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Materials for molten salt facing parts: challenges and opportunities for nuclear thermochemical cycle electrolysis.

FAISAL, N., RAJENDRAN, V., PRATHURU, A. and HOSSAIN, M.

2023

5th International Conference on Structural Nano Composites
NANOSTRUC 2023
Novel Materials for Future
24-26 May 2023
Nicosia, Cyprus
https://nanostruc.info/

Materials for molten salt facing parts: challenges and opportunities for nuclear thermochemical cycle electrolysis

Nadimul Faisal, Vinooth Rajendran, Anil Prathuru, Mamdud Hossain

School of Engineering, Robert Gordon University, Aberdeen, UK

One of the important challenges is to develop coating materials for thermochemical containment vessels and pipes that encounters the highly corrosive and harsh environment produced by the molten salt at high temperature. The aim of this review is to summarise structural and coating materials (mainly thermally sprayed) that can withstand thermochemical cycle corrosive environment. This review presents findings published in the scientific literature related to high temperature aggressive corrosion of materials, specifically geared towards nuclear thermochemical cycles leading to hydrogen production. Data related to materials, composition, synthesis have been gathered. Corrosion environment data such as environment, test time, test results have been reviewed. Structure-property relations of different materials reviewed as a part of this exercise will aid in the material selection process for future development. The overall assessment based on the evidence from previous investigations in this area is that none of the high-performance structural materials (coating, substrates) are likely to survive for an extended period in the high temperature corrosive environment. However, there are means and methods which could be considered to have sustainable coating-substrate assembly and extended lifetime. This review presents challenge and assess opportunities that will warrant efficient hydrogen production with stable thermochemical structure for operation at molten salt reactor (MSR) nuclear plants (e.g., thermochemical electrolysis leading to water splitting and hydrogen production) as well as other power plants, boilers, and waste incinerators.

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Materials for molten salt facing parts: challenges and opportunities for nuclear thermochemical cycle electrolysis

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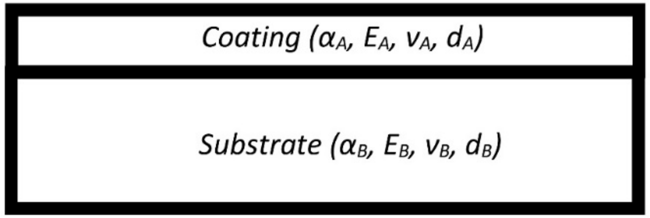
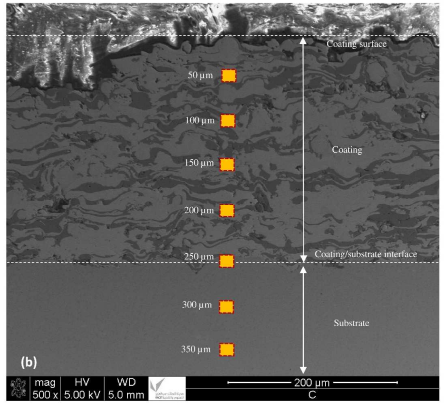
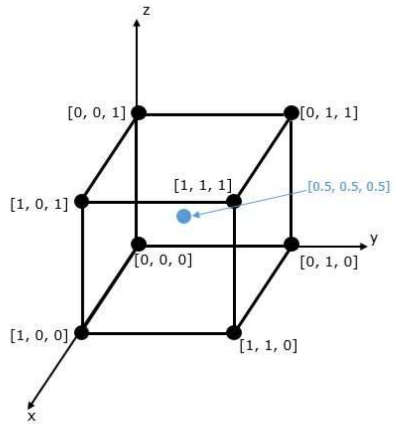
- University of Nottingham (Dr Tanvir Hussain, Dr Federico Venturi, Mr Tunji Owoseni)

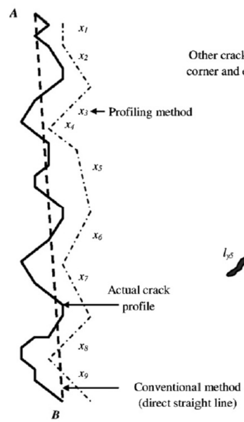
Interest & Motivation

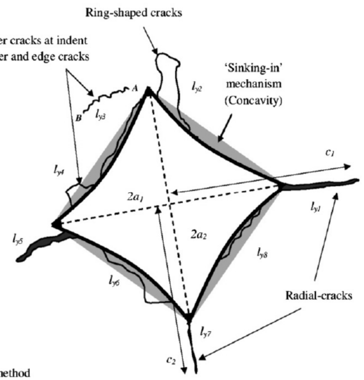


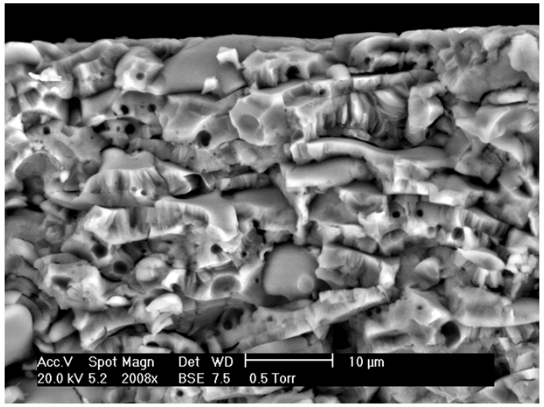


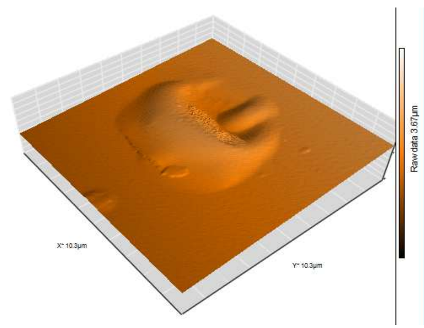
- Developing new applications using thermal spray coatings
- Sensor-based analysis: micromechanical degradation of materials (coatings, thin films, structural materials)
- Corrosion monitoring (electrochemical, acoustic emission)
- Hydrogen as new energy vector





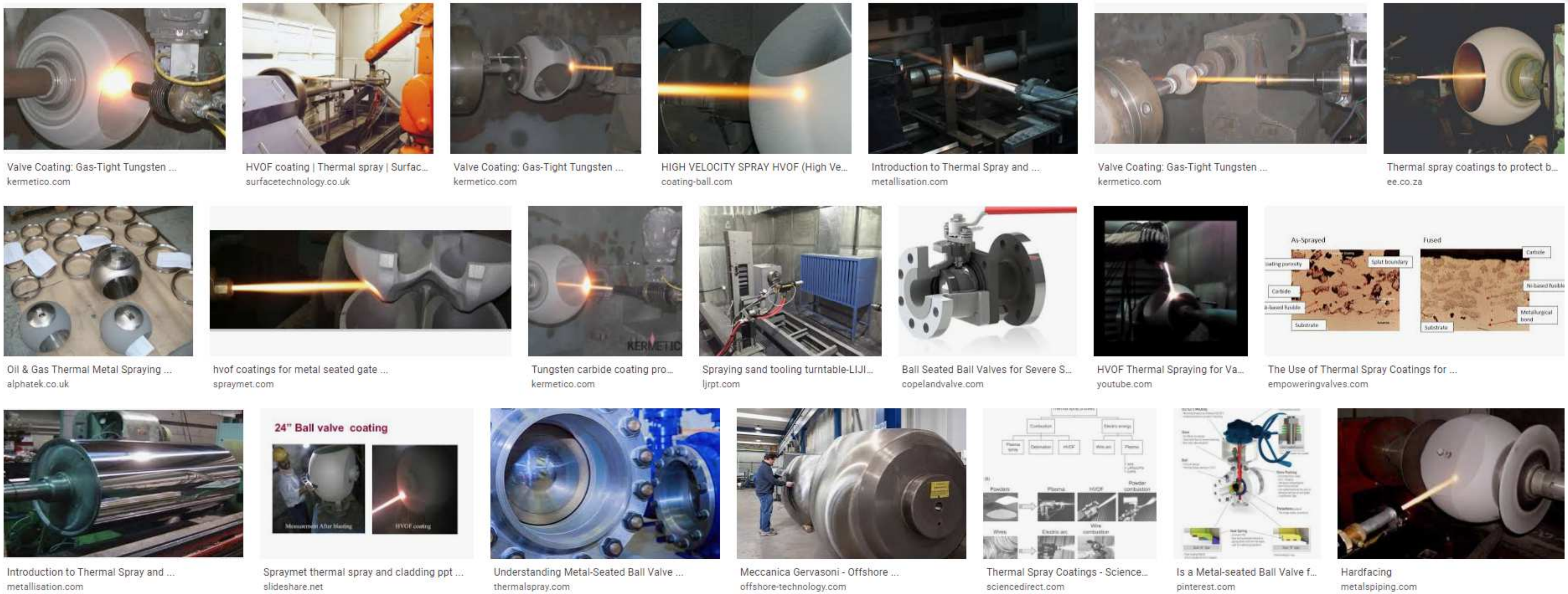




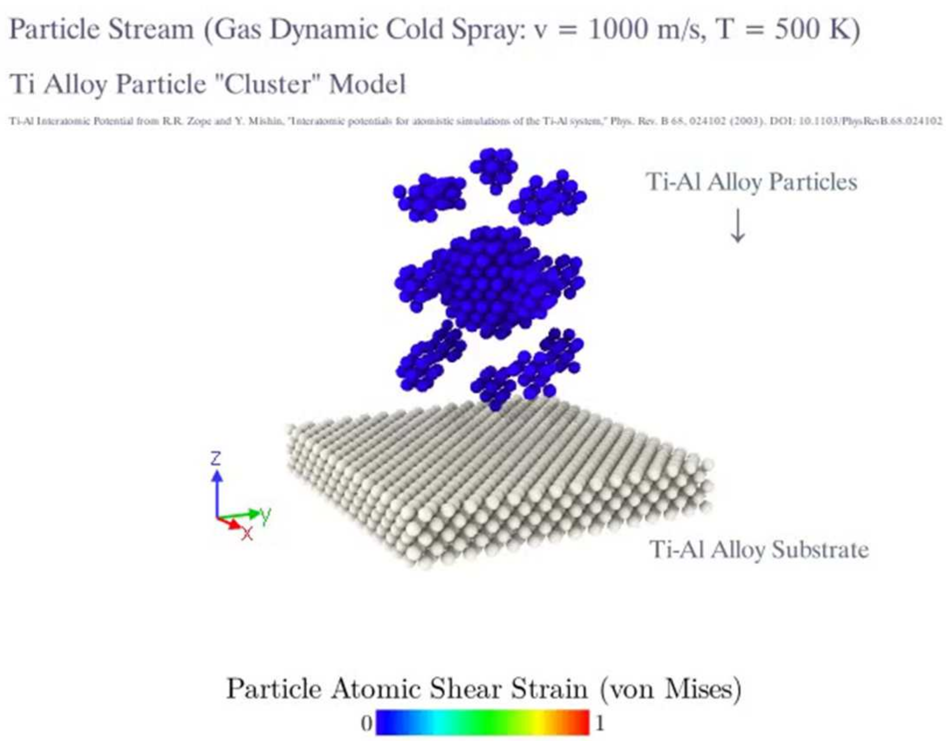


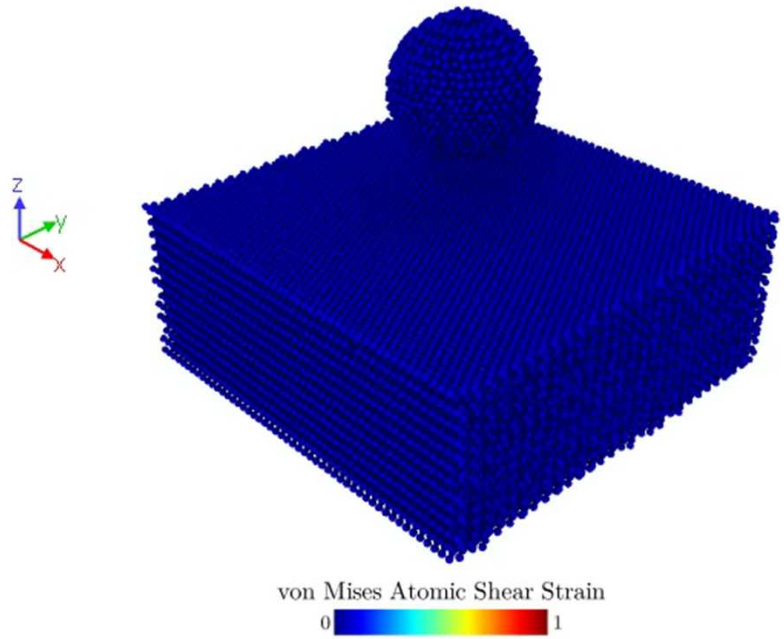
Substrate shape & size during thermal spraying

Google Search: Ball valve thermal spray coatings



Thermal spray feedstock materials





Jordan Davidson, Alexander Muir, Christopher Pegg, Adam White, MEng Group Project, RGU (2018-19) [NAFEMS/IMechE award]

S. Goel, N. H. Faisal, V. Ratia, A. Agrawal, A. Stukowski, Atomistic investigation on the structure–property relationship during thermal spray nanoparticle impact, Computational Materials Science, 84, 2014, p. 163-174

Group 1

H

Hydrogen

1 1.008

Hydrogen

Scottish Government plans

5 GW of low carbon hydrogen production in Scotland by 2030 –

Scottish Government Hydrogen Policy, 2020

- **Forecasted demand** for low carbon hydrogen is in the range of **250-460TWh by 2050** (re. UK Hydrogen Strategy)
- UK has announced an aim of **24 GW capacity of new nuclear by 2050** (re. Powering up Britain The net zero growth plan).

https://www.gov.uk/government/news/uk-government-launches-plan-for-a-world-leading-hydrogen-economy

About H_2 (some numbers)

- **H_2** is a colourless, odourless, tasteless and non-toxic gas.
- **H_2** disperses **3.8 times** as fast as natural gas.
- **H_2** has highest energy per mass of any comparable fuel with **143 MJ/kg** (~3 times greater than that of liquid hydrocarbon fuels).
- 1 kg of **H_2** has the same energy content as 1 gallon (3.2 kg) of gasoline.
- Higher heating value of **H_2** = 3.54 kWh/Nm3 = **39.41 kWh/kg**
- **H_2** gas costs around £10/kg in the UK

Re. Rodl, Wulf and Kaltschmitt, Hydrogen Supply Chains, 2018, 81-109
https://www.drivingelectric.com/electric/1363/where-can-i-buy-hydrogen-and-where-is-my-nearest-hydrogen-filling-station

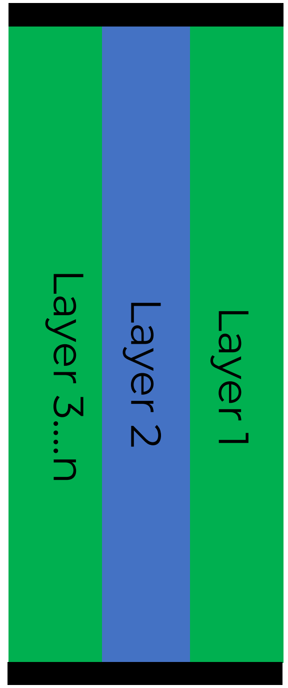
Faraday's laws of electrolysis

(English scientist Michael Faraday in 1833)

- Faraday's laws of electrolysis – **chemical change/current at electrode-electrolyte/electricity/equivalent wight**
- **Splitting a mole of liquid water** to produce a mole of hydrogen at 25°C requires **285.8 kJ** of energy (237.2 kJ as electricity + 48.6 kJ as heat)
- Faraday constant = 96,485 C/mole
- z = 2 (**electrons needed to create a molecule of H2**)
- Electrochemical potential = **1.481 V is required for splitting liquid water**
- Voltage efficiency = Thermal neutral voltage (E)/Cell operating voltage (V)

$$E_o = \frac{\Delta_f H^o}{zF} = \frac{285{,}840\,\frac{J}{mol}}{2 * 96{,}485\,\frac{C}{mol}} = 1.481\ \frac{Volts}{cell}$$

Membrane Electrode Assembly (functional layers)



Materials + Feedstock

Ref. K.W. Harrison, R. Remick, G.D. Martin, A. Hoskin, Hydrogen Production: Fundamentals and Cas Study Summaries, 2010






Sources of high temperature heat energy

- Non-fossil fuel sources of heat (**concentrating solar, nuclear, geothermal, waste heat**) can be used in conjunction with non-fossil fuel sources of electricity (such as **solar, wind, ocean, nuclear**).
- Possible supplies of cheap high-temperature heat for high temperature electrolysis (HTE) are all nonchemical, including **nuclear reactors, concentrating solar thermal collectors, and geothermal sources**.

Note: heat is cheaper than electricity but difficult to hold

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48352/1138-map-nuclear-power-stations-uk.pdf

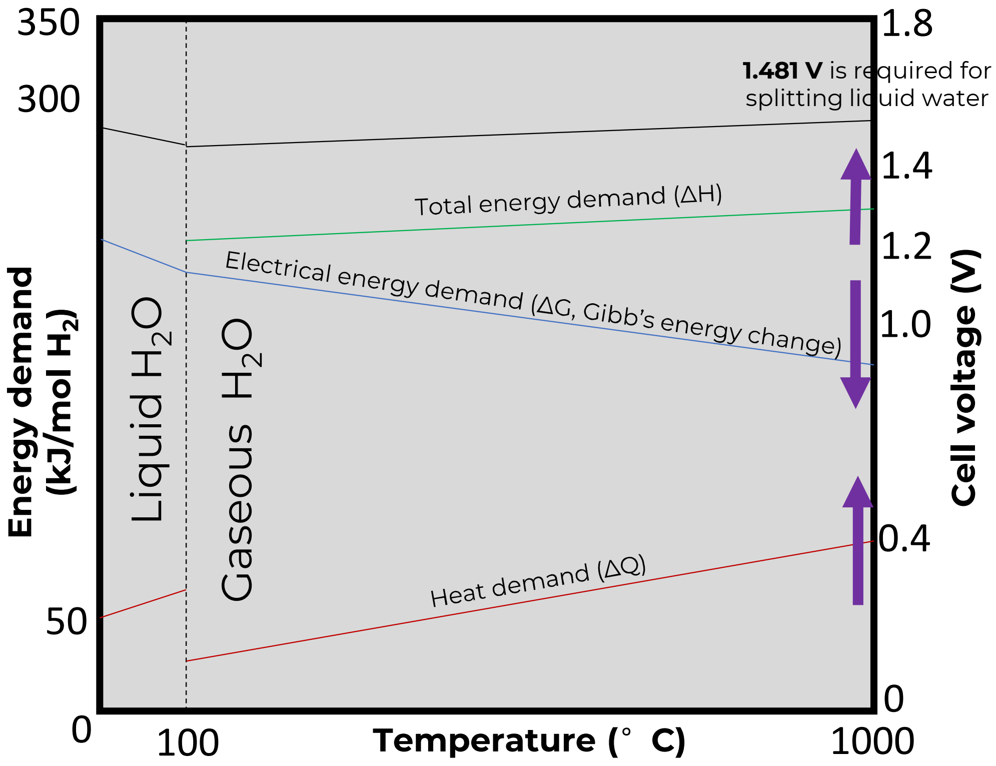
Nuclear reactor power plants usually have a generation end efficiency of 33–35% and about **60% of waste heat**

(Obara & Tanaka, Applied Energy, 292, 2021, 116667)

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

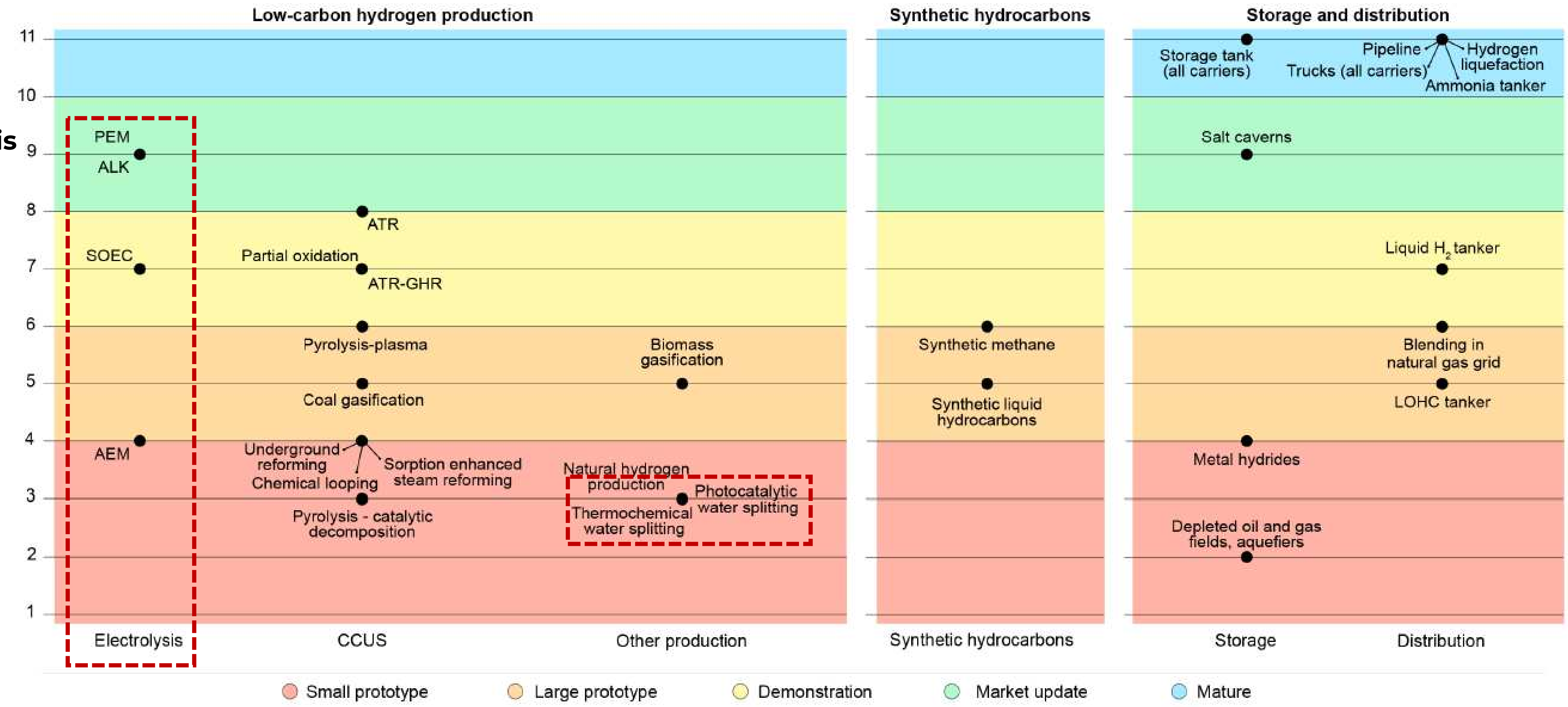


Plot schematically adapted (from Buttler and Spliethoff, 2018)

Electrolysis

- PEM
- AEM
- AWE
- **SOWE**
- **TWS**
- **PWS**
- **PEC**

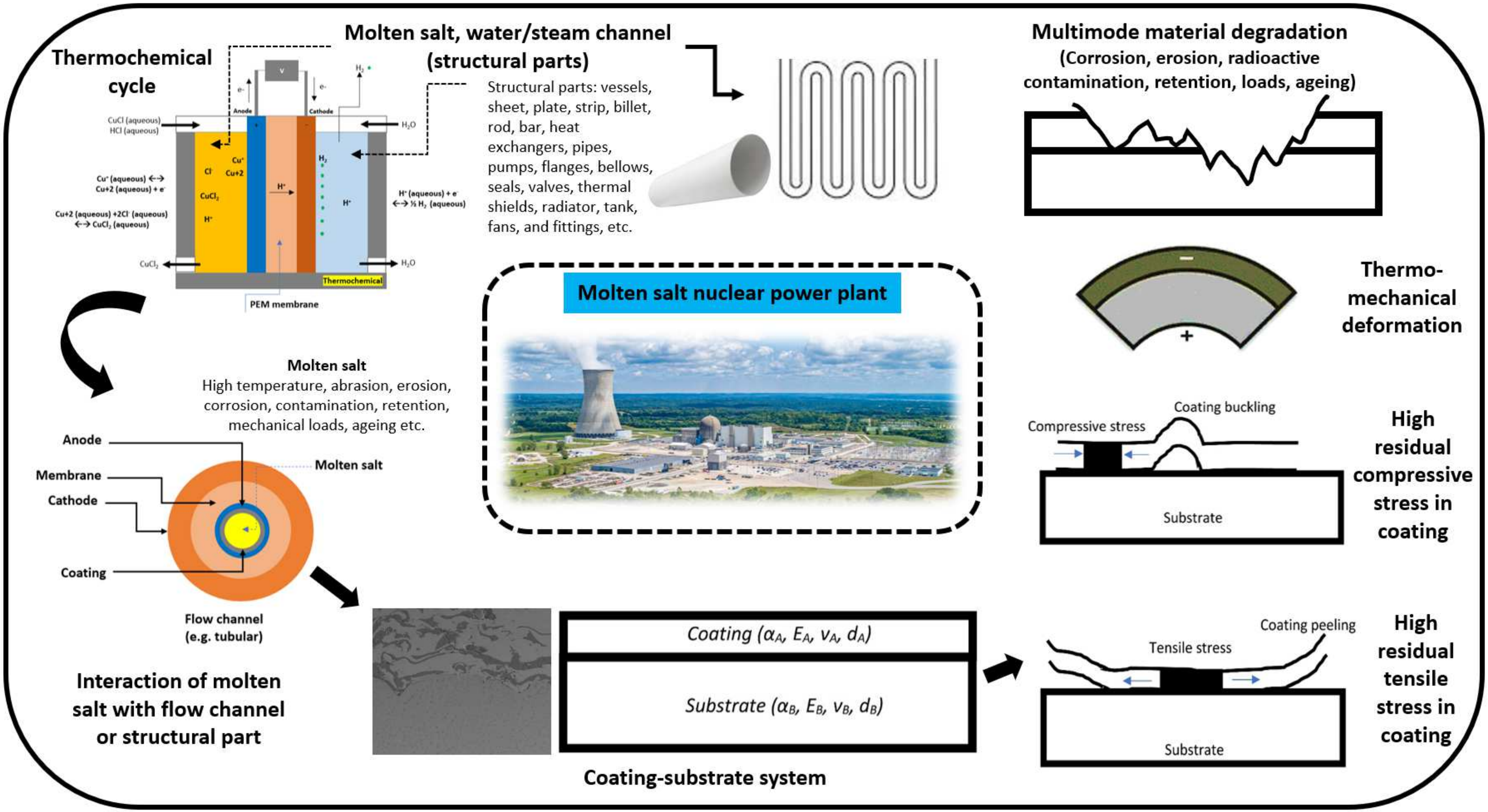
Technology readiness levels of key hydrogen production, storage and distribution technologies



Notes: AEM = anion exchange membrane. ALK = alkaline. ATR = autothermal reformer. CCUS = carbon capture, utilisation and storage. GHR = gas-heated reformer. LOHC = liquid organic hydrogen carrier. PEM = polymer electrolyte membrane. SOEC = solid oxide electrolyser cell. Biomass refers to both biomass and waste. For technologies in the CCUS category, the technology readiness level (TRL) refers to the overall concept of coupling these technologies with CCUS. TRL classification based on Clean Energy Innovation (2020), p. 67.

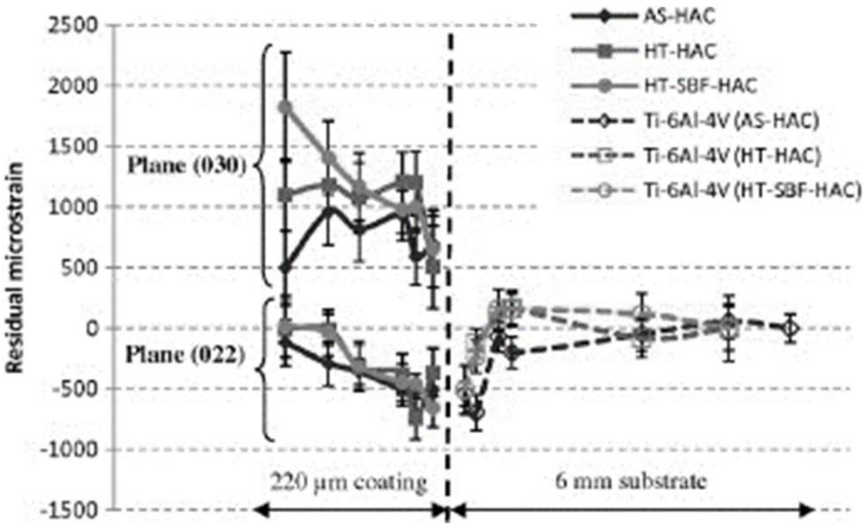
Source: IEA (2020), ETP Clean Energy Technology Guide.

Global Hydrogen Review 2021, https://www.iea.org/reports/global-hydrogen-review-2021

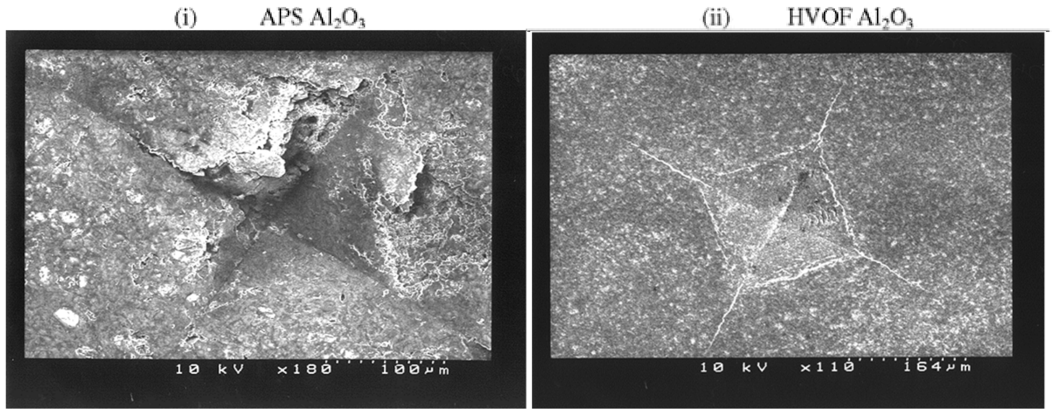


Thermochemical cycle
CuCl (aqueous)
HCl (aqueous)
Cu+ (aqueous) ⟷ Cu+2 (aqueous) + e-
Cu+2 (aqueous) +2Cl- (aqueous) ⟷ CuCl2 (aqueous)
Anode
Cathode
PEM membrane
Thermochemical
H+ (aqueous) + e ⟷ ½ H2 (aqueous)
Molten salt, water/steam channel (structural parts)
Structural parts: vessels, sheet, plate, strip, billet, rod, bar, heat exchangers, pipes, pumps, flanges, bellows, seals, valves, thermal shields, radiator, tank, fans, and fittings, etc.
Multimode material degradation
(Corrosion, erosion, radioactive contamination, retention, loads, ageing)
Molten salt nuclear power plant
Thermo-mechanical deformation
Molten salt
High temperature, abrasion, erosion, corrosion, contamination, retention, mechanical loads, ageing etc.
Anode
Membrane
Cathode
Coating
Molten salt
Flow channel (e.g. tubular)
Interaction of molten salt with flow channel or structural part
Compressive stress
Coating buckling
Substrate
High residual compressive stress in coating
Coating (α_A, E_A, v_A, d_A)
Substrate (α_B, E_B, v_B, d_B)
Coating-substrate system
Tensile stress
Coating peeling
Substrate
High residual tensile stress in coating

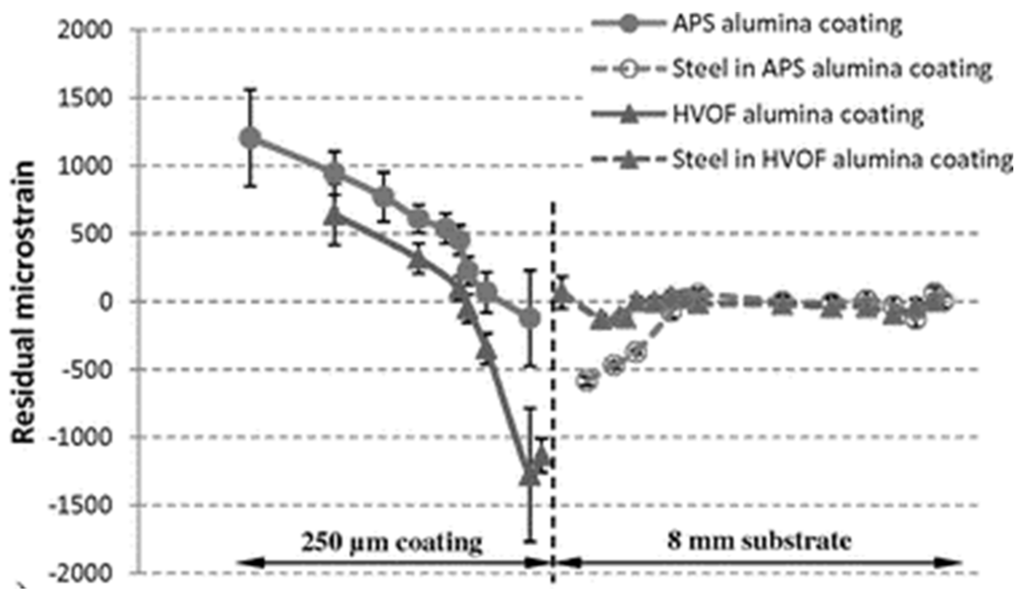
Examples



Al2O3

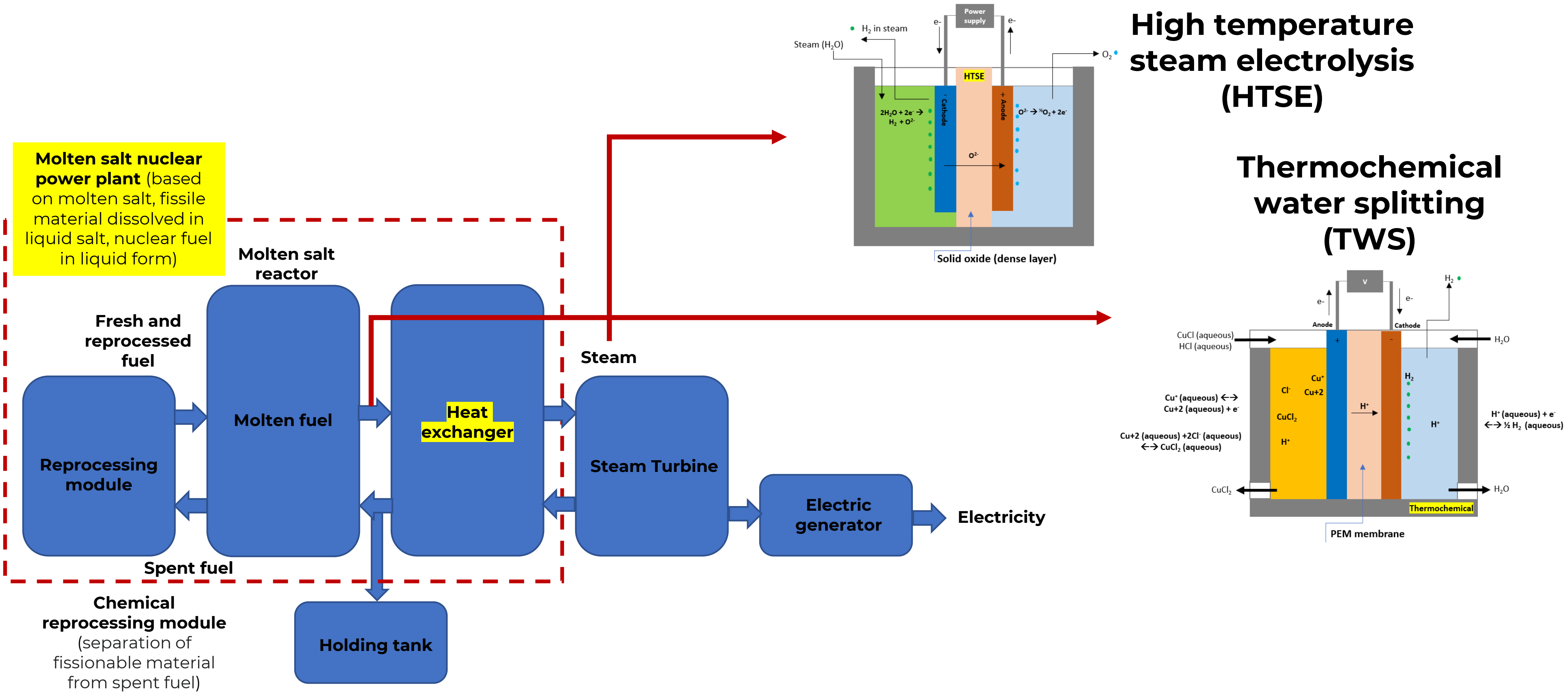


- Residual stress around Vickers indentations is a non-equal biaxial field.
- Both tensile and compressive stresses exist around a sharp indentation and decrease as the distance from the centre of indentation increases.



R. Ahmed, N. H. Faisal, A. M. Paradowska, M. Fitzpatrick, Journal of Thermal Spray Technology, 21(1), 2012, p. 23-40.
R. Ahmed, N. H. Faisal, A. M. Paradowska, M. Fitzpatrick and K. A. Khor, Journal of the Mechanical Behavior of Biomedical Materials, 4(8), 2011, p. 2043-2054

Molten salt reactor

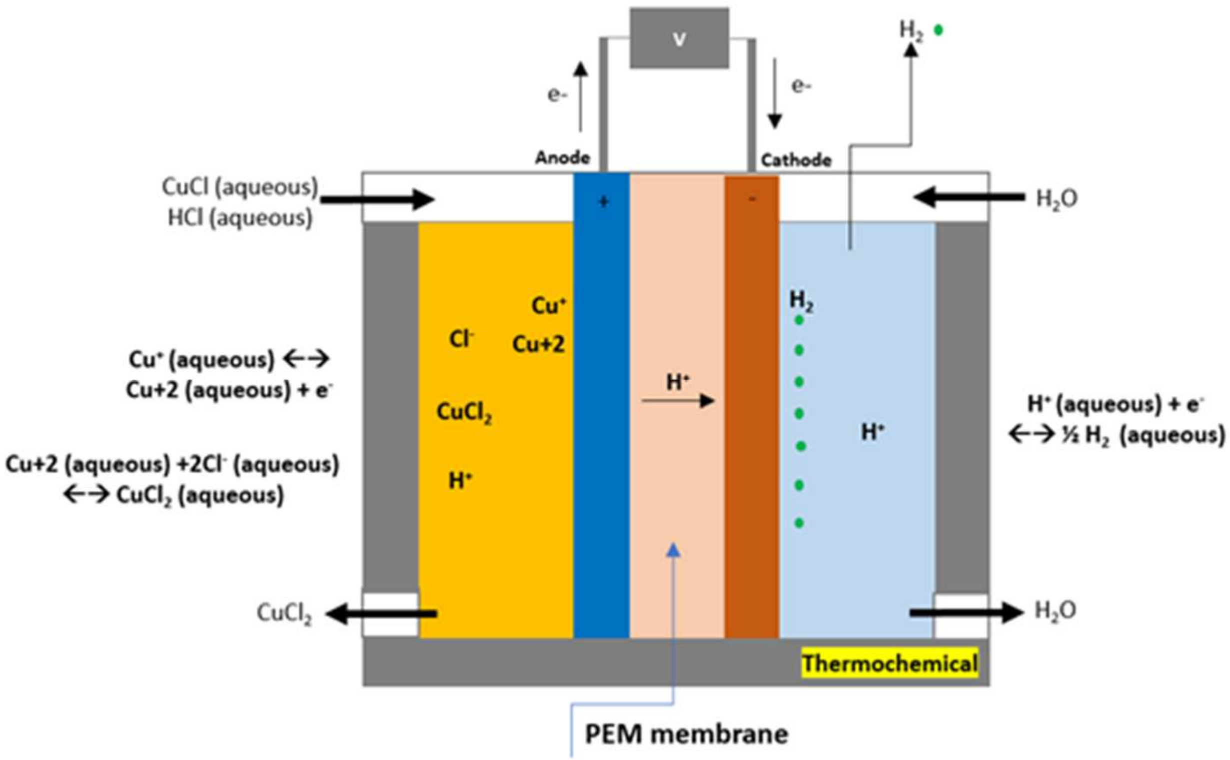


Challenges

- Thermochemical cycles typically involve extreme corrosive environment which impacts the lifetime of a hydrogen generation plant.
- As an example, the Cu-Cl cycle produces corrosive hydrochloric (HCl) acid as a by-product.
- Hydrochloric (HCl) acid presents materials challenges in developing corrosion-resistant materials.

Four-step thermochemical Cu-Cl cycle:

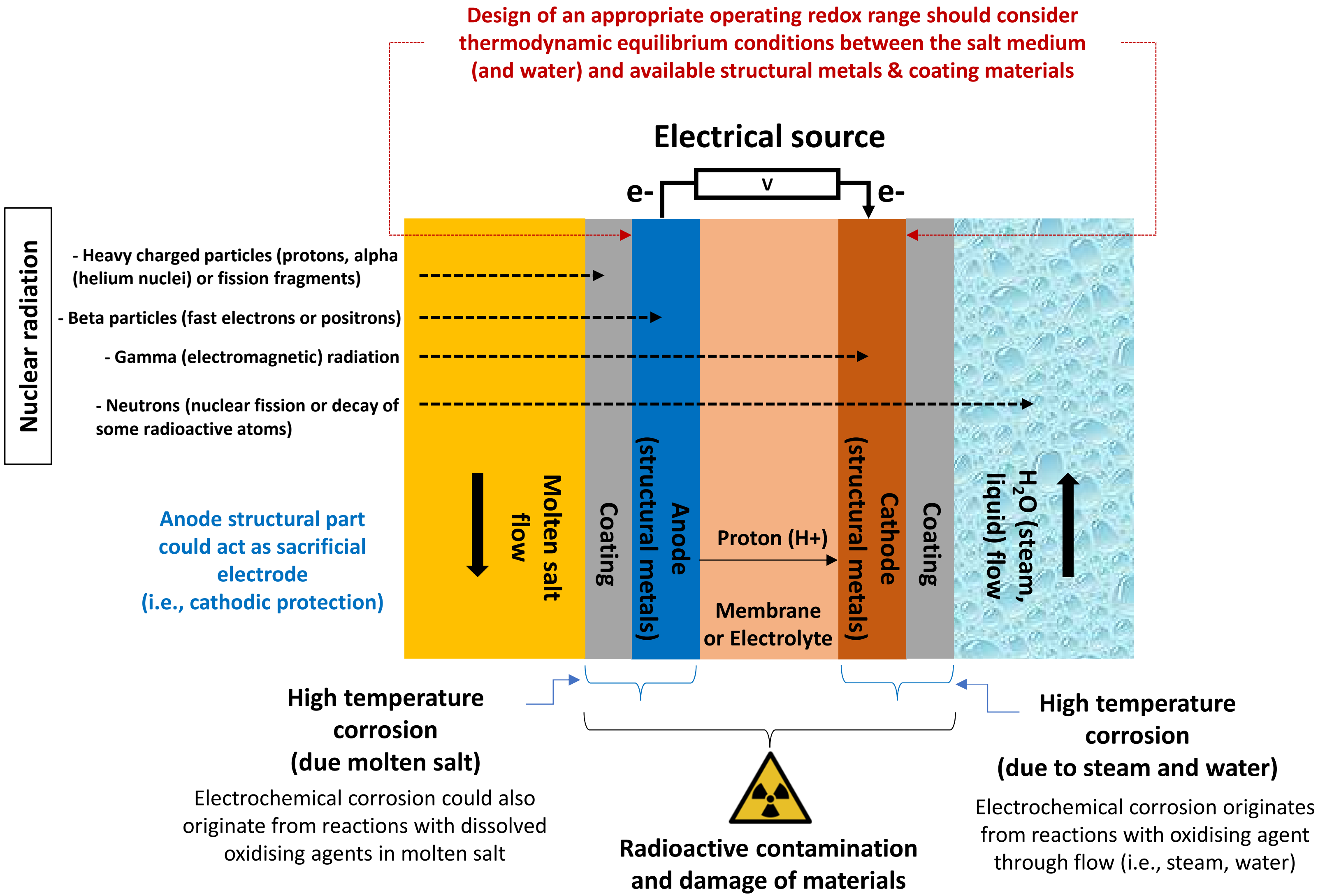
- 2 Cu + 2 HCl(g) → 2 CuCl (l) + H2(g) (430-475 C)
- 2 CuCl2 + H2O(g) → Cu2OCl2 + 2 HCl(g) (400 C)
- 2 Cu2OCl2 → 4 CuCl + O2(g) (500 C)
- 2 CuCl → CuCl2 aq) + Cu (ambient temperature electrolysis)



Examples of corrosive environment

- Molten CuCl
- Molten salt (NaCl, Na_2SO_4,KCl) with gas synthetic air + 10% H_2O
- Molten salt (V_2O_5)
- Molten salt (LiCl-Li_2O)
- Molten LiCl-KCl
- 50wt %Na_2SO_4 and 50wt %V_2O_5 mixture on the substrate
- Calcia-magnesia-alumino-silicate (CMAS) (molten)
- Molten salt (Na_2SO_4 + V_2O_5)
- Water vapour
- Liquid sulfuric acid
- CuCl and HCl
- Molten salt (95%Na_2So_4 + 5%NaCl)
- Molten salt (Na_2So_4-82%$Fe_2(SO_4)_3$)
- Molten salt (Na_2SO_4-60%v_2O_5)

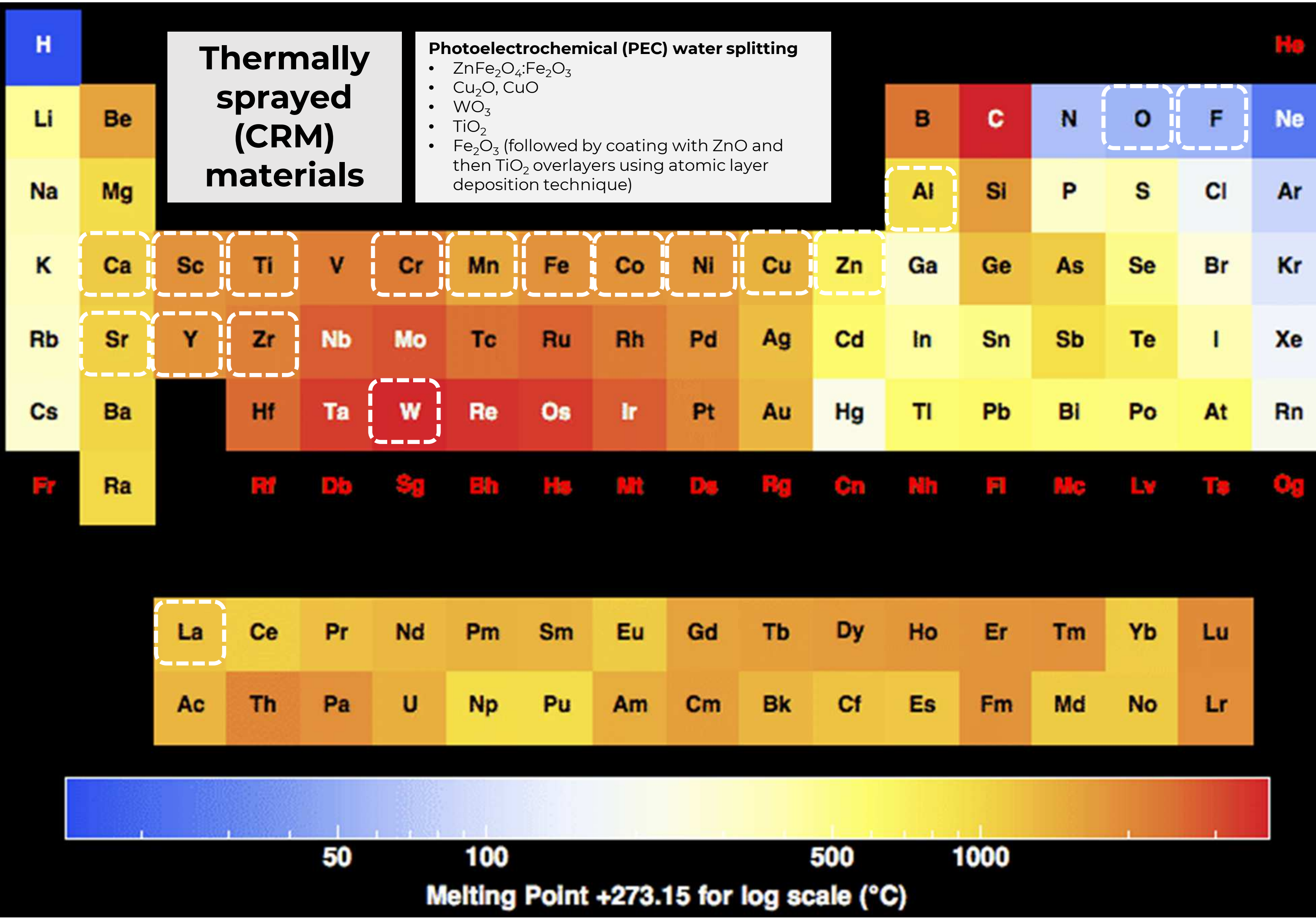
- Molten salt (45wt% Na_2SO_4 + 55wt % V_2O_5)
- Corrosive salts (50wt% Na_2SO_4+50wt%V_2O_5) coated on the substrate 5-7mg/cm^2
- Molten salt ($ZnCl_2$-KCl)
- Coal (boiler environment)
- Modified geothermal fluid
- Air
- Synthetic salt (40 wt% K_2SO_4, 40 wt%Na_2SO_4, 10 wt%KCl and 10 wt%NaCl)
- Molten salt (Fluoride salt)
- Salt mixture (KCl-K_2SO_4)
- Molten salt (NaCl,Na_2SO_4,KCl) with gas synthetic air + 10% H_2O
- Molten salt (FLiNaK)
- Calcia-magnesia-alumino-silicate(CMAS) (molten)
- 75 wt% Na_2SO_4+25 wt% K_2SO_4



Faisal et al., Structural materials and thermal spray coatings for molten salt facing parts: challenges and opportunities for nuclear thermochemical cycle electrolysis (review under preparation), 2023

Variables for Data Analytics

- Feedstock materials
- Substrates
- Density
- Melting point
- Thermal expansion coefficient
- Thermal conductivity
- Electrical resistivity
- Proof stress
- Tensile strength
- Manufacturing process
- Corrosive environment (molten salt, geothermal, solar, oxidation)
- Salt
- Testing temperature
- Coating thickness
- Bond thickness
- Powder particle size
- **Corrosion rate**



Thermally sprayed (CRM) materials

Photoelectrochemical (PEC) water splitting
- $ZnFe_2O_4$:Fe_2O_3
- Cu_2O, CuO
- WO_3
- TiO_2
- Fe_2O_3 (followed by coating with ZnO and then TiO_2 overlayers using atomic layer deposition technique)

Solid oxide water electrolyser (SOWE)

Cathode layer
- Ni (cathode)
- Ni/YSZ (cathode)
- NiO+YSZ (cathode)
- LSM ($La_{0.8}Sr_{0.2}MnO_3$) and LSCF ($La_{0.6}Sr_{0.4}Co_{0.4}Fe_{0.6}O_3$) (cathodes)
- Nickel-zirconia (cathode)

Electrolyte layer
- YSZ (electrolyte)
- 9 mol% YSZ (electrolyte)
- Scandia-stabilized zirconia (electrolyte)

Anode layer
- Calcium or strontium-doped $LaCoO_3$ or strontium-doped $LaMnO_3$ (anode)
- LSCF (anode)
- Strontium-doped manganite (anode)

Other layers
- Al_2O_3 (for sealing & preventing oxidation)
- Manganite-zirconia (inner layer)
- Pure manganite (middle layer)
- Cobaltite (outer bond layer)
- Ni/NiO 50%–YSZ 50% (support electrode layer)
- Ni/NiO 25%–YSZ 75% (electrolyte transition layer)
- 50% YSZ–50% LSM (electrolyte-end transition layer)
- LSM 100% (end electrode)
- Ni (bond layer) (steam/hydrogen side of separator plate)
- Ni-Al (interconnect)

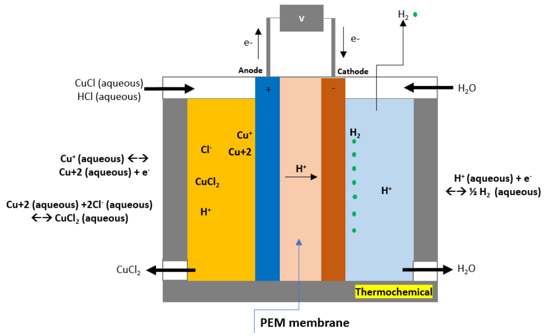
Photolysis water splitting
- TiO_2
- ZnO

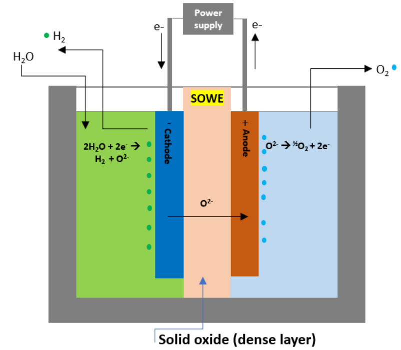
Thermochemical water splitting
- YSZ
- Al_2O_3
- Diamalloy 4006 (bond coat)
- Super hard steel 9172 (bond coat)

https://periodictable.com/Properties/A/MeltingPoint.st.log.html

Faisal et al., **ChemNanoMat** , 8(12), 2022, e202200384 (doi: https://doi.org/10.1002/cnma.202200384)

OTHER MANUFACTURING METHODS AND MATERIALS USED IN HIGH TEMPERATURE ELECTROLYSERS





Solid oxide water electrolysis (SOWE)

Anode
- LSM-YSZ
- LSM
- YSZ
- LSCN-GDC
- LNO
- SSC-SDC73
- BCFN
- BSCF
- PdO/ZrO_2 – LSM-YSZ

Cathode
- LSCM-YSZ
- Ni-1Ce10ScSZ
- Ni-YSZ
- NiO-YSZ
- Ni-YSZ
- NiO-GDC

Manuf. methods
- Sol gel method
- Screen printing
- Ion plating process
- Electrodeposition
- Dry processing
- Spin coating
- Impregnation process
- Slurry coating
- Physical vapour deposition

Thermochemical water splitting (TWS)

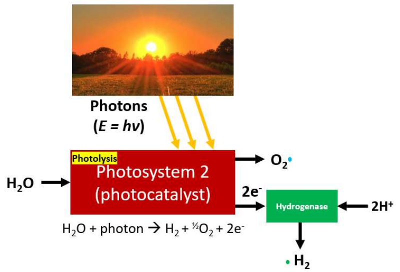
- Ferrite
- Ferrite/zirconia

Manufacturing methods
- Spin coating method
- Aerosol spray pyrolysis

Photolysis water splitting (PWS)

- Rh/Cr_2O_3
- $NiFe_2O_4$
- $NiFe_2O_4$@TiO_2
- $CoO_x/TiO_2/Pt$
- TiO_2
- ZnO
- Au/TiO_2
- Pt/TiO_2
- $NaTaO_3$
- Nitrogen modified TiO_2
- CUO and WO_3 loaded on TiO_2 annotate
- CdS/TiO_2
- CU_2O/ TiO_2
- Ag/TiO_2
- $NaTaO_3$-C
- TiO_2-ZnO
- Ag_2O-TiO_2
- Yttrium and aluminium co-doped ZnO
- Bare TiO_2, Ag_2O-TiO_2, Bi_2O_3-TiO_2, ZnO-TiO_2
- $RuO_2/NaTaO_3$, RuO_2/La: $NaTaO_3$
- B-TiO_2
- Cu-TiO_2

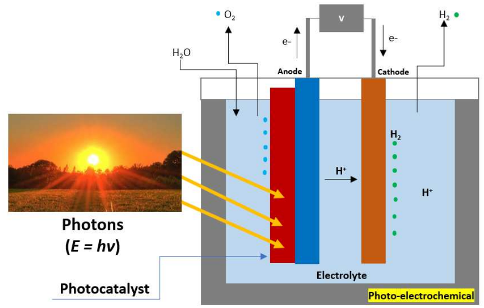
Manufacturing methods
- Photo deposition
- Sol gel method
- Atomic layer deposition
- Spray pyrolysis
- Flame spray pyrolysis
- Aerosol assisted chemical vapour deposition (AACVD)
- Wet impregnation method
- Electrodeposition
- Radio frequency magnetron sputtering
- Ultrasonic spray pyrolysis
- Atmospheric pressure chemical vapour deposition



Photoelectrochemical (PEC) water splitting

- TiO_2
- ZnO
- Cds-TiO_2-WO_3
- Nickel oxide hematite
- C60/hematite, eRGO/hematite, eRGO/C60/Hematite
- α Fe_2O_3
- CdS NPs/Cd NSs
- Nanostructured WO_3 thin film
- $ZnIn_2S_4$
- Pt nanoparticles
- Molybdenum disulfide (MoS_2)
- Mn_2O_3-4TiO_2
- Fe-TiO_2/Zn-Fe_2O_3
- WO_3/TiO_2 nanotube array
- TiO_2 nanoparticles
- WO_3- Fe_2O_3
- $CuBi_2O_4$
- $BiVO_4$, WO_3

Manufacturing methods
- Pulsed laser deposition
- Spin coating
- Photo reduction method
- Sol gel method
- Electrodeposition
- Hydrolysis
- Pulse reverse electrodeposition
- Spray pyrolysis
- Atomic layer deposition
- Aerosol assisted chemical vapour deposition (AACVD)
- Chemical vapour deposition (CVD)
- Wet impregnation method
- Atmospheric pressure CVD
- Inkjet printing
- Dip coating



Opportunity: Materials data analytics

Faisal et al., **ChemNanoMat** , 8(12), 2022, e202200384 (doi: https://doi.org/10.1002/cnma.202200384)

Examples of coating materials used
(high temperature corrosive applications)

For thermally sprayed (coating) materials
- Temperature range tested: 500 to 1320 C
- Testing duration (molten salt): 20-300 hours
- Testing duration (corrosion test): 30-360 hours
- Coating thicknesses: 100-4000 microns
- Feedstock powder size range: 45-90 microns
- Corrosion rates: 14-31 mm/year

- SHS9172 (Cr, Mo, W, Nb)
- Diamalloy 4006 (Ni 20.5Cr 10W 9Mo 4Cu 0.75C 0.75B)
- YSZ
- Al2O3
- Zinc Ferrite
- CuO
- Tantalum
- Lu2Si2O7 + Lu2SiO5
- Cr3C2-NiCr powder blend with 75% LA - 6304 and 25% LA – 7319
- Cr2O3
- NiCrBSi
- Stellite-6 (27%-32% Cr, 4%-6% W, 1%-2% C, 3%-4% Ni, 1%-2% Si, 3%-4% Fe)
- Ni20Cr

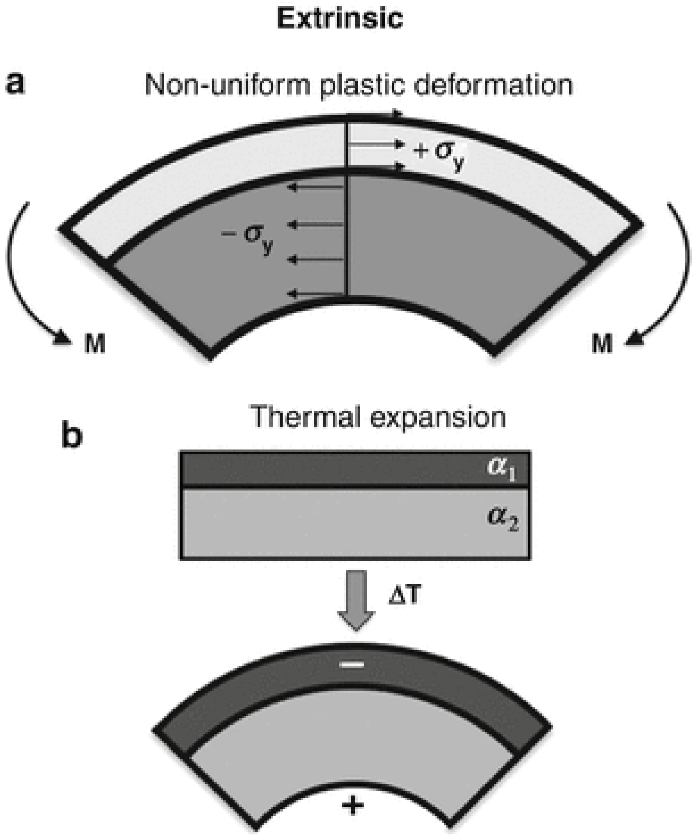
- Ni50Cr
- Ni53Cr
- Ni57Cr
- Ni21Cr9Mo
- MCrAlY
- Ni-5Al
- Fe3Al
- SYSZ (with NiCrAlY bond coat)
- SiO2
- CoNiCrAlY
- Cr3C2-WC-NiCoCrMo

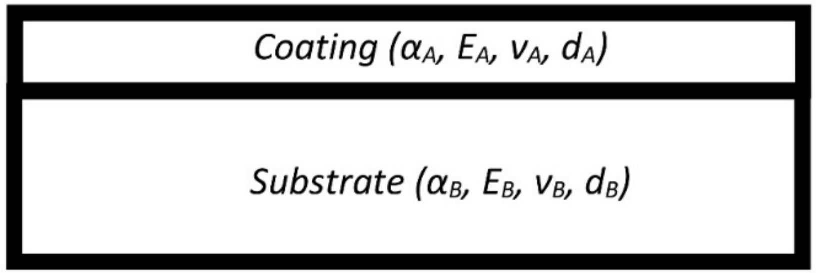
Substrate materials for high temp. application

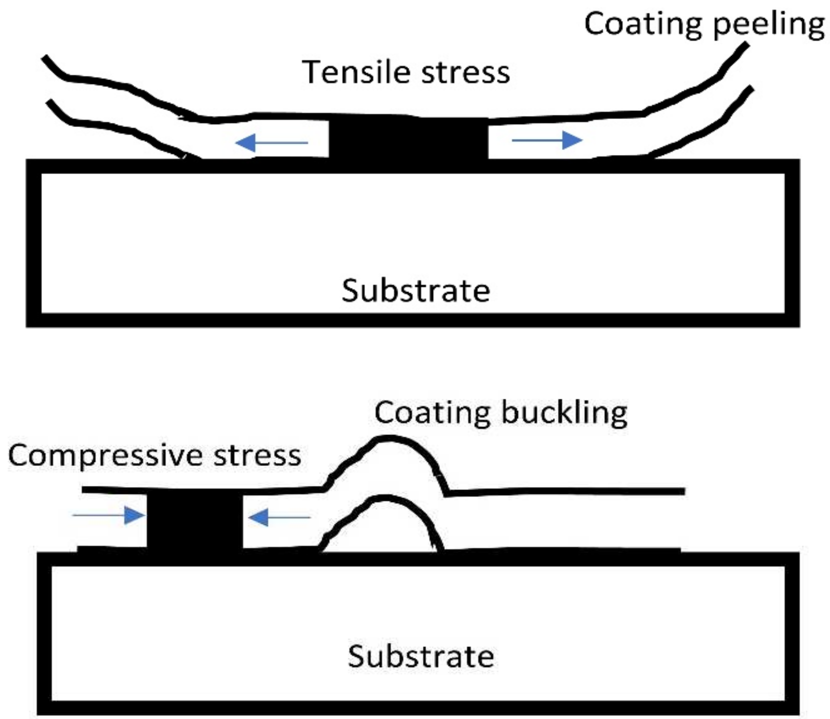
- Mild carbon steel
- Stainless steel (SS) 316L
- Stainless steel 310
- Ferritic stainless steel/Nimonic alloy 263/Iron based alloy (SAN25)
- Stainless steel AL6XN
- Stainless steel 304
- Boiler steel SAE 431
- T24 steel pipes
- SA516 steel
- SA213-T91 (ferritic and austenitic alloy steel)
- AISI P21 is a General Mold Steel grade Tool Steel

- Inconel 625/AL6XN
- Inconel 738
- Inconel 713LC
- Superni 75
- Superni 76
- Superni 718
- Superni 750
- Superfer 800H
- Nickel superalloy (C263)
- Nickel superalloy (IN100)

- Grey cast iron
- Siliconized silicon carbide (SiSiC)
- Alumina
- Mullite ($3Al_2O_32SiO_2$ or $2Al_2O_3$ SiO_2)
- Isotropic graphite (9G540)
- Aluminium 6061







Selection of reliable and sustainable materials (MEA's) with reduced potential needed to split water during electrolysis

Greater use of abundant feedstocks for electrolysis (e.g., water, sunlight, heat, electricity)

Data driven decisions (performance, materials & durability)

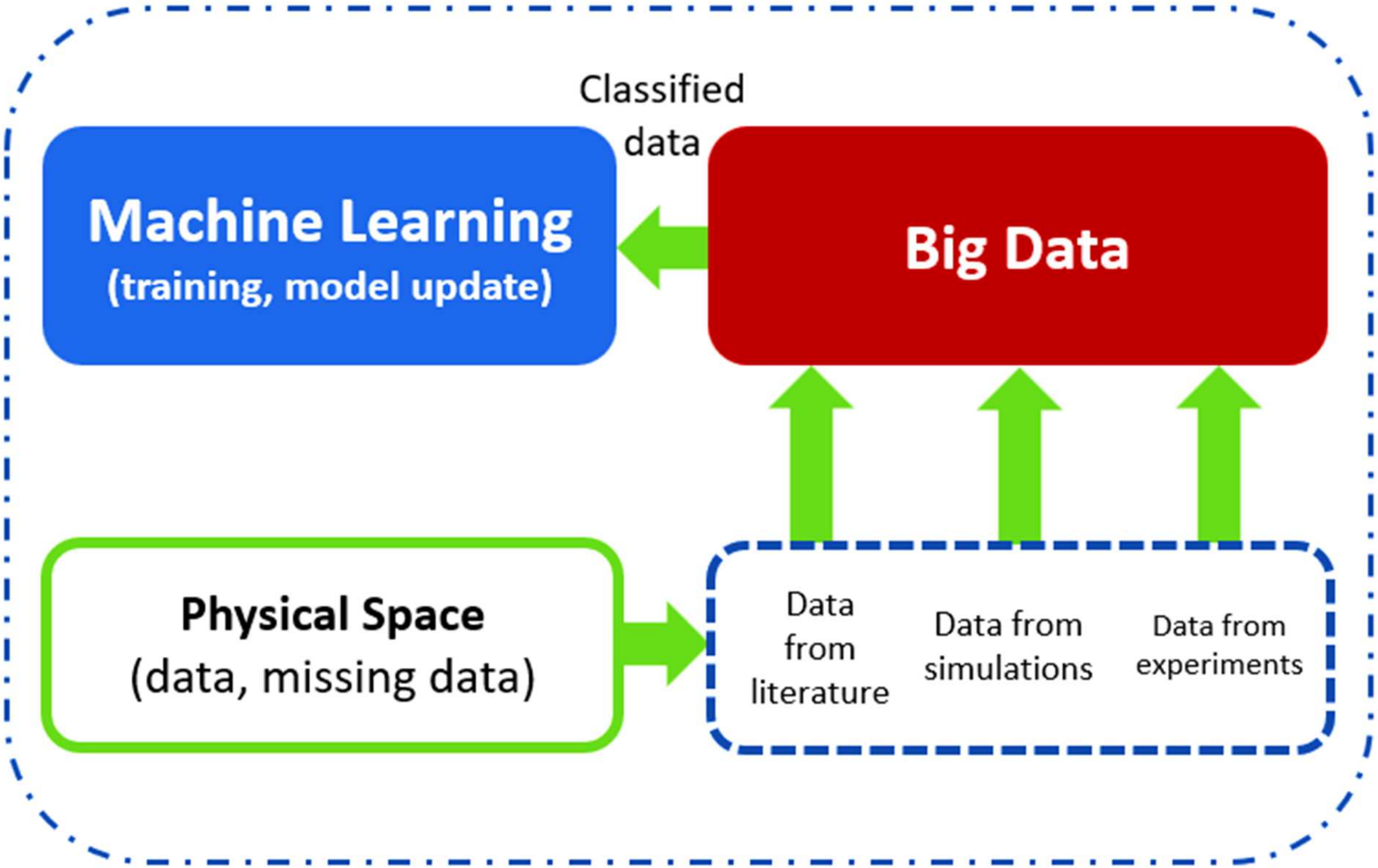
Optimal design of catalysts, transport layer, sealing, bipolar plates, stacks for enhanced electrolysis (e.g., metamaterials). **Reducing cell mass** which do not actively contribute to the electrolyser capacity

Lowering the cost of manufacturing of catalysts & transport layer (by selecting scalable manufacturing methods, automation)

Enhanced working life of MEA's (efficiency, life cycle assessment, self-healing, functional properties, structural health monitoring)

Ethical, legal, geo-political & other global issues, supply chain (materials access, environment, recycling)

Opportunity: Data analytics approach



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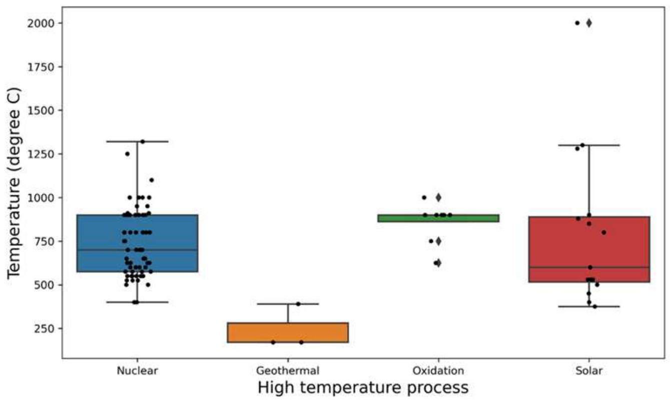
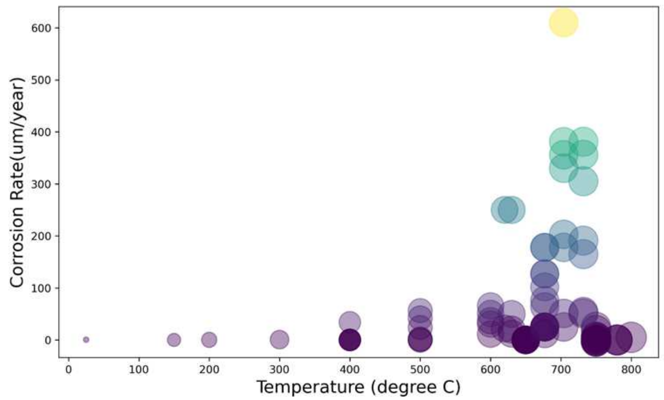
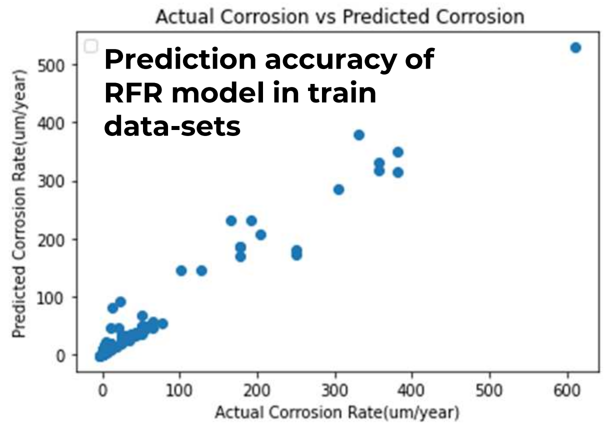
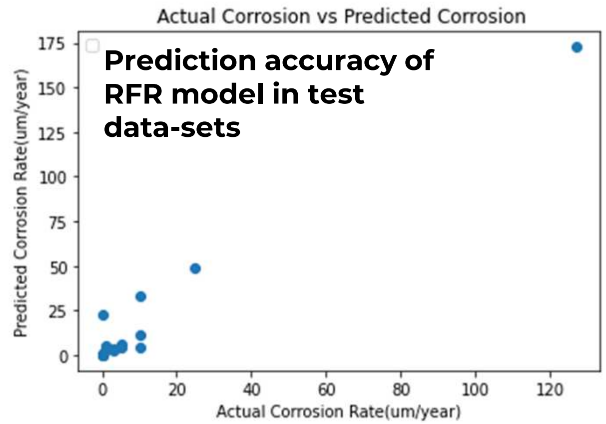
Data Analytics Approach







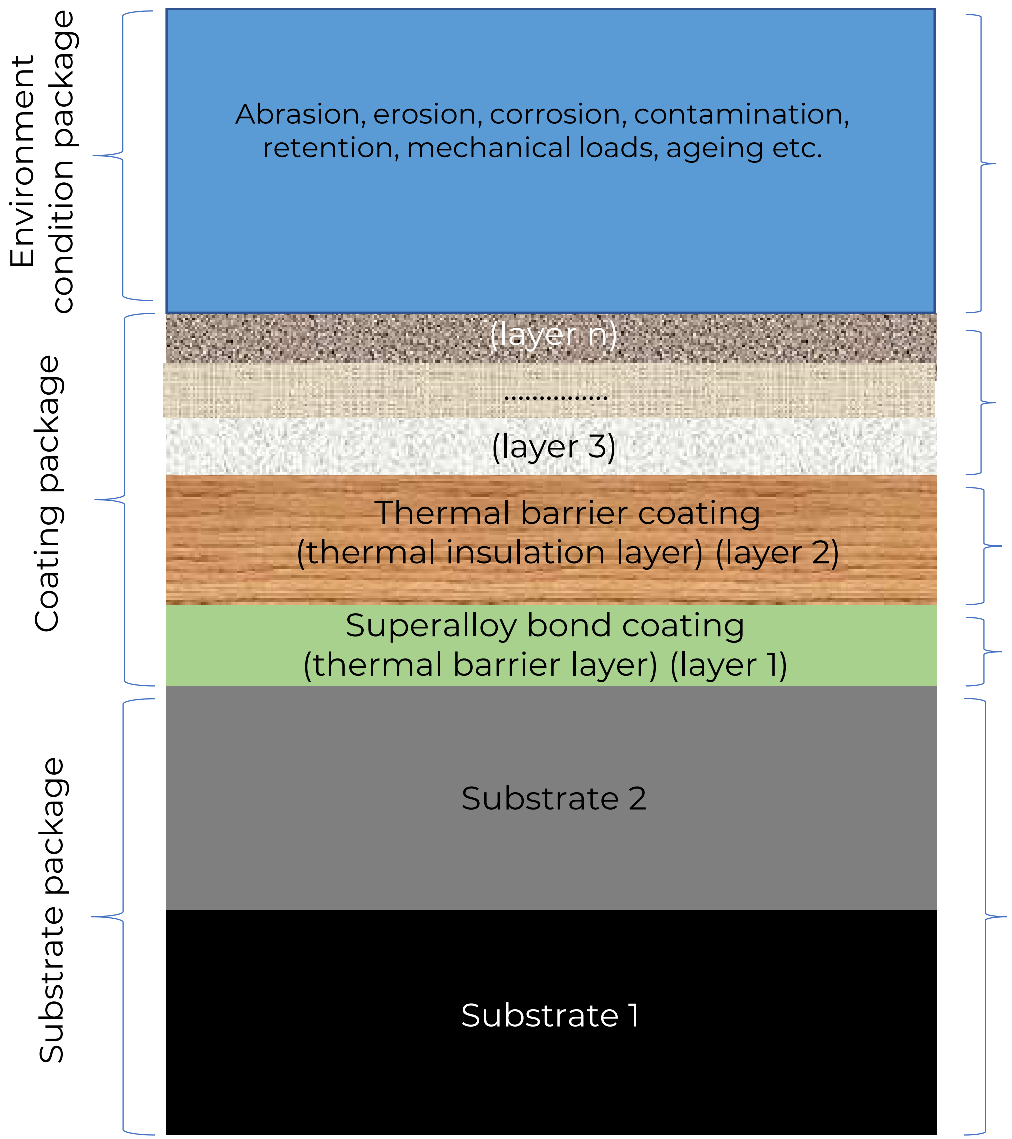


Regression Model	R^2 value for train data-sets	R^2 value for test data-sets
Linear Regression	0.001	-0.972
SVR	-0.150	-0.063
RR	0.240	-3.425
Lasso Regression	0.239	-3.421
ABR	0.929	0.309
GBR	0.986	0.298
RFR	0.961	0.740

R2 accuracy validation of each model between train and test data-sets.

By Vinooth Rajendran, Yakubu Balogun, Ramkumar Muthukrishnan (Robert Gordon University)

Surface and interface issues (high temperature)



Challenges
(measurement, material loss/degradation/retention/contamination)

Functional multiple layers (sacrificial layer with low porosity, resistant against molten salt corrosion, good thermal stability, hardness, and wear resistance, no oxidation or colour change, better thermo-physical properties, and improved chemical inertness against foreign deposits). Need to have lower thermal conductivity values than bottom layer.

Thermal insulating layer (with good adhesion properties).

Thermal barrier layer (to enhance mechanical bonding with top layer, low thermal conductivity, low thermal expansion coefficient); Heat treatment of the layer could provide highest strengthening effect and can influence grain size.

Superalloys substrate (which can be used at high temperature. Creep and oxidation resistance are the prime design criteria).

Opportunity: Substrate-coating design

Modelling – Example (SOEC)
Thermodynamics & Heat Transfer

Modelling scope

- **Geometry, materials, component integration** (stack structure, steady-state/transient, finite volume model, cathode/anode-supported, cell area, boundary conditions, heat losses assumptions, cell operation – ambient pressure & pressure losses within anode/cathode flow channels, physical properties assumed constant, gas properties calculated, gas streams on the cathode/anode assumed to be in co-current flow)
- **Electrochemical** (related to cell voltage, current density, cell temperature, and cathode/anode species concentration; from this electrical energy consumption and heat balance of the cell can be derived)
- **Mass transfer** (e.g., at the anode oxygen ions are converted to molecular oxygen, thus the oxygen mass flow is increasing along the cell)
- **Thermal balance** (heat sources/sinks due to electrochemical reactions, heat transfer between solid structures and gas streams, gas enthalpy changes and heat conduction)

Analysis

- Reduction in temperature gradient
- Temperature control (no control can lead to degradation problems in transient operation, i.e., in coupling with fluctuating energy sources)
- Transient load regime analysis

Opportunity: Develop modelling methods (Multiphysics)

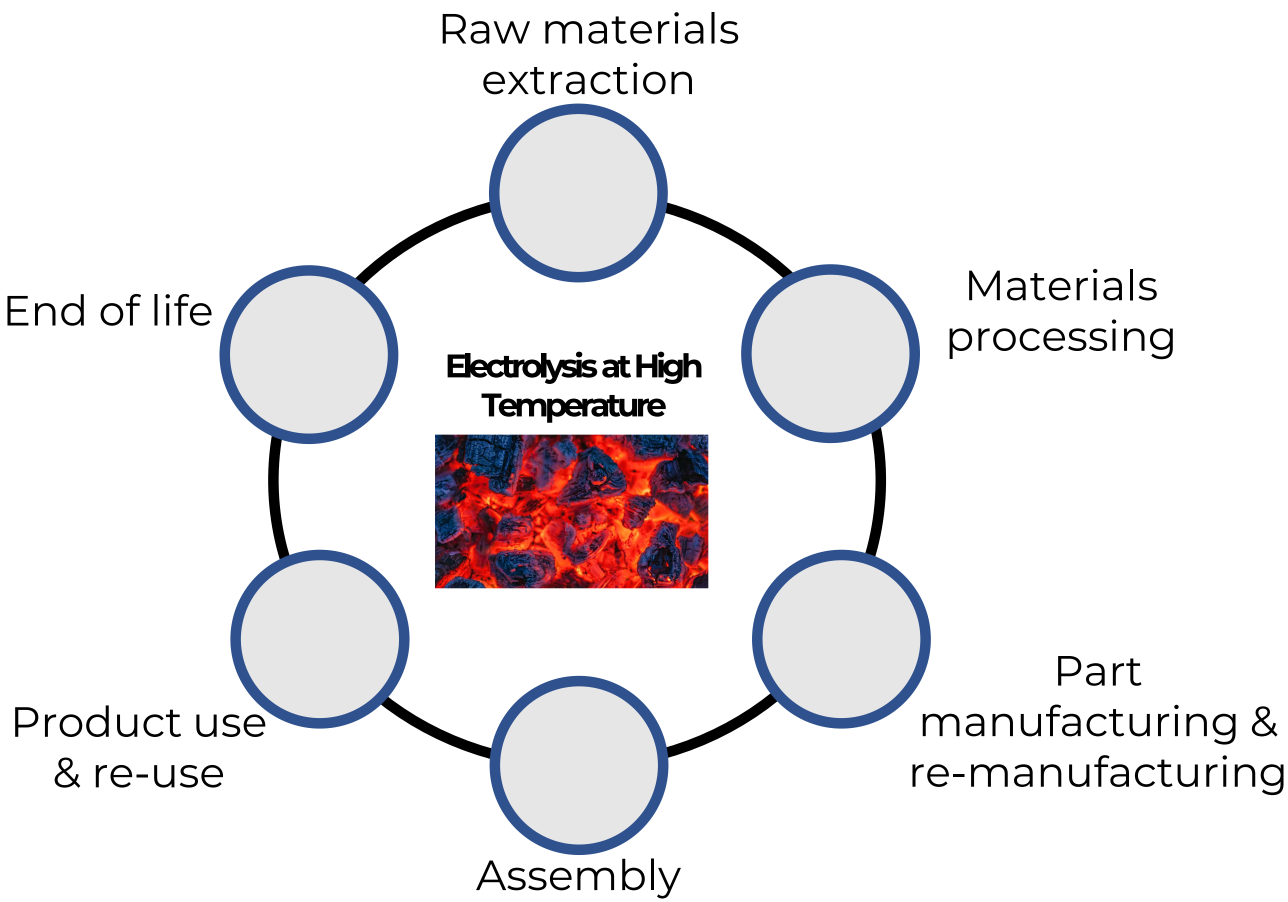
Model input parameters (example)

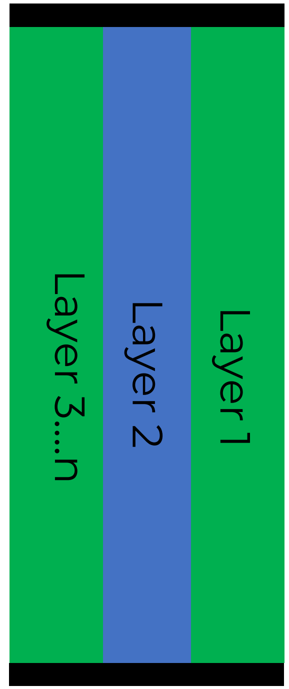
- Cathode channel height
- Anode channel height
- Solid structure thickness
- Interconnect thickness
- Cell length
- Cell width
- Cathode thickness
- Electrolyte thickness
- Anode thickness
- Cathode electric conductivity
- Electrolyte ionic conductivity
- Anode electric conductivity
- Cathode average effective diffusivity
- Solid structure emissivity
- Interconnect emissivity
- Solid structure heat capacity
- Interconnect heat capacity
- Solid structure thermal conductivity
- Interconnect thermal conductivity
- Solid structure density
- Interconnect density
- Cathode stream Nusselt number
- Anode stream Nusselt number
- Transfer coefficient
- Cathode stream inlet temperature
- Cathode stream inlet composition
- Anode stream composition
- Operating pressure
- Average current density
- Steam utilisation factor

Udagawa et al., Journal of Power Sources 166 (2007) 127–136

ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines.

Life Cycle Assessment (LCA)





Understand the contribution of individual components for electrolysis at high temperature

Opportunity: Life cycle assessment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Thank You
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