# Nuclear Hydrogen and Fast Reactors

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**Abstract**

Hydrogen and hydrogen technology are expected to have a key role as energy carriers for technical and economic systems. These are expected to be a new impulse for the integration of nuclear into the grid. Large-scale demonstration projects of the low carbon hydrogen production require major investments by countries and long-term strategies. For the nuclear industry, long-term strategies and substantial investments are required, where both hydrogen production and nuclear power can complement each other in future development. From a technical point of view, these binders are electricity utilization via electrolysis and residual heat via thermochemical cycle or others thermochemical processes. The paper summarizes the current concerns of the hydrogen community in finding solutions based on scientific fundamentals for hydrogen production using nuclear energy.

## INTRODUCTION

The main commercial method of producing hydrogen is steam methane reforming (SMR) from hydrocarbons mixtures. Researchers are currently investigating the possibilities of large-scale production to reduce the carbon footprint of processes that use methane or fossil fuels with carbon capture - a common name for this method is “blue hydrogen”.

The electrolysis of water is also extensively developed as an alternative to steam methane reforming. With some exceptions, the electricity was primarily used for brine electrolysis in chlor-alkali industry, where hydrogen is a by-product, and the method of obtaining is often called “white hydrogen”. The most advanced electrochemical technologies to date are systems using polymer electrolytes or/and alkaline electrolytes.

The electrolysis can be performed at low temperature, when liquid water is used, or at high temperature, (between 700 oC and 800 oC), when water vapor (steam) is used. The main advantage of the high temperature electrolysis is that the dissociation of steam requires less electrical energy compared to liquid water.

The thermochemical cycle means utilization of water and residual high temperature for hydrogen production. This hydrogen pathway comprises the oxidation of a metal oxide or an oxidable compound (e.g. iodine-sulphur) by a reaction with water and, secondly, the recycling of this compound, that takes place at higher temperatures by stripping off one oxygen atom.

Thermochemical cycles and high temperature electrolysis are currently being developed for demonstration projects of large-scale hydrogen production using energy of nuclear reactors. In a more recent language, all methods, which involve obtaining hydrogen with the help of nuclear energy, are called "pink hydrogen". The newest progress referring to nuclear hydrogen are co-authored in another paper [1].

In principle, there are five general methods of obtaining hydrogen using nuclear energy and water decomposition: radiolysis, electrolysis, steam electrolysis, thermochemical and hybrid thermochemical splitting of water. The first method uses nuclear radiation to directly split the water molecule to hydrogen and oxygen. The second is a classical method that uses electricity for water electrolysis. The third means the electrochemical decomposition of water vapour. The last ones directly use high temperature heat and regenerative chemicals to divide the water with or without electricity.

## NUCLEAR HYDROGEN and fast-neutron reactors

Nuclear hydrogen production can be made through low temperature electrolysis, high-temperature electrolysis, thermochemical (thermochemical cycles are included here), and any other hybrid processes. The scope of this paper is to make a current review on the fast neutron reactors under development and see how appropriate they are and what methods can be used to obtain hydrogen.

The fast-neutron reactors are a category of nuclear reactors in which the fission chain reaction is sustained by fast neutrons with the energy above 1 MeV.

### Under construction and in design fast reactors

The main types of fast reactors that are under construction or in design are described in the next paragraphs. The fast reactors are widely regarded as an essential development due to several advantages: quantity of the neutron production, fine balance between the production and removal of neutrons from fission, operating pressure in the reactor, no pressure vessel with associated problems, electric generating efficiency and breeding new fuel. Fast reactors are capable of destroying the longest-lived nuclear waste, transforming it into waste that decays to harmlessness in centuries rather than hundreds of millennia. Reactors can employ metallic fuel, generate a lot of heat in a small space, etc.

The fast reactors are liquid metal cooled and gas cooled. The liquid metals used in fast reactors typically need good heat transfer characteristics. The liquid metal coolants used in fast reactors are the following: sodium and its eutectic sodium-potassium alloy (NaK), mercury (this metal is not expected to be used in future reactors), lead with bismuth and lead-bismuth eutectic alloy (LBE), and tin. The gas used as coolant in fast reactors can be of many different types, including carbon dioxide or helium. The lead-cooled fast reactors are symbolised LFR, those who use sodium are noted NFR and gas-cooled fast reactors are typed GFR.

This study focuses only on the fast reactors under construction or in development. At this time, 25 types of fast reactors are known which are listed in Table 1. Those decommissioned, active, under repair or never operated are not mentioned [2].

The most studied and built fast reactor type is the sodium-cooled one, but the lead-cooled fast reactor also has advantages and piqued the interest of the scientific community.

TABLE 1. FAST-NEUTRON REACTORS

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Acronym** | **Name** | **Coolant** | **Type** | **System Temperature** |
| 1 | ALFRED | Advanced Lead Fast Reactor European Demonstrator | Lead | LFR | 400-480 oC |
| 2 | ALLEGRO | ALLEGRO | Helium | GFR | 530 oC |
| 3 | ASTRID | Advanced Sodium Technological Reactor for Industrial Demonstration | Sodium | SFR | 475 oC |
| 4 | BN-1200 | BN-1200 | Sodium | SFR | 410 oC |
| 5 | BREST-OD-300 | BREST-OD-300 | Lead | LFR | 420-540 oC |
| 6 | CFR-600 | China Fast Reactor 600 | Sodium | SFR | 380-550 oC |
| 7 | CLEAR-I | China LEAd-based Research Reactor | LBE | LFR | 260-390 oC |
| 8 | ELECTRA | European Lead Cooled Training Reactor | Lead | LFR | 400-500 oC |
| 9 | ELFR | European Lead Fast Reactor | Lead | LFR | 400-480 oC |
| 10 | EM2 | Energy Multiplier Module | Helium | GFR | 550-850 oC |
| 11 | FBR-1 & 2 | Fast Breeder Reactors 1 & 2 | Sodium | SFR | 397-547 oC |
| 12 | G4M | Gen4 Module | LBE | LFR | 500 oC |
| 13 | JSFR | Japan Sodium-cooled Fast Reactor | Sodium | SFR | 550 oC |
| 14 | KAMADO FBR | KAMADO FBR | Carbon Dioxide | GFR | 200-400 oC |
| 15 | LFR-AS-200 | Lead-cooled Fast Reactor Amphora-Shaped 200 | Lead | LFR | 420-530 oC |
| 16 | MBIR | Multipurpose fast-neutron research reactor | Sodium | SFR | 330-512 oC |
| 17 | MSFR | Molten Salt Fast Reactors | Molten Salt | MSR | 750 oC |
| 18 | MYRRHA | Multi-purpose hYbrid Research Reactor for High-tech Applications | LBE | LFR | 270-410 oC |
| 19 | PEACER | Proliferation-resistant Environment-friendly Accident-tolerant Continuable and Economical Reactor | LBE | LFR | 300-400 oC |
| 20 | PGSFR | Prototype Gen-IV Sodium-cooled Fast Reactor | Sodium | SFR | 390-545 oC |
| 21 | PRISM | Power Reactor Innovative Small Reactor | Sodium | SFR | 485 oC |
| 22 | SEALER | Swedish Advanced Lead Reactor | Lead | LFR | 420-550 oC |
| 23 | SVBR-100 | SVBR-100 | LBE | LFR | 490 oC |
| 24 | TWR-P | Travelling Wave Reactor-Prototype | Sodium | SFR | 360-500 oC |
| 25 | W-LFR | Westinghouse Lead-cooled Fast Reactor | Lead | LFR | 390-650 oC |

As can be seen from the table above, most reactors operate at temperatures between 400 oC and 500 oC. The vast majority do not exceed 550 and only two stand out with slightly higher temperatures (750 oC and 850 oC). This phenomenon is a limiting factor in the use of the vast majority of thermochemical cycles or high temperature electrolysis. As a punctual remark, the Gas Turbine High Temperature Reactors can work at higher temperatures, 950 oC.

**2.2. Hydrogen production methods**

It should also be noted that the clean hydrogen is not incompatible with the production and delivery of nuclear-produced hydrogen in both short and medium terms. The nuclear hydrogen is covered by the ‘low-carbon hydrogen” definition, but the business case to invest must be associated with the electrolyser capacity, as well as the longer-term associated infrastructure for storage and transportation associated, and with labour force development. Together with these above, the decision to invest in nuclear hydrogen is clearly weakened by long-term energy strategies aim of entirely renewable-based production.

Low-carbon hydrogen generation technologies, such as nuclear power, need to be stimulated in the short term by production and demand, and, in the long term, by the advantages of their inclusion in policy-making. Today’s commercial nuclear hydrogen production option is low-temperature electrolysis. The economics are primarily dependent upon the cost of electricity; thus, the incentive to use lower-cost off-peak electricity for hydrogen production. Economics are grid specific. Other methods that are under research or demonstration are: steam electrolysis or high temperature electrolysis, thermochemical cycles, nuclear steam reforming, nuclear coal gasification or radiolysis of water, which are listed in Table 2 and illustrated in Fig. 1.

The low-temperature electrolysis and chemical reforming are well known, so we will not detail them. The steam reforming of hydrocarbons, including both fossil fuels and biomass, usually requires temperatures over 800°C. The high temperature electrolysis involves electrochemical splitting of steam into hydrogen and oxygen at high temperatures at the range of 800 – 1000 oC. The primary advantage is the efficiency, the process is more favourable from the thermodynamic point of view for electrolysis. In fact, the steam electrolyses works as reversible solid oxide fuel cell.

At the moment, the research and development of thermochemical cycles are at a laboratory and pilot level. There were reported more than 200 thermochemical cycles. Eight cycles have practical potential for the industry: sulphur-iodine (S-I), copper-chlorine (Cu-Cl), cerium-chloride (Ce-Cl), iron-chlorine (Fe-Cl), magnesium-chlorine (Mg-Cl), vanadium-chloride (V-Cl), copper sulphate chlorine-based hybrid cycles. Estimates made for these thermos-cycles are based on studies and experimental tests, demonstration trials and a series of feasibility analyses. The “coldest” are magnesium-chlorine and copper-chlorine thermos-cycle -the maximum temperature does not exceed 450-550 oC and the most studied is sulphur-iodine, where the highest temperature is between 800 oC and 900 oC.

TABLE 1. HYDROGEN PRODUCTION METHODS

|  |  |  |
| --- | --- | --- |
|  | Hydrogen production method | Temperature |
| 1. | Hydrocarbons/methane steam reforming | 700 °C -1 000 °C |
| 2. | Low temperature water electrolysis | <100 °C |
| 3. | Steam Electrolysis | 750 °C - 950 °C |
| 5 | Thermochemical Cycles | 450 °C - 900 °C |



*FIG. 1. Routes for nuclear assisted hydrogen production (adapted from [3]).*

As can be seen from the above and in both the table and the figure, the main methods of obtaining hydrogen require temperatures higher than 450 °C, with the exception of water electrolysis. We could consider lower temperatures at intermediate stages of biomass processing or obtaining bio-hydrogen. It should be noted that the thermochemical cycles are not too low, the vast majority are close to 1000 °C, with the exception of Cu-Cl, Mg-Cl and a few more [4].

An updated review about thermochemical cycles, especially about those with low temperatures (Cu-Cl, 550 °C, and Mg-Cl, 450 °C) was realized by El-Emam et al [5].

## Discussions

The utilisation of energy from nuclear reactors in order to produce hydrogen are of interest from both the use of electricity and residual or waste heat. If the utilization of electricity does not require special conditions or new technologies, heat utilization becomes the challenge. This is why the main research and challenges are moving towards nuclear processes to obtain hydrogen at high temperatures. There are two promising methods: Steam Electrolysis and Thermochemical Cycles, both requiring very high temperatures. From the above mentioned, it can be seen that in principle these values are around 900 °C and can approach 1000 °C. The exception is the Cu-Cl cycle and a few others, where temperatures are around 550 °C.

Gas Turbine High Temperature Reactors can work at higher temperatures, 950 oC, but fast reactors rarely have temperatures of more than 550 °C. Only the Energy Multiplier Module (EM2), a helium-cooled neutron-fast reactor, has the core outlet temperature of 850 oC. The reactor is designed by General Atomics (GA) as a modular, grid-capable power source with a net unit output of 265 MW(e). The commercial operation is scheduled for 2032, after a series of intermediate milestones [2].

This type of reactor is suitable for both steam electrolysis and thermochemical cycles. The sulphur-iodine (S-I) thermochemical cycle is the most advanced from the aforementioned series. The core inlet temperature is also high, 550oC, and this value makes it usable for the copper-chlorine (Cu-Cl) thermochemical cycle. The high temperature of this type of fast reactor makes it the most suitable of the 25 listed, but it must be noted that the available temperature as process heat source is not mentioned.

A second type of fast reactor that has good potential is Molten Salt Fast Reactors (MSFR). It operated at a max fuel salt temperature of 750 °C [2]. This temperature is suitable for a small number of thermochemical cycles and for steam electrolysis, but it is not clear if the fuel salt melting of 565 °C will be a precondition for inlet temperature, and this temperature can be used in the thermal conversion circuit.

Another type of reactor that has potential for high temperature nuclear hydrogen production is Westinghouse Lead Fast Reactor. Its maximum outlet coolant temperature is 650 oC, and the available temperature as process heat source is 630 oC [2]. This temperature makes it usable for the copper-chlorine (Cu-Cl) thermochemical cycle.

There are also eight reactors (ALLEGRO, BREST-OD-300, CFR-600, JSFR, LFR-AS-200, MBIR, PGSFR, and SEALER) that significantly exceed the temperature of 500 °C and reach 550 °C. These are certainly suitable for the Cu-Cl and Mg-Cl thermochemical cycles or other cycles with lower temperatures.

Another category, five reactors, is significantly close, but does not reach 500 °C: ALFRED, ASTRID, ELFR, PRISM, and SVBR-100. In certain circumstances, where some progress is being made and the minimum temperatures at which the above-mentioned thermochemical cycles have unequivocally set working conditions, they have the potential to be used in this field.

What has been discussed for fast reactors is that high temperature electrolysis and most thermochemical cycles are not an option for hydrogen production. The fast reactors must be oriented towards the coupling with hydrogen production by water electrolysis and hybrid Cu-Cl thermos cycles. The coupling with water electrolysis must be seriously analysed because many types of fast reactors have smaller electrical power compared with classical nuclear reactors.

Given the increasing imbalance between supply and demand and the growing contribution of the presence of renewables to this phenomenon, this option must also be considered.

The development efforts of the ALFRED (Advanced Lead Fast Reactor European Demonstrator) system in Romania are recommended to be associated with the production of hydrogen by electrolysis [6]. The Advanced Lead Fast Reactor European Demonstrator (ALFRED) conceptual design has been carried out in the frame of the EU FP7 LEADER (Lead-cooled European Advanced Demonstration Reactor) Project. ALFRED is a 300 MWth pool system developed to demonstrate the viability of the European LFR (ELFR) technology for use in the future commercial power plant [2]. The superheated steam temperature is 450 °C, this means that this system is not good for either stem electrolysis or thermochemical cycles. The only option is the classic electrolysis and the installed power is one that would allow an easy management of the electricity for both power and electrolysis.

While there is considerable interest in the use of thermal energy from high temperature thermal-neutron reactor designs to produce hydrogen in the future, for fast-neutron reactor the focus shall be on the production of hydrogen via electrolysis using electricity. As a result, the nuclear community should adopt positions and made voluntary efforts to explain exactly what means technology neutral and low emission because the lifecycle emissions from nuclear are similar with other renewable, e.g. wind power or less, e.g. PV panels [7, 8].

This review of hydrogen production methods and fast reactors operating conditions may be discouraging, but it should be understood that both issues are a long-term approach. On the long term the hydrogen knowledge will evolve as well and the heat utilization in production process will be studied more and more in order to reach the most useful result. The thermochemistry will be a new field of research for many scientists, especially in the field of nuclear hydrogen. For example, a modified Hybrid Sulfur Cycle (HyS) has been introduced in Japan, to decrease the maximum temperature range to 500-700 oC [9]. This type of thermochemical cycle is sustainable for majority of above-mentioned fast reactors.

The nuclear energy sector offers a new potential for the large-scale production of low-carbon hydrogen. The production of low-carbon hydrogen represents a possible new mission for nuclear reactors that is potentially larger than the current emission-free electrical production.

## Conclusions

The fast-neutron nuclear reactors is usable for low-carbon hydrogen production, and this technology can contribute to the reduction of CO2 emissions. Due to the installed capacity, much smaller than conventional reactors, the fast reactors are easier to integrate into the current energy systems characterized by large discrepancies between the demand and supply of electricity, the imbalance caused also by the growing share of renewables. The most suitable method for hydrogen production using fast reactors is water electrolysis at low temperatures. Other promising methods for nuclear hydrogen, such as steam electrolysis and thermochemical cycles are suitable for the majority of actual developing fast reactors, the exceptions are the few that operate at temperatures above 500-550 oC.

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