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A Review and Analysis of Nuclear Hydrogen Production in Generation IV Reactors

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Abstract
Hydrogen is becoming increasingly vital as a chemical element in the progress of human civilization. Hydrogen finds application in the creation of ammonia, the manufacturing of nitrogen-based fertilizers, and a wide range of organic compounds, including methanol and propulsion fuel for space exploration missions. Additionally, there are ongoing experiments in the automotive industry to harness hydrogen-based fuel cells as an alternative power source. In modern technology, multiple methods and strategies for hydrogen production originate from diverse sources, such as fossil fuels, renewable energy, nuclear energy, and more. Generation IV nuclear reactors significantly affect the production of hydrogen. These reactors operate at elevated temperatures, and at these temperatures, heat transfer processes are more efficient for producing significant quantities of hydrogen. Within the realm of hydrogen production, both thermochemical and electrolysis (hybrid) techniques offer promising potential, particularly when integrated with Generation IV nuclear power reactors. This study undertakes a comparative analysis of various nuclear Generation IV reactor types concerning their capacity for substantial hydrogen production techniques while also exploring potential adaptations.

Keywords: Hydrogen, Generation IV Reactor, Electrolysis, Sulphur-Iodine, Steam Reforming, GFR, VHTR

I. Introduction
The use of hydrogen is anticipated to grow in the future, encompassing its role as an energy carrier, a key ingredient in producing fertilizers, and a part of refining crude oil.

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Global hydrogen consumption reached approximately 95 million metric tons in 2022 [1]. The vast majority of hydrogen is sourced from fossil fuels such as methane, naphtha, or coal, leading to large greenhouse gas emissions. Alternative techniques for manufacturing hydrogen with reduced CO_2 emissions, such as solar, wind, or nuclear power, are currently being studied. High-temperature nuclear reactors provide a feasible solution for large-scale hydrogen production with a lower carbon footprint. There are three key areas where hydrogen is used today and is projected to be used in the future. First is ammonia production; about 60% of hydrogen was used to make ammonia in 2022 [2]. The yearly increase in ammonia output between 2021 and 2022 was 0.4%, an increase that is believed to continue in the immediate future [2]. Second is the refining of crude oil. Hydrogen is used in massive quantities to upgrade and purify fossil fuels; however, some hydrogen is created within the refinery as a by-product of catalytic cracking. The usage of lower-grade crude oils, such as sand oil, with a higher number of pollutants such as sulfur and nitrogen, is predicted to increase in the future, resulting in an increased need for hydrogen. Third is hydrogen as an energy carrier; hydrogen gas works as an electrical energy transport mechanism and must be created from some form of fundamental energy. With only water as a by-product, hydrogen can be used to propel cars in internal combustion engines, fuel cells, or jet engines in airplanes. The use of hydrogen in automobiles has risen significantly by 45% in 2022 compared with 2021 [2]. The potential market for hydrogen as an energy carrier is immense [1,2].

Generation IV reactors can be the greatest contributors to hydrogen production. Generation IV reactors are operated at high temperatures of approximately >500 °C. Under these elevated temperatures, hydrogen, as well as electricity, is produced efficiently **[*3*]**. This study undertakes a comparative analysis of various nuclear Generation IV reactor types concerning their capacity for substantial hydrogen production techniques while also exploring potential adaptations.

This paper provides an overview of the hydrogen cogeneration process in Generation IV nuclear reactors, specifically focusing on the higher coolant outlet temperature compared with Generation III reactors. The paper also offers a comprehensive review of different Generation IV nuclear reactor types in terms of their ability to generate significant amounts of hydrogen and investigates potential modifications that can be made. One additional objective of the study was to determine the hydrogen generation efficiency in the Generation IV reactor.

II. Related Works

In the publication "Hydrogen Production by Nuclear Heat," authors Leanne M. Crosbie and Dr. Douglas Chapin introduced a highly cost-effective method for hydrogen production. Their research examines three methods for hydrogen production, which include steam methane reforming, the sulfur–iodine (S–I) thermochemical water-splitting cycle, and advanced electrolysis of water. During electrolysis, the application of electricity results in the separation of water molecules, leading to the production of hydrogen. In the steam reforming process, hydrogen is generated by the high-temperature reaction between steam and water. In the S–I thermochemical water-splitting cycle, nuclear heat is harnessed to break down H_2SO_4, where H_2O, SO_2, and I_2

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combine to yield H_2SO_4. Subsequently, HI undergoes dissociation to produce hydrogen, with the noteworthy aspect that the S–I cycle results in no CO_2 emissions. Although steam reforming is the more cost-effective option, both processes carry an inherent developmental risk [4].

The cost efficiency of producing hydrogen using the coolant in a high-temperature gas-cooled reactor (HTGR) is made possible by the elevated temperature of the coolant. In the report produced by the Japan Atomic Energy Agency (JAEA) titled *Future Plan on Environmentally Friendly Hydrogen Production by Nuclear Energy*, by Shusaku Shiozawa et al., it was disclosed that the high-temperature gas reactor (HTGR) is a requirement for Japan's future of fuel-cell vehicles and for establishing an HTGR hydrogen cycle that is integrated with a fast breeder reactor. This report also emphasizes their efforts in hydrogen generation through nuclear heat from the HTGR (JAEA). The advancement of nuclear technology and hydrogen production through nuclear heat was catalyzed by the Generation IV International Forum (GIF). The GIF introduced six reactors: the gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), very high-temperature reactor (VHTR), molten salt–cooled fast reactor (MSFR), supercritical water-cooled reactor (SCWR), and sodium-cooled fast reactor (SFR). These six reactors were chosen because of their safety, sanitation, and sustainability. Among these reactors, the current configurations of the SCWR and SFR are incapable of producing hydrogen because of the low temperature of the coolant [5].

In 2000, the High-Temperature Gas-Cooled Reactor Test Module (HTR-10) was constructed; HTR-10 now operates in China. Helium gas serves as a coolant. The He gas transmits its thermal energy to water in a secondary heat exchanger, resulting in the formation of high-pressure steam. Then, this steam is used to power a traditional steam turbine, which then produces electricity. The objective of the project, known as the HTR-10GT project, was to connect a direct He turbine cycle to the existing HTR-10 reactor through research and development. This project employs a direct gas turbine cycle to transform nuclear energy into electrical energy. A portion of the reactor's 10 MW of power is used to manufacture hydrogen when it is connected to a facility that makes the H_2 gas. Previous research and development projects have suggested that hydrogen could be produced using nuclear heat from HTGRs [6].

III. Methodology

Per the self-evaluation recommendations of the International Atomic Energy Agency (IAEA), there are four methods for collecting data and information concerning the application of nuclear security:

- surveys,
- interviews,
- document reviews,
- observations, and
- other methods.

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Regarding the sequence of the methods, no clear guidelines are provided by the IAEA. To obtain quantitative data, surveys will serve as predominant means of collecting information. In this section, we will examine the six Generation IV technologies—VHTR, SFR, SCWR, GFR, LFR, and MSFR.

The VHTR is the only concept among the six Generation IV technologies described by GIF that can produce hydrogen with great efficiency. Moreover, a study is required to assess the feasibility of hydrogen production. To maintain a separation between the nuclear island and production facilities, it is essential to install coolant gas pipes, valves, and heat exchangers. In this paper, we will evaluate the efficiency of the VHTR and the calculation of hydrogen production using the S–I process.

Formulas for the efficiency calculation of VHTR are as follows. For thermal efficiency,

$$\eta = 1 - r_{\mathrm{p}}^{\frac{1-k}{k}}, \tag{1}$$

where the pressure ratio r_{p} is defined as

$$r_{\mathrm{p}} = \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}}. \tag{2}$$

For maximum net-work output,

$$T_2 = \sqrt{T_1 T_3}. \tag{3}$$

The thermal efficiency of an S–I process is calculated as follows [7]:

$$\frac{H_2\ generation\ rate\ \times HHV(H_2)}{Net\ heat\ used + \left(\frac{Net\ electricity\ consumed}{Power\ production\ efficiency}\right)}, \tag{4}$$

where $HHV(H_2)$ is the higher heating value of H_2.

IV. Hydrogen Production in Nuclear Power

The swift performance of nuclear energy allows it to generate zero carbon or hydrogen. Nuclear-based technologies used in hydrogen production have gained remarkable traction in producing hydrogen economically and environmentally. Some of these technologies are the advanced electrolysis of water, the S–I thermochemical water-splitting cycle, and steam reforming of methane. All of the technologies listed use nuclear heat to produce hydrogen.

The process of electrolysis involves electrical energy to separate water into hydrogen and oxygen. This process of hydrogen production can be combined with highly effective

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nuclear power plants [8]. The half-reactions of water ions are the basic reactions that allow electrolysis to occur. The reactions are the following [4]:

$$2H_3O^+ + 2e^- \rightarrow H_2 + 2H_2O \text{ [cathode]}$$
$$3H_2O \rightarrow 12O_2 + 2H_2O^+ + 2e^- \text{ [anode]}$$
$$H_2O \rightarrow H_2 + {}^1/_2\, O_2$$

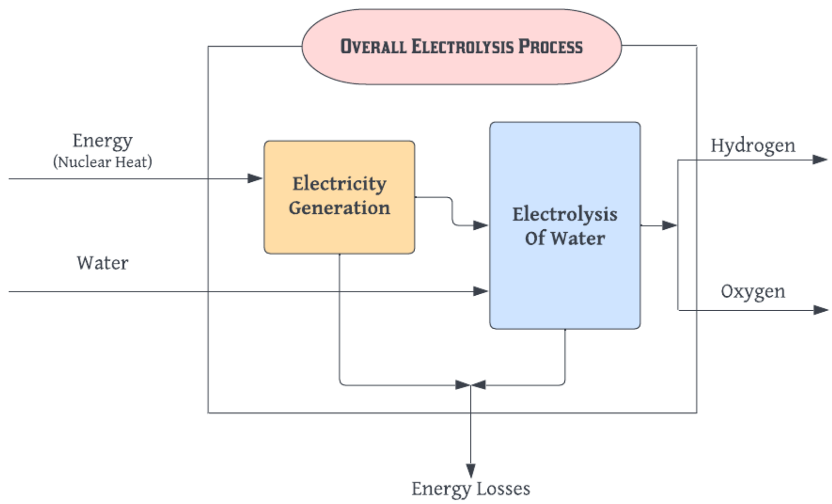

Figure 1. Electrolysis process diagram.

A minimum of 120 MJ/kg of heat or electrical energy is needed to create 1 kg of H_2. To create 1 kg of H_2, less electrical energy is needed when the heat energy is higher. Generation IV reactors are operated at >500 °C, so less electrical energy is needed. Hydrogen generation and electrical efficiency gains are both enhanced by higher operating temperatures. The primary issue with this process is the high levels of energy loss when converting nuclear energy to electricity. As a result, thermodynamic efficiency for electrolysis ranges from 30% to 35% [3].

Thermochemical water splitting uses elevated temperatures to break down water into oxygen and hydrogen via a series of catalytic chemical reactions. A thermochemical cycle that splits water is called the S–I procedure; comprising three chemical processes, it induces the dissociation of water [4]. The reactions for this cycle are the following:

$$H_2SO_4 \rightarrow H_2O + SO_2 + {}^1/_2\, O_2 \text{ (850 °C minimum)}$$
$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \text{ (120 °C minimum)}$$
$$2HI \rightarrow H_2 + I_2 \text{ (450 °C minimum)}$$
$$H_2O \rightarrow H_2 + {}^1/_2\, O_2$$

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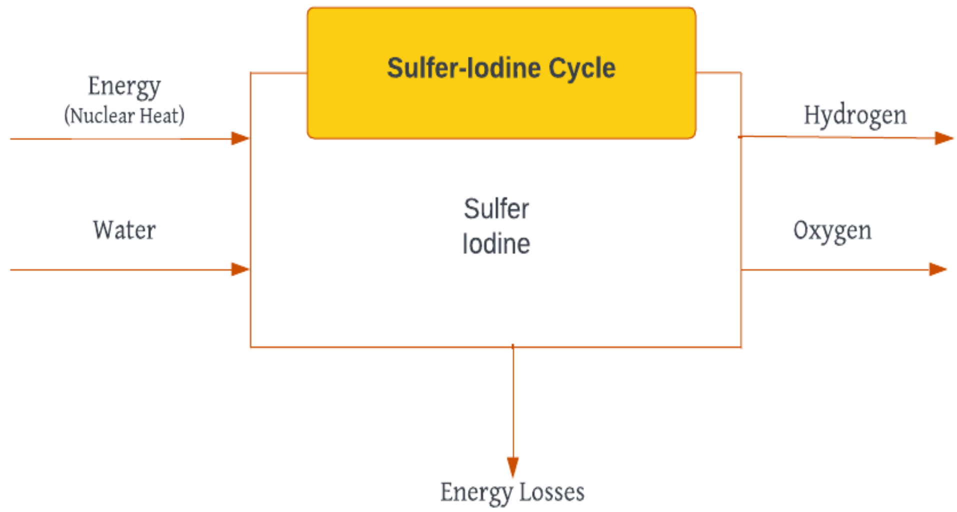

Figure 2. S–I process diagram.

One or more endothermic, high-temperature chemical processes are used to introduce heat energy into a thermochemical cycle. Exothermic, low-temperature processes reject heat. Except for water, all of the reactants are renewed and recycled. The disintegration of H_2SO_4 consumes most of the input heat in the S–I cycle. In this cycle, hydrogen is produced in the weakly exothermic breakdown of HI. The temperature range of this cycle is from low (<300 °C) to high (<950 °C) [3], and at these temperatures, H_2 is produced. Generation III and IV reactors can generate these temperatures. Generation IV reactors can provide not only electricity but also the heat required for elevated temperature processes in hybrid thermochemical cycles [3].

In hydrocarbon processing industries, the most widely used hydrogen production technology is steam reforming of methane. In this process, methane reacts with steam at high temperatures.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CO + H_2O \rightarrow CO_2 + H_2$$

In this process, two reactions occur. The first reaction is extremely endothermic and happens at elevated temperatures with a catalyst. In the second reaction, CO_2 is produced. In a subsequent separation procedure, CO_2 is eliminated, and hydrogen is filtered.

A very high temperature (700–1000 °C) is required in the steam reforming process [9]. A helium-cooled nuclear reactor can attain the temperatures required in a steam reforming reaction. The reactant loss can be prevented by employing a nuclear reactor. In the steam reforming process, the nuclear heat system provides heat via a secondary loop to the CH_4/H_2O (steam) combination [4].

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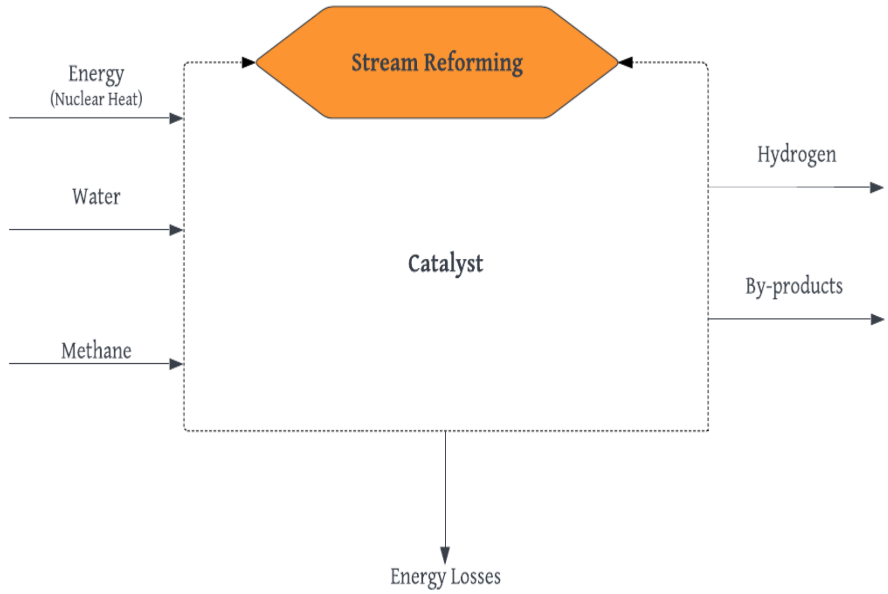

Figure 3. Flow diagram of a hydrogen production system.

V. Generation IV Reactors for the Production of Hydrogen

The limitation on the temperatures of the moderator and coolant decreases the energy efficiency of a conventional reactor. Because of heat losses and environmental discharge, nearly two-thirds of nuclear energy will be lost. The coolant temperature of the reactor must be increased to make greater use of the nuclear fuel sources. Within the context of the Generation IV initiative, six different kinds of reactors are being researched and created for improved energy efficiency. Table 1 at the end of this section provides a summary of all six reactors.

a. Gas-Cooled Fast Reactor

The foundation of the GFR is a closed fuel process with a fast-spectrum reactor cooled by helium at an elevated temperature. When a fast neutron spectrum is combined with fully recycled actinide in GFR systems, it provides the advantage of low radioactive waste creation. The prismatic blocks create the active core. One possible fuel design is a composite ceramic, which means the fuel is ceramic fuel with tightly packed, covered (uranium, plutonium) carbon kernels or ceramic-clad, or fiber, solid-solution metal fuels. The current standard fuel design consists of a ceramic plate mixture with just a hexagonal internal structure that contains tiny fuel cylinders. Because of the need for a high density of heavy nuclei in the fuel, actinide carbides (mixed Pu–U carbides) and actinide nitrides are used as the reference fuel. Silicon carbide is used in the matrix [10].

GFRs operate at approximately 850 °C [3]. By using the high operating temperature of the helium coolant, the thermal efficiency of the cycle can be employed for hydrogen generation. The schematic diagram of a GFR is depicted in Figure 4.

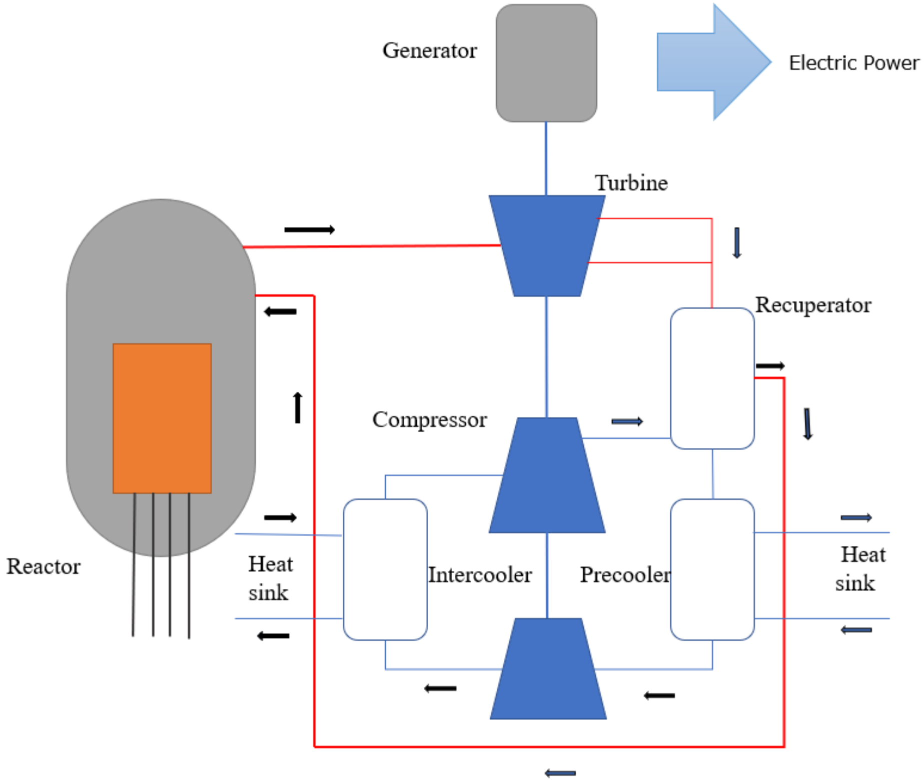

Figure 4. Schematic diagram of GFR system.

b. Very High-Temperature Reactor

Based on extensive experience, VHTRs are helium-cooled, graphite-moderated reactors and are mostly an update of high-temperature GFRs. In a VHTR, the helium coolant output temperature is capable of exceeding 1000 °C. These elevated temperatures make it possible to produce electricity and hydrogen with an efficient thermochemical process [11]. In the case of hydrogen production, 170 MW of total thermal power (600 MW) is used [7]. In hydrogen production, the S–I process is used [12]. Also, notably, because of the higher temperatures, the VHTR offers much larger challenges for high-alloy refractory materials, as well as graphite moderators [7].

The core of VHTR systems contains fuel in tristructural-isotropic (TRISO) particle form, and alternate fuels such as U–Pu, U–Th, mixed oxide (MOX), and Pu can be used as needed. There are two core configurations of VHTR, and they are well-adapted to thermochemical cycles and steam electrolysis in elevated temperature or hybrid systems [3].

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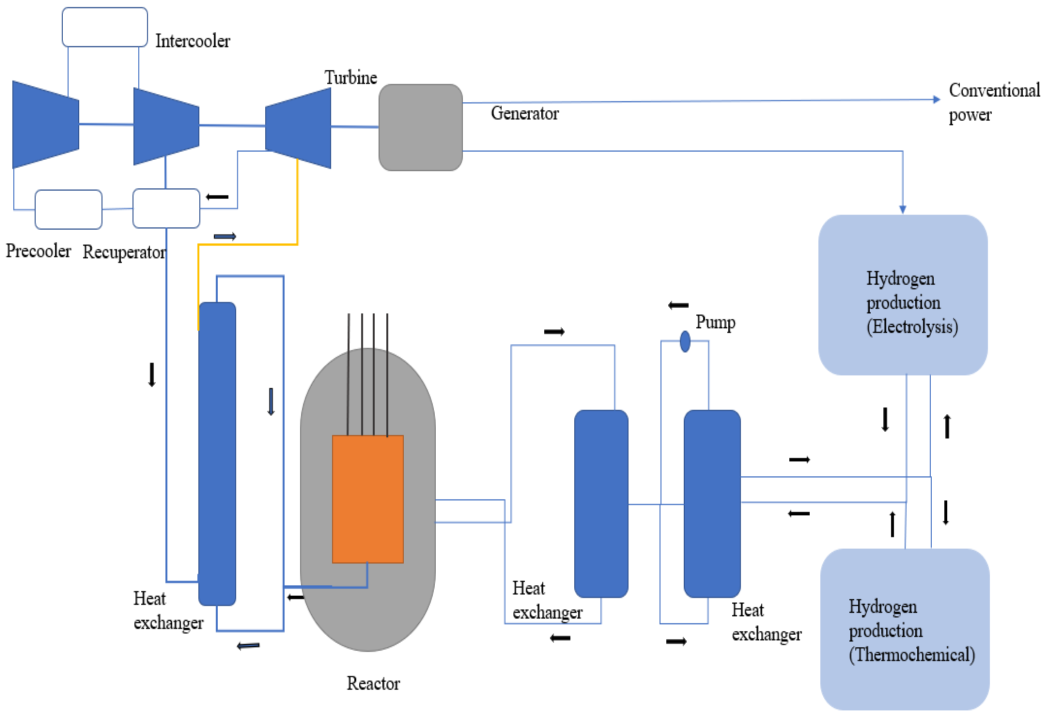

Figure 5. Schematic diagram of VHTR with hydrogen production system.

c. Lead-Cooled Fast Reactor

Full actinide recycle fuel cycles run in an LFR, which consists of high-temperature operation and a fast neutron spectrum. Cooling for LFRs is conducted by either molten lead or Pb–Bi eutectic, both of which have good thermodynamic properties that support low-pressure operation and are comparatively inert regarding interaction with air or water. Lead acts as a shield against gamma rays, ensuring that in the event of coolant leakage, there is no risk of explosion within these systems. Lead coolant in LFR systems considerably increases the reactor's safety over current nuclear designs [3].

The lead coolant outlet temperature is 550 °C, which must be increased to produce hydrogen. When lead coolant and nitride fuel are integrated with elevated-temperature structural elements, the long-term reactor coolant output temperature may be raised to 750–800 °C. Because new structural materials and nitride fuel must be produced, the needed research and development is more important than what is necessary for the options that operate at 550 °C [10].

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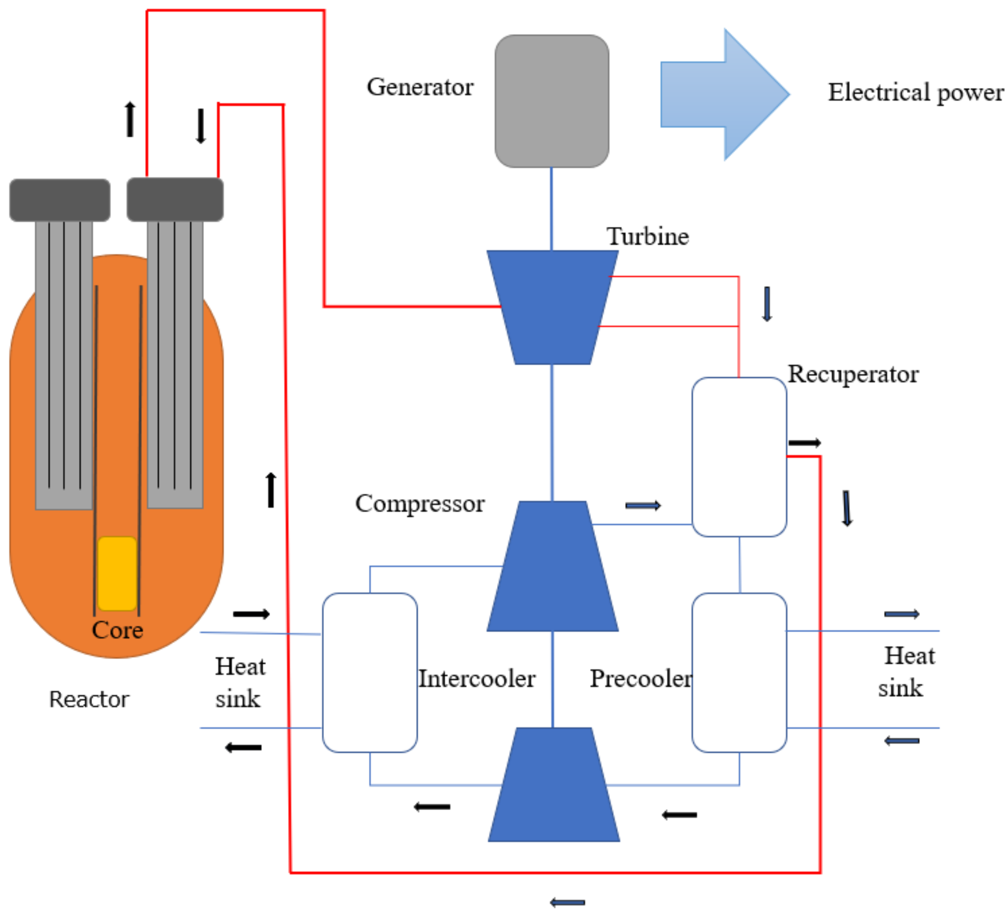

Figure 6. Schematic diagram of LFR system.

d. Molten Salt–Cooled Fast Reactor

The MSFR is distinguished by its core, in which the fuel is dissolved in molten fluoride salt. It will incorporate the thorium fuel cycle, actinide recycling, a closed thorium/uranium fuel cycle without uranium enrichment, greater reliability, and negligible effluents [13].

The operating temperature of molten salt ranges from 700 °C to 1000 °C. The temperature of the steam becomes supercritical at this point because of heat transfer from the coolant, leading to a high thermal efficiency. Hydrogen, oil refineries, and shared oil can be produced at these high temperatures [14].

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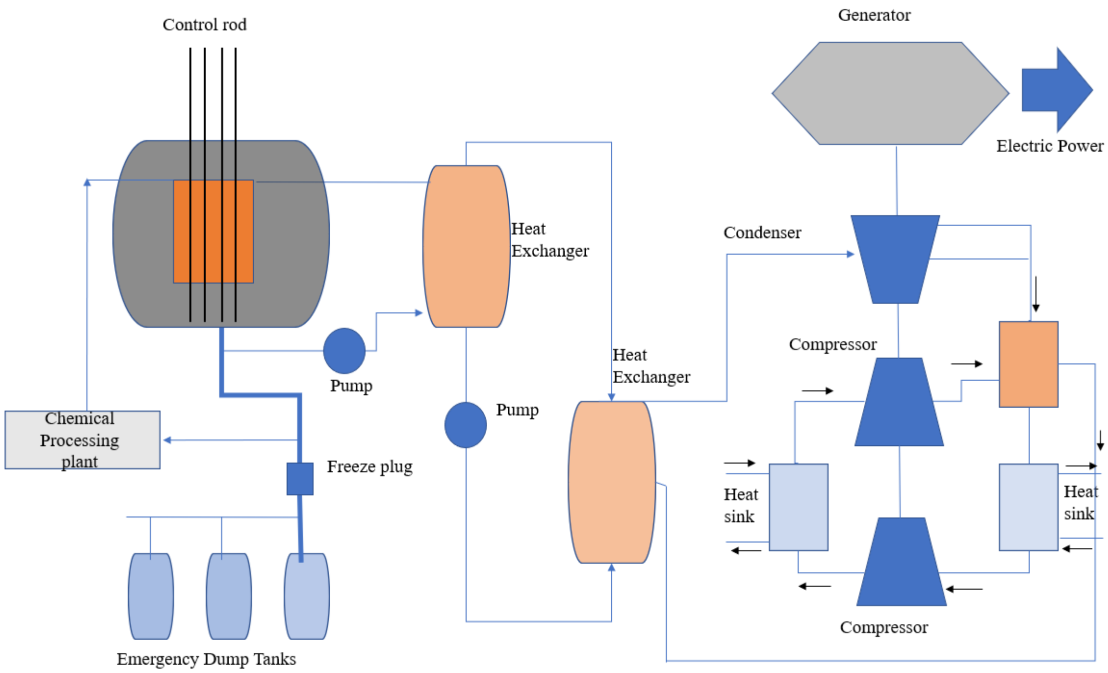

Figure 7. Schematic diagram of MSFR system.

e. Supercritical Water–Cooled Reactor

An SCWR is essentially a light water–cooled, high-temperature reactor that operates above the thermodynamic critical point of water (374 °C, 22.1 MPa) [10]. Having two models, the supercritical water (25 MPa and 510 °C) rotates the turbine directly, so there is no need for a secondary steam system. SCWR systems are simpler to construct than other reactor types because they do not require steam dryers or separators. SCWR has tiny turbine systems. The initial investment is lower than that required for typical light-water reactor (LWR) systems. Several SCWRs are currently in development, and with their advancement, the potential for hydrogen becomes evident [10].

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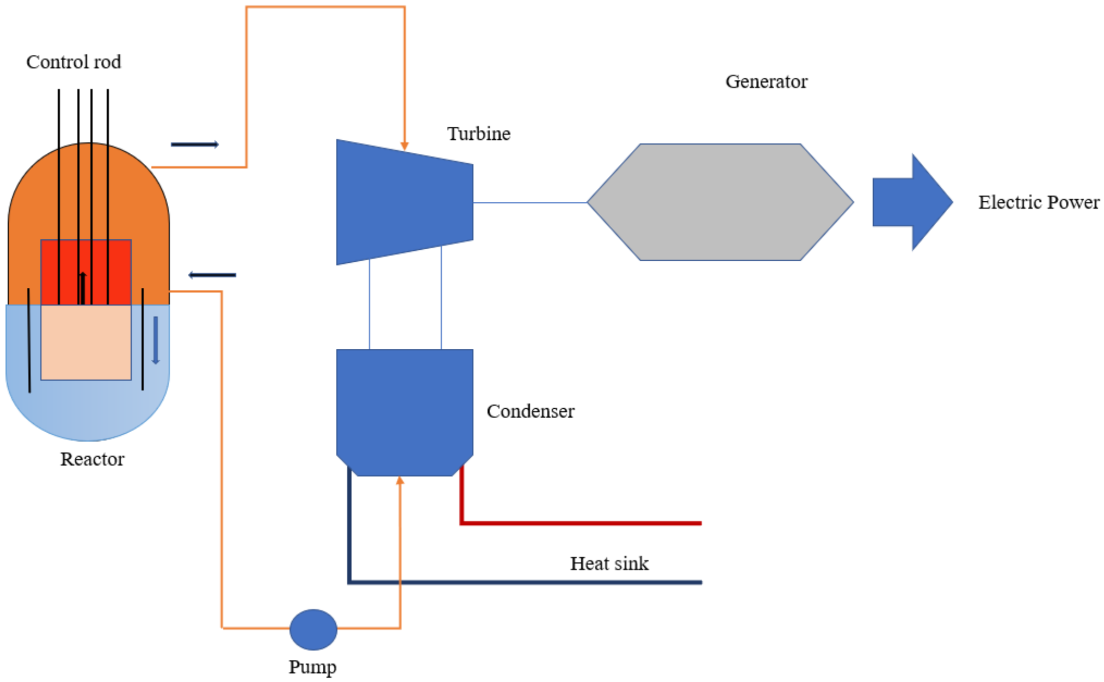

Figure 8. Schematic diagram of SCWR system.

f. Sodium-Cooled Fast Reactor

The reactant cooler in SFRs consists of liquid sodium, supporting a closed fuel cycle that involves complete transuranic (TRU) recycling for sustainability. This ability enables a high density of power at minimal pressure. Although the internal pressure of the reactor is minimal, the structural response may be significant depending on the surrounding conditions. During the construction of the reactor's internal components, it is crucial to consider the seismic impact induced by the SFR, which can be mitigated through the implementation of a seismic isolation system. SFR facilitates electricity generation, and there is a potential for hydrogen production in later stages [3].

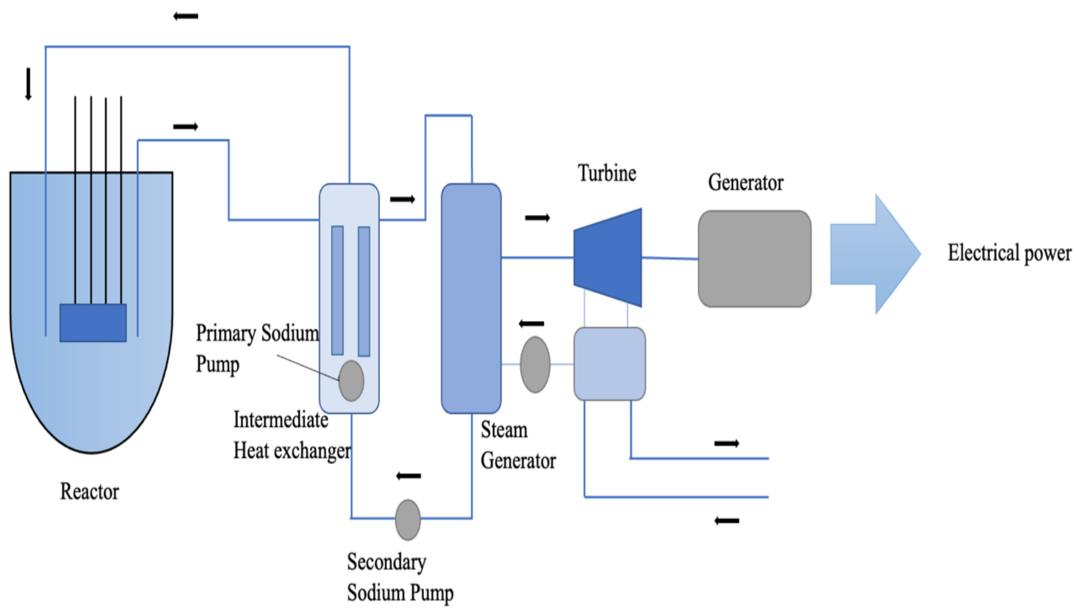

Figure 9. Schematic diagram of SFR.

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Table 1. Overview of Generation IV reactors [10, 15]

	Coolant outlet temperature (°C)	Pressure (MPa)	Coolant	Fuel	Uses
GFR	850	9	Helium	Uranium-238 and 20% plutonium	Electricity and hydrogen production
VHTR	900–1000	—	Helium	UO_2 in the form of TRISO-coated particles in a prism or pebble bed	Electricity and hydrogen production
LFR	480–570	0.1	Lead/lead–bismuth	Metal alloy or nitride fuel with uranium-238 and TRU	Electricity and hydrogen production
MSFR	700–1000		Fluoride salt	Liquid mixture of sodium, zirconium, and uranium fluorides	Electricity and hydrogen production
SCWR	510–625	25	Water	UO_2	Electricity production
SFR	500–550	~0.1	Sodium	MOX, minor actinides	Electricity production

VI. Efficiency Calculation

Figure 10 shows the power generation cycle using a gas turbine based on the VHTR. Table 2 presents the temperatures of the Brayton Cycle.

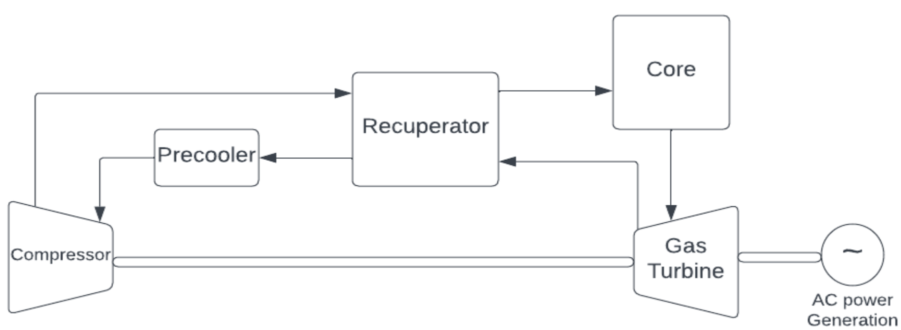

Figure 10. Power generation cycle using gas turbine based on VHTR.

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Table 2. Temperatures of the Brayton Cycle

Compressor inlet temperature T_1 (K)	Compressor outlet temperature T_2 (K)	Reactor core outlet temperature T_3 (K)	Turbine outlet temperature T_4 (K)
301	606.73	1223	606.73

By employing the data provided in the table and Equations (1–3), the efficiency of a VHTR using a simple Brayton cycle is 50.37%.

The calculation for the thermal efficiency of an S–I process is as follows using Equation (5):

$$\eta = \left(8.52 \left[\frac{\mathrm{N \cdot m^3}}{\mathrm{s}}\right] \times 12.76 \left[\frac{\mathrm{MJ}}{\mathrm{Nm^3}}\right]\right) / \left(170\ \mathrm{MW_{th}} + \frac{25.4}{50.37\%}\right) = 49.32\%. \qquad (5)$$

VII. Results

Using the same method as the previous section, we can get the efficiencies of other Generation IV reactors, which are shown in Table 3.

Table 3. The efficiency of Generation IV reactors [10]

Generation IV reactor	Thermal efficiency (%)
VHTR	>50
GFR	48
SCWR	41–44
MSFR	44–50
LFR	33–40
SFR	39

VIII. Conclusion

Innovation within the nuclear sector plays a crucial role in devising long-term solutions to reduce greenhouse gas emissions and facilitate the transition to a future characterized by lower CO_2 levels. Technologies centered around nuclear reactors are poised to contribute significantly to the generation of clean energy by addressing the need for various industries such as transportation, heating, cooking, and hydrogen production in the global effort to combat climate change. Nuclear stands as a key component for achieving a future characterized by reduced energy consumption. Generation IV reactors produce elevated temperatures to facilitate efficient hydrogen production. Despite the inherent challenges associated with advanced technology, VHTR and GFR stand out as the leading contenders for attaining elevated outlet temperatures. Using the coolant heat from the LFR, MSFR, SCWR, and SFR for hydrogen production is also feasible. However, this approach results in a reduction of electricity available for the power grid system. If proper and new structural materials can handle the very high temperature, then reactors can be used for hydrogen production and electricity generation, as well. However, the VHTR and GFR feature a notably high

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outlet temperature for the coolant, which will be used in the S–I process, steam reforming process, and electrolysis process for the production of hydrogen.

IX. References

1. International Energy Agency. *Hydrogen*. https://www.iea.org/energy-system/low-emission-fuels/hydrogen.
2. International Energy Agency. *Global Hydrogen Review 2023*, 2023. https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf.
3. Sahin, S.; Sahin, H. M. Generation-IV reactors and nuclear hydrogen production. *International Journal of Hydrogen Energy* **2020**, *46* (57), 28936–28948. DOI: 10.1016/j.ijhydene.2020.12.182.
4. Crosbie, L. M.; Chapin, D. Hydrogen Production by Nuclear Heat. Presented at GENES4/ANP2003, Kyoto, Japan, September 15–19, 2003.
5. Hori, M.; Shiozawa, S. *Research and Development for Nuclear Production of Hydrogen in Japan*; Japan Atomic Energy Agency: Japan, 2005.
6. Sun, Y.; Xu, J.; Zhang, Z. *R&D Effort on Nuclear Hydrogen Production Technology in China*; Institute of Nuclear and New Energy Technology, Tsinghua University: Beijing, China, 2005.
7. Pioro, I. L., ed. *Handbook of Generation IV Nuclear Reactors*; Woodhead Publishing Series in Energy; Woodhead Publishing: 2016. DOI: 10.1016/C2014-0-01699-1.
8. Shiozawa, S.; Ogawa, M.; Hino, R. *Future Plan on Environmentally Friendly Hydrogen Production by Nuclear Energy*; Japan Atomic Energy Agency: Oarai, Ibaraki, Japan, 2005; 311–1394.
9. Hydrogen and Fuel Cell Technologies Office. *Hydrogen Production: Natural Gas Reforming*. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.
10. International Atomic Energy Agency. *Hydrogen Production Using Nuclear Energy*; NP-T-4.2; International Atomic Energy Agency: Vienna, 2013.
11. Sivertsson, V. Hydrogen Production Using High Temperature Nuclear Reactors: A Feasibility Study. Thesis, Uppsala University, Uppsala, Sweden, 2010.
12. Shin, Y.; Chang, J.; Lee, T.; Lee, K.; Kim, Y. A Cooling System for the Secondary Helium Loop in VHTR-Based SI Hydrogen Production Facilities. *International Journal of Hydrogen Energy* **2013**, *38* (14), 6182–6189. DOI: 10.1016/j.ijhydene.2012.12.121.
13. Delpech, S.; Merle-Lucotte, E.; Heuer, D.; Allibert, M.; Ghetta, V.; Le-Brun, C.; Doligez, X.; Picard, G. Reactor Physic and Reprocessing Scheme for Innovative Molten Salt Reactor System. *Journal of Fluorine Chemistry* **2009**, *130* (1), 11–17. DOI: 10.1016/j.jfluchem.2008.07.009.
14. Gen-IV International Forum. *GIF R&D Outlook for Generation IV Nuclear Energy Systems*; Organisation for Economic Co-operation Nuclear Energy Agency: Paris, 2009.
15. World Nuclear Organization. *Generation IV Nuclear Reactors*, 2020. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx.

16. Bellona. *Hydrogen from methane reforming + CCS*, 2020. https://www.frompollutiontosolution.org/hydrogen-from-smr-and-ccs.
17. Naterer, G.; Fowler, M.; Cotton, J.; Gabriel, K. Synergistic Roles of Off-Peak Electrolysis and Thermochemical Production of Hydrogen from Nuclear Energy in Canada. *International Journal of Hydrogen Energy* **2008**, *33* (23), 6849–6857. DOI: 10.1016/j.ijhydene.2008.09.011.
18. Alemberti, A.; Carlsson, J.; Malambu, E.; Orden, A.; Cinotti, L.; Struwe, D.; Agostini, P.; Monti, S. ELSY—The European Lead Fast Reactor. In *Proceedings of International Conference on Fast Reactors and Related Fuel Cycles: Challenges and Opportunities FR09*, Vienna, 2009; International Atomic Energy Agency: Vienna, 2009; 91–92.
19. Fujiwara, S.; et al. Hydrogen Production by High-Temperature Electrolysis with Nuclear Reactor. *Progress in Nuclear Energy* **2009**, *50* (2–6), 422–426. DOI: 10.1016/j.pnucene.2007.11.025.
20. Abram, T.; Ion, S. Generation-IV Nuclear Power: A Review of the State of the Science. *Energy Policy* **2008**, *36* (12), 4323–4330. DOI: 10.1016/j.enpol.2008.09.059.
21. World Nuclear Organization. *Hydrogen Production and Uses*, 2021. https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx.
22. Rachkov, V. I.; Poplavskii, V. M.; Tsibulya, A. M.; Bagdasarov, Yu. E.; Vasiliev, B. A.; Kamanin, Yu. L.; Osipov, S. L.; Kuzavkov, N. G.; Ershov, V. N.; Ashirmetov, M. R. Concept of an Advanced Power-Generating Unit with a BN-1200 Sodium-Cooled Fast Reactor. *Atomic Energy* **2010**, *108*, 254–259. DOI: 10.1007/s10512-010-9286-z.