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Structural design and analysis of a high temperature solid oxide steam tubular electrolyser.

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2023

ROBERT GORDON UNIVERSITY ABERDEEN

Structural Design & Analysis Of A High-Temperature Solid Oxide Steam Tubular Electrolyzer

METASIS Project

EP/W033178/1

Scalable <u>meta</u>material thermally sprayed catalyst coatings for nuclear reactor high temperature solid oxide steam electroly<u>sis</u> (METASIS)

Robert Gordon University
Researchers
- <u>Dr Victoria Kurushina</u>, PDRF
- Vinooth Rajendran, RA

Investigators
- Prof Nadimul Faisal
- Prof Mamdud Hossain
- Dr Anil Prathuru

University of Surrey
Researcher
- Dr Ajith Soman, PRDF

Investigators
- Dr Bahman Horri
- Dr Qiong Cai

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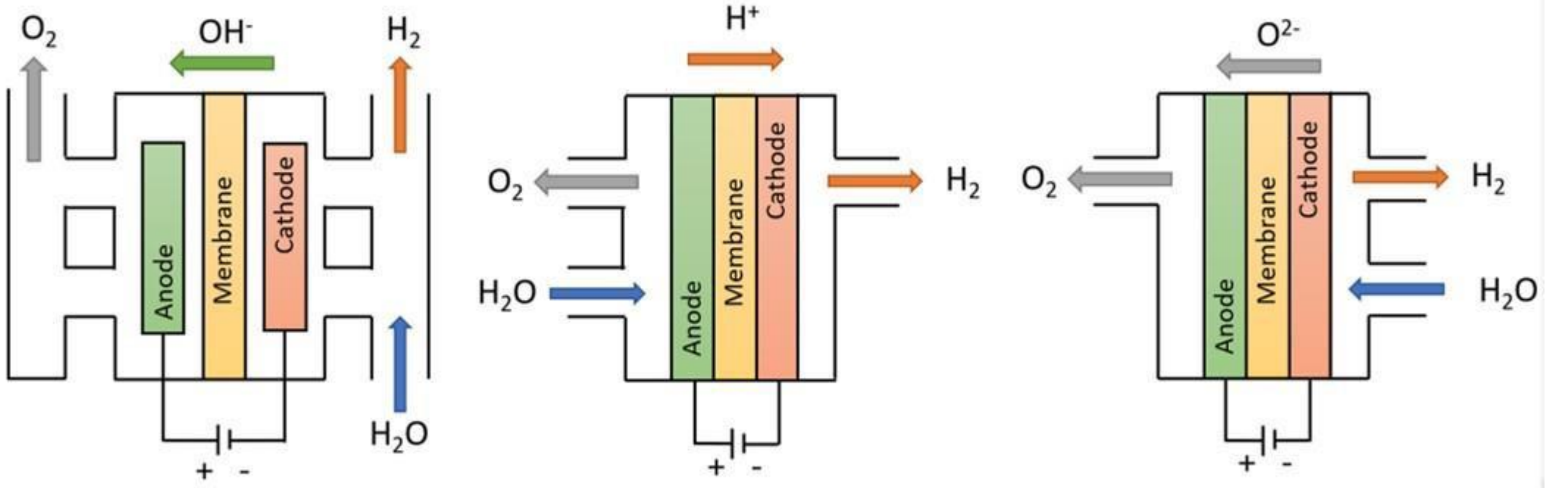
Water electrolysis (WE) for hydrogen production

Dominant technologies:

- *proton exchange membrane electrolysis cells* (PEMEC);
- anion exchange membrane electrolysis cells (AEMEC);
- *alkaline water electrolysis cells* (AWEC);
- *solid oxide steam electrolysis cells* (SOSEC);
- thermochemical water splitting (TWS);
- photolysis water splitting (PWS);
- photoelectrochemical water electrolysis cells (PECWEC).

CURRENT STATUS OF TECHNOLOGY



PEMEC – mature

AWEC – commercial

SOSEC – demonstration

S – SOLID
O – OXIDE
S – STEAM
E – ELECTROYSIS
C – CELL

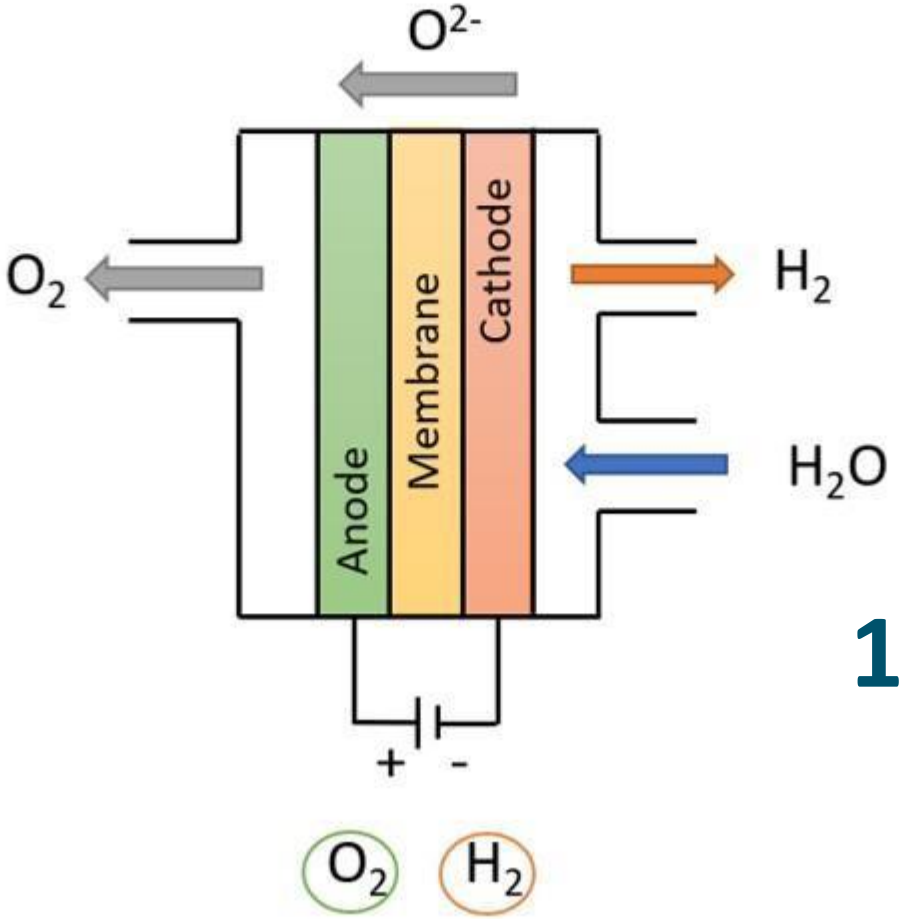
S – SOLID
O – OXIDE
E – ELECTROYSIS
C – CELL

E – ELECTROYSIS
C – CELL

Solid oxide steam electrolysis explained

2 Anions of oxygen pass through the electrolyte (membrane/solution), attracted by the anode, where they loose extra electrons and form zero-valence molecules that exit the gas channel

$O^{2-} - 2e^{-} \rightarrow O_2$



3 Cations of hydrogen gain electrons at the cathode, powered by the external electrical circuit, and the formed molecules of hydrogen leave the gas channel at the outlet, mixed with the remainder steam

$2H^{+} + 2e^{-} \rightarrow H_2$

1 Steam supply at high temperature into the gas channel and splitting into ions of oxygen and hydrogen at the cathode

$H_2O \rightarrow 2H^{+} + O^{2-}$

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Electrolysis cell technologies in review

Characteristics	Units	AEC	PEMEC	SOEC
Operating temperature	^oC	60-80	50-80	650-1000
Current density	A/cm^2	0.2-0.4	0.6-2.0	0.3-2.0
Cell voltage	V	1.8-2.4	1.8-2.2	0.7-1.5
Operating pressure	bar	< 30	< 200	< 25
Production rate	m^3/h	< 760	< 40	< 40
Stack lifetime	hours	60 000 - 90 000	20 000 - 60 000	10 000
Stack energy	kWh/m^3	4.2-5.9	4.2-5.5	>3.2
Capital cost	euro/kW	1 000 - 1 200	1 860 - 2 320	> 2 000

Innovations for electrolysis technology

Areas of innovation

Cell
- membrane;
- electrodes;
- electrolyte;
- gas channels;
- other

Stack
- connectors;
- sealing;
- gas channels;
- other

System
- new set-up or chemistry;
- operation;
- integration with existing systems;
- other

Manufacturing
- scale;
- method;
- design;
- automation;
- other

Supply chain
- volume;
- competition;
- other

Cell-level design decisions

- Cell geometry
  - Planar cells
  - Tubular cells

- Support type
  - Cathode-supported cell
  - Electrolyte-supported cell
  - Anode-supported cell

Cathode-supported cell

+ Good cell stability during electrochemical process

- High resistance for polarization

Electrolyte-supported cell

+ High mechanical robustness
+ Good gas diffusion properties

- High ohmic losses in the thickened electrolyte layer

Anode-supported cell

+ Lower operating temperature
+ Low ohmic resistance
+ Lower costs of material
+ Considered to be easier for fabrication

- Lower mechanical reliability

SOSEC technology development

Challenges

- ❑ Electrode degradation:
    - ❑ Delamination;
    - ❑ Interdiffusion;
    - ❑ Particle agglomeration;
    - ❑ Corrosion;
- ❑ Performance enhancement;
- ❑ Lack of characterization;
- ❑ Commercialization.

Directions of development

- o Operation at lower temperature conditions;
- o Integration with existing systems of power plants;
- o Reducing costs;
- o Reducing the cell degradation;
- o Material innovation and optimization of electrochemistry;
- o Manufacturing innovation.

Integration of electrolysis cell technology and gas reactors

Gas Reactor Type	Temperature Range (°C)
High-Temperature Gas-Cooled Reactor (HTGR)	750 - 950
Very High-Temperature Gas-Cooled Reactor (VHTR)	900 - 1600
Gas-Cooled Fast Reactor (GFR)	850 - 1000
Molten Salt Reactor (MSR)	600 - 800
Pebble Bed Reactor (PBR)	400 - 950

SOEC Type	Temperature Range (°C)
High-Temperature SOEC (HT-SOEC)	800°C - 1000°C
Intermediate-Temperature SOEC (IT-SOEC)	600°C - 800°C
Low-Temperature SOEC (LT-SOEC)	Below 600°C

Integration of electrolysis cells with nuclear power plants:

- **by arranging energy transfer to EC**

1) using excess heat going through heat exchangers;
2) using excess electricity available as a part of cycles of electricity consumption;
3) using energy/electricity from a power plant and energy/electricity from a renewable energy source at the same time;

- **by utilising end chemical products**

A) carbon dioxide
B) oxidant
C) natural gas
D) biogas, etc.

Downside of technology

- High costs at present, including use of precious metals.
- Currently, hydrogen takes significant storage volume per unit of energy.
- Production and manufacturing process of the cells and the stack may not be entirely ecologically-friendly, while hydrogen fuel is ecologically friendly.
- Related to this, recycling of cells is an open research question.

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Objectives & Work packages

- Development of large-scale and hierarchical length scale cathode catalyst layer (tubular metasurface) using thermal spray coating technique (using air plasma spray) for an enhanced structurally stable SOSE cell design;
- Development of a customised SOSE cell design with a tubular electrode assembly for an integration with high temperature steam line (with higher thermo-mechanical and electro-chemical performance and long-term structural stability).

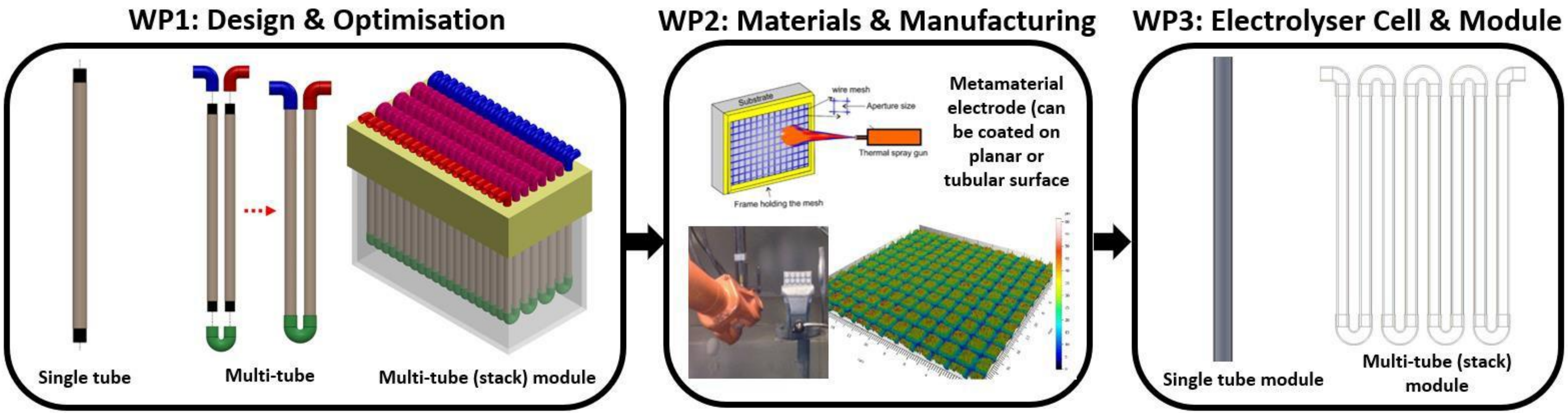
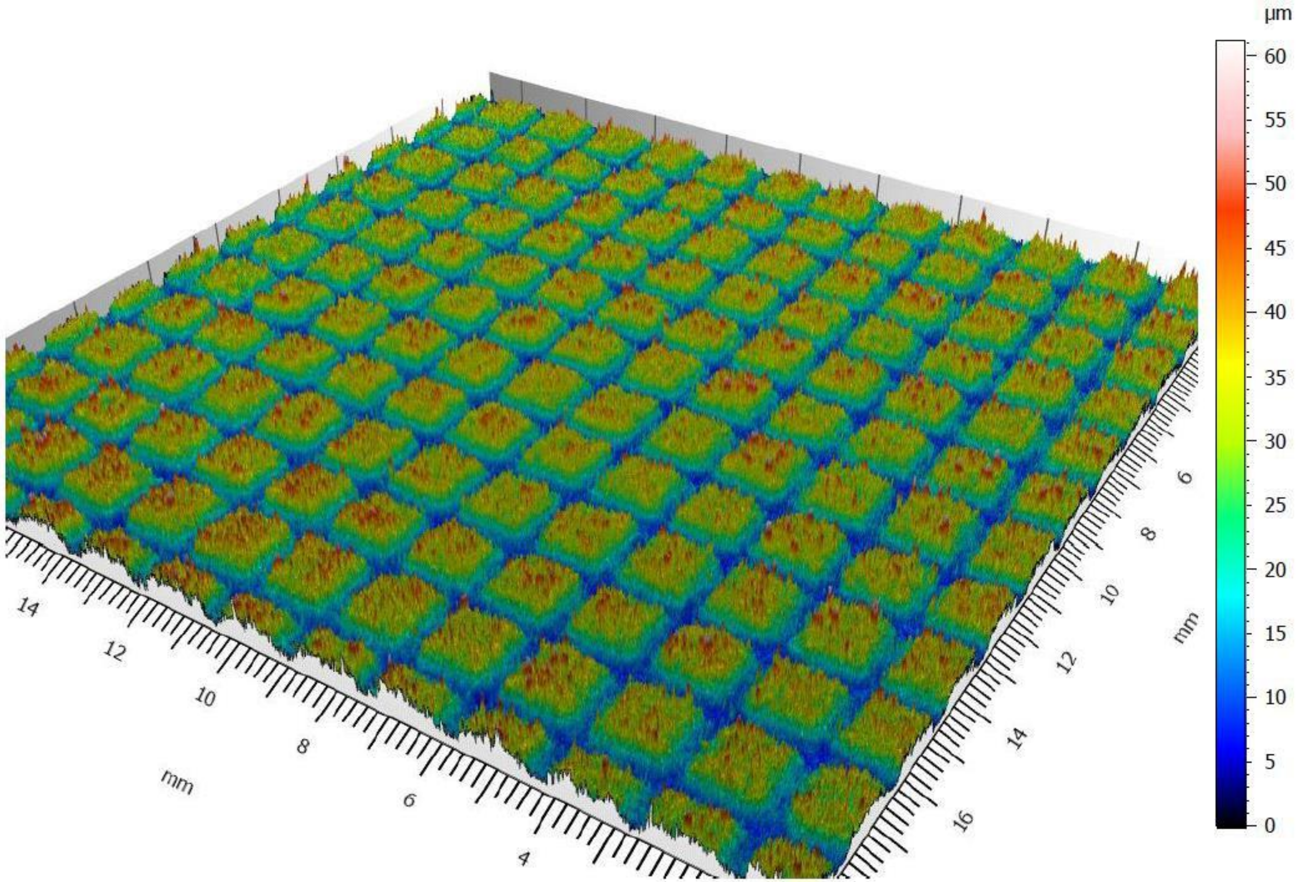


Fig. 1 METASIS methodology.

Work packages & Tasks

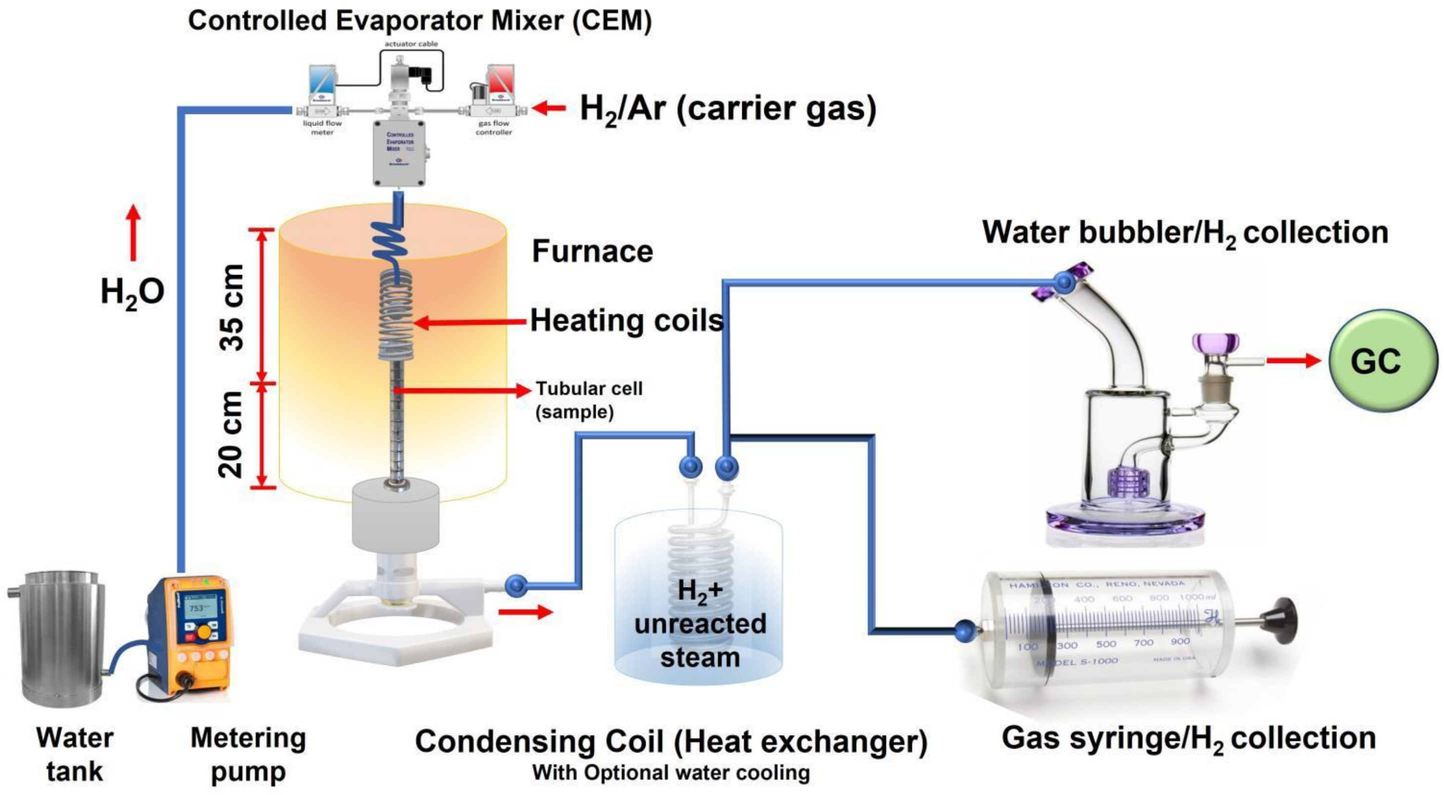
- **WP1 (Electrolyser design and optimisation)**
  - Task 1.1. Benchmarking of electrolyser
  - Task 1.2. Structural analysis
  - Task 1.3. Computational fluid dynamics
- **WP2 (Materials selection, manufacturing, and electrode cell development)**
  - Task 2.1 Materials selection and processing
  - Task 2.2. Electrode materials comparison
- **WP3 (Scaled manufacturing of electrolyser cell with metasurface design)**
  - Task 3.1. Manufacturing of tubular electrode with metasurface cathode
  - Task 3.2. Prototype testing and validation



METASIS experimental tests

Our targets

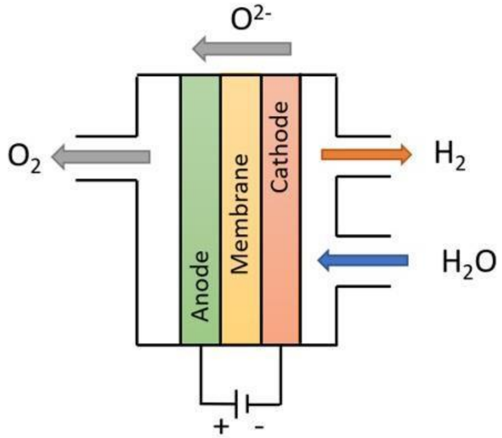
- Improving Efficiency
- Lower cost
- Durability
- Scalability & System integration



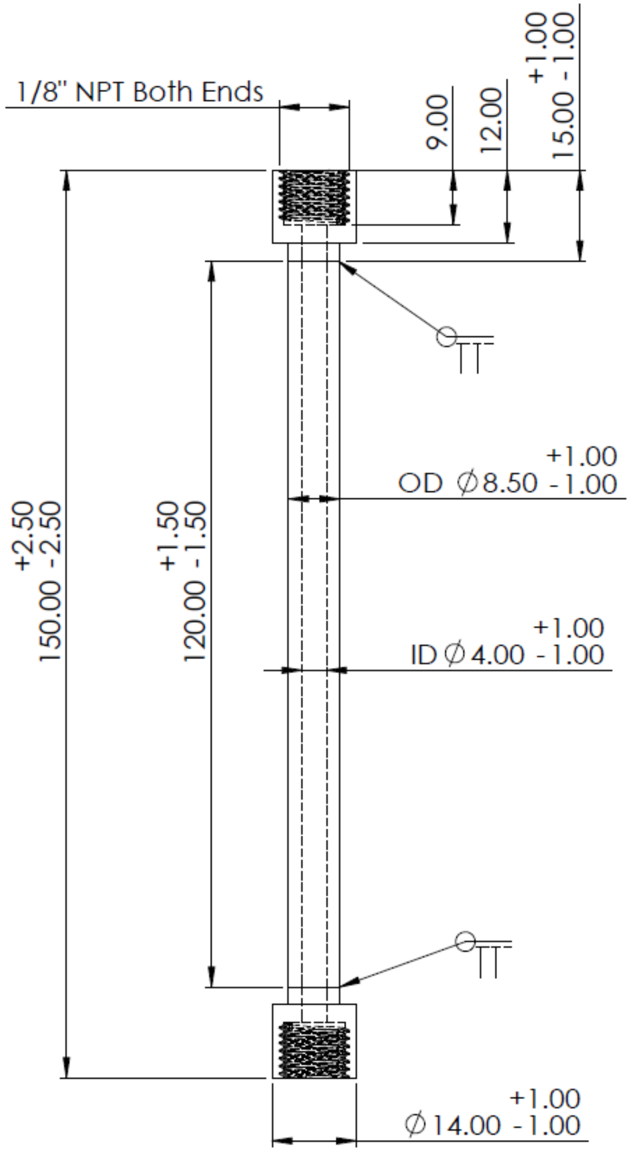
Material characterization tests to be performed in the Robert Gordon University

High temperature tests to be performed in the University of Surrey

SOSE design & optimisation stages



Stages	Objectives	Status
1. Principal structural design	• Defining principal components and geometry of the stack; • Optimisation of parts for three major use cases (assembly, tube replacement, high-temperature operation); • Price and size optimization of components; • Creating the final CAD model for production and manufacturing the laboratory prototype;	ongoing
2. Structural analysis	• Mechanical strength assessment; • Thermal deformation analysis and/or high-temperature testing;	next stage
3. Computational fluid dynamics (CFD) analysis	• Benchmarking the 3D CFD model with unresolved electrolyte with available literature for planar or tubular cells; • Electrochemical characterization and optimization of a single tubular cell; • Simulation, analysis and optimization of main flow channels (steam & air supply) for the stack; • Multiphysics analysis for a single tubular cell and for the stack.	further work



Wall thickness of supporting layer for a tubular cell

Analytical estimates for *thin-walled* structures

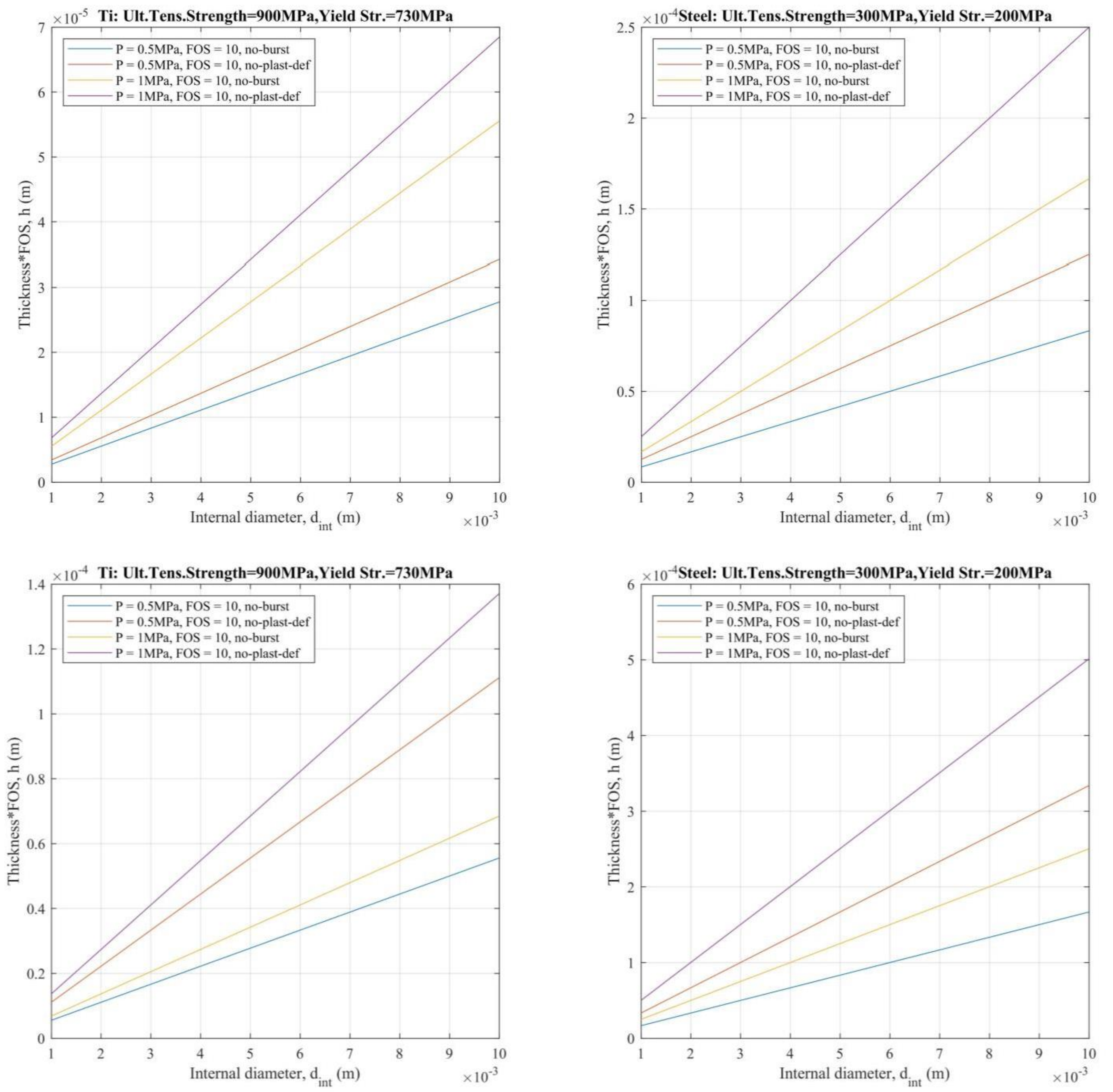
Types of analysis

FEA

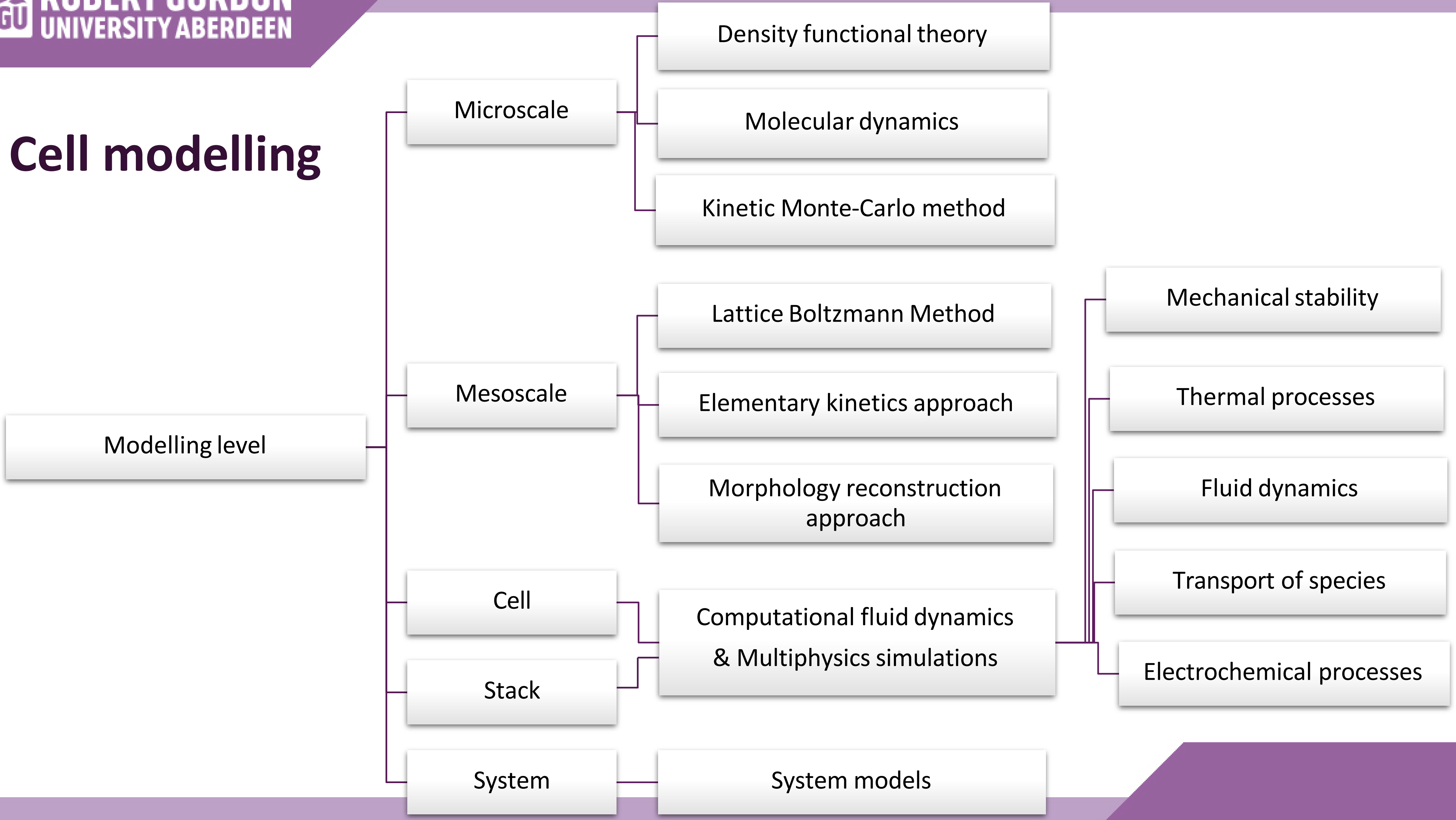
Analytical estimates for *thick-walled* structures

Factors:
- High temperature
- Safety factor
- Gas channel pressure
- Ultimate tensile strength
- Yield strength

Challenges:
Data availability for the specific material tested at the high-temperature bandwidth

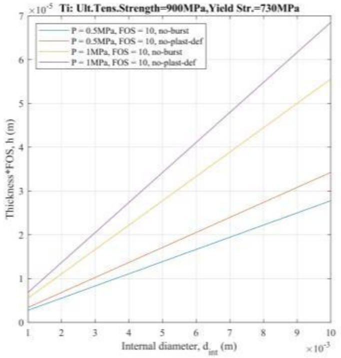


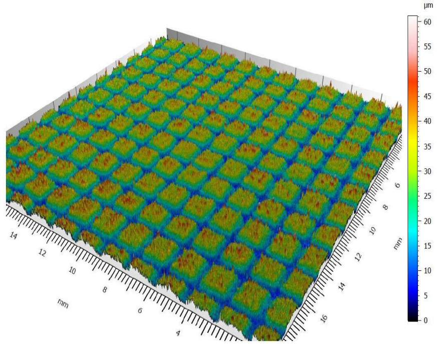
Cell modelling



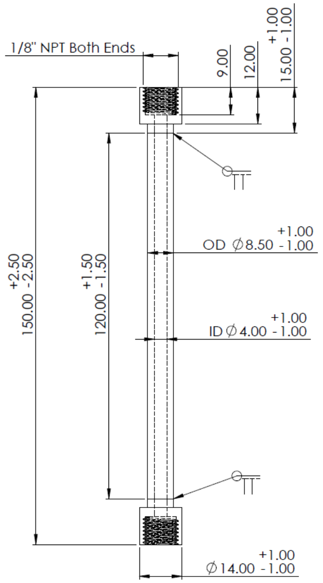
Concluding remarks

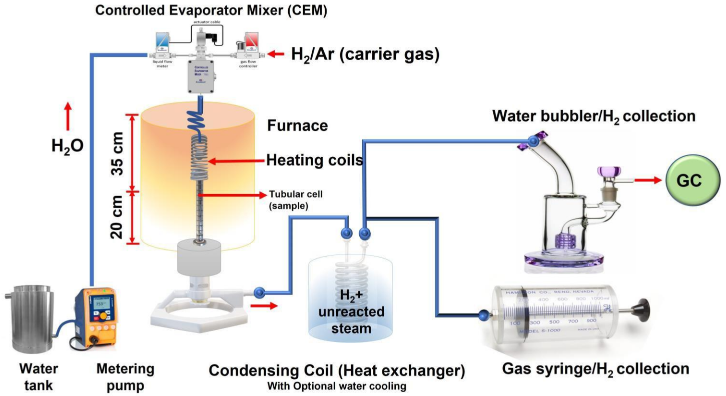
- ✓ SOEC technology is expected to be widely used for hydrogen production in 2030s.
- ✓ Materials degradation challenge at high temperature operations.
- ✓ Large scale catalysts manufacturing appears challenging.
- ✓ Supply issues with exotic & high temperature materials.
- ✓ Present study proposes the individual tubular cell and stack design for the high temperature operation.
- ✓ High temperature experimental program for the tubular cell is designed.
- ✓ Joint effect of metasurface and porosity at the cathode layer is considered to optimize the cell performance.
- ✓ Future work may include design optimization at the stack level.

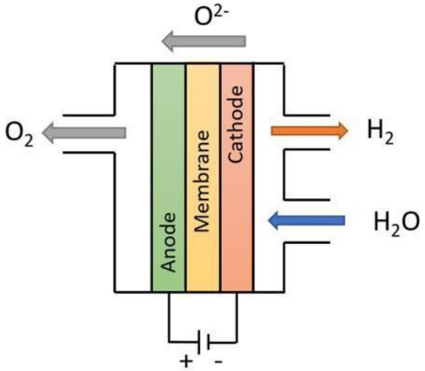

Ti: Ult.Tens.Strength=900MPa,Yield Str.=730MPa
P = 0.5MPa, FOS = 10, no-burst
P = 0.5MPa, FOS = 10, no-plast-def
P = 1MPa, FOS = 10, no-burst
P = 1MPa, FOS = 10, no-plast-def
Thickness*FOS, h (m)
Internal diameter, d_int (m)



Thank you


1/8" NPT Both Ends
OD Ø8.50 +1.00 -1.00
ID Ø4.00 +1.00 -1.00
Ø14.00 +1.00 -1.00
150.00 +2.50 -2.50
120.00 +1.50 -1.50
9.00
12.00
15.00 +1.00 -1.00


Controlled Evaporator Mixer (CEM)
H2/Ar (carrier gas)
H2O
Furnace
Heating coils
35 cm
20 cm
Tubular cell (sample)
Water bubbler/H2 collection
GC
H2+ unreacted steam
Water tank
Metering pump
Condensing Coil (Heat exchanger)
With Optional water cooling
Gas syringe/H2 collection


O2-
O2
Anode
Membrane
Cathode
H2
H2O
+
-