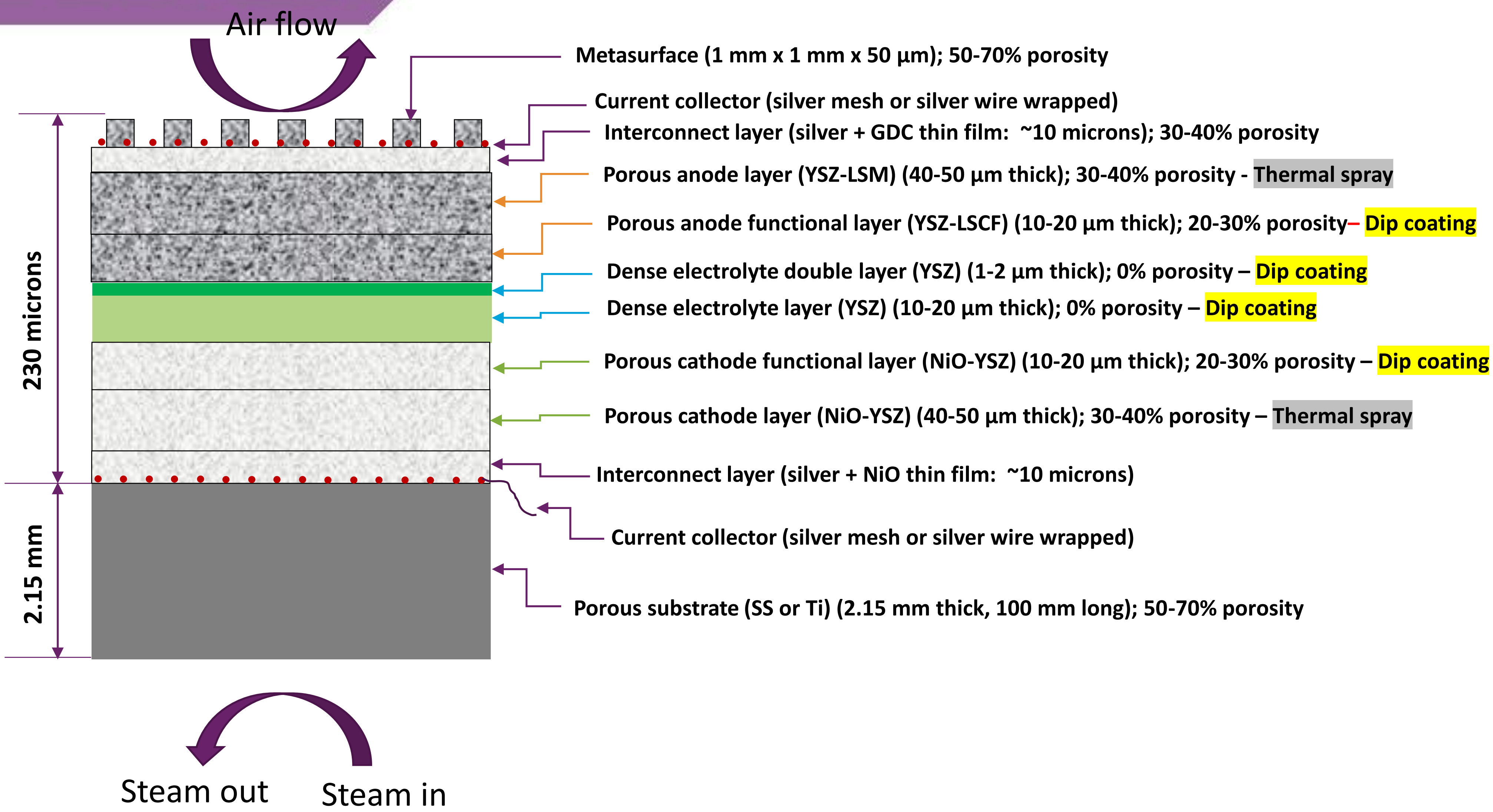
Cathode: $H_2O + 2e^- = H_2 + O^{2-}$
Anode: $O^{2-} = ½\ O_2 + 2e^-$
Overall: $H_2O = H_2 + ½\ O_2$

Cathode: Ni-YSZ porous, 500 µm
Electrolyte: YSZ dense, ion conductor, 20 µm
Anode: LSM-YSZ, 50 µm
Length: 0.4m

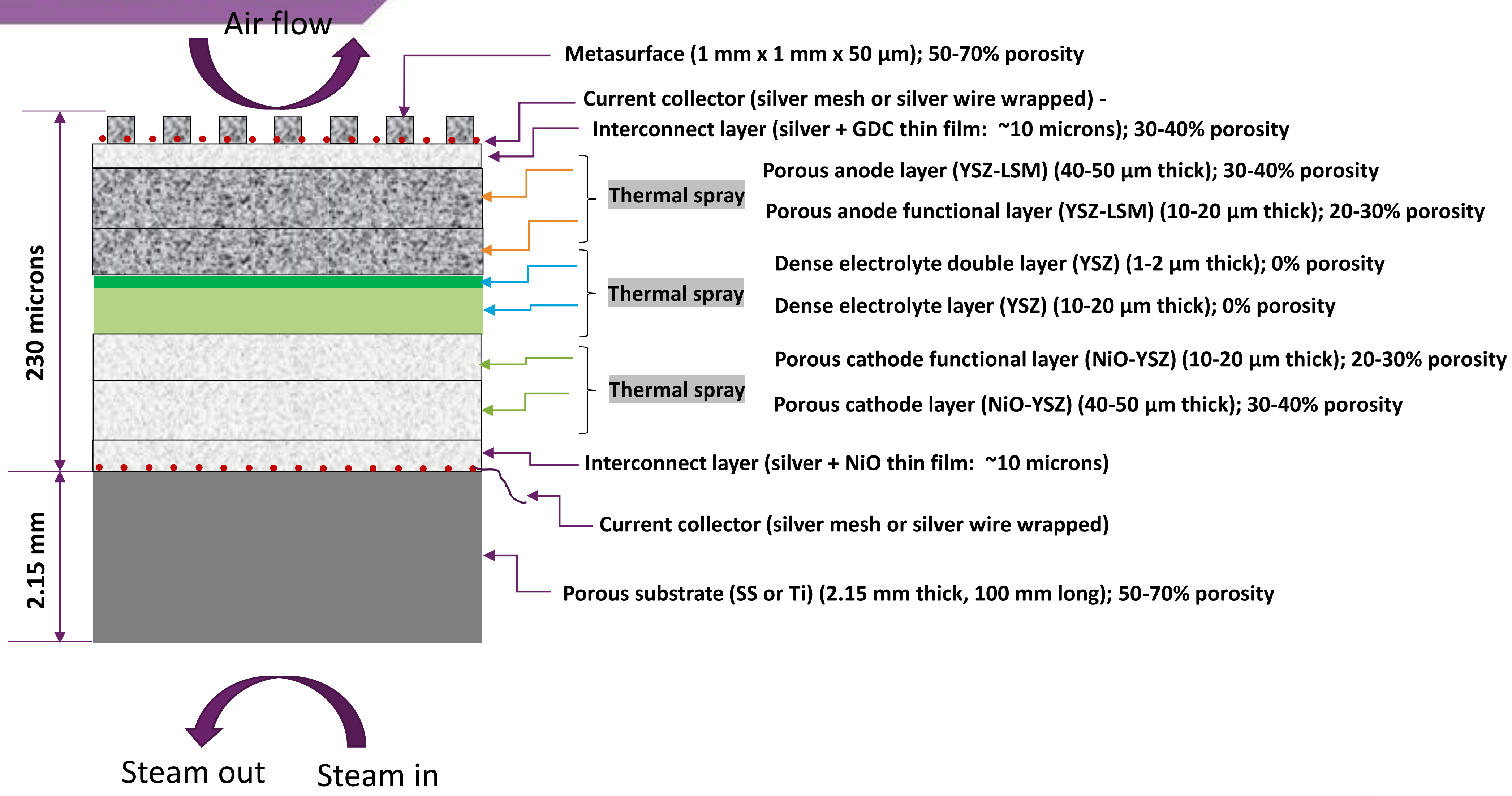
Plan A – Dip coating



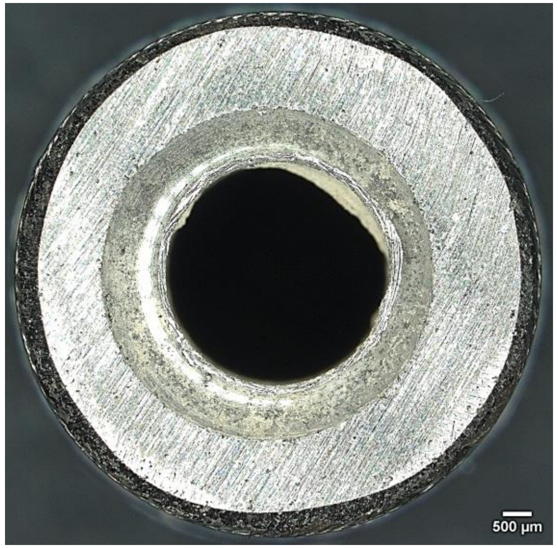
Plan B - Dip coating and thermal spray



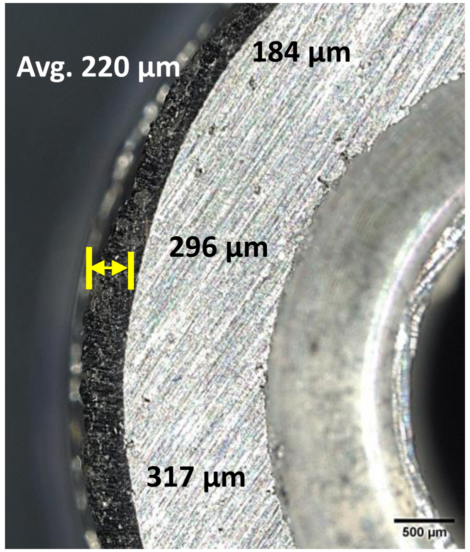
Plan C - Thermal spray



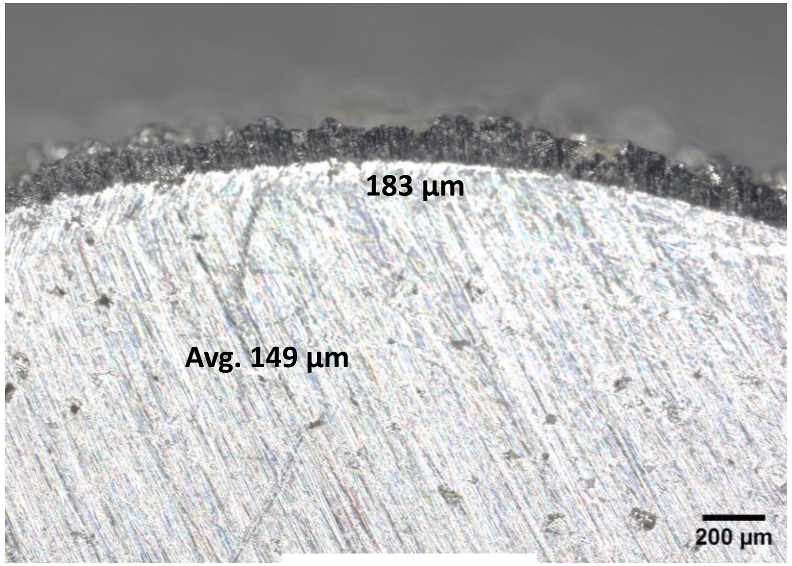
Optical images of Ag coated SS & Ti tube support



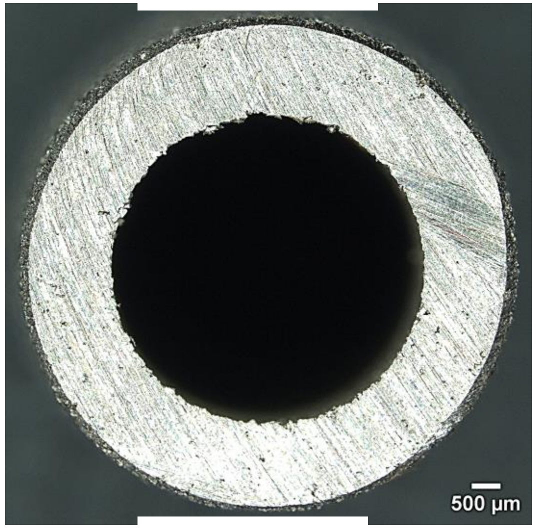
SS/Ag-20X



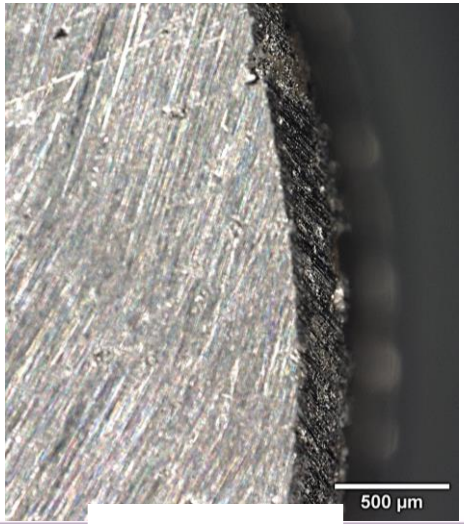
SS/Ag-50X



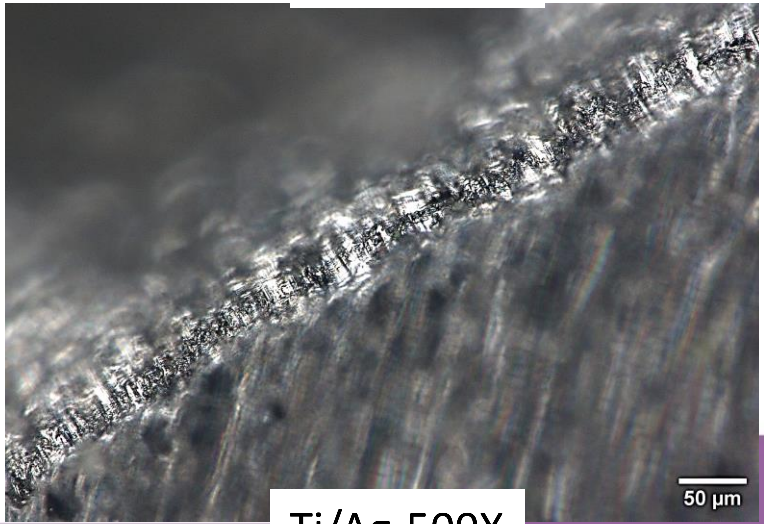
Ti/Ag-100X



Ti/Ag-20X

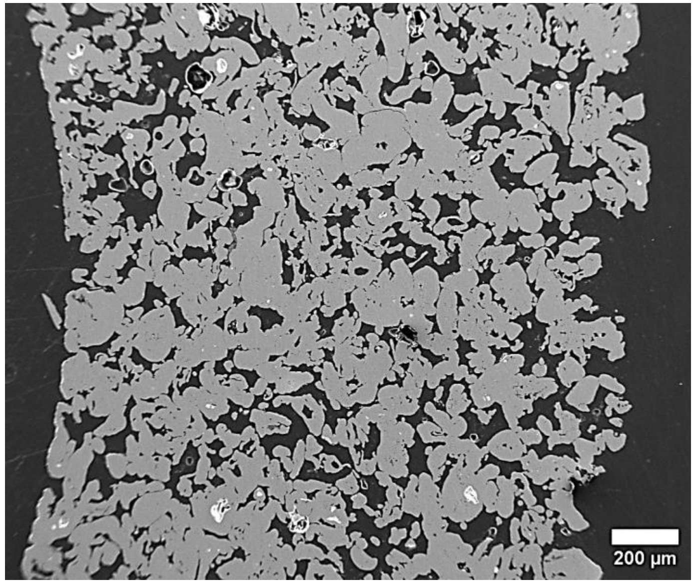


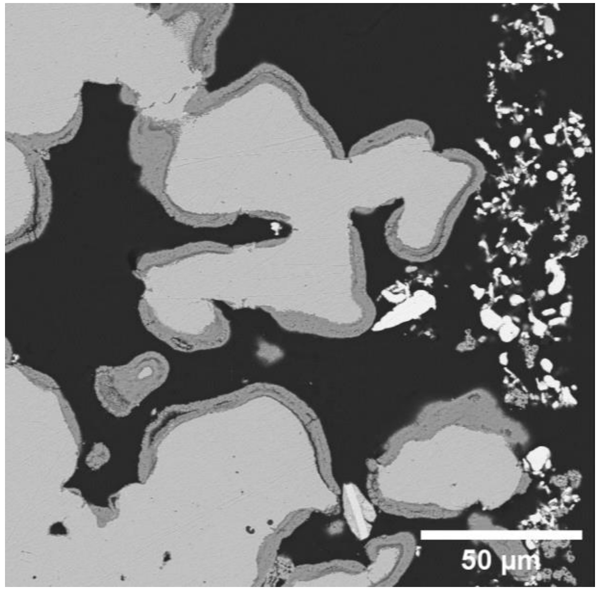
Ti/Ag-100X



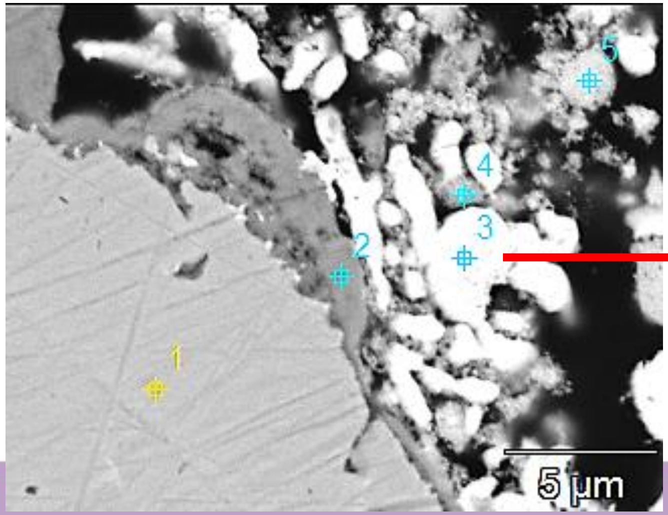
Ti/Ag-500X

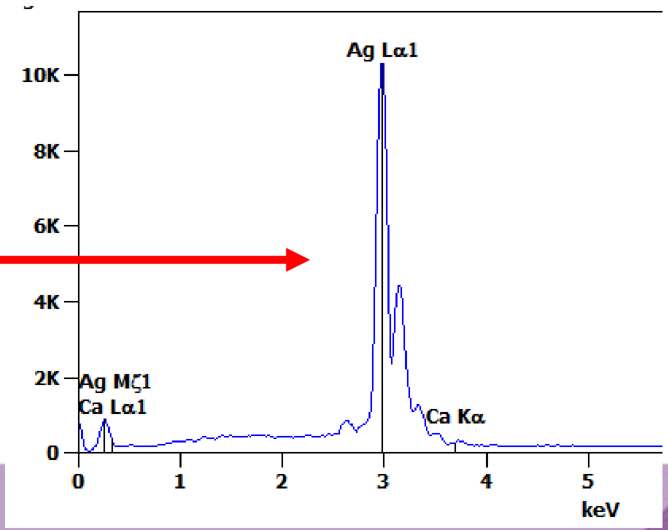
Cross Sectional SEM of Ag coated SS tube support (Sintered @ 800°C/2 hrs)





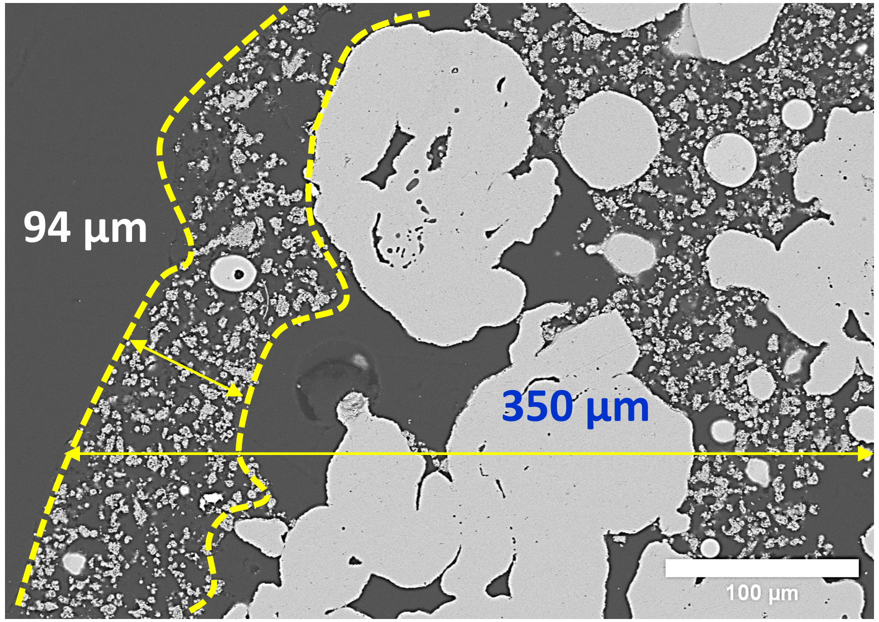
- Ag Layer thickness avg. 65 µm and depth (inside the pores ~ 356 µm)



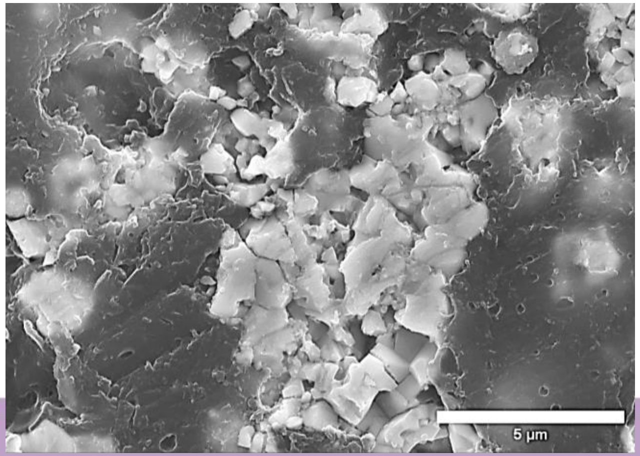


Pt: 3

Cross sectional morphology of tubular SS supported NiO-YSZ (60:40 wt%) cathode layer



Back Scattered Electron image & Elemental mapping of SS/Ag/NiO-YSZ coating



Combinations	Area %
Steel	36.48
Mounting Resin	43.08
ZrO2	1.53
2NiO	11.42
Ag	0.60
Ni rich	6.89

Properties of layers

Property	Units	Silver	Cathode	Electrolyte	Anode
Density	kg/m^3	10490	5682	7082	6600
Melting point	°C	961	2003	2609	1760
Young's modulus	GPa	83	144	128	145
Shear modulus	GPa	30	118	109	90
Poisson's ratio		0.37	0.26	0.26	0.28
Thermal expansion coefficient	µm/m·°C	19	12.1	11.4	13
Tensile yield strength	MPa	54	264.78	24.5	47.975
Ultimate yield strength	MPa	660	467	223	180

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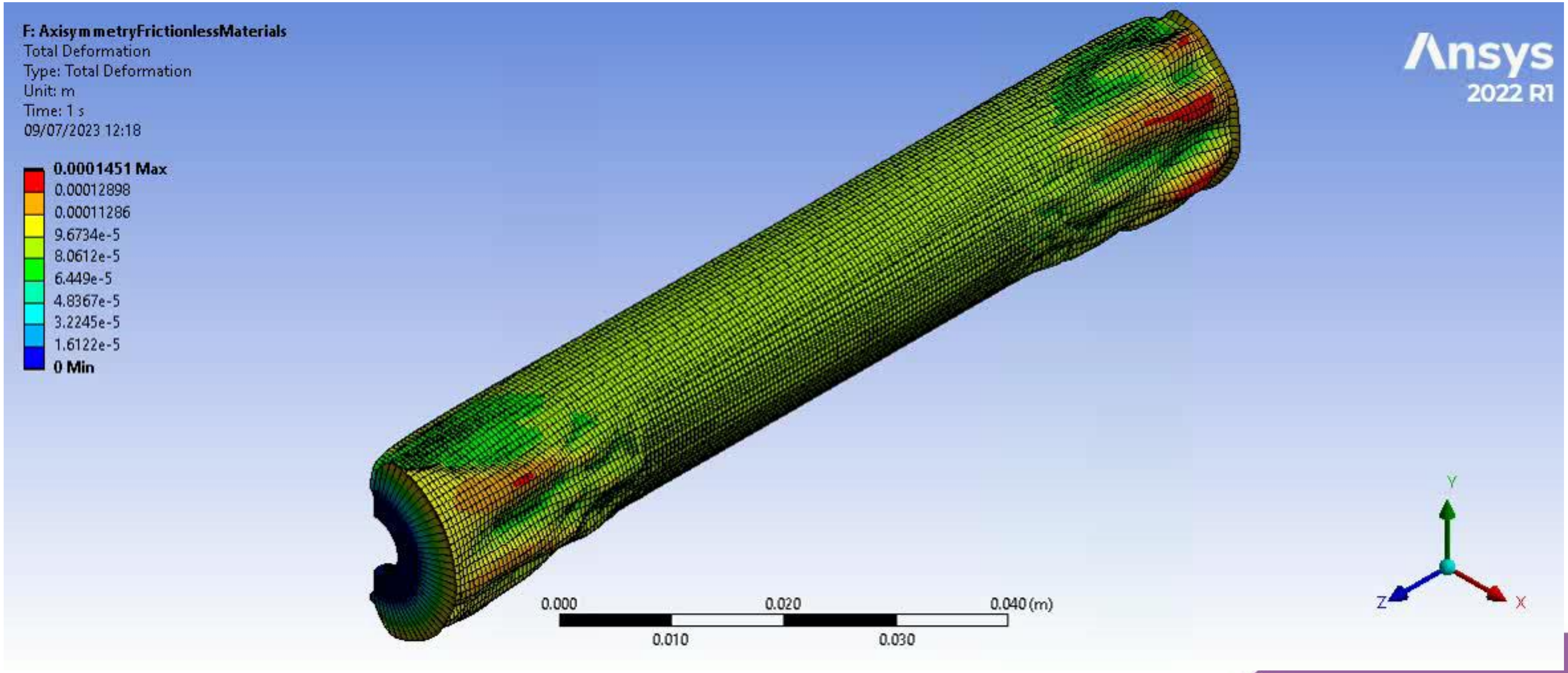
Total deformation

- Fixed-fixed connections
- No porosity
- 800 ^{o}C thermal load
- 1 MPa internal pressure
- Titanium substrate
- 6 layers



SOEC in Bangladesh

- Waste Steam from Garment Factory
- Waste Steam and Electricity from Rooppur Nuclear Plant

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Any Question?