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Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle

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ABSTRACT

The high temperature nuclear reactor provides a new way to produce hydrogen with high efficiency. In the present work, the feasibility of using a VHTR for both electricity generation and hydrogen production is analyzed. The nuclear reactor is combined with a gas turbine, a steam turbine and a system for the delivery heat for high-, medium- and low-temperature processes. Industrial-scale hydrogen production via thermochemical water decomposition is considered, using high- and medium-temperature processes. Specifically, sulphur-iodine (S–I) and copper-chlorine (Cu–Cl) thermochemical cycles are examined. These water splitting cycles permit the conversion of water into hydrogen and oxygen at much lower temperatures than the direct thermal decomposition of water. Both cycles are considered promising routes for continuous, efficient, large-scale and environmentally benign hydrogen production without CO_2 emissions. The results show that the combination of a high temperature helium reactor, with a combined cycle for electric power generation and hydrogen production, may reach an efficiency of around 50%. The power plant cycle analyzed in the present paper is complex and it is difficult to determine conditions under which all target objectives are fulfilled: high thermodynamic efficiency for combined production of electricity and high-temperature heat which can be used to produce hydrogen.

Introduction

There are several nuclear reactor types in use nowadays around the world. Almost all are either of the PWR (pressurized water reactor) or the BWR (boiling water reactor) types. Most of the light water reactor power plants now operating are based on the pressurized-water reactor and they have relatively low thermal efficiencies. Similar to "conventional" coal-fired power plants, the nuclear units operate on a Rankine cycle but, for safety reasons, the temperature and pressure of the steam are much lower in the nuclear plant than in fossil

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fuel plants. As a consequence of lower steam parameters, especially temperature, typical thermal efficiencies of PWRs are about 33% and of BWRs are about 30% [9].

The efficiency of supercritical thermal power stations can reach 47–49% [33]. These plants are mostly fueled by coal and, for combined cycle gas and steam turbine plants, can achieve efficiencies of 58–60% [33]. Modern advanced thermal power plants may reach thermal efficiencies as high as 62% [6]. In spite of such achievements, such plants remain significant emitters of carbon dioxide. For this reason, reliable non–fossil fuel plant, such as nuclear power plants, are becoming increasingly attractive. However, current nuclear power plants have lower thermal efficiencies, with the best light water reactor power plant having a maximum efficiency of about 34–35%. A comparison of the steam pressure and temperature of current nuclear plants with the fossil-fuel plants shows that the thermodynamic efficiency of the current nuclear technology has not improved for many decades. Almost all current nuclear power plants, as well as the coming Generation III + plants, are not achieving thermal efficiencies as high as those for other advanced thermal power plants. The difference in thermal efficiencies between fossil-fuel plants and nuclear plants can be up to 30% [25].

One relatively straightforward option for increasing thermal efficiency involves raising the steam temperature with natural gas. In such a system, a thermal efficiency of around 40% is possible [9,33], which is similar to that for standard fossil-fueled power plants. Furthermore, for gas cooled reactors it is now possible to increase the reactor temperature from 850 °C to 950 °C due to technological advancements [6]. The modern gas cooled reactor is inherently safe, and thus can provide a stable and flexible option suitable for various energy supply applications. The development of such reactors is informative. First a continuous operation High Temperature Reactor (HTR) with an outlet temperature of 950 °C was successfully developed in 2010 [10]. By applying the existing technologies embodied in the HTGR and gas turbine, a nuclear power station was able to exceed a 50% thermal efficiency [29]. Typically, the high temperature gas reactor (HTGR) and the gas turbine modular helium reactor (GT-MHR) [2] refer to direct closed Brayton Cycle systems [17]. In the case of the very high temperature reactor (VHTR), the molten salt reactor (MSR) and the liquid fluoride thorium reactor (LFTR) [14], indirectly heated cycles are typically used. It has been shown that thorium, being four times more abundant in the earth's crust than uranium ores, is also a promising nuclear fuel. The liquid fluoride thorium reactor base plant, using high quality heat exchangers and turbomachinery with a 1200 K inlet temperature, can achieve a thermodynamic efficiency of 50 percent for electrical power generation [26].

The diversity of HTGR/VHTR power cycles is large [17,24]. Different power cycle configurations can be coupled to the same nuclear system depending on applications. This type of reactor is also a good candidate to produce hydrogen and its cycle configuration can vary depending on the technology to be used [13]. Recent studies on the thermal performance of such plants have been reported. In the HTGR regenerative cycle, the working fluid is helium and the thermal efficiency has been reported to be as high as 47.9% [34] identified the variables have the greatest influence on performance for each configuration and predicted efficiencies as high as 47.5% for the direct combined cycle layout. For a simple layout consisting of a two compression stages, a single stage turbine and a recuperator [23], determined optimum thermal efficiencies by parametrically varying temperature and pressure. The author found that the thermal efficiencies vary from 45% to nearly 52%, for a reactor outlet temperature of 850–1000 °C.

The results described above suggest that new Generation IV nuclear reactor plants should be considered fro implementation in the future, in large part because they appear to be capable of thermal efficiencies ranging from 40 to 50% if not higher. The high efficiencies are particularly advantageous because a low efficiency not only has a negative impact economically, but also environmentally due to extra thermal pollution. Therefore, future efforts to enhance nuclear power plant thermal efficiency appear to be merited.

Hydrogen energy can form an important element of energy policies for reducing carbon emissions. It can act as an energy carrier for transportation, fuel cells or as a commodity for the chemical industry. Hydrogen can be produced using off-peak electricity or continuously and stored for peak period use, e.g., in solid oxide fuel cells (SOFC). Hydrogen can be produced by several methods, including high-temperature electrolysis, steam reforming of natural gas, and high-temperature thermochemical processes.

At present, almost all hydrogen is produced by steam reforming of natural gas and from refinery streams. Each production process requires a large amount of thermal and/or electrical energy. The energy for this purpose can be produced in high or very high temperature nuclear reactors [11,22]. One of the most economical approaches for hydrogen production [4] using thermal energy are thermochemical cycles which use a series of chemical reactions and high temperature to convert water to hydrogen and oxygen. The maximum estimated theoretical efficiency for sulfur-iodine and copper–chlorine cycles is about 74%, but in practice, due to thermodynamic losses, these cycles exhibit similar overall thermal efficiencies, ranging from 37 to 54%. For conventional electrolysis, the overall thermal efficiency of hydrogen production can vary from 30% to 41% [35,36]. The cost for hydrogen production using thermochemical processes should be lower than for electrolysis because heat is converted directly to hydrogen, whereas electrolysis requires electricity produced with a thermal efficiency on the order of 40%. But it has been shown [21] that the overall efficiencies for hydrogen production using high temperature electrolysis can exceed 50% when reactor outlet temperatures are above 850 °C. Taking into account technical problems when introducing high temperature thermochemical processes having similar efficiencies, high temperature electrolysis also appears to be promising.

Of the various thermochemical processes, one of the leading candidates is the sulfur-iodine (S–I) process:

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \quad (\text{at } 120^{\circ}C) \tag{1}$$

$$2H_2SO_4 \rightarrow 2SO_2 + 2H_2O + O_2 \quad (\text{at } 850^{\circ}C) \tag{2}$$

$$2HI \rightarrow I_2 + H_2 \quad (\text{at } 450^{\circ}C) \tag{3}$$

This process requires water and heat, and consists of three main chemical reactions. The net reaction is water splitting to hydrogen and oxygen, and the other materials in this process are recycled. The first reaction, catalytic decomposition of sulfuric acid, requires heat at very high temperature (at least 850 °C) and low pressure. Higher temperatures may improve efficiency and usually imply more engineering challenges of scale-up, such as tougher demands on component materials. The 850 °C temperature is thus considered as a lower limit required for the process. Additionally, low pressure helps ensure safety by lowering the risks of pressurization in a chemical plant and reducing high temperature stresses.

Most of the other thermochemical cycles for hydrogen production require very high temperatures (above 800 °C). A notable exception is the copper–chlorine (Cu–Cl) cycle, which requires 600 °C in the simple three step version and only 530 °C in the more complex four or five step versions [20]. The Cu–Cl cycle also exhibits higher yield kinetics for the oxygen and hydrogen generation reactions. This could be a significant advantage of the Cu–Cl cycle, which has attracted much attention and interest. Variations of the Cu–Cl cycle consisting of different intermediate steps have been reported in the literature and in recent years primarily four and five step methods are being examined from various perspectives, including scale-up challenges and overall energy efficiency improvement [20].

The four-step copper–chlorine cycle usually consists of the following exothermic or endothermic reactions:

$$2Cu + 2HCl \rightarrow 2CuCl + H_2 \quad (\text{at } 450^\circ C) \tag{4}$$

$$4CuCl \rightarrow 2Cu + 2CuCl_2 \quad (\text{in solution of HCl}) \ (\text{at } 30\text{–}80^\circ C) \tag{5}$$

$$\begin{gathered} CuCl_2 + nH_2O \rightarrow CuOCuCl_2 + 2HCl + (n-1)H_2O \\ (\text{where n is 5–30}) \ (\text{at } 375^\circ C) \end{gathered} \tag{6}$$

$$2CuOCuCl_2 \rightarrow 4CuCl + O_2 \quad (\text{at } 530^\circ C) \tag{7}$$

The hydrogen product and oxygen by-product are produced in the first and last of the above reactions, respectively. The major advantages of this four step cycle relative to the five step cycle are a smaller number of reactions and the same required peak temperature of 530 °C. It is also possible to operate this process using only three reactions, but in that case the peak input temperature increases from 530 °C to 600 °C, raising heat losses and decreasing cycle efficiency. It is noted that the lowest temperature requirement for the set of reaction is in the range 30–80 °C, which is important to the overall cycle analysis. The Cu–Cl cycle has been identified by Atomic Energy of Canada Limited as an advantageous thermochemical cycle for hydrogen production which can integrate well with the supercritical water-cooled nuclear reactor [28]. Also, this thermochemical cycle can effectively utilize low-grade waste heat, such as could be obtained at the gas turbine exit in the gas turbine high temperature reactor system (GTHTR).

To meet the requirement for high efficiency in S–I [16] or Cu–Cl thermochemical processes while allowing operability, the process heat supply temperature needs to be at least about 50 °C higher than minimum cycle requirement. The high pressure needed to achieve an outlet temperature in the required range eliminates in practice the pressurized water reactor (PWR) from thermochemical hydrogen production applications. For HTRs [3] the typical outlet temperature is around 800 °C, which is usually too low to drive the S–I cycle. This temperature is also too low for high efficiency electrical generation using a gas turbine [26]. In order to allow more efficient electricity generation and thermal conditions suitable for most thermochemical processes, a new type of reactor called the Very High Temperature Reactor (VHTR) has been proposed Nuclear Energy Agency [20]. This type of reactor is a helium-cooled reactor with a gas outlet temperature at least of 950 °C; the reactor is graphite-moderated and has a ceramic core. Triso multi-layer small particles are used as a fuel.

To produce hydrogen using thermal energy, an additional specialized heat exchanger usually has to be installed in the system. There are three main approaches (Fig. 1.) considered for connecting high temperature reactors to the combined cycle. The first, which is the simplest, utilizes one main direct gas loop. The next two approaches utilize indirect loops with gas–gas or gas-water heat exchangers or a steam generator. The direct gas configuration exhibits simplicity and has an efficiency of about 45%. Unfortunately, using the same gas for the reactor and turbomachinery (e.g., the turbine) may result in contaminated gas if significant care is not taken. The indirect gas–gas loop helps resolve that problem since it separates the primary reactor side from the secondary gas turbine side. In that configuration, if high gas pressure is maintained in the secondary loop, secondary gas will flow to the reactor in the case of a rupture in the heat exchangers. In such a situation, the reactor is safer. Since the helium turbine is still in the development phase [15], the secondary loop may not use pure helium as a working gas, but instead a mixture of gases, for example, He–N_2 or He–Xe or CO_2. This allows the use of presently available gas turbines [19].

The secondary side can connect not only the turbine, but also any process heat applications, such as a hydrogen production plant, without the risk of contaminating them. In the third type of configuration, the gas-water approach, a steam turbine is used for power generation. The gas-to-water cycle can be carried out with indirect heat exchangers or using a steam generator directly to transfer the thermal energy carried by helium to the water. In a configuration with a steam generator and a steam turbine, the electrical efficiency obtainable with modern steam turbines can reach 40%. In the gas-water configuration, a steam generator or a heat exchanger is required, which in the case of a leakage will permit water to enter the nuclear reactor core. This can lead to various very serious and dangerous situations. Note that water is a good moderator and may increase reactivity if it flows to the reactor core so, to prevent such a situation, an additional heat exchanger may be required.

First generation gas-cooled reactors use a steam generator to accommodate an indirect Rankine cycle for electricity generation. At that time, the temperature was too low to accommodate direct Brayton cycles. Also gas turbine developments in the past did not allow closed cycles which are required in the case of a nuclear reactor as a heat source

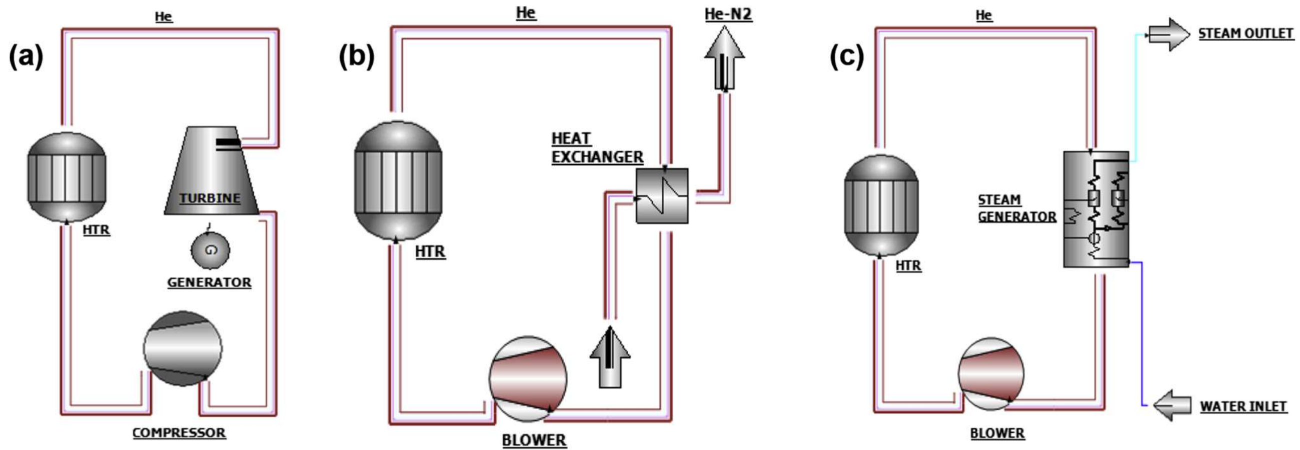

Fig. 1 – Three main nuclear reactor connection concepts: (a) direct, (b) indirect gas–gas, (c) indirect gas–water.

for radioactivity reasons. Recent work from MIT [7] has demonstrated the possibility of using air Bratyon cycles for nuclear power generation. In such cases, an addition heat transfer loop is required between the primary loop and the power cycle to prevent radioactive transfers and releases. The new generation VHTR can accommodate a Brayton cycle for the generation of electricity and additionally can use remaining heat for an indirect Rankine cycle [12]. The configuration with a direct Brayton cycle presented in Fig. 1a is simpler than the indirect Brayton (Fig. 1b) or Rankine cycle (Fig. 1c), and also provides higher safety levels. The long-term target is that the VHTR will have a primary closed loop used mainly to generate electricity using a gas turbine unit with helium as a working fluid. Additionally, it is possible to connect in parallel or series to the gas turbine a heat exchanger which can be used to provide heat for high temperature processes. In order to increase plant efficiency, relatively hot helium gas from the turbine unit will flow through a second heat exchanger before returning to the reactor. That heat exchanger transfers waste heat for medium temperature processes. A secondary high temperature heat transfer loop can provide process heat for non-electrical energy production while for the medium temperature secondary loop the target can be additional electrical or non-electrical energy production. In some situations a tertiary heat transfer loop may be required to further isolate the nuclear reactor from potentially dangerous processes and from possible contamination. That loop will significantly increase safety. Any additional heat exchanger decreases the probability of contamination in an accident, but adds additional components that reduces the overall plant efficiency and increases cost. It is proposed in many analyses that the high temperature processes should be located 1 km–3 km from the nuclear reactor, a distance that is technically and economically acceptable [16] despite the losses of pressure and temperature. However, according to the analysis provided by the Next Generation Nuclear Plant (NGNP) project, adequate nuclear safety can be achieved for the distances between the VHTR and other installations of less than 1 km [5]. Estimations of the required separation distance between the reactor and hydrogen plant vary significantly in the literature. Sochet et al. [31] recommended only 0.5 km while Smith et al. [30] recommended this separation distance to be as short as 120 m.

The selection of medium and high temperature secondary loops depend on the specific process heat applications. Although this type of configuration involves many potential heat applications, in the present paper we consider nuclear hydrogen production for the high temperature loop and electricity generation using classical steam turbines or Cu–Cl hydrogen cycle for the medium temperature loop. The objectives are to evaluate the net electrical power for the gas turbine and steam turbine as well as thermal cycle efficiency, so as to improve understanding of these processes. The focus is also on the total electrical power of the proposed plant when hydrogen production is added. Optimal parameters for various levels of hydrogen production are proposed. The chemical process shutdown configuration when one or even none of the secondary heat loops are working is also investigated to show the possible consequences for a process production break.

Analysis of power plant cycle

A summary of previous design data for high temperature reactor systems is presented in Table 1. In the present study, we focus more on the closed helium Brayton cycle and on the heating process for hydrogen production. To design and construct a power unit for this system [18], the designer must select not only the appropriate turbo-machinery and heat exchangers but also the optimal (or best in some respect) design and operating parameters for them. Since the efficiency of a Brayton cycle is strongly dependent on the turbine inlet temperature and pressure ratio, if helium is used as a working fluid the upper limit for the turbine temperature can be higher than for other gases. This is because helium does not interact with material structures, and potentially permits higher thermal efficiencies. Since it does not cause significant corrosion of nuclear reactor structures, helium can also be directly used as the reactor coolant under very high temperature conditions [1]. This characteristic of

Table 1 – Data for the very high temperature nuclear reactor plant.

Parameter	HTR Gas turbine plant concepts			
	GTMHR	GTHTR300	ANTARES	VHTR NGTCC
Power [MWt]	600	600	600	350
Thermodynamic cycle	Inter-Cooled Recuperated Brayton Cycle	Recuperated Brayton Cycle	Combined Cycle	Combined Cycle
Power conversion working fluid	He	He	He/N_2	He
Reactor inlet/outlet temperature [°C]	491/850	587/850	355/850	400/950
Turbine inlet temperature [°C]	850	850	800	950
Reactor gas pressure [MPa]	7.1	7.0	5.5	7.1
Compression pressure ratio	2.86	2	2	1.94
Plant Net Power [MWe]	286	274	280 (80 Gas Turbine, 200 Steam Turbine)	180 (50 Gas Turbine, 130 Steam Turbine)
Thermal efficiency [%]	47.6	45.6	47.0	51.5
Number of compressor stages	9	6	4	6
Turbine blade cooling	Uncooled	Uncooled	Uncooled	First two stages cooled

Source: [18]

helium increases the operational lifetime of system components which constantly contact the high temperature coolant. Although the core reactor, as well helium, can withstand temperatures of 1300 °C and above, at present, because of limitations associated with other system components, the reactor outlet temperature is limited to about 1000 °C.

The thermal efficiency of the plant cycle presented in Fig. 2 is evaluated for a variation of the hydrogen production power and reactor outlet temperature from 850 °C to 1000 °C. This temperature range is the most appropriate to utilize heat in the hydrogen production process. The design parameters used in cycle analysis are summarized in Table 2.

A thermodynamic analysis of gas and steam hybrid cycle for a high temperature nuclear reactor is the focus of the present work. The plant considered is shown in Fig. 2. The system operates with three independent loops. The first main nuclear reactor loop of the system is a helium loop where helium at a rate of 264.12 kg/s and a pressure of 6 MPa is heated to a temperature in the range of 900–1000 °C and enters the first heat exchanger (IHX1). In this heat exchanger heat from the high temperature helium gas is transported to the secondary loop, where the working fluid is a mixture of 50% of helium and 50% of nitrogen, on a volume basis. Cold helium is circulated back to the reactor using a helium blower. In the reactor, the working gas is reheated. Note that the reactor is constructed so that, if the gas pump does not work properly, generated heat is transferred to the surroundings using only natural convection. In operation, helium coolant enters the reactor core at the bottom and flows up through the

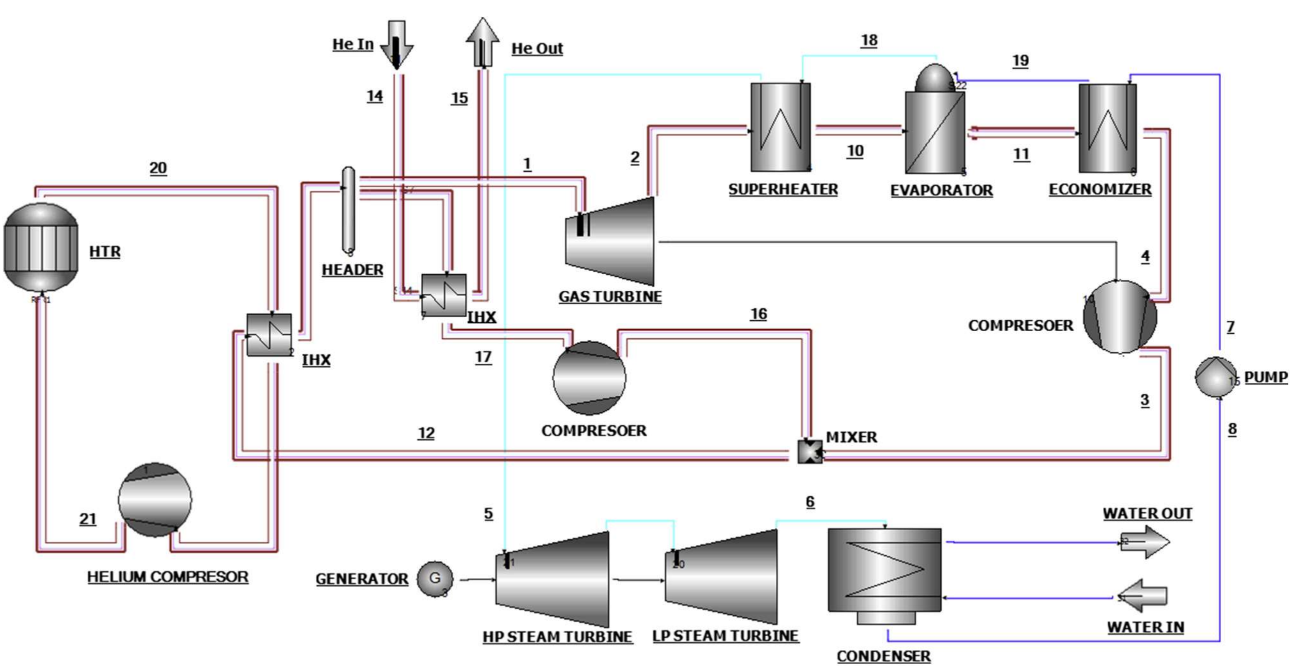

Fig. 2 – Schematic of reference VHTR design integrated with hydrogen production.

Table 2 – Summary of design parameters used in cycle analysis of gas and steam hybrid cycle for high temperature nuclear reactor.

Parameter	Value
Nuclear reactor thermal power	600 MWt
Reactor outlet temperature	850–1000 °C
Primary/secondary loop pressure	6 MPa
Gas turbine inlet temperature	765–950 °C
Gas turbine pressure inlet	6 MPa
Generator efficiency	98%
Isentropic gas turbine efficiency	90%
Isentropic steam turbine efficiency	90%
Heat exchangers IHX efficiency	97%

vessel. Then coolant is redirected at the top to flow through the reactor core from top to bottom, providing additional heating. This exposes the core barrel to the cooler inlet helium, rather than the hotter outlet helium, thereby reducing the operating temperature of the barrel material, but also decreasing heat losses from the reactor wall and preventing natural convection. Because the reactor is not thermally isolated and has a safety system for heat loss due to natural convection. It is important to keep the reactor inlet temperature low, but not too low. The system must provide an inlet temperature precisely at the value required by HTR.

The He–N_2 gas mixture at a mass flow rate of 880 kg/s is heated to a temperature of 850–950 °C in the first heat exchanger (IHX1) and then split into two flows. The flow division is made according to the design requirement to provide the required heat rate for the thermochemical process. For the S–I process, the mass flow rate required to achieve a thermal power of 60 MW for the hydrogen production process demands that 0.083 of the mean flow directly enters a second heat exchanger (IHX2). The remaining flow fraction of 0.917 directly enters the gas turbine, wherein it expands to a pressure of about 3 MPa (for $z = 2$) and a temperature of about 536 °C, depending on the specific case. After exiting the gas turbine, the mixture of gases flows through a steam generator system consisting of a superheater, an evaporator and an economizer where steam is produced under pressure and temperature. The exact values vary depending on the reactor temperature and compressor compression ratio. The steam generated in the system passes through high and low pressure turbines, where sequential expansions occur to a pressure about 80 kPa and a temperature above 120 °C. After exiting the turbine, the steam enters the condenser where it is cooled to 90 °C and returned to the steam generator. The He–N_2 mixture leaving the steam generator system enters the gas compressor where it is compressed to a constant pressure of about 6 MPa. The compressed gas flows through the main heat exchanger IHX1 where is heated again. The high-temperature hydrogen production process carried out via the thermochemical sulfur-iodine cycle is realised using heat from the IHX2 heat exchanger. Because decomposition of sulfuric acid H_2SO_4 occurs at 850 °C, process heat must be extracted from the mainstream (before the gas turbine). In the present paper, it is assumed that the efficiency of the S–I process does not exceed 48%, based on the analysis of Wang et al. (2009).

Cycle efficiency

In order to implement the proposed concept, it is important to know the energy efficiency of the power plant cycle for electrical energy production combined with heat production for hydrogen production. The thermal efficiency of the power conversion units can be defined as follows:

$$\eta_e = \frac{\dot{W}_{GT} - \dot{W}_C + \dot{W}_{ST} - \dot{W}_P}{\dot{Q}_{reac}} \tag{8}$$

where $\dot{W}_{ST}$ and $\dot{W}_{GT}$ are the total steam turbine and gas turbine workload power, $\dot{W}_C$ and $\dot{W}_P$ are the compressor and circulator (blower or/and pump) workload in the primary and secondary side respectively, $\dot{Q}_{reac}$ is the nuclear reactor thermal power.

The net electrical power output of the gas turbine can be calculated as follows:

$$\begin{aligned} P_{GT} &= \eta_{gen} \cdot \dot{m}_{He-N_2} \cdot (\dot{W}_{GT} - \dot{W}_C) \\ &= \eta_{gen} \cdot \dot{m}_{He-N_2} \cdot \left[\eta_{igt} \cdot (h_1 - h_2) - \eta_{ic} \cdot (h_3 - h_4)\right] \end{aligned} \tag{9}$$

where η_{gen} is the generator efficiency, $\dot{m}_{He-N_2}$ is the mass flow rate of the working fluid mixture (50% helium and 50% nitrogen, on a volume basis), η_{igt}, η_{igt} are the isentropic efficiencies of the gas turbine and the compressor, and h is specific enthalpy. The subscripts on the specific enthalpies denote the working fluid at the inlet and outlet of the gas turbine and of the compressor.

The net electrical power output of the steam turbine can be expressed as follows:

$$\begin{aligned} P_{ST} &= \eta_{gen} \cdot \dot{m}_S \cdot (\dot{W}_{ST} - \dot{W}_P) \\ &= \eta_{gen} \cdot \dot{m}_S \cdot \left[\eta_{ist} \cdot (h_5 - h_6) - \eta_p \cdot (h_7 - h_8)\right] \end{aligned} \tag{10}$$

where $\dot{m}_S$ is the mass flow rate of the steam, and η_{ist}, η_p are the isentropic efficiencies of the steam turbine and the pump. The specific enthalpy h of working fluid is evaluated at the inlet and outlet of the steam turbine and of the pump. The gas turbine outlet temperature is calculated as follows:

$$T_{GTout} = T_{GTin} - \eta_{iGT} T_{GTin} \left[1 - \left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{11}$$

where P is the absolute pressure, T temperature and γ ratio of specific heats for the gas working fluid. The subscripts out and in denote turbine outlet and inlet conditions, respectively.

The computations were made with partial support of the GateCycle [8] application used for design and steam turbine power evaluation of plant systems.

Results and discussion

The total plant net electrical power output and thermal efficiency of the HTR system without hydrogen generation (i.e., PH2 = 0 MW) are determined (see Fig. 3). The main thermodynamic assumptions invoked in the calculations and the input parameter values are provided in Tables 1 and 2.

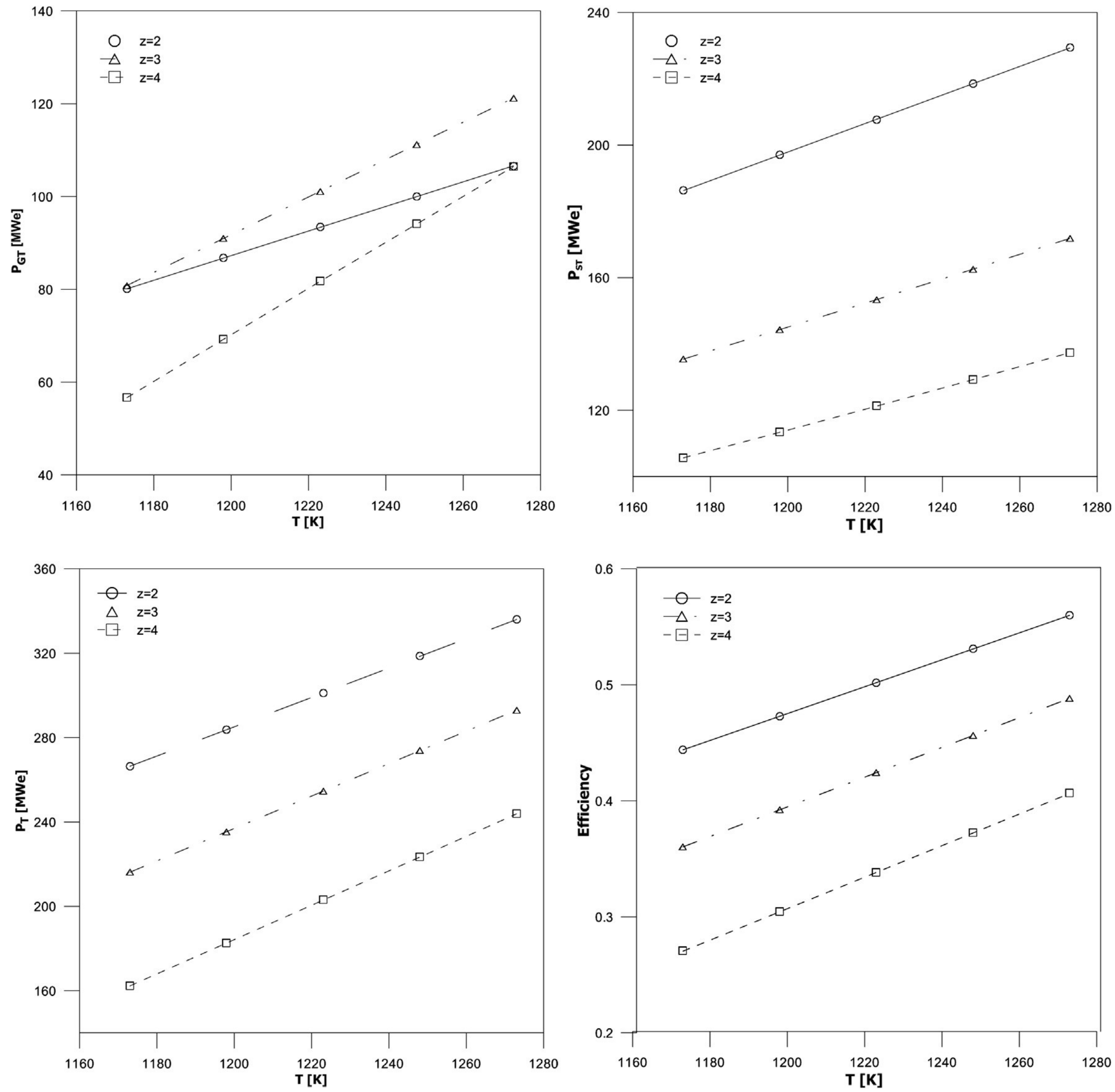

Fig. 3 – Variation of net electrical power output and cycle thermal efficiency with reactor outlet temperature T for various compressor values of compression ratio z.

The gas turbine, for a compression ratio z = 2 and for a nuclear reactor helium outlet temperature of 900 °C, yields an net electrical power of about 95 MW whereas the steam turbine output net electrical power is 170 MW. In this case the energy efficiency is 45%. When the nuclear reactor outlet temperature is raised to 1000 °C, the net electrical power rises to 130 MW and 210 MW for the gas turbine and the steam turbine, respectively. The electrical efficiency rises to as high as 55%. For a 1 percentage point gain in the energy efficiency, the reactor outlet temperature is elevated by about 10 K. The diagrams in Fig. 3 also show that, for a higher compression ratio, the net electrical power and thermal efficiency both decrease. The gas turbines have a thermodynamic advantage in that they can effectively utilize very high temperatures. In the present case, we analyze the point of maximum gas turbine efficiency. When the reactor outlet temperature is fixed and the compressor pressure ratio rises from z = 2 to z = 4, the gas turbine thermal efficiency is observed to attain the highest thermal efficiency for about z = 3 and that efficiency is about 4 percentage points greater than for the efficiency for the case where z = 2. It is also possible to obtain an efficiency rise of up to 2 percentage points if a compressor inter-cooling stage is applied or a simple heat recuperator is used. In this case, the optimal pressure ratio should be established for each individual case depending on the number of turbine or compressor stages and the reactor outlet temperature. As shown in the literature [37,27], the direct cycle with a gas turbine may yield an additional increase in gas turbine efficiency of about 3 percentage points. In the case of a direct cycle, a helium gas turbine is required, which is not available in the market yet.

Fig. 4 shows the net electrical power and thermal efficiency for the system with hydrogen generation. It is technically possible to have all the nuclear reactor thermal power used for hydrogen production, but if such a process is interrupted then a large amount of heat will not be absorbed and the reactor

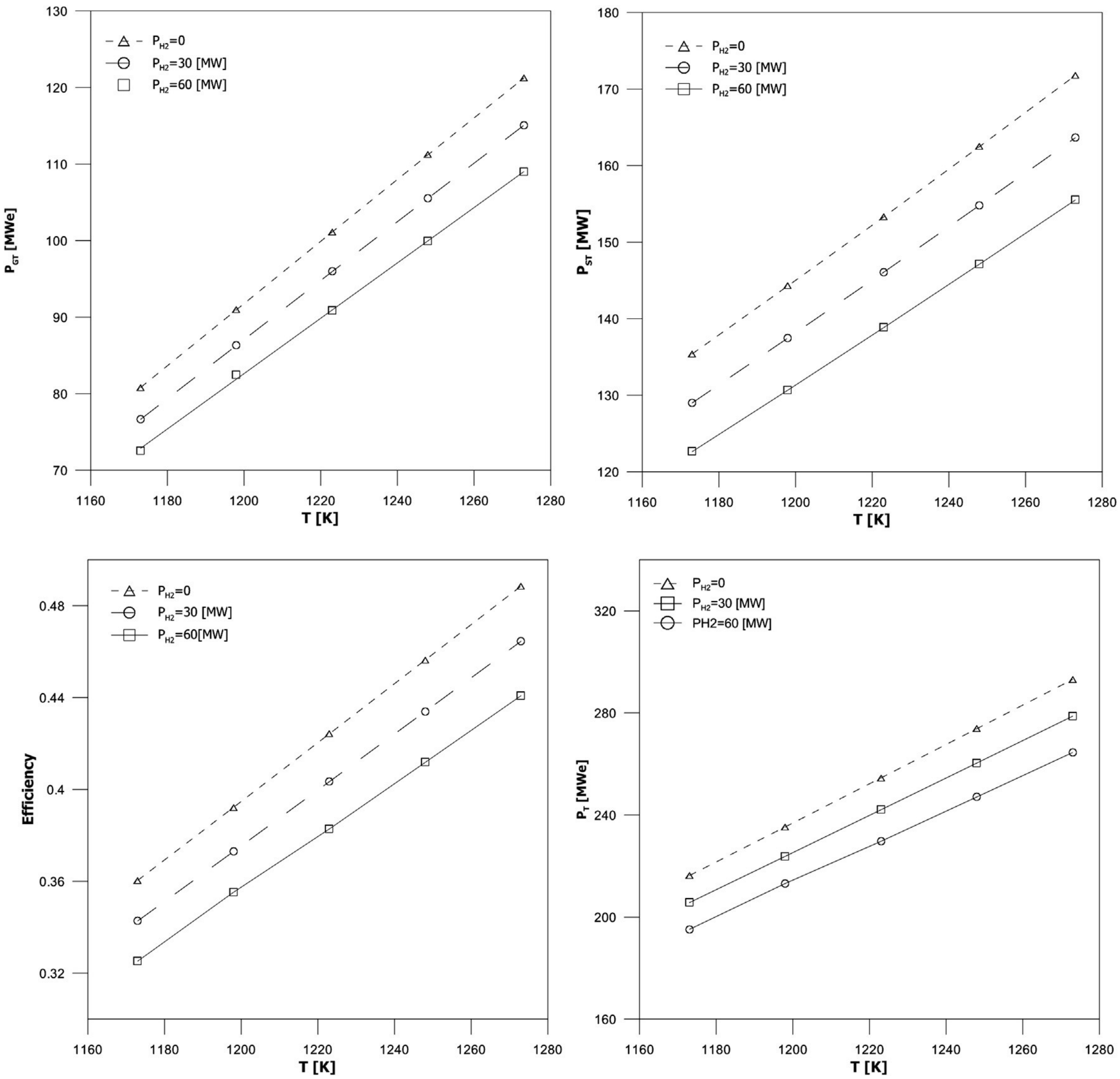

Fig. 4 – Variation of net electrical power output and cycle thermal efficiency with reactor outlet temperature *T* for various hydrogen production thermal power levels.

will have to be shut down in emergency mode. The maximum reactor thermal power spike that does not significantly affect the operation of the reactor is about 10% of the total reactor power. Thus to protect the nuclear reactor it is assumed in this work that up to 60 MW of thermal energy is used for hydrogen generation using the thermochemical process and at the same time the thermal power used for electrical energy production is decreased by the same factor. The cases considered are PH2 = 0, 30, 60 MW. When thermochemical hydrogen process operates, the cycle electrical energy efficiency decreases approximately 1 percentage point for each 10 MW of thermal power used for hydrogen production. The net electrical power output of the steam or gas turbine decreases, and as a consequence the overall energy efficiency decreases, as the total power used for hydrogen production rises, but the efficiency decrease is not linear and depends on reactor outlet temperature. When reactor outlet gas temperature *T* is high, more electrical energy can be produced from the same quantity of thermal energy. As a consequence, the decrease in net electrical power output is larger for higher outlet temperature *T*. The S–I process conversion is estimated to be about 48% [35].

In Fig. 5 the net electrical plant power and thermal efficiency of the Cu–Cl hydrogen production process are shown. As for the S–I process examined previously, the Cu–Cl thermochemical cycle conversion is examined for thermal power inputs of PH2 = 30 and 60 MW. In this configuration, the second heat exchanger (IHX2) is mounted after the gas turbine. The gas turbine inlet and outlet temperatures (equal in this case to the temperature required for the hydrogen heat exchanger) are presented in Fig. 6. In the case of hydrogen production using the Cu–Cl process, only the gas turbine working fluid flow rate can be independent of the hydrogen production thermal power levels. Additionally because the energy conversion efficiency for a gas turbine is higher than for a steam turbine, a higher overall system efficiency is possible when process heat is extracted after and not before the gas turbine. When 10% of the reactor thermal power is

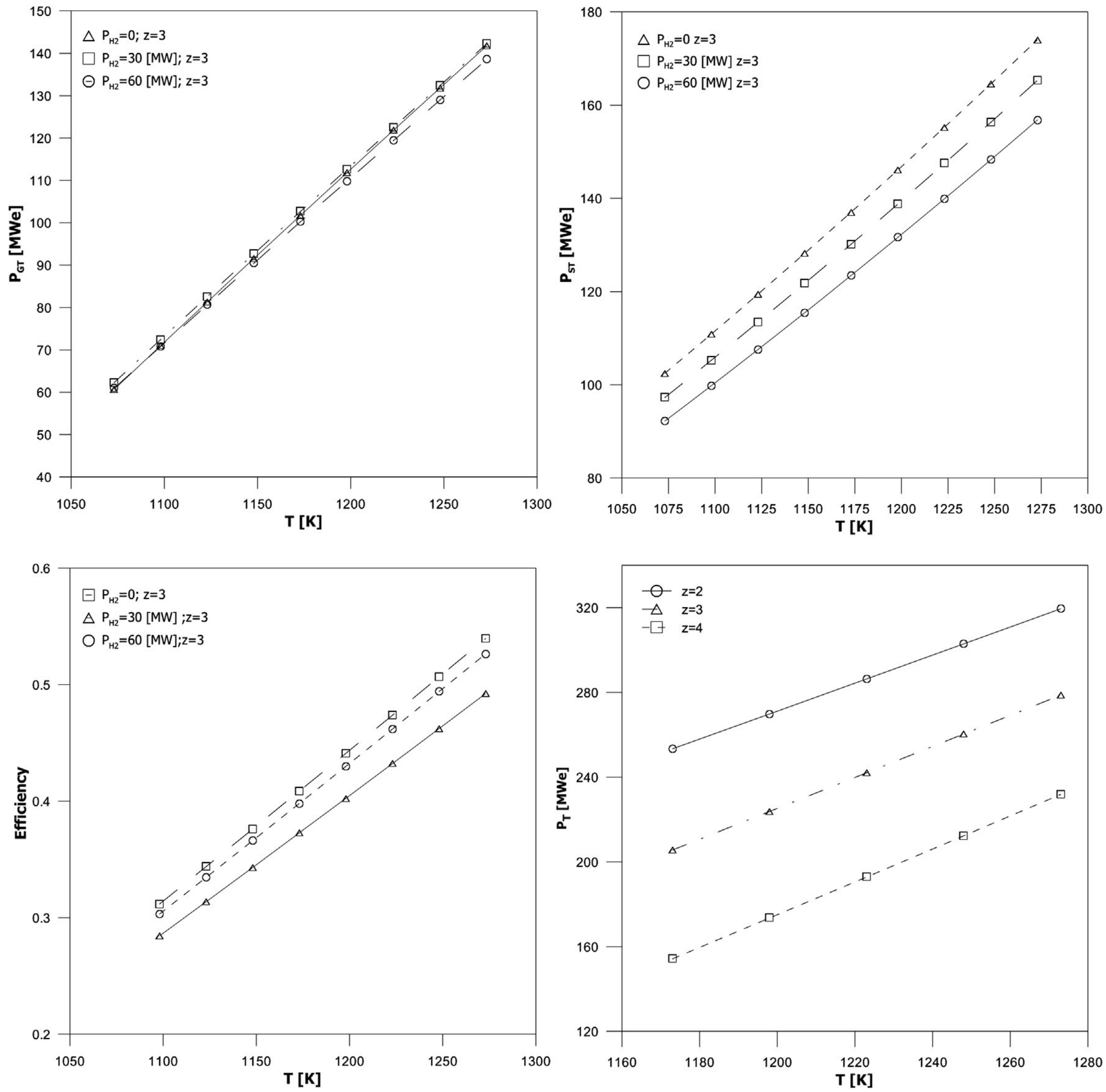

Fig. 5 – Variation of net electrical power output and cycle thermal efficiency with reactor outlet temperature *T* for various hydrogen production thermal power levels.

used for the thermochemical process then the overall cycle efficiency is up to about 10% lower, depending on location where the process heat is extracted (after or before the gas turbine).

Conclusions

High and very high temperature nuclear reactors can be used to produce electrical energy and hydrogen with S–I or Cu–Cl thermochemical cycles. The power conversion system has been analysed with hydrogen production in order to maximize the cycle efficiency. A helium Brayton cycle is known to be the most suitable for the VHTR because helium is a chemically stable and inert gas. Since the helium turbine is still in the development phase, an indirect cycle is used. In the present work, a secondary loop with He–N_2 drives the gas turbine and is available at present. The secondary side also connects process heat applications (hydrogen production) and the steam turbine system. For hydrogen production with the S–I or Cu–Cl thermochemical cycles, heat used for the process decreases the heat available for the gas and steam turbines or for the gas turbine only. To obtain an optimal efficiency and corresponding conditions, several reactor outlet gas temperatures and compressor compression ratios are considered for various hydrogen production rates. The resulting system power output rates and efficiencies are determined. The high cycle pressure allows a low number of turbine stages. In presently considered system, the compressor pressure ratio should be low (between $z = 2$ and $z = 3$). Increasing this parameter causes the plant efficiency to decrease significantly.

All cycles considered (with almost any other parameters settings) exhibit an increase in efficiency if the reactor outlet temperature is raised. More rapid increases in efficiency and power output rate are observed for the gas

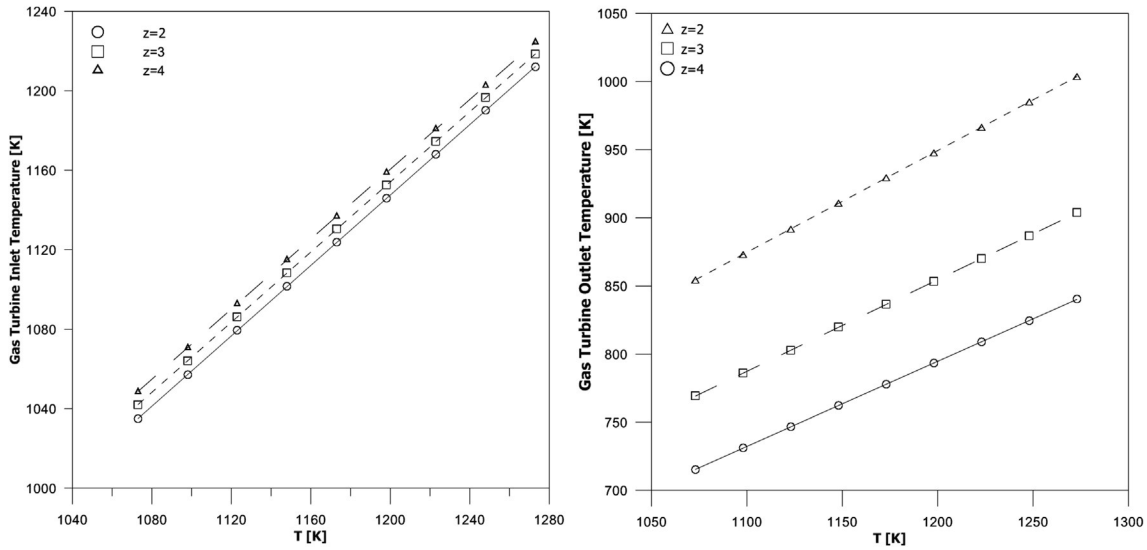

Fig. 6 – Variation of gas turbine inlet and outlet temperatures with reactor outlet temperature T for various values of compression ratio z.

turbine than for the steam turbine. Increasing the reactor outlet temperature from 900 °C to 1000 °C leads to an increase in plant power output rate as well as an increase in efficiency from 45% to 55%. Certainly the temperatures are by far not only parameter to improve efficiency. Other parameters like isentropic or mechanical efficiencies of the turbines or the compressor, and heat exchanger efficiencies, have significant influences. The production of hydrogen with the S–I process is possible if the primary helium gas temperature is at least 900 °C. The Cu–Cl process can be advantageous, both generally and especially if the system cannot operate with such a high temperature or if the system lifetime is potentially significantly decreased due to the high temperature. In that case, the reactor outlet temperature required for the process can be about 800 °C or lower. The resulting temperature exiting the gas turbine is about 612 °C, which is sufficiently high for hydrogen production via the Cu–Cl process. At such low temperatures, the thermal cycle efficiency declines to 39%. A further decrease in efficiency to 37% is obtained due to heat transport to the hydrogen production process. The cycle presented here has potential to improve the efficiency not only by raising the reactor core outlet temperature or gas/steam temperature, but also by permitting cycle modifications, e.g., introducing more steps in a gas turbine or compressor with intercooling between compressor stages [32].

High or very high temperature reactors used for electricity and hydrogen production have significant future potential to improve efficiency by raising the reactor outlet temperature or steam temperature. Only the VHTR with TRISO fuel is capable of operating at the temperatures required for very efficient hydrogen production. Small unit size, safety, low operation and maintenance costs, modular construction and high temperature may offer benefits for various applications beyond electricity generation (e.g., district heating, heating for refinery, metallurgical, petrochemical operations, and other high and low temperature process heating). In addition to the benefit of high efficiency energy conversion, hydrogen production or other thermal processes that require large amounts high temperature heat can be accommodated with such nuclear reactors.

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Nomenclature

P_{GT}	Gas turbine net power, MW_e
P_{ST}	Steam turbine (low and high pressure) net power, MW_e
P_T	Total electrical system power, MW_e
T	Nuclear reactor outlet temperature, K
Q_{reac}	Nuclear reactor thermal power, MW
h_i	Specific enthalpy of working fluid at point i
$\dot{m}_{gas}$	Working fluid mass flow rate, kg/s
z	Compressor compression ratio
η_ι	Isentropic efficiency of turbomachine
He	Helium gas
$He–N_2$	Helium and nitrogen gas mixture
H_2O	Water or steam

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