Permeation rates of H/He through a Pd foil for isotope separation applications in the exhaust stream of a fusion reactor.

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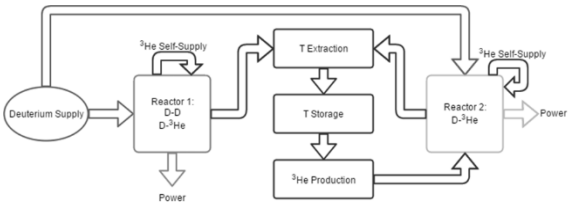
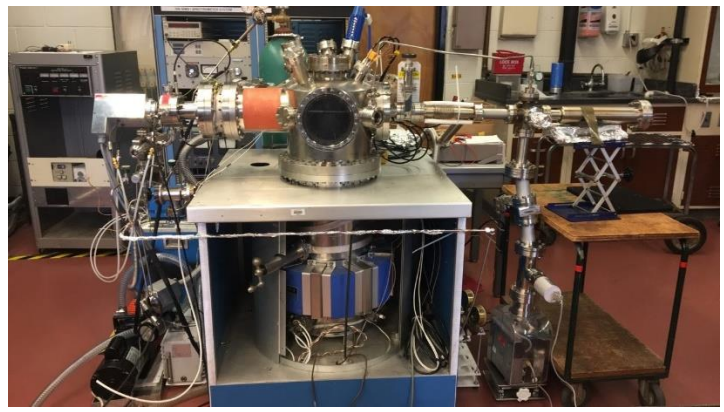
Field-Reversed Configuration (FRC) fusion devices are a type of magnetic confinement device that utilizes odd-parity rotating magnetic fields to induce closed field lines. The D-^{3}He fuel is aneutronic, however, deuterium atoms in the plasma can fuse with each other to either produce tritium (T) or ^{3}He. The T must be extracted in order to have a clean plasma, and in the future can then be stored, and through the decay of T it can breed more ^{3}He fuel. High Z, large surface area materials, such as Palladium (Pd), have been shown to exhibit superpermeability of atomized and ionized H in a plasma. Pd has a high H sorption rate and high permeability through conversion of H to a metallic hydride when heated to high temperatures, which increases H diffusion. At low temperatures, surface oxides and carbides dissolve, decreasing Pd impurities. We will report data on H/He permeability in Pd foil at a temperature range of 300-800 K, focusing on the effects of pressure and temperature.

Background

The purpose of this summer project was to test the permeability of Hydrogen and Helium in Palladium foil for isotope separation while focusing on the effects of temperature and pressure. This project can be applied to reducing tritium inventory in the exhaust stream of a fusion reactor, such as ITER (International Thermonuclear Experimental Reactor). This project was designed to be eventually tested in the exhaust stream of the Princeton Field Reversed Configuration (PFRC) fusion experiment to determine viability of its application in the PFRC as a fusion rocket engine. The PFRC fusion experiment is a type of magnetic confinement device that utilizes odd-parity rotating magnetic fields to induce currents and maintain closed field lines[1]. The D-^{3}He fuel is aneutronic, however, deuterium (D) atoms in the plasma can fuse with each other to produce either Tritium (T) or ^{3}He. The Tritium must be extracted in order to have a low radioactivity plasma, and to limit D-T reactions resulting in high energy neutrons. By introducing a material with selective permeability, such as palladium (Pd) , we can separate Hydrogen and Helium isotopes[2].



The first objective of this project was to design and build an experimental setup that would closely simulate the chamber used on the actual PFRC experiment, while still closely monitoring for changes in pressure, temperature, and partial pressures in the system. The system was designed to have two separate vacuum chambers which were connected by a holding pipe. At the end of the holding pipe that extended approximately 10 centimeters into chamber 1 and directly faced the plasma source, the circular palladium foil with a diameter of 1 centimeter and a width of 1 millimeter was sealed in between two mini-conflat flanges. Two ion gauges were attached to the chambers to measure pressure, one on each chamber. Two RGA probes were attached to each chamber to measure the partial pressures of gases present. To create the vacuum conditions required for the experiment, an integrated pumped was connected to the bottom of chamber 2 and a turbo and rough pump were connected to chamber 1.

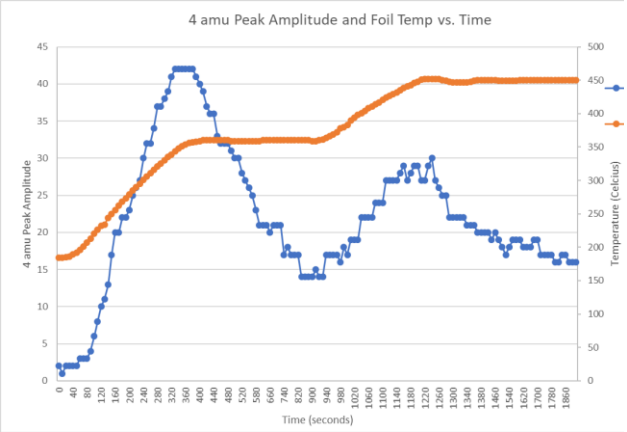


The chambers were pumped down simultaneously to approximately 10^{-7} torr. A portion of the experiments conducted required an ion beam, so an ECR plasma source was attached to chamber 1 and could be supplied using argon or deuterium gas. Currently, the role of the ECR plasma source in selective permeation is still under investigation. Finally, one of the project objectives was to test how the temperature of the Pd foil affected the permeation rate. Using nichrome wire inside of a heat shield that was powered with 10-200 watts, the foil the foil was heated to range of temperatures.

Progress

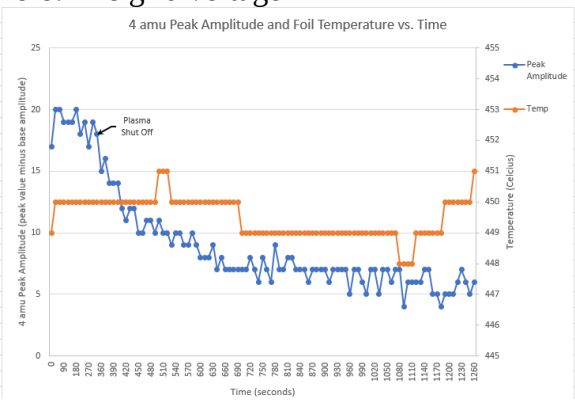
At its basis, this summer project was meant to test the viability of isotope separation using a palladium foil. The experimental set-

up was designed as to be a first draft preliminary “test bed”. The purpose of the project was not to design a final prototype that would be in the exhaust stream of a fusion reactor, but rather to collect accurate data rates from Hydrogen and Helium permeation. Our preliminary experiment tested permeation rates using an argon plasma and deuterium gas. The temperature in the main experimental chamber was steadily raised from 523 to 773 kelvin over the course of two hours. Data from the mass spectrometer, ion gauges, and thermocouples every minute for two hours to watch for changes in pressure and temperature in both chamber one and two and change in electron signals in chamber two. The temperature was raised in 25-degree increments. And then each held steady for 15 minutes while data was recorded. As temperature increased, the amount of deuterium in chamber two rose. In addition, no presence of argon was detected by the chamber 2 RGA (Residual Gas Analyzer) , which suggests that the deuterium actually permeated through the foil as argon has a very low permeability rate through Palladium.



From the preliminary results we extracted from the original experiment, it was apparent that permeation was occurring through the palladium. To better understand how and why permeation was exactly occurring, several different permeation experiments were designed and executed. From this, the first experiment that was conducted was looking again at the effects of temperature over time. There were three separate trials for this experiment, the first raised the temperature from 573 to 723 K throughout the course of seven minutes, the second trial raised the experiment from 523 to 623 K for approximately six minutes, and the third trial raised the temperature from 473 to 623 K and then from 623 to 723 K during ~20 minutes. The first trial showed the peak amplitude, which measured the amount of electron signals that were received by the RGA in chamber 2, to be consistent in matching the rise of the temperature of the foil. However, when the temperature was kept constant, the peak amplitude began to slowly fall back down. During the second trial, the temperature was raised quicker and held constant for a longer time. The resulting graph shows how drastically the permeation rate falls when the temperature is being held constant. Finally, the third trial was intended to test how drastic this effect was at different temperature ranges. The foil was heated rapidly, and the resulting peak shows a large peak in deuterium electron signals. Once again, however, when the temperature remained constant for a period the electron signals fell noticeably. The next experiment was designed to test the relevance of the plasma source in the rate of deuterium permeation. In this experiment, the plasma source was on when the experiment began, and once we were at a constant temperature of ~680 kelvin the source was shut off and the deuterium electron signals detected by the RGA in chamber 2. Though deuterium was still being leaked into the chamber at constant pressure, the deuterium peaks declined considerably in the absence of the plasma beam. It is worth noting that this was an argon plasma beam, and deuterium was leaked into the chamber separately. Once it

was evident that the presence of a plasma source in aiding in the permeation of deuterium through palladium the next experiment was designed to determine the role of an ionized plasma source. To test, the argon plasma source was turned on and the grid voltage and beam current were set to zero. The grid voltage



was then raised in 100 volt increments and held at that voltage for three minutes before being raised another 100 volts. It was suspected that a higher ion beam source current would have a stronger positive effect on deuterium permeation. However, the rate of permeation through the foil and into chamber two remained constant despite the increase in voltage.

Future Work

From the results extracted from the data of our preliminary experiments it is reasonable to suggest that using Pd foil in in the exhaust stream of a fusion device to separate hydrogen and helium isotopes is a viable option. It is now important to begin investigating how to apply our findings to a prototype that could be applied to a fusion reactor. In the future, it will be important to test permeation rates using Deuterium and He-4, to see the rate at which they both are able to permeate through. The actual proposed fusion engine will use deuterium and He-3, however due to the scarcity of the He-3 isotope the permeation experiments will use He-4. In addition, it will be important to calculate and compare the amount of tritium that is permeating through the barrier to the percentage in the main chamber. Future work should also investigate the change in permeation rate when the width of palladium foil is varied to decide which is the most efficient. Most importantly, this project must be tested in the exhaust stream of an FRC fusion device to determine the best configuration for the permeation apparatus. Finally, in addition to the FRC, we must determine the viability of this permeation apparatus on a larger scale in reducing the tritium inventory in ITER.

Impact on Laboratory and National Missions

This project and internship were both funded by the United States Department of Energy. In addition to the DOE and Princeton University, the FRC is partially funded by NASA Innovative Advanced Concepts (NIAC) initiative and ITER. However, it is worth noting neither NIAC nor ITER contributed funding to this summer project. This summer projects pushes forward the development of an FRC as a fusion propulsion engine. This project is important because it removes the need for the FRC to have heavy neutron shielding enclosing the reactor, thus greatly reducing the weight and removing the need to perform maintenance every 3-4 months due to damage to the reactor wall. This makes the FRC as a deep-space rocket engine viable. This project aligns with the laboratory's mission to enable fusion to power the United States, world, and beyond.

Conclusions

This project was designed to test the H and He isotope separation through a permeable palladium membrane and how efficient it was at removing select isotopes from the

exhaust stream of a fusion reactor. The initial experiments were looking at the roles of the plasma source and ion beam in addition to the roles of temperature and pressure on permeation. The first experiment tested the effects of varied temperature on the palladium foil. Our initial results showed that deuterium levels fell when the temperature was held constant. A possible explanation is that when the metal of the chamber and experiment were heated rapidly more deuterium that was embedded in the chamber walls had been released and were permeation through the foil. Our next experiment was looking at the role of the plasma source in permeation. From our results, the plasma source plays a large role in permeation rates. The sharp decline in deuterium electron sources could be because the plasma source was crucial in accelerating deuterium atoms into the palladium foil. When the plasma source was cut off, the rate of permeation fell considerably because they weren't being accelerated through. Finally, after varying the grid voltage for the ion beam and seeing very little change in the permeation rate, it was believed that the grid voltage and beam current play little part in permeation. To conclude, the rate of permeation through a palladium foil is proportional to the temperature of the foil. Palladium has shown to be a strong choice for a high-z material.

References

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