

Employing of ZrCo as a fuel source in a discharge-type fusion neutron source operated in self-sufficient mode

Shunsuke Kenjo ^{a,1,*}, Yasuyuki Ogino ^a, Keisuke Mukai ^b, Mahmoud Bakr ^{b,2,3}, Juro Yagi ^b, and Satoshi Konishi ^b

^a Graduate School of Energy Science, Kyoto University, Uji, Kyoto 611-0011, Japan

^b Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan

* Corresponding author: kenjo.shunsuke.83e@st.kyoto-u.ac.jp

1 Present address: National Institute for Quantum and Radiological Science and Technology, Rokkasho, Aomori, Japan.

2 Present address: Physics Department, Faculty of Science, Assiut University, Assiut 71516, Egypt.

3 Present address: Faculty of Science, Galala University, Alsokhna, 43511, Egypt.

Abstract

A discharge-type fusion neutron source generates neutrons by fusion reactions of hydrogen isotope atoms. In order to operate the fusion device based on the deuterium–tritium (D–T) fusion reaction, the tritium inventory is required to be decreased. In the present work, a self-sufficient system was installed into the fusion device for reducing the amount of hydrogen isotope fuel gas. The fuel gas was supplied and recovered with an intermetallic compound ZrCo in a sealed chamber in this system. A deuterium–deuterium operation was maintained for more than 60 min with stable discharge voltages, and the temperature of the ZrCo bed was changed to improve the neutron production rate. Factors that influenced the pressure inside the chamber were determined and optimized. Gas analysis using a quadrupole mass spectrometer indicates a dilution of the deuterium fuel was caused by hydrogen isotope exchange between the supplied deuterium gas and the absorbed protium on the chamber and electrodes surface. This system's hydrogen isotope control method and the amount of fuel were proposed for a D–T operation.

Keywords: Intermetallic compound, Hydrogen storage, Hydrogen isotope effect, Nuclear fusion, Neutron source

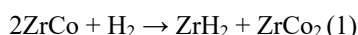
1. Introduction

A fusion neutron source, a discharge-type, has many advantages, including simple configuration, compact system, minimal start-up and maintenance, and operational easiness [1–5]. The neutron source generates neutrons by applying high voltage and inducing a glow discharge plasma. In the discharge plasma, fusion reactions occur by accelerated ions between two electrodes. In order to increase the neutron yield, applying higher voltage and increasing current are the most effective methods. The applied voltage has an opposite dependence on the gas pressure inside a vacuum vessel. The neutron source has been studied for various applications such as landmine detection, cancer therapy, medical isotope production, and radiography [6–8]. When the neutron source's deuterium–tritium (D–T) operation is achieved, the number of generated neutrons is expected to increase by two orders of magnitude due to the collision cross-section increase of the D–T reaction in comparison to the deuterium–deuterium (D–D) reaction. Thus, the applications of the fusion neutron source increase. In addition, the neutron source can be employed for conducting a D–D neutron transport experiment in order to examine the tritium breeding performance of a fusion blanket mock-up [9]. Tritium self-sufficiency is essential for a D–T fusion reactor, and the tritium breeding ratio has to be larger than unity [10]. It is desired to conduct neutron transport experiments with D–T neutron sources in order to simulate similar conditions as fusion reactors. So far, no D–T neutron transport experiment employing a discharge-type fusion neutron source has been conducted because of the difficulty of using tritium as fusion fuel.

The typical operation of the fusion neutron source is based on the D–D fusion, in which D₂ fuel gas is continuously supplied and pumped out to keep the pressure in the range of 0.5–2.0 Pa and maintain the discharge. This system requires much fuel, and it is problematic to use tritium because of a vast inventory and environmental issues. A possible solution is sealing the chamber and employing a metal getter, which recovers and delivers hydrogen isotope gas depending on temperature. Yamamoto et al. operated the fusion device in this way, which fueled D–T mixing gas, and measured neutron production rate (NPR) [11]. However, the amount of the supplied fuel was not enough to sustain the discharge for more than 2 min. An additional experiment installed on the same system was conducted, and a discharge was sustained for more than 1 hour by supplying H₂ gas [12]. However, the sealed system's D–D operation has not been performed before conducting the present work. Moreover, in the sealed system, a long-term D–D operation will affect the gas composition inside the chamber with time; hence it is required to investigate the effect of a long-term operation on the gas composition change.

In the present work, a new self-sufficient system was constructed to reduce the amount of hydrogen isotope fuel. In order to supply and recover hydrogen isotope fuel in a sealed vacuum vessel, an intermetallic compound ZrCo was employed. Uranium has been used for supply and recovery of hydrogen isotope because of a large hydrogen storage ability and rapid absorption and desorption kinetics. However, uranium is highly pyrophoric and a nuclear material. Therefore, alternative hydrogen supply and recovery materials have been studied and ZrCo has been a candidate material for ITER storage and delivery system [13–15]. ZrCo has a large hydrogen storage capacity and can absorb hydrogen isotope until the hydrogen-to-ZrCo molar ratio reaches 3. The material shows moderate equilibrium pressure depending on temperature. Equilibrium pressures are different with hydrogen isotopes [16,17]. The rapid supply and recovery abilities are attractive characteristics of ZrCo [14,18]. Reportedly, catalytic Pd and Ni coatings on ZrCo samples improved hydriding kinetics [19,20]. On the other hand, a Ni coating is also beneficial for a dehydriding reaction [20]. Furthermore, ZrCo exhibits favorable properties such as easiness of handling, low pyrophoricity, and non-radioactive. For example, the activation process of ZrCo is much easier than TiFe [21]. Therefore, ZrCo is a promising material for a self-sufficient system.

It has been reported, however, that ZrCo has the drawback of the disproportionation reaction [22–24], and the reaction can be written as follow:



The products of the reaction are stable, and the hydrogen storage capacity of ZrCo is attenuated. The reaction occurs at high hydrogen pressure above 400 °C [22]. When supplying hydrogen isotope until high pressure, high temperature is needed. In order to remove the stable products of the reaction, evacuation at high temperature is effective. This process reverses the reaction [22]. Kou et al. reported the reproporationation reaction occurs even under hydrogen atmosphere [25]. The hydrogen storage capacity of ZrCo lost after repeated absorption–desorption cycles depending on parameters such as temperature and hydrogen pressure [26]. The disproportionation reaction causes this degradation. In order to improve the anti-disproportionation ability and the cycle stability of ZrCo, a Ni coating [20] and elements substitutions employing such as Ti, Ni, and Fe were conducted [27–29]. Besides these researches, the effects of these substitutions on the disproportionation reactions were investigated with first-principal calculations [30–32]. In this study, the pressure inside the chamber is around 1 Pa, and the high temperature is not necessary. Therefore, these problems can be avoided.

The present study aims to demonstrate a D–D operation with a self-sufficient system employing a ZrCo sample and reveal the effect of the gas composition change inside the chamber during the operation. First, the ZrCo sample was prepared and installed into the self-sufficient system. Then, a stable D–D operation and NPR control via the temperature changes of the ZrCo sample were demonstrated. Moreover, the gas compositions inside the chamber before and after the operation were analyzed. The results of the operation and gas analysis are discussed and concluded in the last section.

2. Method

2.1 Sample Preparation

A ZrCo sample was prepared by arc melting in argon atmosphere. A zirconium rod (99.2% pure) and a cobalt ingot (99.9% pure) were covered with a zirconium foil (99.2% pure) and melted few times. The sample was heated at 500 °C for 4 hours while evacuating, which is a suitable procedure for a rapid activation [33]. Then, the sample was activated through multiple hydriding–dehydriding cycles by supplying deuterium gas and changing the temperature between 100 and 300 °C. The procedure broke the ingot into a powder. Finally, evacuation was conducted at 500 °C to let the powder release the absorbed deuterium. The crystal structures of the powders before and after the evacuation were investigated by powder X-ray diffraction (XRD) using Co-K α radiation.

2.2 Fusion device

A schematic drawing of a fusion device is shown in Fig. 1. A cylindrical cathode was put in a stainless steel (SS) chamber, which was negatively biased. Two grounded cup-shaped anodes were located at both ends of the chamber. Both the cathode and the anodes were made of SS. The temperature of the chamber surface was measured with a thermocouple. The cylindrical chamber was connected with a gas analysis system and a fuel supply–recovery system.

A fuel supply–recovery system was designed to supply and recover D₂ fuel with a ZrCo sample by controlling the temperature of a ZrCo bed. The ZrCo bed was a U-shaped SS tube, 1/2-inch diameter, which was coiled by a sheathed heater and covered with a thermal insulator. Approximately 1 g of the ZrCo sample before the activation process was put in the U-shaped tube. A thermocouple was injected into the tube. A 1 L tank was installed to measure the amount of the D₂ fuel supplied to the ZrCo sample.

A gas analysis system had a 1 L tank between the chamber and a quadrupole mass spectrometer (QMS) to sample the gas inside the chamber for gas analysis. In addition, the system was designed to evacuate the chamber with a rotary pump (RP) and a turbo molecular pump (TMP) before supplying the fuel from the ZrCo sample. The pressure inside the chamber was measured with a Pirani gauge and a capacitance manometer (CCMT–1D).

Produced neutrons were measured with a GE Reuter Stokes ^3He gas-filled detector. The detector was placed below the chamber and surrounded with polyethylene blocks (50 mm $\times$ 50 mm $\times$ 395 mm and 50 mm $\times$ 25 mm $\times$ 395 mm) to moderate neutrons and lead sheets (2 mm thickness, rolled twice) to shield X-ray (Fig. 2). The distance between the chamber and the detector was 285 mm. The calibration was conducted using a ^{252}Cf spontaneous fission neutron source which was placed on the chamber for 12 hours. A calibration factor was obtained from the measured count and the number of source neutrons.

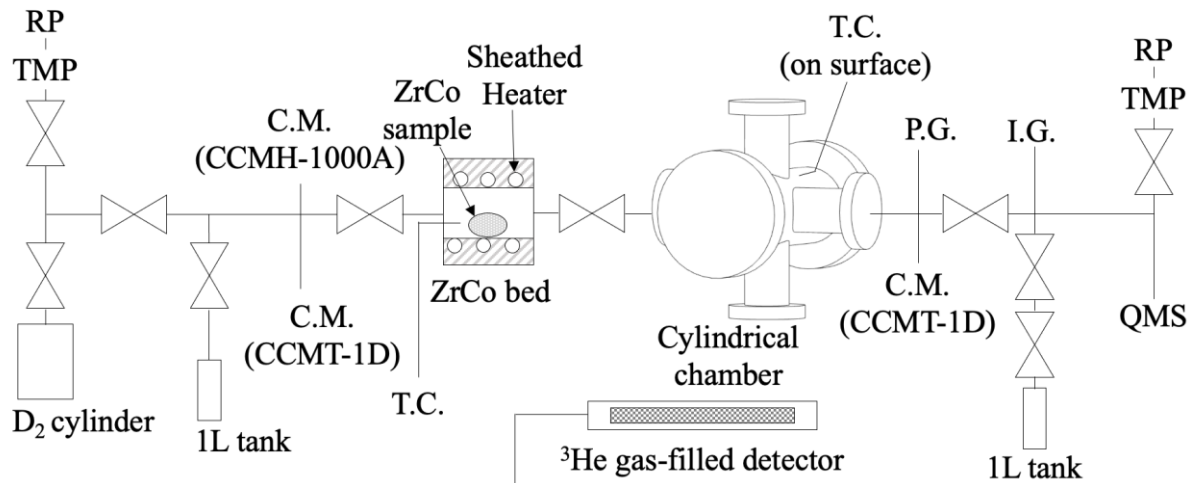


Fig. 1 A schematic drawing of the fusion neutron device with a self-sufficient system. The left side of the chamber is the fuel supply–recovery system. The right side of the chamber is the gas analysis system. RP, TMP, C.M., T.C., P.G., I.G., and QMS denote rotary pump, turbo molecular pump, capacitance manometer, Pirani gauge, ion gauge, and quadrupole mass spectrometer, respectively.



Fig. 2 The ^3He gas-filled detector under the chamber. Lead sheets and polyethylene blocks surrounded the detector.

2.3 Operation procedure

Before the operation, the ZrCo sample was activated in the same procedure as mentioned in Sec. 2.1. Then, the D_2 fuel gas was supplied from the ZrCo sample by the following five steps.

- (1) The sample was heated at 500 °C while pumping. The procedure cleaned up the sample surface and returned the disproportionated products to ZrCo.
- (2) After natural cooling of the sample below 100 °C, D₂ gas was supplied. The amount of the supplied gas was equivalent to almost the same molar quantity of the ZrCo sample, which was the center of the plateau region [13].
- (3) The ZrCo–D sample was heated up to 300 °C for reactivation, which removed the oxide layer [34].
- (4) The heater was turned off and the sample was naturally cooled close to room temperature.
- (5) The sample was heated up gradually to supply the D₂ gas and then high voltage was applied to the system. The current was set to 3 mA to prevent overheating of the chamber.

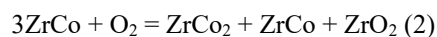
2.4 Gas analysis

Measurements were conducted before and after the operation. When measuring the gas inside the chamber, firstly, the gas was sampled in the 1 L tank. Then, the tank was evacuated during measurement with QMS. The valve next to the tank controlled the gas flow rate from the tank to QMS to keep the pressure below 10^{−2} Pa (i.e. operation pressure of QMS). Analyses were conducted in the condition that a baking procedure was conducted before the operation. The baking procedure was conducted for more than 72 hours at around 130 °C. Furthermore, the ZrCo sample was heated at 500 °C while evacuating in order to remove the absorbed protium. The measured ion currents were integrated and divided by the sum of each channel to obtain the ratio of gas species. Partial pressures of the hydrogen isotope gas were calculated by multiplying the ratio of the hydrogen isotope gases by the pressure inside the chamber.

3. Results and discussion

3.1 Characteristics of the ZrCo sample

XRD patterns of the ZrCo (–D) samples are shown in Fig. 3. The diffraction patterns of the sample after the hydrogenation (Fig. 3a) are indexed by ZrCoD₃ and ZrO₂. The patterns indicate that the ZrCo sample absorbed D₂ and the deuterium-to-ZrCo molar ratio was 3. In addition, the ZrO₂ phase is found in the patterns. ZrO₂ was probably produced during the activation procedure. The sample was heated around 300 °C to absorb deuterium. At this temperature, O₂ and H₂O were degassed from the SS enclosure and reacted with the sample. The sample was exposed to air while transferring the sample to the XRD apparatus. However, the oxidation reaction of ZrCo is slow at room temperature. The oxidation reaction can be written as follow [35]:



Zr is enriched at surface when the ZrCo is oxidized [36], which explains that ZrCo₂ patterns are not observed. The XRD pattern of the sample after the evacuation (Fig. 3b) indicates that the absorbed deuterium was emitted entirely. ZrO₂ was produced for the same reason as above. In addition, minor peaks of the ZrCo₂ and ZrD₂ phase are seen. The peaks suggest that the disproportionation reaction occurred, and the products of the reaction remained even after the evacuation at high temperature.

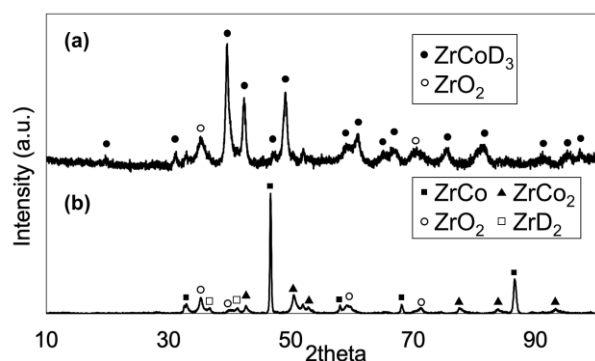


Fig. 3 X-ray diffraction patterns from the ZrCo samples (a) before the evacuation (hydrogenating) and (b) after the evacuation (dehydrogenating).

3.2 Neutron source operation

Temporal changes of the temperature, pressure, current, and voltage are shown in Fig. 4. A discharge was maintained for more than 60 min with stable voltages. First, the ZrCo bed was heated in order to supply deuterium.

Then, the discharge was initiated by applying high voltages. In order to increase the voltages and generate more neutrons, the pressure is necessary to be decreased. From this point of view, the heater was turned off to let the ZrCo sample absorb deuterium. However, the pressure increased because of the increase in the chamber surface temperature, consequently lowering the applied voltage. When the chamber and electrodes surface are heated, the absorbed gases are released, which increases the pressure; hence the applied voltage decreased from 29 to 27 kV. After 140 min, the chamber's pressure increased drastically because of the deuterium emission from the ZrCo sample enhanced by the temperature rise of the ZrCo bed. These results suggest that the chamber temperature must be kept constant to suppress the decrease of the applied voltage. Therefore, the chamber was continuously cooled using a fan supplying cold air to the chamber surface. The following results were performed under stable temperature of the chamber surface.

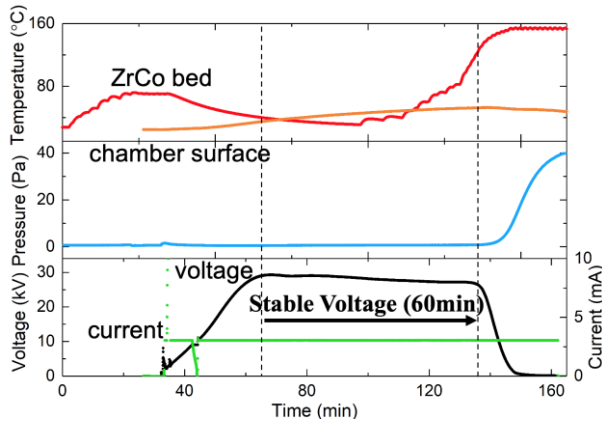


Fig. 4 Temporal changes of parameters during an operation. The operation was maintained for more than 1 hour with stable voltages (black line). The pressure inside the chamber (blue line) increased according to the chamber surface temperature (orange line) while the ZrCo bed temperature (red line) was decreased, which caused the voltage decrease. The current (green line) was constant at 3 mA.

The operation profile, including the temperature of the ZrCo bed, the pressure in the chamber, the applied voltage, and NPR, are shown in Fig. 5. NPR was controlled by altering the temperature of the ZrCo bed. First, the temperature of the ZrCo bed was increased to supply D_2 gas. Following the temperature, the gas pressure inside the chamber was increased. After the temperature reached to 135 °C, the temperature was kept constant. However, the pressure was increased gradually, and it took time to reach a constant value. Reportedly, ZrCo requires at most 10 hours to show the equilibrium pressure [13]. The temperature was lowered to 114–116 °C and maintained for more than 15 min (Reg.1). The voltage was 14.5–14.7 kV. Then, the temperature was lowered again to 95–96 °C (Reg.2). The voltage reached 16.2–16.6 kV. NPR was measured in Reg. 1 and Reg. 2, with a measurement time of 10 sec. The NPRs in Reg. 1 and Reg. 2 were measured to be 317 and 498 n/sec, respectively, in which the background of NPR was 27 ± 10 n/sec. These results indicate that the NPR was improved by decreasing the ZrCo bed temperature. The measurement was stopped because of system errors, and the discharge disappeared during 8–11 min and 171–182 min. It caused sharp increases in the pressures. However, after applying voltage, the pressures were recovered soon.

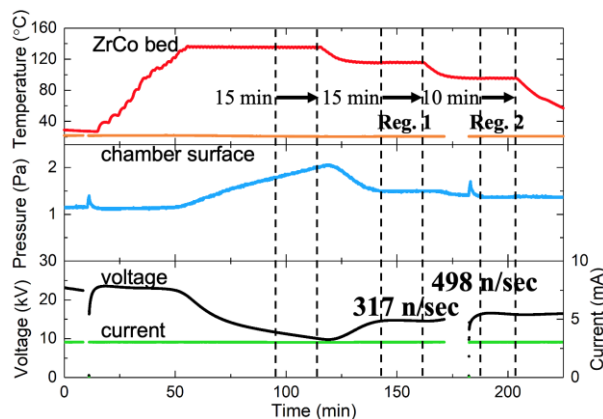


Fig. 5 Control the neutron production rate (NPR) via changing the ZrCo bed temperature (red line). The pressure inside the chamber (blue line), the applied voltage (black line), and NPR were controlled according to the change of the ZrCo bed temperature. The chamber surface temperature (orange line) and the current (green line) were constant. The measurement was stopped during 8–11 min and 171–182 min because of system errors.

After the operation, the gas inside the chamber was absorbed by the ZrCo sample. The pressure drop during natural cooling is shown in Fig. 6. Soon after the operation, the pressure increased up to 2.0 Pa. The change corresponds to the contribution of the pressure drop caused by the gas consumption by the discharge. The pressure started decreasing after 30 min, and it reached less than 0.2 Pa. The result suggests that the device has the potential to be operated at higher voltage and generate more neutrons. Under the present configuration, however, it took time to cool the ZrCo bed and absorb D_2 gas. The practical solutions are installing a new configuration into the bed, coating the ZrCo sample with catalytic Pd and Ni, and employing other hydrogen storage materials. A thin double-layered annulus metal hydride bed has been developed to fasten heat transfer and largen the sample surface area [37,38]. Moreover, a promising candidate material is uranium, which shows a higher hydriding performance [39] and moderate equilibrium pressure for operating the device.

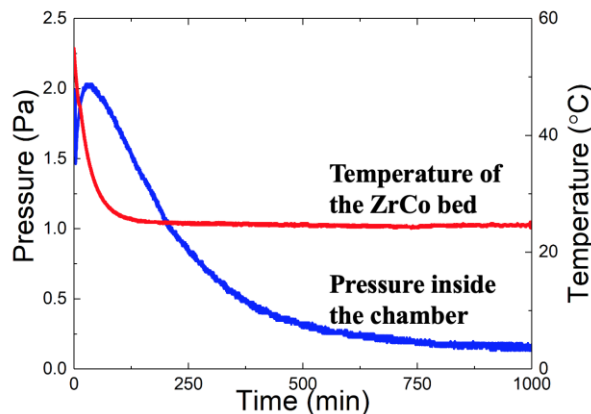


Fig. 6 Temporal changes of the ZrCo bed temperature (red line) and the pressure inside the chamber (blue line) after the operation.

3.3 Pressure stabilization

The gas pressure inside the chamber is affected by four factors: (i) absorption–desorption of the ZrCo sample; (ii) gas consumption by the discharge; (iii) gas release from the chamber and electrodes surface; and (V) inflow of air. The amount of the fuel consumption by the D–D fusion reaction can be calculated from the number of generated neutrons. The same device as the present work generated almost 2×10^5 n/sec [9]. Given that half of the D–D reaction generates neutron and 3He , the number of the D–D reactions in operation for 1 hour is 3.6×10^8 , which is equivalent to 4.1×10^{-8} Pa. Hence the deuterium consumption by the D–D reaction does not affect the pressure change. When the discharge is induced, however, accelerated ions hit the inner surface of the chamber and electrodes [5], which consumes the fuel (gas consumption by the discharge). On the other hand, the absorbed gas on the surface is released when the surface temperature is heated up. When ions hit the surface, their kinetic energy transfer to the surface in the form of thermal energy, which heats up the surface [40]. The amount of air inflow was negligibly small; hence the effect of inflow was limited in the present work. The scenario implies that the pressure will be stabilized when the following relational expression is satisfied.

$$\Delta P_{ZrCo} + \Delta P_{discharge} + \Delta P_{surface} = 0 \quad (3)$$

where ΔP_{ZrCo} , $\Delta P_{discharge}$, and $\Delta P_{surface}$ are pressure changes due to absorption–desorption of ZrCo, gas consumption by the discharge, and gas release from the chamber surface and electrodes, respectively.

Fig. 7 shows the behavior at the ignition of a discharge. Before the discharge ignition, the pressure inside the chamber increased drastically according to the ZrCo bed temperature. Soon after starting the discharge, the pressure dropped. After the pressure drop, the pressure increased again and reached equilibrium. Consumption of some of the gas caused by the discharge can explain the pressure drop. The result indicates that in order to ignite and sustain a discharge, it is necessary to supply more fuel than the gas consumption by the discharge.

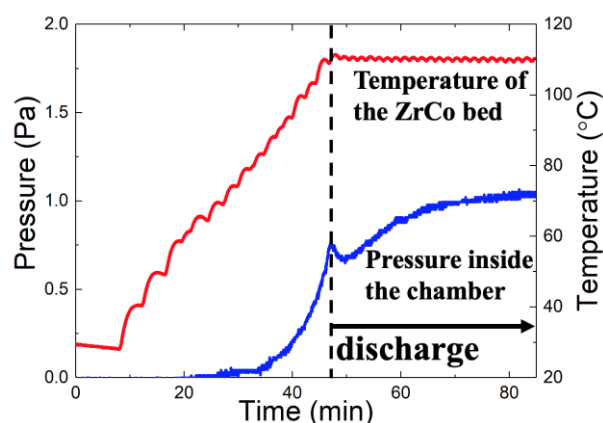


Fig. 7 Pressure drop at the discharge ignition. As the temperature of the ZrCo bed (red line) increased, the pressure inside the chamber (blue line) increased. Once the discharge was induced, the pressure dropped and then increased.

The influence of the released gas from the chamber and electrodes surface on the gas pressure is shown in Fig. 8. After the applied voltage and the current became constant, the current was increased from 3 mA to 30 mA. The amount of the gas consumption by the discharge increased because the number of ions increased. So, the gas consumption resulted in the pressure dropped. However, the pressure sharply increased according to the increase in the chamber surface temperature. The chamber surface was heated from 21 °C to 25 °C. It took 20 min to achieve the constant voltage. The result indicates that the amount of the released gas was more than the amount of the consumption in the operation.

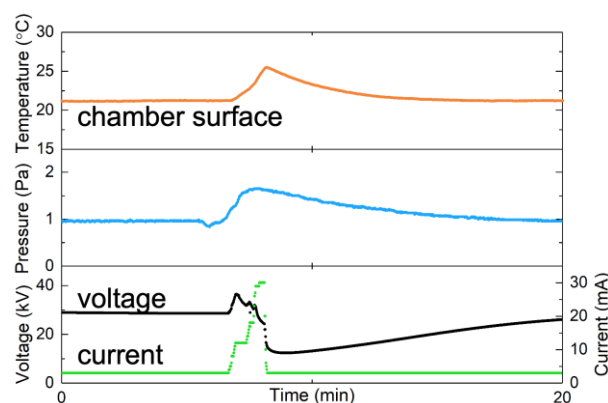


Fig. 8 The effect of the current increase (from 3 to 30 mA) on the temperature of the chamber surface and the pressure. The pressure inside the chamber (blue line) initially dropped caused by the gas consumption but thereafter increased by the chamber temperature increase (orange line).

3.4 Fuel dilution

Temporal changes of the voltage and NPR in an operation after a baking procedure are shown in Fig. 9. During the operation, NPR was measured with a measurement time of 30 sec. The applied voltage increased with time from 33 kV to 53 kV. On the other hand, a decrease in NPR was observed. Compared with the NPR at 3 mA and 53 kV assumed from ref. 9, the measured NPR was almost one-fourth smaller than expected. The difference means that NPR decreased despite the increase in the applied voltage.

Partial pressures of the hydrogen isotope gas before and after the operation are shown in Fig. 10. Before the operation, the hydrogen isotope gas consisted mainly of deuterium, which formed D₂. After the discharge, however, the amount of the protium was increased, and the amount of the deuterium was decreased. The results mean that isotope exchange occurred and the deuterium fuel was diluted with protium.

The ratios of H₂O, HDO, and D₂O were almost the same before and after the operation. The results indicate that H₂O was not a source of protium. The changes in the amount of CO + N₂ and O₂, gas species in air, were insignificant. The results suggest that the air inflow into the chamber was limited. A ZrCo sample can work as a getter material, because Zr reacts with N₂ and O₂; Co reacts with CO [41]. However, in the operations, the sample temperature was below 200 °C and these reactions were slow at this temperature. An increase in the amount of CO₂ was observed. It was released from the chamber and electrodes surface because of heating.

These results indicate that hydrogen isotope exchange was occurred between the supplied deuterium and the absorbed protium in the chamber surface and electrodes. Because of the hydrogen isotope exchange, the amount of the deuterium gas decreased; on the other hand, the absorbed deuterium increased. Furthermore, ZrCo shows inverse isotope effect at low temperature [42]. Therefore, the solid phase has a predominant affinity for deuterium, which contributes to the increase in the amount of the protium in the gas phase. These mean that fuel dilution, which is the NPR decrease caused by the decrease in the deuterium fuel gas inside the chamber, was occurred.

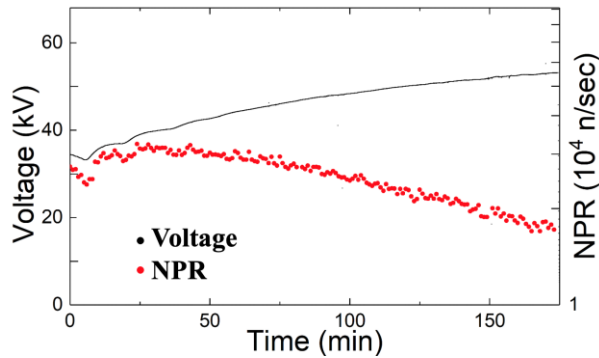


Fig. 9 Temporal changes of the voltage and neutron production rate (NPR). Despite the increased voltage, NPR gradually decreased with time.

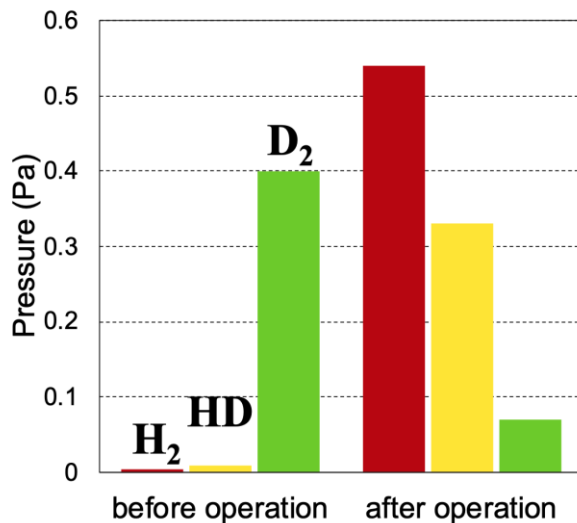


Fig. 10 Partial pressures of the hydrogen isotope gas before and after the operation.

In the case of supplying tritium, it is necessary to avoid fuel dilution. Therefore, before an operation, protium needs to be removed by supplying deuterium gas and causing isotope exchange between the protium and the deuterium. When supplying the tritium gas after removing the protium, the amount of the tritium gas would decrease because of isotope exchange between the tritium and the absorbed deuterium, whereas the amount of the deuterium gas would increase. Consequently, the amount of the gas species that cause the D–T reaction is not decreased. Furthermore, the cross-section of the D–T reaction is larger than that of the D–D reaction by two orders of magnitude. Therefore, when supplying the same amount of tritium as the deuterium in the present study, the D–T reaction would occur dominantly. Moreover, when conducting an operation longer than the present study, the ratio of the deuterium gas to the protium gas reaches equilibrium and NPR would become constant. When NPR reaches constant, the amount of the deuterium exchanged with the protium would be revealed. From this amount, the amount of the tritium required to sustain the deuterium-to-tritium ratio of the gas inside the chamber to be 1 during a stable operation could be calculated.

The amount of the fuel required to sustain an operation consists of two factors: (i) the amount of the gas to control the applied voltage and (ii) the amount of the gas consumption by the discharge. During an operation, the pressure inside the chamber is maintained around 1 Pa to control the applied voltage. Therefore, the amount of the gas inside the chamber during an operation depends on the chamber volume. On the other hand, the amount of the gas consumption by the discharge is determined by the number of ions hit into the chamber and electrodes surface. The number of ions depends on current. Moreover, the amount of the gas consumption is affected by the surface areas of the chamber and electrodes. Thus, the amount of the fuel is determined by the chamber volume, current, and surface areas of the

chamber and electrodes. In the present study, the pressure inside the chamber was almost 1 Pa during the operation, and the gas consumption of the discharge was 0.85 Pa. By multiplying the chamber volume (i.e. 3.8 L), the amount of the fuel was roughly calculated to be 7 Pa·L. When it comes to tritium, the amount equals to almost 10^{10} Bq.

In this study, if fuel dilution did not occur, NPR is expected to be 10^5 n/sec. Therefore, when a D–T operation is achieved, NPR is expected to be 10^7 n/sec. Furthermore, voltage and current have the potentials to be increased. Therefore, NPR will improve more than 10^7 n/sec. However, when the current is increased, the temperature of the chamber and electrodes also increase. In order to avoid an increase in the temperature, one promising method is the increase of the electrode areas, especially the cathode area. The cathode is in the chamber, and it is not easy to be cooled down. An increase in the cathode area means reducing the current density. The method is expected to reduce the heat generation. On the other hand, the chamber and anodes could be cooled by water cooling.

4. Conclusion

A discharge-type fusion neutron source with a self-sufficient system was developed in this study in order to reduce the amount of hydrogen isotope fuel. A ZrCo sample was employed for supplying and recovering deuterium fuel in a sealed vacuum vessel. The neutron source was operated based on the deuterium–deuterium fusion reaction for more than 60 min with stable voltages for the first time. Neutron production rate (NPR) was controlled via the temperature of the ZrCo bed during the operation. The pressure inside the chamber was affected by absorption–desorption of the ZrCo sample, gas consumption by the discharge, and the gas release from the chamber and electrodes surface. The effects of these factors on pressure stabilization were revealed. During the operation, NPR decreased with time despite the increased applied voltage caused by the dilution of the deuterium fuel gas. In order to occur the deuterium–tritium (D–T) reaction dominantly, protium in the system needs to be removed before an operation. Furthermore, the amount of fuel required to sustain the operation was revealed based on the present work. When the D–T operation is achieved, NPR is expected to reach more than 10^7 n/sec.

Acknowledgments

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