NATIONAL NUCLEAR LABORATORY

GAMECHANGERS
DELIVERING NUCLEAR INNOVATION

# Challenge: Technologies to scale thermochemical methods of hydrogen production

Hydrogen has the potential to play a significant role in tackling climate change and is one possible pathway to a low carbon energy future.  We are looking for innovations that could overcome the barriers to scaling commercial deployment of thermochemical methods of hydrogen production from water.

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## Summary

When partnered with a high temperature heat source, thermochemical (with purely heat input) and electro-thermochemical (where at least one process step could be electrochemically driven) hydrogen production from water has potential cost and efficiency benefits compared to hydrocarbon based or solely electrochemical hydrogen production methods (i.e. electrolysis).

The nuclear industry has been at the forefront of this pioneering technological development worldwide as the technology is compatible with the high heat output of certain reactor types that could lead to reduced cost of hydrogen. Additionally, technology associated with thermochemical cycles could be coupled to other heat sources including, for example concentrated solar systems.

However, there are currently no industrial solutions utilising this technology and both technical and commercial barriers remain. These need to be overcome to enable informed technology, investment and policy decision-making which could assist in moving the technology towards commercialisation.

We are interested in innovations that draw on any and all relevant UK and international capability including technology transfer opportunities from any relevant sector such as bulk chemical manufacture, power generation, catalysis and control / safety systems. We are interested in working with partners over the long-term to help develop solutions that could expedite demonstration of hydrogen generation at pilot scale and beyond.

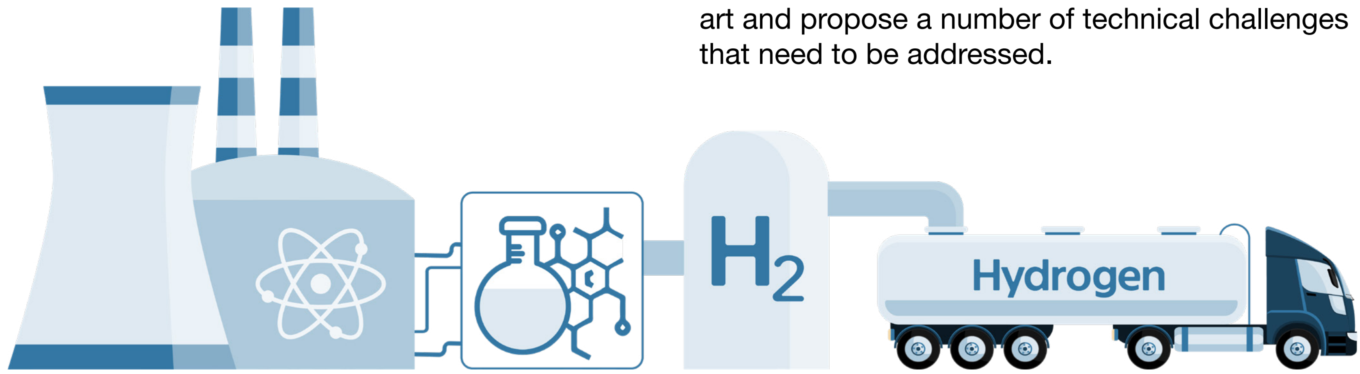
### Figure 1: Example schematic of the supply chain for hydrogen produced via a nuclear powered thermochemical process

## Introduction

Deep decarbonisation of all our energy usage is one pathway to meet our climate goals of being Net Zero by 2050. This includes pivoting industry, transportation and home heating away from burning fossil fuels as a heat source and towards cleaner energy vectors such as hydrogen. Current hydrogen production requires a methane feedstock and results in large quantities of greenhouse gas emissions; approximately 10kg of $CO^2$ per 1kg of hydrogen. Only a very small proportion of the hydrogen used today is produced using a low carbon techniques such as electrolysis. Hydrogen is synthesised mainly for the purposes of manufacturing fertiliser and for fossil fuel refining, although in the future its use could be much more widespread. For example it could be used for transportation, domestic heating and energy storage.

Thermochemical cycles use intermediate chemical and, in some cases, electrical steps and reactants in a cyclical process to liberate hydrogen from a feed of water or steam. These are typically based on autocatalytic cycles that utilise different chemical intermediates to lower the energy input required to liberate hydrogen from water. As a result of this use of chemistry and catalysts, some cycles could offer higher efficiencies than purely electro-chemical routes. Over the last few decades, a number of thermochemical processes have been theorised or investigated that operate across a range of temperatures and utilise several intermediate steps including electrolysis and scrubbing steps.

Many of these approaches have only been developed to comparatively low technology readiness levels and numerous technical challenges exist that would need to be overcome if the commercial viability and scale up of this technology is to be proven. To realise this, expertise must be brought together from across a number of industry sectors. In the following sections we will set out the current state-of-the-art and propose a number of technical challenges that need to be addressed.



## Current practice

The Department for Business, Energy and Industrial Strategy (BEIS) put forward its Hydrogen Strategy this year, which aims to develop a 5GW capacity to generate low carbon hydrogen by 2030. The strategy notes that a ramp-up will be required to meet the UK's decarbonisation goals. There is also a need for the development and deployment of both first-of-a-kind and next-of-a-kind technologies to meet this target. Analysis by the Climate Change Committee suggests 250-460TWh of hydrogen could be needed in 2050, making up 20-35 per cent of UK final energy consumption. The Hydrogen Strategy also notes the potential for production of hydrogen by thermochemical means, but considers it to be a future technology and it is not therefore used to help underpin the 2030 target.

Hydrogen production worldwide is currently centred around steam reformation of methane, with small contributions from conventional electrolysis techniques. R&D efforts are underway to decarbonise the production of hydrogen and to potentially scale up manufacture to meet the demand for a low carbon energy carrier.

There are hundreds of potential thermochemical and electro-thermochemical cycles that each rely on different chemistry and temperature input. Three cycles that have been the subject of the greatest attention include the Cu-Cl Cycle (electro-thermochemical), the S-I Cycle (thermochemical) and the HyS Cycle (electro-thermochemical) presented below.

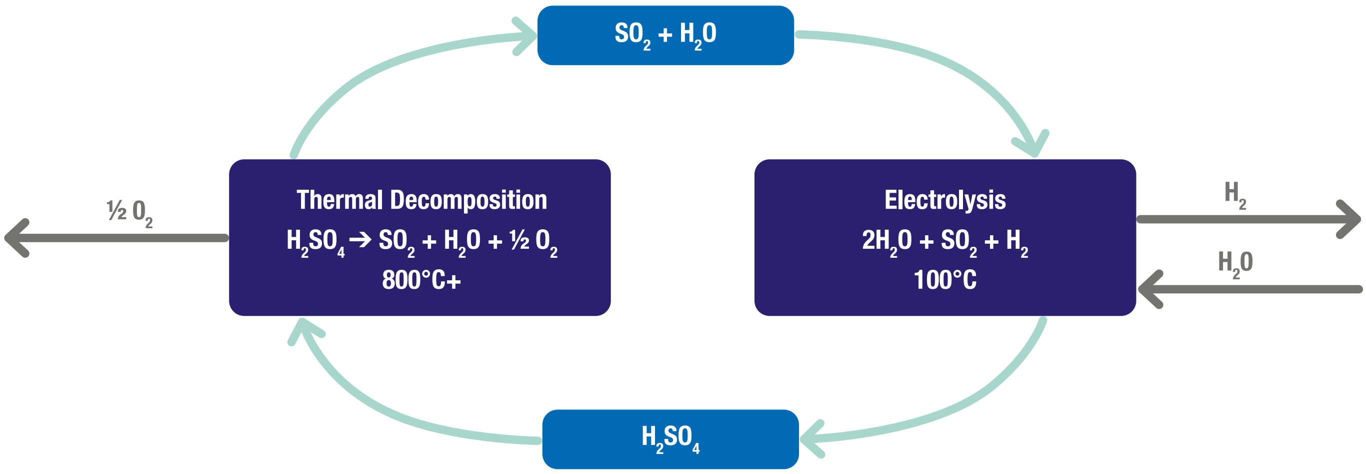



**Figure 2: The Hybrid-Sulphur (Westinghouse) Thermochemical Process**

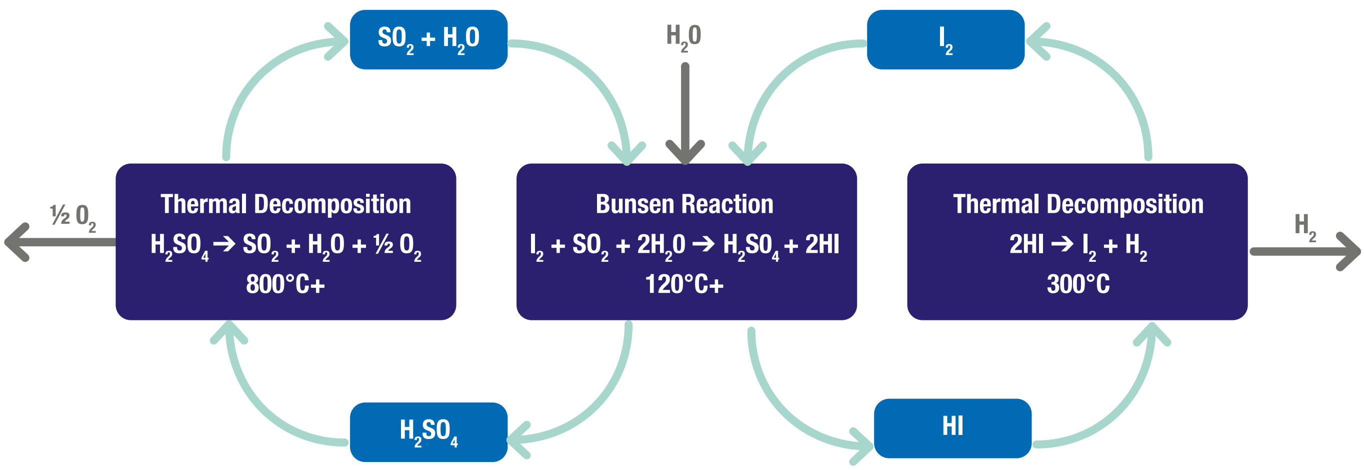



**Figure 3: the Sulphur-Iodine Thermochemical Cycle**

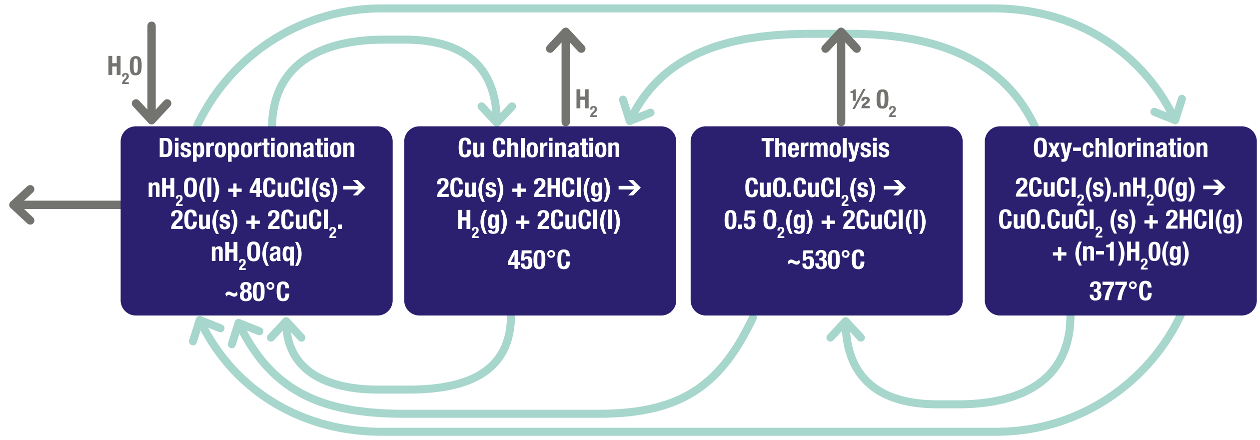



**Figure 4: The Copper-Chlorine (Four Step Variation) Thermochemical Process**

## Challenge aims

Current thermochemical hydrogen R&D utilises lab scale rigs which produce hydrogen on the scale of tens of grammes per hour and run for tens of hours. The challenge is to scale up and commercialise the current rig-scale operations to reach commercial scale with the capability to run for thousands of hours and produce hundreds of tonnes of hydrogen per day.

The pathway to a commercial solution will likely require a series of experiments and tests at increasing scale up to commercialisation. Along this path there will be a series of technical challenges including those relating to control and safety systems, materials handling, materials integrity and many others. It is understood therefore that long term programmes may be required and we encourage participants to consider the future challenges that may emerge in scaling from pilot scale to commercialisation and how long term partnership with NNL and other organisations can help de-risk and accelerate this process.

To achieve the challenge aims the following areas need to be considered:

**Improvement of the thermal efficiency of thermochemical processes for industrial scale synthesis that will typically employ catalysts**

Due to the high temperatures of thermochemical processes, extra steps or catalysts which reduce process temperature are employed. Some cycles contain some process steps which are in the very high temperature range of 600-950°C. Techniques that reduce this temperature could improve overall efficiency and increase the yield and economic viability of solutions. In addition the reduction of environmental degradation will improve the longevity of the rig.

**Mitigating or reducing the corrosion and fatigue of vessels and pipework due to environmental degradation, including the effects of thermal shock, and embrittlement from hydrogen assisted acidic attack.**

Based on previous rig tests, there are a number of mechanisms known to limit the life of thermochemical systems. Most, if not all thermochemical cycles utilise acids kept at high temperatures, which chemically attack the pipework and vessels in rigs. As reactants need to be heated up between steps there is also fatigue due to thermal shock of these vessels. Complex intermediate reactions often result in a precipitate forming as a by-product which coat chemical reactors and can ingress into pumps and valves, limiting their life. Chemical attack by this acid is often accelerated by the formation of this precipitate. As hydrogen gas is evolved in these processes a further enhanced attack can be seen from the embrittlement of metal piping due to hydrogen ingress.

**Development of modular approaches for the manufacture and maintenance of chemical test rigs and pilot scale plants operating at high temperatures and in the presence of corrosive feedstocks**

Commercial thermochemical systems could have potentially onerous maintenance schedules and the frequency of shut-downs may not match that of the nuclear systems providing the heat and electricity input. It is therefore hoped that the modular manufacture and construction and standardised design of chemical test rigs will reduce the capital expenditure for research and commercial deployment, reducing the maintenance burden and shutdown times should failures occur.

**Development of control systems for the operation of laboratory and pilot scale rigs and commercial designs.**

There are dozens of high-performance components that will need to be monitored and controlled to optimise any thermochemical cycle. Cycles can include several processes common to chemical plants including electrodialysis, control of complex chemical pathways with delicate equilibria, slurry transport and high-pressure compression of gases. Careful control of these operations is key to minimising O&M costs of any future plant.

The technology proposed via this challenge is expected to be one that can realistically be included as part of a thermochemical rig, pilot plant or commercial system. Early stage concepts covering any aspect of thermochemical systems are also welcomed.

## Benefits to the NNL Clean Energy Focus Area

Unlocking thermochemical hydrogen technology to produce hydrogen at scale could expedite the transition to a hydrogen economy, provide opportunities to widen the exploitation of high temperature nuclear reactors, provide alternative hydrogen production solutions that de-risk overall national low carbon hydrogen production targets and could offer opportunities for accelerated scale-up at reduced cost.

The National Nuclear Laboratory (NNL) is building a capability in nuclear powered hydrogen production with the aim of developing an evidence base and overcoming barriers to deployment and to support UK research and demonstration. By utilising cross-sector expertise and technology in the wider supply chain, opportunities to collaborate are likely to be found that will enable this goal to be achieved more quickly.

The milestones towards a pilot plant are as follows:

- Laboratory Scale Batch demonstration of thermochemical routes
- Rigs (likely 100 kWth – 1 MWth)
- Pilot Plant (likely 10-50MWth)
- Commercial Demonstrator
- Commercial Rigs Each Producing tonnes/$H_2$/day

We therefore welcome responses targeted at overcoming challenges at any and all stages of development and scale-up pathway to move forward thermochemical and electro-thermochemical production of hydrogen.

## Constraints

The following constraints have been identified. They should be considered as guidance and not absolute in all cases.

**Safety:** Thermochemical plants at any scale will be likely to be handling acids at high temperature and evolving hydrogen gas, so any solution presented will need to consider and mitigate these hazards if applicable during deployment.

**Operational:** Rig scale plants are expected to be working in a batch process. Near-continuous operation of pilot scale plants are expected to mature to commercialisation on a timescale such that it could couple with a high temperature nuclear reactor when they become available.

**Wastes:** Thermochemical processes generally generate a hydrogen rich stream of off-gas and an oxygen rich stream of off-gas. Depending on the cycle utilised, there can be wastes generated as a result of environmental degradation. For example for some cycles iodine gas can precipitate into and around components.

## Likely functional requirements of a future thermochemical pilot plant

There are a number of functional requirements to consider with this challenge, which relate to the production of hydrogen only.

Pilot plants of the future are envisaged as producing hydrogen:

- At a rate from round 2kg/s to 4kg/s running in a near continuous fashion.
- Using thermochemical processes which use highly corrosive acids such as hydrochloric or sulphuric acid.
- Via a range of process steps with temperatures ranging from 300 to 950°C.
- Using heat from a coupled thermal heat source, which could include heat from nuclear heated steam.
- Using key components including liquid-liquid separators and flash tanks. Process steps can include separation techniques such as hydrolysis, spray-drying, pyrolysis, electrodialysis and precipitation.

Please note the figures quoted in this section act as a guide only.

## What Next?

Game Changers are hosting a workshop for this challenge where delegates will have the opportunity to meet the challenge owners. Details are available on the Game Changers website www.gamechangers.technology

If you have new ideas or innovations which can be applied to address this challenge, we invite you to join us.

If you'd like more information about the funding available through the Game Changers programme, please visit our Funding Process (gamechangers.technology)

The deadline for applications to this challenge is **18th November 2021 at 12 noon**

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