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Investigation of Hydrogen Production Rate of V-Cl Thermochemical Cycle Integrated Into Hybrid Reactor

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Anahtar Kelimeler

Hibrit Reaktör
Nükleer Hidrojen
Vanadyum-Klorür
V-Cl Termokimyasal Çevrim

Graphical/Tabular Abstract (Grafik Özet)

In this study, a neutronic analysis of a hybrid reactor was performed by mixing 50% TRISO-coated CANDU spent fuel with 50% Th. The hydrogen production rate of the integrated plant was analyzed via the V-Cl thermochemical cycle. / Bu çalışmada %50 TRISO-kaplı CANDU kullanılmış yakıt ile %50 Th karıştırılarak hibrit reaktörün nötronik analizi yapılmıştır. Hibrid reaktöre entegre edilen tesisin hidrojen üretim miktarı V-Cl termokimyasal çevrimi yoluyla analiz edilmiştir.

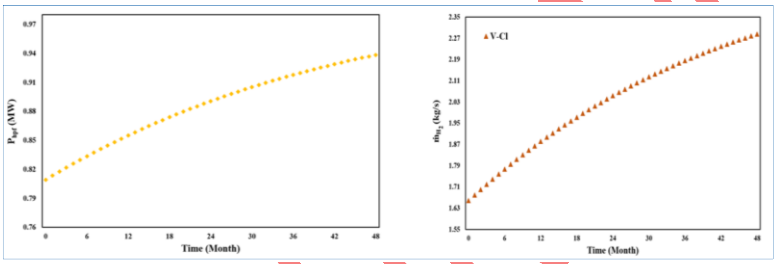

Figure A*: Time-dependent thermal power and hydrogen production mass for the V-Cl thermochemical cycle /* ***Şekil A:*** *V-Cl termokimyasal cevrimi için zamana-bağlı termal güc ve hidrojen üretim miktarı*

Highlights (Önemli noktalar)

- *Hydrogen production by V-Cl thermochemical cycle / V-Cl termokimyasal çevrimi ile hidrojen üretimi*
- *Neutronic Analysis and hydrogen production analysis of hybrid fission-fusion reactor / Hibrit fisyon-füzyon reaktörünü nötronik Analizi ve hidrojen üretim analizi*
- *Effect of TRISO-coated CANDU spent fuel and Th nuclear fuel mixture on the amount of hydrogen production / TRİSO-kaplı CANDU kullanılmış yakıtı ile Th nükleer yakıt karışımının hidrojen üretim miktarına etkisi*

Aim (Amaç): *Investigation of the effect of a mixture of 50% TRISO-coated CANDU spent fuel and 50% Th nuclear fuel on H_2 production in a hybrid fission-fusion reactor. / Hibrid fisyon-füzyon reaktöründe %50 TRISO-kaplı CANDU kullanılmış yakıtı ile %50 Th nükleer yakıt karışımının H_2 üretimine etkisinin incelenmesi.*

Originality (Özgünlük): *Investigation of time-dependent H_2 production potential of V-Cl thermochemical cycle integrated into hybrid fission-fusion reactor. / Hibrid fisyon-füzyon reaktörüne entegre edilen V-Cl termokimyasal çevriminin zamana bağlı H_2 üretim potansiyelinin incelenmesi.*

Results (Bulgular): *A total of approximately $2.57*10^5$ tons of H_2 was produced during the operation period of the V-Cl thermochemical cycle hydrogen production facility integrated into the hybrid fission-fusion reactor. / Hibrid fisyon-füzyon reaktörüne entegre edilen V-Cl termokimyasal çevrimli hidrojen üretim tesisinin operation periodunda toplam yaklaşık olarak $2.57*10^5$ ton H_2 üretilmiştir.*

Conclusion (Sonuç): *The hybrid reactor with TRISO-coated CANDU spent fuel and Th nuclear fuel mixture is a good energy source for H_2 production plant. / TRISO-kaplı CANDU kullanılmış yakıtı ile Th nükleer yakıt karışımlı Hibrid reaktörü H_2 üretim tesisi için iyi bir enerji kaynağıdır.*

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Abstract

Neutronic analyses were performed in a hybrid reactor using 50% TRISO-coated CANDU spent nuclear fuel and 50% Th mixture as fuel and natural Li as coolant. The XSDRNPM/SCALE nuclear code program was used for neutronic analyses. Under these conditions, the hybrid reactor operated for 48 months. TBR and M values were calculated from neutronic analyses. At the beginning of the 48-month operation period, the TBR value was approximately 1.176, while at the end of the operation period, this value was approximately 1.196. The M value was calculated as approximately 1.653 and 1.869 at the beginning and end, respectively. Additionally, the rate of hydrogen production in the hydrogen production facility integrated into the reactor was examined. The vanadium-chloride (V-Cl) thermochemical cycle was preferred as a method for hydrogen production. The approximate hydrogen production rate at the beginning and end of the 48-month operation period of the plant was calculated as 1,659 kg/s and 2,287 kg/s. As a result, it seems that the hybrid reactor and vanadium chloride (V-Cl) thermochemical cycle are preferable for hydrogen production.

Hibrit Reaktöre Entegre Edilen V-Cl Termokimyasal Çevriminin Hidrojen Üretim Miktarının İncelenmesi

Makale Bilgisi

Araştırma makalesi
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Öz

Yakıt olarak %50 TRİSO kaplı CANDU kullanılmış nükleer yakıtı ve %50 Th karışımı ve soğutucu akışkan olarak doğal Li kullanılan hibrit reaktörde nötronik analizler yapılmıştır. Nötronik analizler için XSDRNPM/SCALE nükleer kod programı kullanılmıştır. Bu şartlarda hibrit reaktör 48 ay çalışmıştır. Nötronik analizlerden TBR ve M değeri hesaplanmıştır. 48 aylık çalışma süresinin başlangıcında TBR değeri yaklaşık olarak 1,176 iken çalışma süresi sonunda bu değer yaklaşık olarak 1,196'dır. M değeri ise başlangıçta ve bitişte sırasıyla yaklaşık olarak 1,653 ve 1,869 olarak hesaplanmıştır. Ayrıca reaktöre entegre edilen hidrojen üretim tesisinde hidrojen üretim miktarı incelenmiştir. Hidrojen (H2) üretim yöntemi olarak vanadyum-klorür (V-Cl) termokimyasal çevrimi tercih edilmiştir. Tesisin 48 aylık çalışma süresi başlangıcında ve bitişinde ise yaklaşık olarak hidrojen üretim miktarı 1,659 kg/s ve 2,287 kg/s olarak hesaplanmıştır. Sonuç olarak hibrit reaktör ve vanadyum klorür (V-Cl) termokimyasal çevriminin hidrojen üretimi için tercih edilebilir olduğu görülmektedir.

1. INTRODUCTION (GİRİŞ)

Scientific studies and technological developments continue unabated to enable people all over the world to live a healthier, more comfortable, and more peaceful life. These developments and industrialization have provided comfort and economic growth. Energy is needed to achieve all these developments [1]. Until recently, this energy source was generally fossil fuels. The combustion of fossil fuels produces numerous emissions, such as CO, CO_2, ash, and NO_x. While some of these are easily biodegradable, others are persistent and harm the environment. Numerous efforts are underway to reduce these emissions. The goal is to reduce the use of fossil fuels, which are a major source of emissions, and, if possible, to eliminate them altogether. To address this problem, renewable

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energy sources have begun to be used instead of fossil fuels [2,3]. Several methods are used for these renewable energy sources, examples of which include biomass, solar photovoltaics, geothermal power, and hydropower. Nuclear power plants, although not renewable energy sources, provide low carbon emissions and continuous energy, and are therefore considered environmentally friendly. Furthermore, hydrogen, while not a renewable energy source itself, is a clean and sustainable energy carrier when produced with clean energy [4].

Şener and Acar [5] performed neutronic analyses of the SOMBRERO fusion reactor using 2%, 6%, and 10% UO_2 fuel at constant fuel zone thickness. TBR and M values were obtained from the neutronic analysis. Using the obtained M value, the H_2 production rate of the Mg–Cl thermochemical cycle integrated into the reactor was investigated. Özkaya and Acır [6] integrated Fe–Cl, Cu–Cl, and Co–Cl thermochemical cycle hydrogen production plants into the PACER fusion reactor and compared their hydrogen production potential. Acır and Özkaya [8] performed neutronic analyses of the PACER fusion reactor using the MCNP nuclear code. A mixture of 98% FLiBe and 2% MAF4 was used as molten salt fuel in the reactor. Fe–Cl, Mg–Cl (option I), and Mg–Cl (option II) thermochemical cycles were preferred in the hydrogen production facility. The hydrogen production potential of the hydrogen production facility integrated into the PACER fusion reactor was investigated with these cycles. Genç [9] conducted neutronic analysis of the APEX fusion reactor under different conditions, and the obtained energy was used in hydrogen production tests. In the hydrogen production facility, hydrogen production quantities were calculated and compared using SMR, S–I, and HTE hydrogen production methods. Asal et al. [17] performed neutronic analyses at 10% ThC + 90% FLiBe and different ^{6}Li enrichment ratios in the APEX fusion reactor using TRISO thorium fuel. Then, the hydrogen production capacity of the Co–Cl and Cu–Cl thermochemical cycle hydrogen production facility integrated into the reactor was investigated. As a result, the highest performance was calculated as 12.74 kg/s at a 90% ^{6}Li enrichment ratio with the Cu–Cl thermochemical cycle.

Pinsky et al. [7] investigated the hydrogen production amounts of proton exchange membrane electrolysis (PEM), alkaline water electrolysis, solid oxide electrolysis cells (SOEC), sulfur-iodine (S-I), hybrid sulfur (HyS), copper chloride (Cu-Cl) and calcium bromide (Ca-Br) cycles by taking advantage of both electricity generation and heat generation features of the nuclear hybrid energy system and compared them with the SMR method. Batgi and Dinçer [10] obtained a new Mg-Cl cycle with only heat input, without the electrolysis step of the three-step Mg-Cl thermochemical cycle. Then, Exergy and energy analyses of the obtained cycle were performed.

Safari and Dincer [16] developed and analyzed an integrated system consisting of a biomass gasification unit fed by the macroalps Clodophora glometara, a V-Cl thermochemical cycle, and a Brayton cycle. As a result, 850 kW power production and 23.42 kg/h hydrogen production were calculated. This system offers 53.2% energy and 52.6% exergy efficiency. In a related study, Hai et al. [18] reported that the system consists of a three-step V-Cl thermochemical cycle, an absorption cooler gasifier, gasifier, and Proton Exchange Membrane (PEM) fuel cell integration. The energy, exergy, carbon dioxide emission rate, and exergo environmental impacts of this proposed system were analyzed. Dashtizadah et al. [19] performed an economical and technical evaluation of hydrogen production from steel plant waste heat using V-Cl thermochemical cycle and proton exchange membrane electrolyzer. Three different scenarios were determined and, among them, the best scenario, the V-Cl thermochemical cycle, has the capacity to produce 203,018 tons of hydrogen per year with 43.71% energy efficiency and 56.64% exergy efficiency. Furthermore, Isaq and Dinçer [20] simulated the four-step V-Cl thermochemical cycle in the ASPEN Plus environment. Hydrogen and electricity co-production was calculated by integrating the V-Cl thermochemical cycle and the helium-closed Brayton cycle into the Small Modular Reactor (SMR). The system achieved a specific hydrogen production rate of 9.63g/kWh, and the total energy and exergy efficiencies were calculated as 16.94% and 21.42%, respectively.

In this paper, unlike previos studies, time-dependent neutronic and hydrogen production calculations of hybrid fusion reactor integrated with hydrogen production unit have been examined. As a novelty of the study, the hydrogen production potential of the V-Cl thermochemical cycle as time-dependent was investigated in the hydrogen production facility integrated with the hybrid reactor.

In this study, 50% TRISO-coated CANDU spent fuel and 50% Th nuclear fuel mixture were used as fuel in the reactor. This ratio was taken as a constant in order to ensure the consumability of both Th nuclear fuel and TRISO-coated CANDU spent nuclear fuel and because the main purpose of the subject is hydrogen production. Natural Li contains

7.5% 6Li and 92.5% 7Li isotopes. The 6Li isotope absorbs thermally energetic neutrons to yield tritium, and the reaction is exothermic. The 7Li isotope absorbs thermally energetic neutrons to yield tritium, and the reaction is endothermic. Natural Li was preferred in this study because it contributes a large amount to the tritium production in the reactor. Neutronic analyses of the reactor were performed with XSDRNPM/SCALE. The V-Cl thermochemical cycle, one of the newest thermochemical cycles, was found to be one of the best methods. The study also investigated the use of the V-Cl thermochemical cycle as a hydrogen production method during the 48-month plant operation period using data obtained from neutronic results.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Hybrid Fusion-Fission Reactor (Hibrit Füzyon-Fisyon Reaktörü)

The cross-sectional view of the fusion-fission hybrid reactor is given in Figure 1. The first wall with a thickness of 1.3 cm, made of SS-304 construction material, is located 300 cm away from the D-T neutron source. Then there is the fuel zone where 50% TRISO-coated CANDU spent fuel and 50% Th nuclear fuel are used. The fusion-fission hybrid reactor has three cooling zones with thicknesses of 12, 5, and 4 cm, and Li is used as the coolant in these zones. The ratio of the coolant volume to the fuel volume is taken as Vm/Vf = 5. Behind each of these cooling zones are carbon zones with thicknesses of 4, 6 and 16 cm. In the calculation, the facility factor was 100% and the neutron load was 5 MW/m2. Under these conditions, the neutronic analysis of the reactor was performed and the hydrogen production potential of the hydrogen production facility integrated into the reactor was examined. The parameters used in the study are given in Table 1. The hydrogen (H2) production facility integrated with the modified hybrid reactor is given in Figure 2.

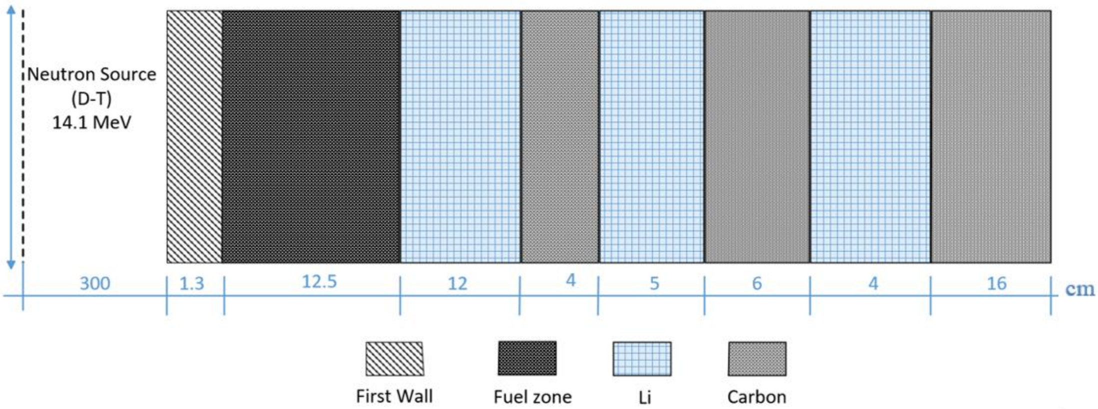

Figure 1. Blanket geometri of the hybrid reactor (Hibrit reaktörün manto geometrisi) [11]

Table 1. Technical specifications of the hybrid reactor (Hibrit reaktöre ait teknik özellikler)

Parameter	Value
Fusion energy gain, Q	4
Neutron particles fraction, x_n	0.8
Alpha particles fraction, x_a	0.2
Auxiliary system fraction, x_{aux}	0.05
Isotope separation system fraction, x_{isp}	0.05
Intermediate heat exchanger efficiency, η_{ihx}	0.9
Gas turbine efficiency, η_{gt}	0.6
Reaction efficiencies	0.9

*The SGT5-8.000H gas turbine operating with an efficiency of over 60% was taken as reference and calculations were made by taking the gas turbine efficiency as 60% [21].

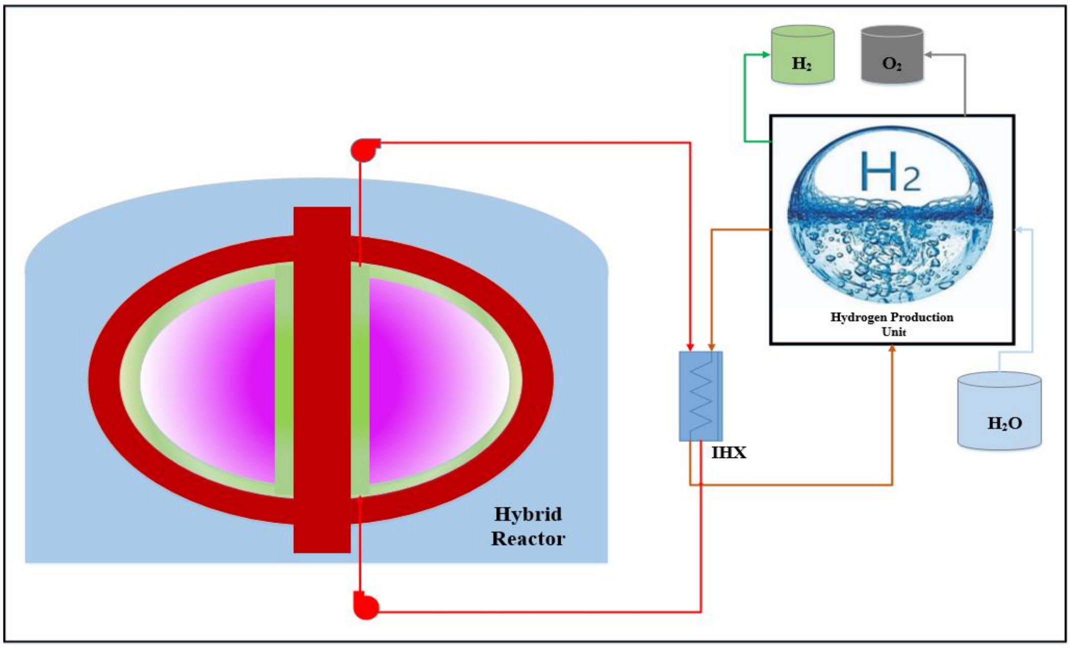

Figure 2. General flow diagram of hybrid reactor system with hydrogen production facility (Hidrojen üretim tesisli hibrit reaktör sisteminin genel akış şeması)

When comparing thorium fuel to uranium fuel, it is estimated that there are approximately three times as many thorium nuclear fuel as uranium nuclear fuel. This makes Thorium fuel naturally advantageous. However, since Th nuclear fuel cannot make fissile fuel on its own, it requires a fissile initiator. In this study, TRISO spent fuel was preferred as the fissile initiator required by the thorium nuclear fuel. In addition, TRISO particles used in the Gas Turbine Modular Helium Reactor (GT-MHR) were used in the calculations to achieve a high degree of combustion and to minimize nuclear waste [22]. The basic structure of the 2.2 mm diameter TRISO fuel is given in Figure 3. TRISO fuel is a multilayer-coated particle-type fuel. When Figure 2 is examined, the small spherical mixed WG-Plutonium/thorium fuel core in the center is surrounded by a porous carbon layer. Then, the inner pro carbon layer, SiC and outer pro carbon layer are the layers that constitute the TRISO spent fuel, respectively [23].

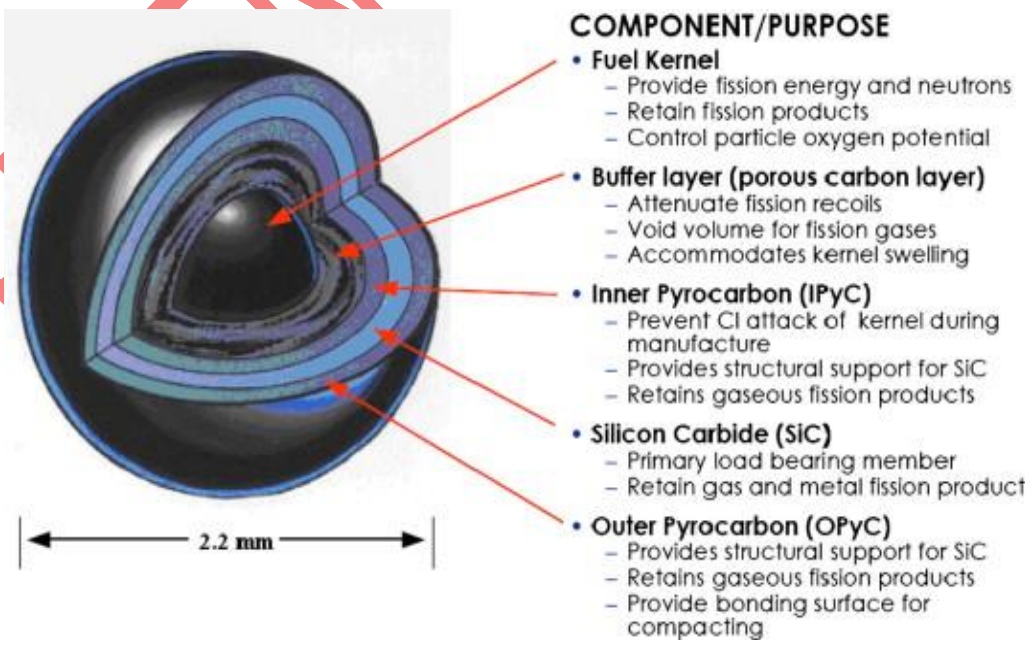

Figure 3. Basic structure of TRISO fuel (TRISO yakıtının temel yapısı) [23]

When it comes to the usage advantages of TRISO fuel, its multi-layered structure traps the fusion products, while the fuel particles remain intact even in classical nuclear accidents such as core meltdowns, indicating that the fuel is highly safe. Other advantages of TRISO fuel include its stability at temperatures up to 1600-1800 ^{0}C, the ability to reduce the production of long-lived actives, easier waste management and a lower likelihood of leakage into the environment [24].

2.2. Vanadium Chloride (V-Cl) Thermochemical Cycle (Vanadyum Klorür (V-Cl) Termokimyasal Çevrimi)

Thermochemical cycles are preferred for reasons such as high efficiency, low electricity consumption and no carbon emissions. The V-Cl thermochemical cycle requires less heat energy compared to many thermochemical cycles.

At this stage, a three-step V-Cl thermochemical cycle hydrogen production facility was integrated into the hybrid reactor, and the hydrogen production potential was investigated. The V-Cl thermochemical cycle is a pure cycle and requires only heat energy. The heat required for the V-Cl thermochemical cycle was calculated as 284.62 kJ/mol. All stages of the V-Cl thermochemical cycle, which is a clean hydrogen production method, are given in Figure 4. Equation 1 is the first step of the reaction, and at 798 K, VCl3 decomposes into VCl2 and Cl2. In this first step, an endothermic reaction occurs [16].

$$\boldsymbol{2VCl_{2(s)} \xrightarrow{798\,K} Cl_{2(g)} + 2VCl_{2(s)}} \tag{1}$$

In the second stage of the reaction, the Cl_2 gas produced in the first step reacts with H_2O at 373K to form HCl and O_2 gas. The step, which is an endothermic reaction, is called the reverse Deacon reaction [16]. This process is given in equation 2.

$$H_2O_{(g)} + Cl_2 \xrightarrow{373\,K} 1/2O_{2(g)} + 2HCl_{(g)} \tag{2}$$

An exothermic reaction occurred in the last step of the V-Cl thermochemical cycle, and this reaction is given in Equation 3 [16]. In this step, the VCl_2 produced in the first step and the HCl produced in the second step react at 573 K to produce VCl_3 and H_2.

$$\boldsymbol{2HCl_{(g)} + 2VCl_{2(g)} \xrightarrow{573\,K} H_{2(g)} + 2VCl_{3(g)}} \tag{3}$$

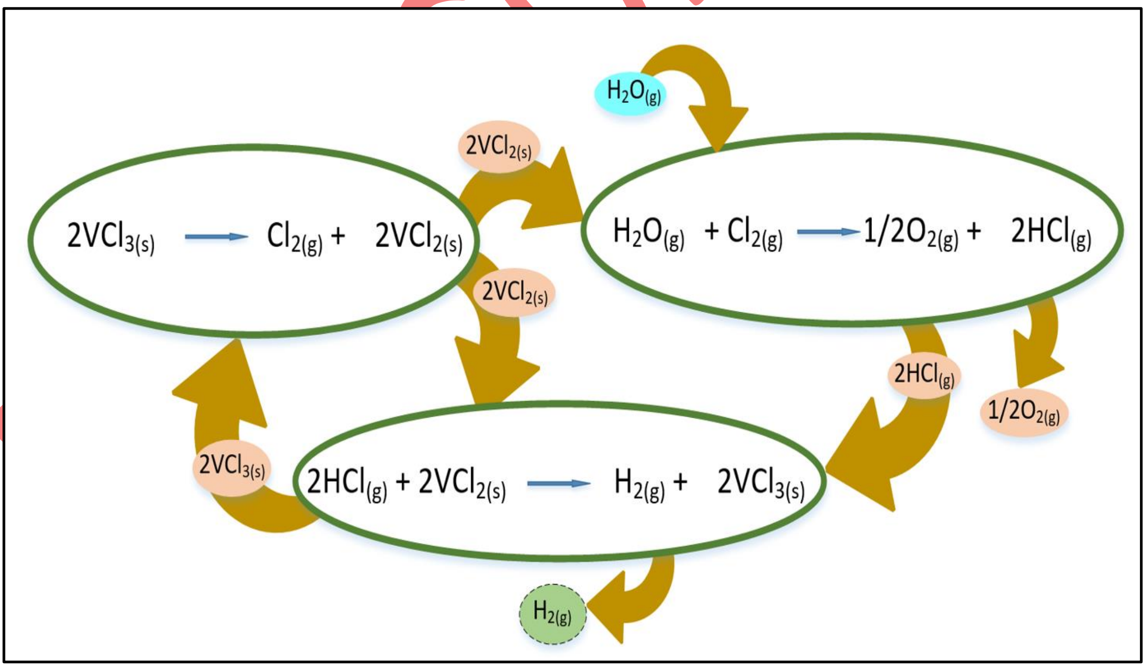

Figure 4. V-Cl thermochemical cycle schematic view (V-Cl termokimyasal döngüsünün şematik görünümü)

The heat required during the process is calculated by the following eqs (5-7) [6,8,12-14].

$$\dot{E}_{in} = \dot{E}_{out} \tag{5}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum n_{in} H_{in} = \dot{Q}_{out} + \dot{W}_{out} + \sum n_{out} H_{out} \tag{6}$$

$$\bar{h}(T) - \bar{h}_o = AT + B\frac{T^2}{2} + C\frac{T^3}{3} + D\frac{T^4}{4} - \frac{E}{T} + F - H \tag{7}$$

Where, $\dot{\boldsymbol{E}}$ is total energy transfer (kW), $\dot{\boldsymbol{Q}}$(kW) is heat, $\dot{\boldsymbol{W}}$ (kW) is work, $\overline{\boldsymbol{h_0}}$ (kJ/mol) is standard enthalpy, $\bar{h}$ (T) is sensible enthalpy. T represents 1/1000 of the temperature K given in the reaction. A-H indices are the SHOMATE values of the compounds belonging to the V-Cl thermochemical cycle given in Table 2 [6,8,12,13]. The SHOMATE equation is a method used to calculate data such as heat capacity and enthalpy using polynomial equations. There are many polynomial coefficients in the literature. However, the SHOMATE equation is one of the most used and accurate methods [15].

Table 2. Shomate data of compounds belonging to the V-Cl thermochemical cycle (V-Cl termokimyasal çevrimine ait bileşiklerin shomate verileri)[15]

Com.	T (K)	h°f (kJ/mol)	A	B	C	D	E	F	G	H
Cl_2 (g)	798-373	0	33.050	12.2294	-12.0651	4.3853	-0.159494	-10.8348	259.029	0
HCl(g)	373-573	-92.312	32.124	-13.4580	19.868	-6.854	-0.049	-101.62	228.68	-92.312
O_2 (g)	0.373	0	31.322	-20.235	57.866	-36.5	-0.007	-8.903	246.8	0
H_2O(g)	0.373	-241.826	30.092	6.832514	6.793435	-2.5344	0.082139	-250.881	223.3967	-241.82
H_2 (g)	0.573	0	33.066	-11.363	11.432	-2.7720	-0.0158	-9.9810	172.70	0

VCl_3 and VCl_2 compounds do not have SHOMATE values. These compounds are calculated using equations 8 and 9 below [16].

For VCl_3;

$$\bar{h}(T) - \overline{h_o} = (22.99)T + (1.96*10^{-3})\,T^2 + (1.68*10^5)T^{-1} - 7592 \quad (8)$$

For VCl_2;

$$\bar{h}(T) - \overline{h_o} = (17.25)T + (1.36*10^{-3})\,T^2 + (0.71*10^5)\,T^{-1} - 5502 \quad (9)$$

3. RESULTS AND DISCUSSION (Sonuçlar ve tartışma)

A measure of the sustainability of the hybrid reactor is the tritium breeding ratio (TBR). For the reaction to continue on its own in the reactor, the TBR value must be greater than 1.05. The value of tritium obtained from ^{6}Li given in equation 10 is T_6, and the value of tritium obtained from ^{7}Li in equation 11 is T_7. The TBR value is calculated by the sum of T_6 and T_7 given in Equations 10 and 11, as in Equation 12 [12].

$$6Li + n \longrightarrow He + T6 + 4{,}7484\ MeV \quad (10)$$

$$7Li + n \longrightarrow He + T7 + n - 2{,}467\ MeV \quad (11)$$

$$TBR = T7 + T6 \quad (12)$$

As seen in equations 10 and 11, an endothermic and an exothermic reaction occur as a result of the reaction of ^{6}Li and ^{7}Li with low-energy neutrons. The inlet and outlet temperatures of the natural Li coolant were calculated based on the 48-month operation period of the hybrid reactor. Depending on the thermal power of the hybrid reactor, the inlet temperature of the Li coolant is ~620 K, and the outlet temperature is ~820 K [25, 26]. This is a sufficient value to meet the requirements of the V-Cl thermochemical cycle.

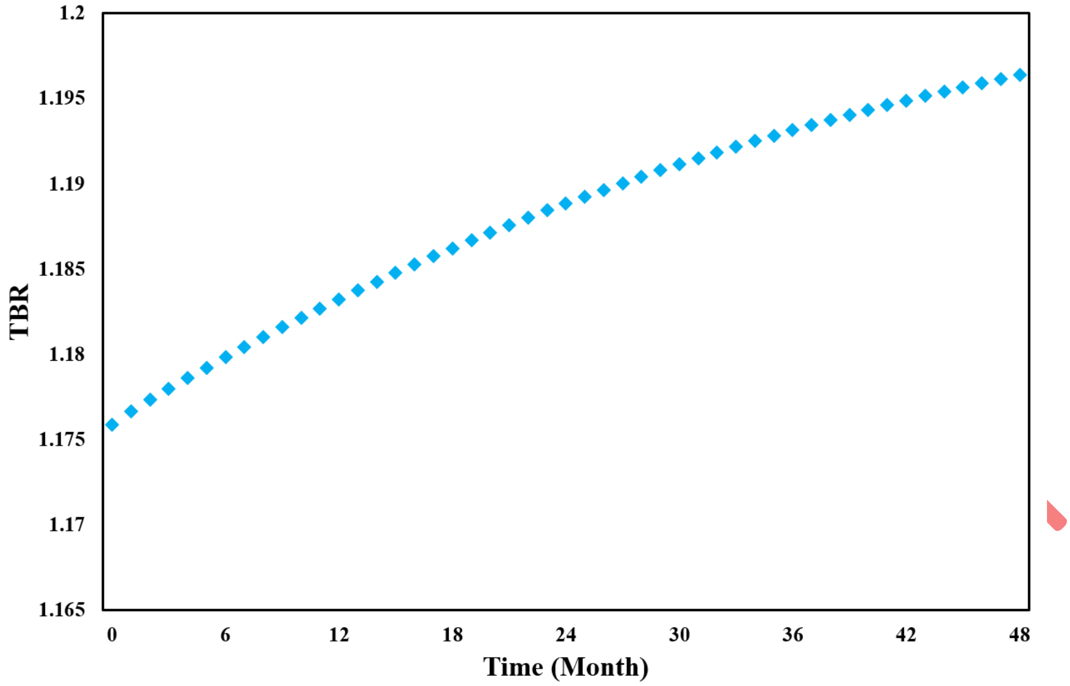

Figure 5. Tritium breeding ratio (TBR) depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and 50% Th nuclear fuel(%50 TRISO kaplı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı tritium üretim oranı (TBR))

The TBR value obtained from the fusion-fission hybrid reactor over time is shown in Figure 5. The reactor was self-sustaining for 48 months. The initial and 48-month TBR values of the 50% TRISO-coated CANDU spent nuclear fuel and 50% Th nuclear fuel mixture were calculated to be approximately 1.176 and 1.197, respectively.

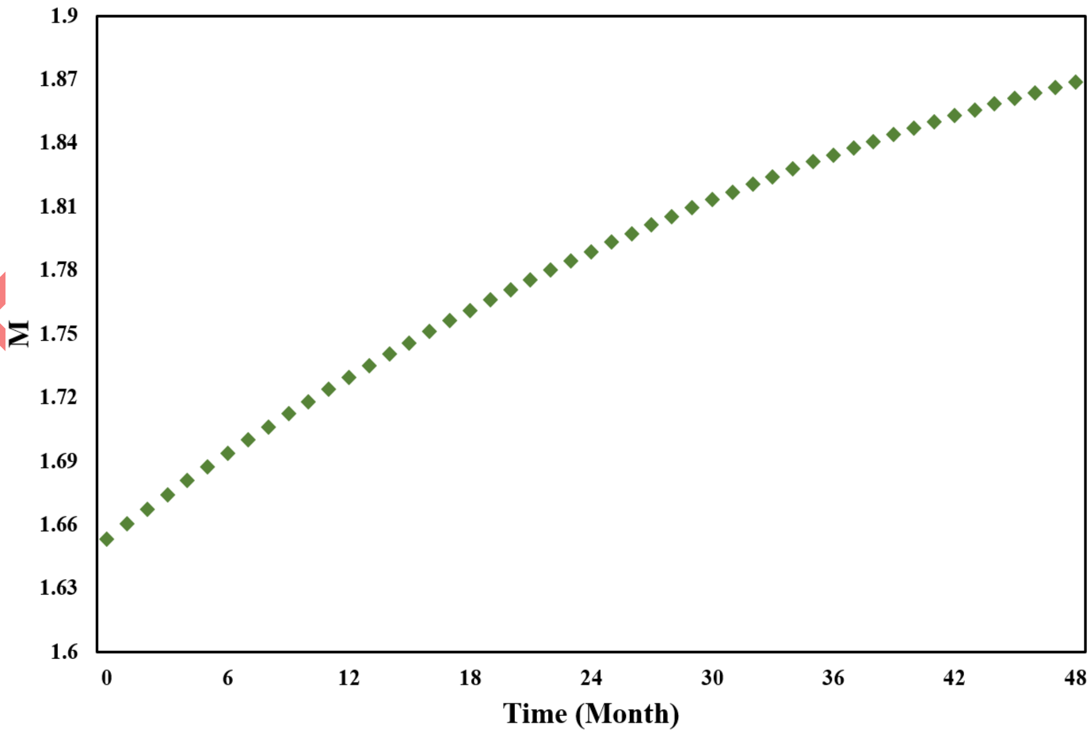

Figure 6. Energy multiplication factor (M) depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and 50% Th nuclear fuel (%50 TRISO kaplı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı enerji çoğaltım faktörü (M))

The initial and final values of the data obtained from the neutronic analyses of the fission-fusion hybrid reactor using 50% TRISO-coated CANDU spent nuclear fuel and 50% Th nuclear fuel are detailed in Table 3.

Table 3. Initial and finish value depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and 50% Th nuclear fuel (%50 TRISO kaplamalı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı başlangıç ve bitiş değeri)

	T_6	T_7	TBR	M
initial	0.92174	0.25412	1.17586	1.65303
finish	0.94043	0.25595	1.19638	1.8687

The energy production of the hybrid fusion-fission reactor was calculated using equation 13 [5,6,8,13,17].

$$M = 1 + \frac{200Mev<\Phi*\Sigma_f> + 4.786\,MeV*T_6 - 2.467\,MeV*T_7}{14.1\,MeV} \quad (13)$$

Where, 200 MeV is the energy released as a result of the fission reaction, $\Phi \left(\frac{noutron}{cm^2/_s}\right)$ is the neutron flux, Σ_f (cm^{-1}) is s the microscopic cross section of the fission and 14.1 MeV is the energy of a neutron.

The energy multiplication factor (M) was obtained as a result of the reactions occurring with the 50% TRISO-coated spent CANDU fuel and 50% Th nuclear mixture used in the reactor. The M value obtained after 48 months of operation of the hybrid reactor is given in Figure 6. When Figure 6 is examined, the value was calculated to be approximately 1.66 at the beginning, while the value at the end of 48 months was calculated to be approximately 1.87. The presence of fissile material (Th) in the coolant not only produces high-quality nuclear fuels but also enhances energy multiplication through additional fission reactions. That is, depending on the fissile material, power production (M) has increased continuously for 48 months.

The total thermal power and thermal power ratio required by the V-Cl thermochemical cycle hydrogen production facilities integrated into the hybrid fusion-fission reactor are calculated with the equations (14,15) given below [5,6,8,13,17].

$$\psi = \frac{1}{\eta_{ihx}*\eta_{ds}[Q*(x_a+x_n*M)+1]*[\eta_{gt}+\varepsilon-\eta_{gt}*x_{net}]} + \frac{\varepsilon}{[\eta_{gt}+\varepsilon-\eta_{th}*x_{net}]} + \frac{x_{aux}+x_{isp}}{\eta_{ihx}*[\eta_{gt}+\varepsilon-\eta_{gt}*x_{net}]} \quad (14)$$

$$P_{hpf} = (1-\psi)*(1+\varepsilon)*\eta_{ihx}*\frac{P_f}{Q}*[Q*(x_a+x_n*M)+1] \quad (15)$$

The symbols used in equations 14 and 15 are given in Table 1. The thermal power ratio and total thermal power required by the H_2 production facility are given in Figures (7, 8). The thermal power ratio increased depending on the M value over 48 months. The thermal power ratio, which is approximately 0.362 at the beginning, reaches 0.391 after 48 months. When Figure 8 is examined, it is seen that the total thermal power increases in parallel with the M value. The total thermal power is ~ 0.809MW at the beginning and ~ 0.938 MW in 48 months.

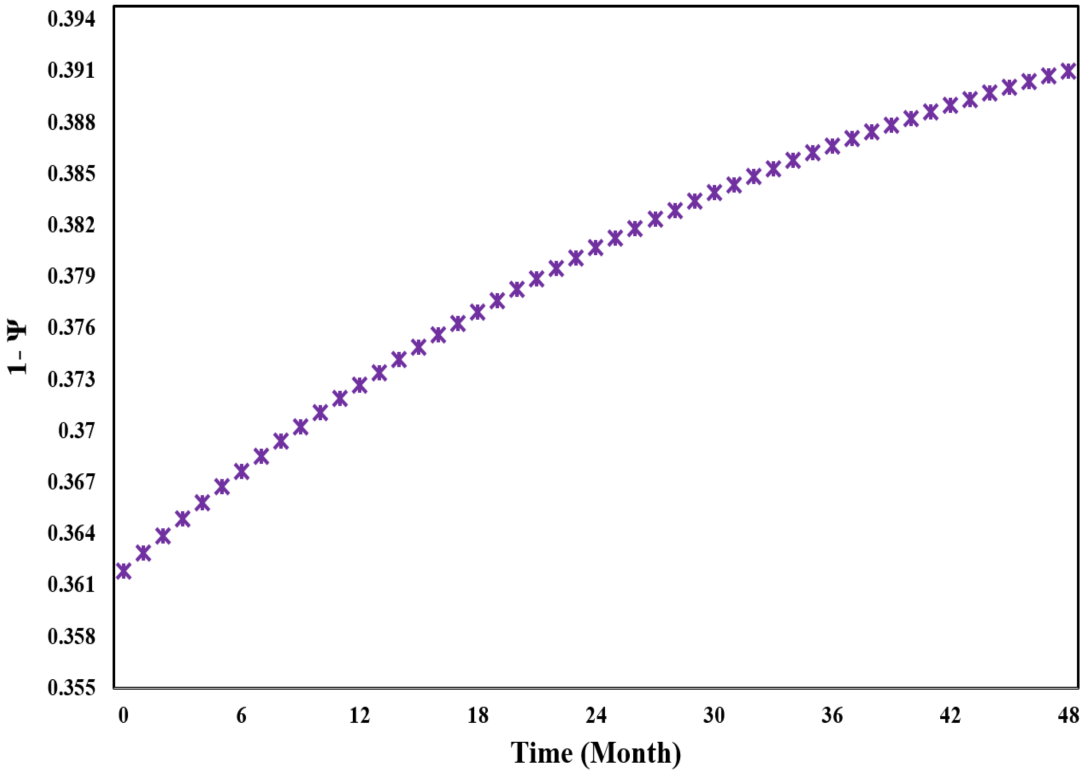

Figure 7. Thermal pawer ratio (1- ψ) depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and 50% Th nuclear fuel(%50 TRISO kaplı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı termal güç oranı (1- ψ))

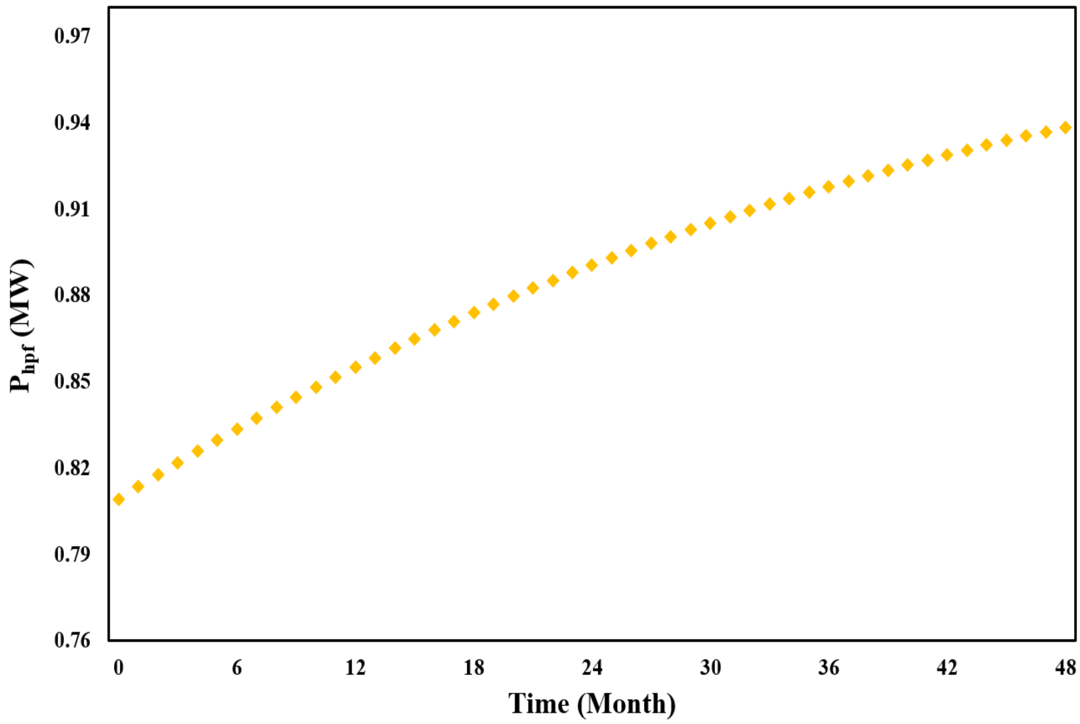

Figure 8. Total thermal power (P_{hpf}) depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and 50% Th nuclear fuel (%50 TRISO kaplı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı toplam termal güç (P_{hpf}))

The hydrogen mass flow equation of the vanadium chloride thermochemical cycle used in the hydrogen production facility is calculated by the equation (16-18) given below [6,8,13].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (16)$$

$$\dot{m}_x = \frac{P_{hpf}}{q_{tot}} \quad (17)$$

$$\dot{m}_y = \dot{m}_x * \frac{u_y}{u_x} * \eta \quad (18)$$

Where $\dot{m}$ is the mass flow rate, u (g/mol) is the molar mass of the compound, η is the efficiency of the reactions, and q_{tot} (MJ/kg) is the total energy. The in and out indices are used as examples of reactants and products for each chemical; the x and y indices are used as examples for each element.

The hydrogen production rate of the V-Cl thermochemical cycle hydrogen production facility integrated into the hybrid fusion- fission reactor is given in Figure 9.

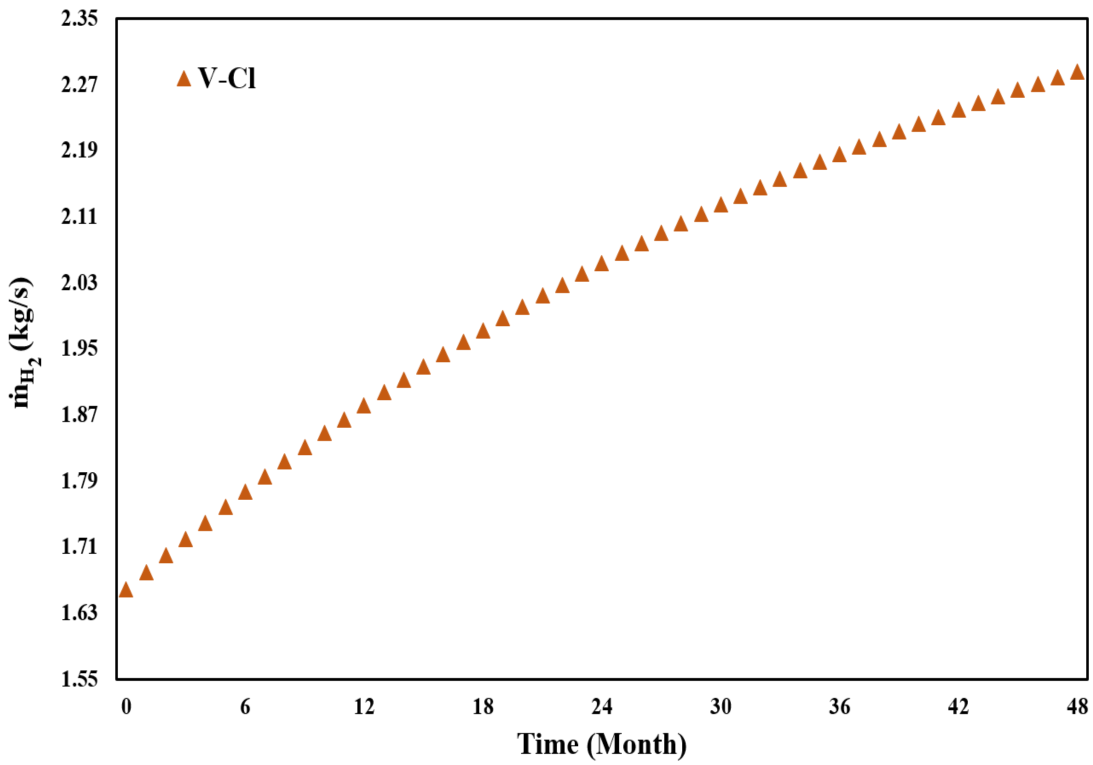

Figure 9. Hydrogen production amount ($\dot{m}_{H_2}$) depending on time for a mixture of 50% TRISO coated CANDU spent nuclear fuel and50% Th nuclear fuel (%50 TRISO kaplı CANDU kullanılmış nükleer yakıt ve %50 Th nükleer yakıt karışımı için zamana bağlı hidrojen üretim miktarı ($\dot{m}_{H_2}$))

The hydrogen production rate of the V-Cl thermochemical cycle hydrogen production facility, integrated into the hybrid fusion-fission reactor and using 50% TRISO-coated CANDU spent fuel and 50% Th nuclear fuel, increases continuously for 48 months, depending on the M value increase. The total amount of hydrogen produced in the V-Cl thermochemical cycle hydrogen production facility integrated into the reactor was calculated as approximately 2.57*10^5 tons at the end of the 48-month operation period. Generally speaking, the hybrid fusion-fission reactor and the V-Cl full chemical cycle hydrogen production method showed good performance.

Table 4 compares the hydrogen production results obtained in this study with the results of different thermochemical cycles given in the literature. Generally, the hydrogen production of the hybrid reactor appears to have good performance compared to literature results.

Table 4. Comparison of the amounts of hydrogen produced for various hydrogen production cycles (Çeşitli hidrojen üretim çevrimleri için üretilen hidrojen miktarlarının karşılaştırılması)

Reference	Type	Cycle	H_2 Production rate (kg/s) (initial value)
Present work	Hybrid reactor	V-Cl	1.659
Ref [5]	SOMBRERO fusion reactor	Mg-Cl	5.9203
			8.12686
Ref [8]	PACER fusion reactor	Fe-Cl	~13
		Mg-Cl (optio I)	~39
		Mg-Cl (option II)	~26
Ref [12]	APEX fusion reactor	SMR+WGS+MCS	218
		SMR+WGS	100
		SMR	60
		HTE	8.60
		S-I	8.40
Ref [13]	PACER fusion reactor	Fe-Cl	7.36
			10.96
Ref [16]	biomass	V-Cl	23.42 kg/h

4. CONCLUSIONS (SONUÇLAR)

In this study, recent developments on thermochemical cycling were examined and then the H_2 production potential of the V-Cl thermochemical cycle was investigated by integrating the V-Cl thermochemical cycle hydrogen production unit into the hybrid fusion-fission reactor. This method promises sustainable hydrogen production. The study results are listed as follows;

- ❖ The TBR and M values of the hybrid fusion-fission reactor using 50% TRISO-coated CANDU spent fuel and 50% Th nuclear fuel showed a continuous increase during the 48-month operation. The TBR and M values at the 48-month operation presentation were approximately 1.197 and 1.87, respectively.
- ❖ During 48 months of operation under these conditions, the thermal power ratio increased by approximately 8% and the total thermal power increased by approximately 16%.
- ❖ The rate of hydrogen produced in the hybrid fusion-fission reactor V-Cl thermochemical cycle hydrogen production facility increased by approximately 38% during the study period.

As a result, it is seen that 50% TRISO-coated CANDU spent fuel 50% Th nuclear fuel hybrid fusion-fission reactor is a good energy source for a hydrogen production facility and is preferable for hydrogen production facilities. In addition, the H_2 production potential of the vanadium chloride thermochemical cycle has made it promising for the commercialization of its use in hydrogen production facilities as a sustainable hydrogen production method.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Medine ÖZKAYA*:** She carried out the numerical analysis, analyzed the results and wrote the article.

Sayısal analizleri yapmış, sonuçlarını analiz etmiştir ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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