Characterizing a Cryosorption Pump for Collecting Tokamak Exhausts

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I. Abstract

SPARC, a high-field toroidal tokamak being constructed by Commonwealth Fusion Systems, will utilize the fusion reaction between tritium and deuterium. The exhaust gas contains hydrogen isotopes, helium ash, and inert gases used to control the plasma. High-vacuum turbomolecular pumps evacuate this gas from the torus. Cryosorption pumps accept gas from these pumps and deliver the effluent to the Torus Exhaust Purification system, where unspent hydrogen is recovered and purified. Cryosorption pumps can selectively pump hydrogen at high speeds in the presence of inert gases. A novel prototypic cryosorption pump was constructed and packed with molecular sieve 4A that is cooled to liquid nitrogen temperatures (-196 °C). The pump design requires a hydrogen capacity of 28 sL with an effective pump speed of 120 sL/second at 1 torr under predicted conditions. Its hydrogen capacity and pumping speed below 1 torr were measured to determine viability in the final application. Precooling with helium was found to have a thermalizing effect in the pump, allowing for a 1,740 % increase in hydrogen capacity (0.25 sL to 4.6 sL) at a pumping speed of 0.5 sLpm. Future experiments will test alternative cooling systems to maximize cooling uniformity during pump operation.

II. Introduction

Commonwealth Fusion Systems is a startup company based in Cambridge, Massachusetts with the goal of demonstrating the viability of fusion as a commercial energy source. They have begun construction of SPARC, a high-field, toroidal, magnetically confined fusion device (*see figure 1)*. SPARC will use novel high-temperature superconducting magnets to confine plasma and will utilize the fusion

reaction between the components of deuterium-tritium (DT) fuel.[1] Gaseous DT will be injected into the device, whereupon the fuel mixture is heated to tens of million degrees Celsius. This is achieved by running high current through the gas (induced by a changing magnetic field in the central coil), high frequency electromagnetic waves similar to those in a microwave oven, and injection of high-speed deuterium atoms.[2]

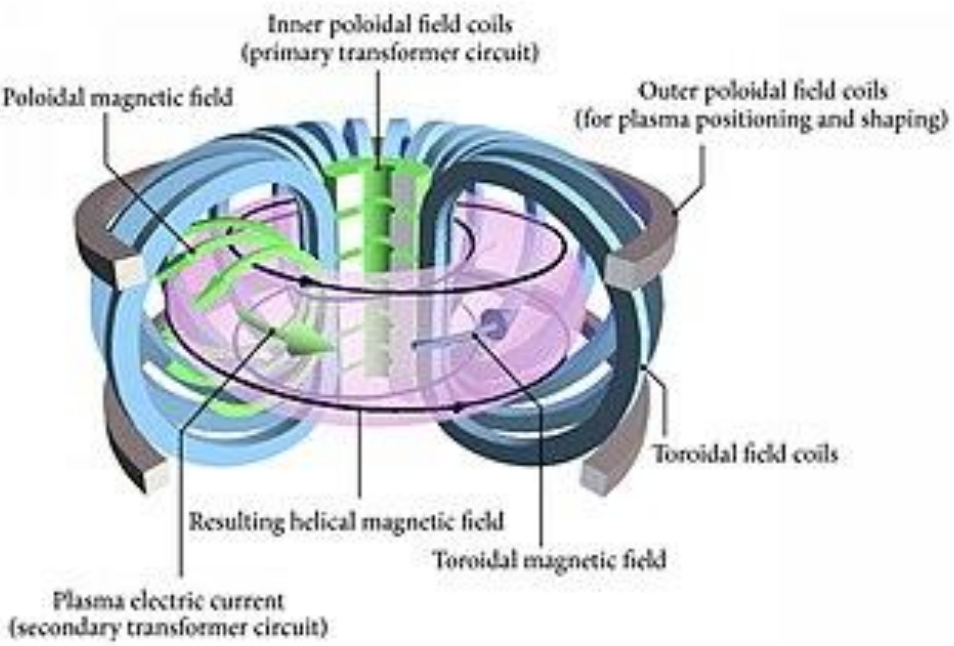

Figure 1.
High-level overview of the magnetic confinement of plasma in a toroidal fusion reactor like SPARC. This figure demonstrates how the toroidal and poloidal magnetic fields allow researchers to confine and form the toroidal plasma shape as well as how the central coil acts as the primary of a transformer to induce high current in the plasma "coil," which acts as the secondary.

At these high temperatures, the DT mixture will turn into plasma, which can be confined and compacted by high strength magnetic fields shown in figure 1. Under these conditions, D and T atoms will collide with each other with sufficient energy to

overcome Coulomb repulsion (the effect of like charges repelling) and fuse. When the hydrogen nuclei combine, they form a single helium nucleus, which releases around 18 MeV and a free neutron each reaction due to the lower binding energy of helium.[3] The purpose of SPARC is to demonstrate this fusion reaction and prove that a net energy gain can be achieved.

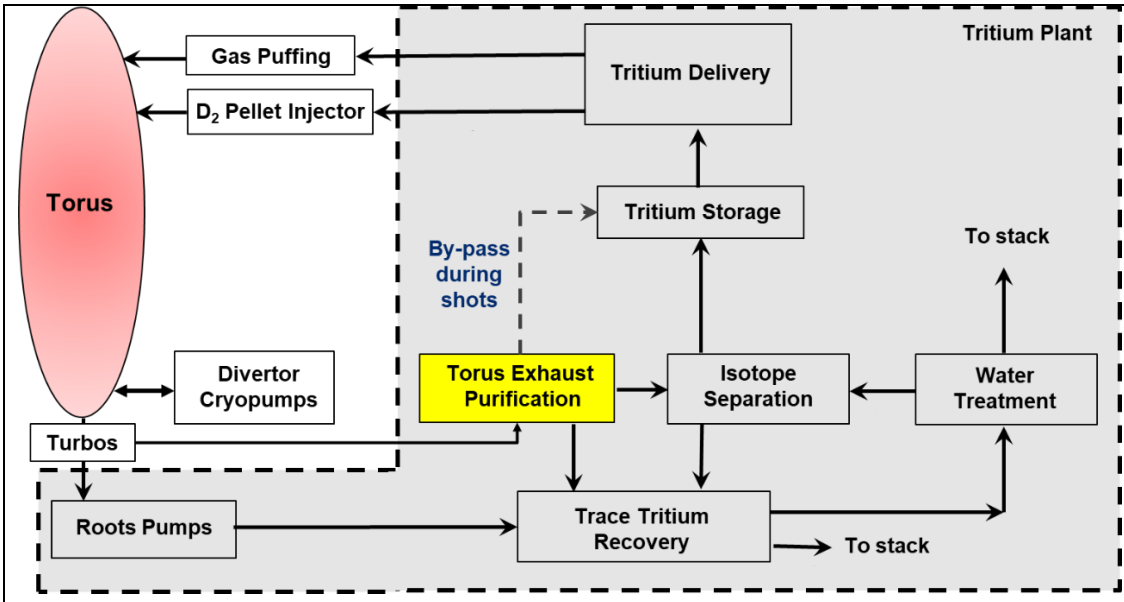

Figure 2.
Schematic diagram[4] of the tritium handling infrastructure to be used in SPARC. After a shot, turbomolecular pumps evacuate the torus. In low tritium operation, exhaust is sent directly to Trace Tritium Recovery (TTR). When there is high tritium pressure, exhaust is handled by Torus Exhaust Purification (TEP). This system separates hydrogen species (which are sent to isotope separation) from waste gas (which is sent to TTR). At isotope separation, tritium and deuterium are separated from protium (hydrogen with one proton and no neutrons in its nucleus) and the correct DT mixture is sent back to the torus to be used in subsequent shots.

As this reaction occurs, helium and inert gasses used for cooling build up in the reactor, necessitating a system to collect and purify exhaust gasses. Since only a small amount of DT is consumed in each shot, SPARC must also have the ability to recover unspent fuel from the effluent exhaust gas mixture. The Torus Exhaust Purification (TEP,

see figure 2) system is being developed by LLE to separate hydrogen species from waste gas. During high tritium pressure operation, effluent from the torus is pumped into TEP by high-vacuum turbomolecular pumps. A high-speed secondary pump is needed to maintain a low pressure at the effluent side of the turbo pumps and collect a volume of hydrogen and deliver it to TEP when needed. A prototypic cryosorption pump was tested to determine its viability in this application.

The torus turbomolecular pumps evacuate gas from the reactor. These pumps require vacuum to be pulled on the exhaust side; the requirement for SPARC is a maximum exhaust pressure of 1 torr. Cryosorption pumps are used for this application not only for their ability to collect hydrogen from the torus effluent stream, but also for their lack of hydrocarbon oil that most other pumps use. Hydrocarbons introduce contaminants which can be eliminated by using cryosorption pumps.

These pumps utilize cryosorption, which is the adsorption of gas onto the surface of a material at cryogenic temperatures (-196 °C). [5] The pump is packed with molecular sieve 4A, a highly porous material having ample surface area which hydrogen can be deposited onto. Characterization of this pump will test the effectiveness of the cooling system to bring molecular sieve to cryogenic temperature, and the ability of the heating system to recover deposited hydrogen. It will also measure the hydrogen capacity at pressures below 1 torr with the goal of reaching 28 sL.

III. Experimental Setup

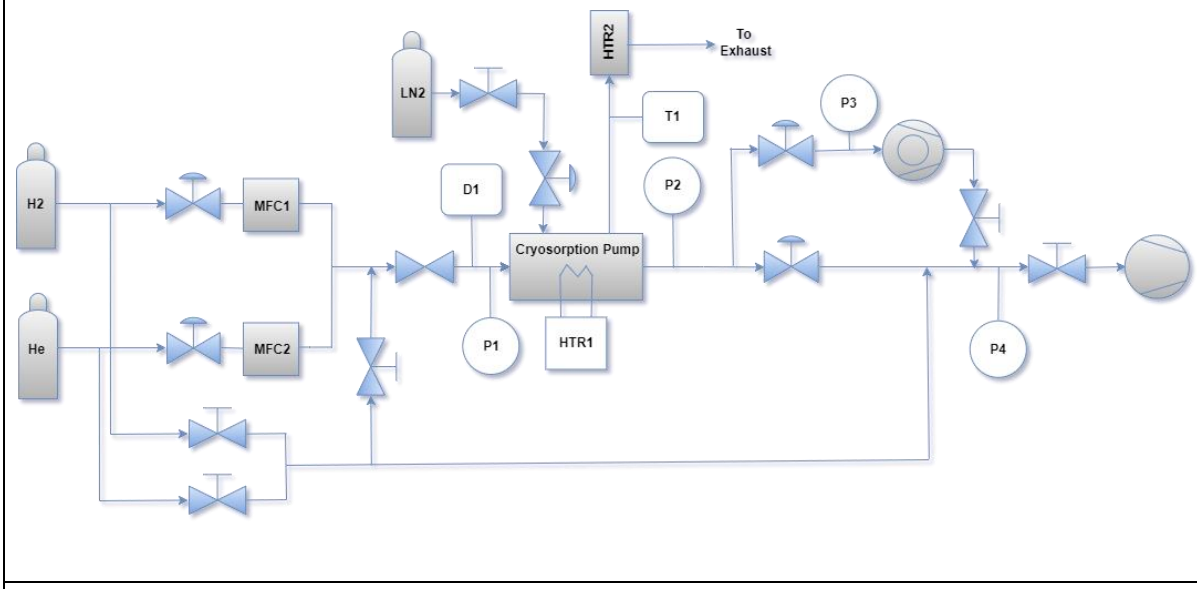

Figure 3.
Schematic of the experimental test stand to characterize the cryosorption pump.

The experimental test stand (*see figure 3*) contains 2 mass flow controllers (MFC1 and MFC2) that can supply precise amounts of hydrogen (H2) and helium (He) to the cryosorption pump. Just upstream of this pump, the influent dewpoint (D1) and pressure (P1) are measured before entering the cryopump. This pump contains an internal heater (HTR1) as well as an internal liquid nitrogen (LN2) coil that heat the molecular sieve during bakeout and regeneration and cool it for actual operation. Liquid nitrogen is boiled off at the effluent (HTR2) and exhausted. Temperature (T1) is monitored here to make sure that liquid nitrogen is not leaking out of the test stand. The cryopump is backed by a turbo pump and roughing pump and the system can be configured to use one or both. The

pressures at each of these pumps (P3, P4), including the cryopump (P2) are measured as well.

IV. Temperature Control of Cryosorption Pump

Bakeout of the cryopump (*shown in figure 4a*) involves heating of the molecular sieve to 400 °C while drawing vacuum downstream of the pump. This is required to completely purge the pump of all gas adsorbed to the molecular sieve as well as to remove water and inert gasses that may be present. Over the course of 50 minutes, the temperature was raised to the target temperature with internal heaters as well as external heater tape to ensure uniform heating of the molecular sieve. The temperature was measured with 3 thermocouple bundles: one at the center, one in the middle, and one towards the outer edge of the pump. Each bundle contains 3 thermocouples to measure temperature at 3 different depths: top, middle, and bottom.

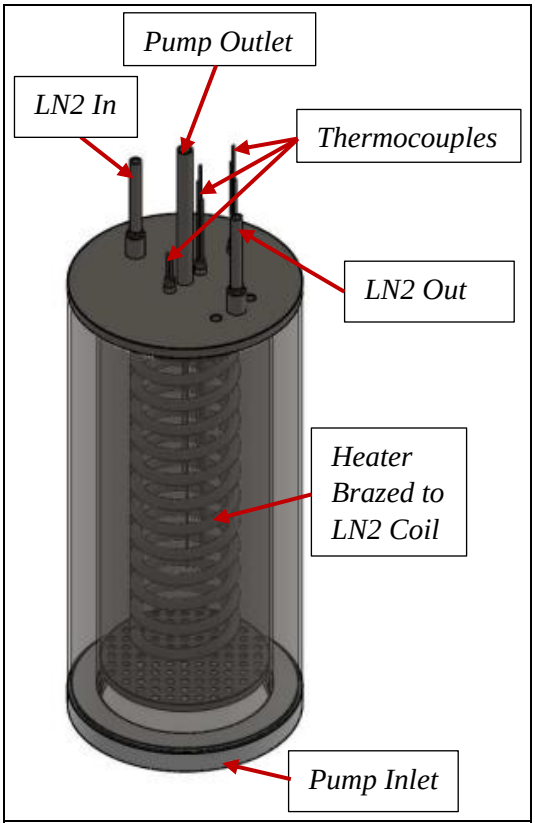

Figure 4a.
This is a 3D rendering of the cryosorption pump design. The pump is transparent to show the inlet, outlet, LN2 and heating coils, as well as the 3 thermocouple bundles.

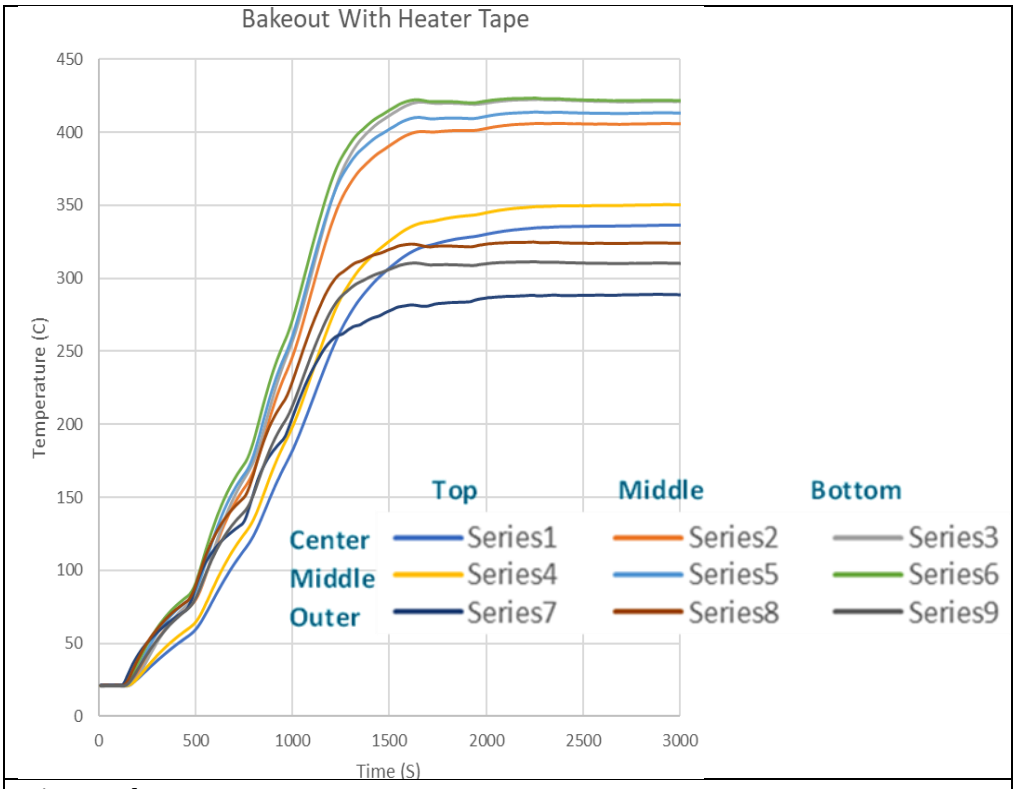

Figure 4b.
Example bakeout run showing thermocouple temperature in Celsius over time at nine different locations. Temperatures reach steady state in around 30 minutes, but there are large temperature variations throughout the volume of the pump.

During bakeout, temperatures (*see figure 4b*) increased from room temperature to steady-state temperature in around 1750 seconds. There was, however, a large difference in temperature (150 °C) measured by thermocouples in different locations of the pump. A minimum of 275 °C was measured at the top-outer thermocouple, while a maximum of 425 °C was measured at the inner and middle-bottom thermocouples. Based on the thermocouple readings, the top and outer parts of the molecular sieve bed are being heated less than the rest, indicating potential insulation issues through the jacket of the pump as well as the sheaths of the thermocouples. If the pump had been recently exposed

to atmosphere, it was left at this steady state temperature until the dewpoint sensor read that the pump effluent was dry.

After bakeout, the contents of the cryopump must be cooled to cryogenic temperatures by first bringing the temperature down to 50 °C with gaseous nitrogen, then cooling down the rest of the way with liquid nitrogen. It was demonstrated that the thermal conductivity of the molecular sieve is poor, but that adding helium gas during liquid nitrogen cooling is effective in bringing temperature down further and more uniformly.

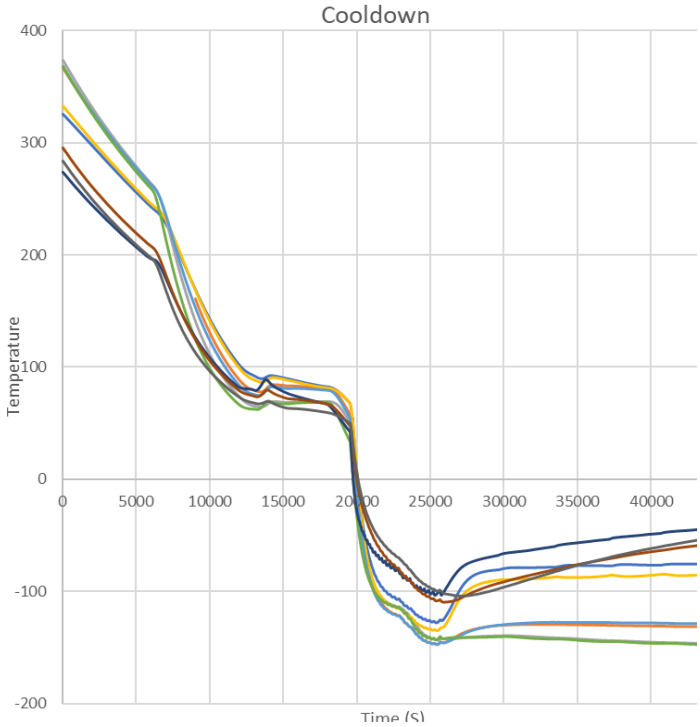

Figure 5a.
Thermocouple temperatures (°C) in the cryopump over time. This is a preliminary cooling in two stages: first gaseous, then liquid nitrogen after 20,000 s. At the end of this run there are large temperature differentials within the pump (color codes as in figure 4b).

The bulk of the cooling is handled by gaseous nitrogen, which is fed through the pump with a mass flow controller. This effectively removes heat, bringing internal temperatures to the 70 to 90 °C range. At this point, nitrogen was evacuated from the pump and liquid nitrogen was fed through internal coils to bring the temperature down even further to range from -100 to -150 °C. An insulation problem became apparent after this minimum

temperature was reached (*see figure 5a)* as the temperatures diverged over time to a 100 °C temperature difference from the warmest to the coolest thermocouple. The system was left running for several hours with automated liquid nitrogen filling and the temperatures reached a steady state, but the large temperature differences were retained. Similarly to the heating run in figure 4b, the farthest from the target temperature, and the most affected by insulation issues, are the top and outer thermocouples.

When helium was pumped into the volume of the cryopump, there was a significant cooling effect (*as seen in figure 5b*): while the minimum temperature stayed close to -170 °C, the warmest dropped significantly from -30 to -140 °C, bringing the overall temperature difference down to 20 - 30 °C. It was evident that the thermal conductivity of the molecular sieve in vacuum conditions was not enough for the liquid nitrogen coil to uniformly cool the volume of the pump. The temperature difference was brought closer to an acceptable level because the helium gas was convectively cooled and was able to reach the places in the pump that were experiencing conduction to the outside. When the helium was pumped out in preparation for hydrogen dosing, there was a sharp increase in temperatures. This warming can be attributed to conduction along the sheaths

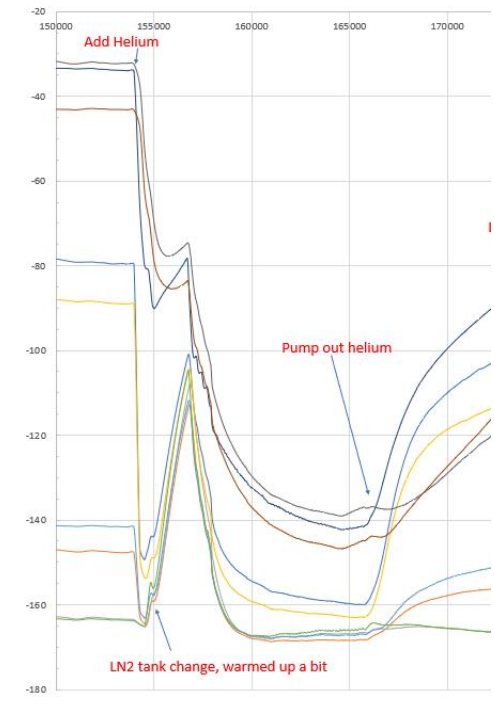

Figure 5b.
Continuation of run in fig. 5a with an expanded temperature scale. This demonstrates the effect of adding helium during cooling to cool further and increase temperature uniformity.

of the shorter, top-level thermocouples, which saw the sharpest rise in temperature (*see figure 5b).* In future designs, the thermocouples will be chosen to eliminate conduction along the metal sheath and improve the accuracy of temperature measurements.

V. Hydrogen Dosing

In a new run, hydrogen was introduced and regulated by a mass flow controller. Three dosing schemes were tested: Hydrogen was flowed at 0.5 sLpm without helium precooling and yielded a capacity of 0.25 sL of hydrogen. At the same flow rate, the addition of helium precooling increased the capacity to 4.6 sL. The third dose was done at 5 sLpm with precooling and yielded 2.3 sL hydrogen capacity. During hydrogen dosing, the temperature was measured with the aforementioned thermocouples and the upstream pressure was measured with a 10 torr transducer.

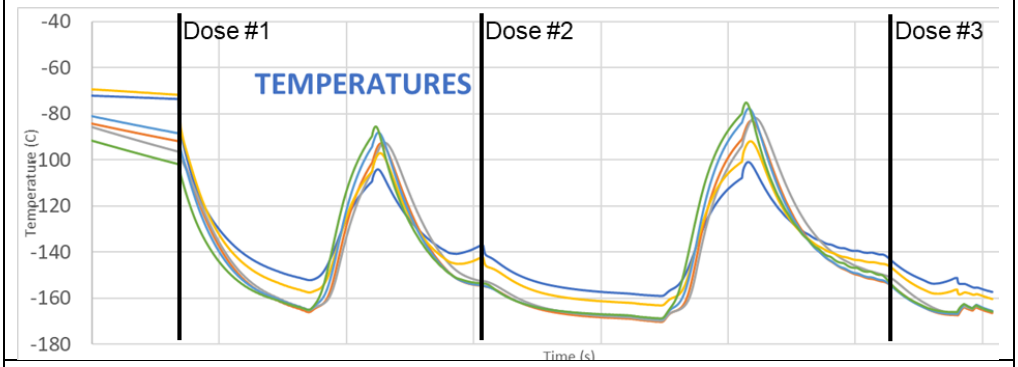

Figure 6a.
Temperature readings during hydrogen dosing run (each time interval corresponds to 2000 seconds). Each bold vertical line represents the start of a dose. Temperatures decrease as hydrogen is added, then spike when the hydrogen is baked off. Doses 2 and 3 use helium to bring the temperature down after the spike rather than immediately flowing hydrogen. Color codes as in figure 4b.

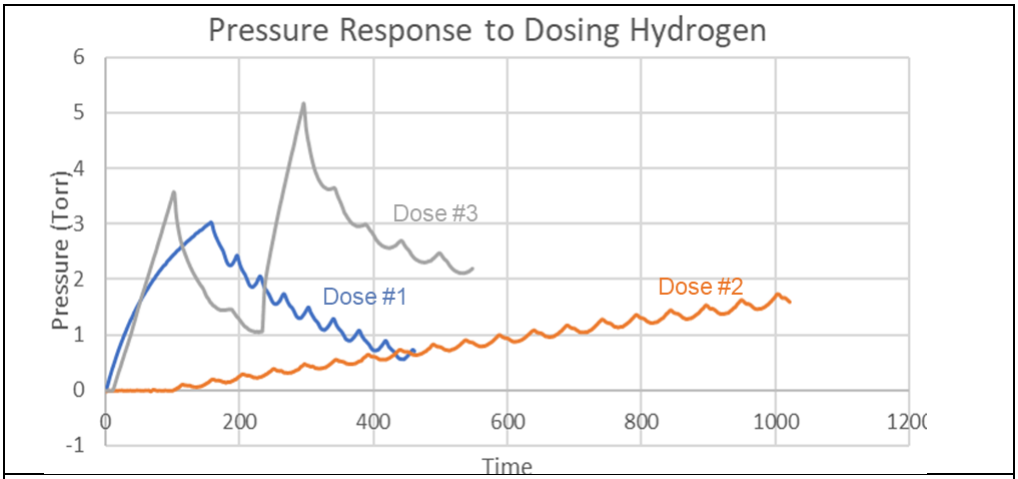

Figure 6b.
Overlay of pressure over time (s) during three dosing schemes, each starting when hydrogen began flowing into the pump. Capacity was calculated based on the amount of hydrogen that flowed before the pressure reached 1 torr.

The first of 3 doses began when the pump was still "partially" cooled, meaning that there were large temperature variations throughout the pump. When hydrogen was added at the start of Dose #1, it brought the temperature down with the same convective effect that helium had (*see figure 5b)*. The beginning of the run occurred at higher temperatures, however, which resulted in a quick increase in pressure (*see figure 6b Dose #1)*, surpassing the 1 torr threshold in 30 seconds. Based on this reading, the hydrogen capacity was calculated with the following equation:

$$C = F * t$$

where C is hydrogen capacity in sL, F is hydrogen flow rate in sLpm, and t is time to threshold in minutes. With 0.5 sLpm for 0.5 m, the capacity was measured to be 0.25 sL for Dose #1. Directly following subsequent doses, hydrogen was "regenerated" from the molecular sieve. The bed was heated to around -100 °C and helium was flowed to purge the hydrogen that was cryosorbed to the molecular sieve.

Precooling the sieve bed (done for Doses #2 and #3) involved allowing 5 torr of helium into the pump volume while cooling with liquid nitrogen. This brought the temperatures down back to their previous levels before the second addition of hydrogen (*figure 6a).* The effect of bringing the temperature down before flowing hydrogen was demonstrated in Dose #2. The pressure upstream of the pump rose significantly slower compared to the first dose, thus allowing for a much longer time to threshold and a greater capacity (*see figure 6b Dose #2)* of 4.6 sL (0.5 sLpm for 9.2 m) compared to 0.25 sL without precooling.

The third dose demonstrated the effect of increasing the flow rate of hydrogen to 5 sLpm. This proved to negatively affect the capacity as the pressure sharply rose to the 1 torr threshold in 27.6 seconds (*see figure 6b)*. The capacity measured in this run was 2.3 sL. This was greater than that of the non-precooled run but half that of the precooled run with 0.5 sLpm flow rate.

VI. Conclusion

SPARC requires a pumping system to evacuate exhaust gas from the device's volume. High powered turbomolecular pumps used for this purpose need to be backed by secondary pumps at the effluent side. Cryosorption pumps are a good candidate to back the turbo pumps for several reasons. They can pump at high speeds up to ultra-high vacuum, they do not introduce contaminants, and they can selectively retain hydrogen species on cryogenically cooled molecular sieve. We sought to test the hydrogen capacity and thermal properties of a novel cryopump designed specifically for SPARC.

Molecular sieve 4A is not a very effective conductor of heat and a large volume of it is packed into the cryosorption pump. Thus, it proved very difficult to maintain uniform temperature within the pump, although conduction through the sheaths of the thermocouples caused readings to be higher than what they are supposed to be. The efficacy of an adsorbent material depends greatly on the temperature, [6] so the large temperature differentials inside the pump had a potentially detrimental effect on the performance of the pump.

During hydrogen dosing, it was measured that precooling the sieve with 5 torr of helium increased capacity by a factor of 17.2 (from 0.25 to 4.6 sL) at a hydrogen flow rate of 0.5 sLpm. Increasing the flow rate to 5 sLpm decreased the capacity to 2.3 sL, so 0.5 sLpm was the preferred flow rate of those tested. Despite lack of thermal insulation to the outside of the pump and the lack of thermal conductivity inside the pump, the addition of helium proved to significantly increase internal conductivity and, thus, hydrogen capacity.

The next steps for this cryosorption pump should be centered around the thermal issues that were encountered. A better (or double) vacuum jacket around the pump should eliminate the need for other insulation materials and significantly reduce conduction from the atmosphere. Better insulated thermocouples are a necessity to ensure accurate temperature measurements. New cooling designs should be explored including liquid nitrogen-cooled baffles, or the addition of conductive material interspersed with the molecular sieve.

Eventually, once thermal issues are resolved, the ability to reliably contain tritium is very important and will be necessary for implementation in a commercial fusion reactor.

VII. Acknowledgements

I would like to thank Dr. Stephen Craxton for his unwavering support during as well as after the conclusion of the program. Also, many thanks to Dr. Walter Shmayda and Dr. Eric Dombrowski for giving me valuable hands-on experience in research and teaching me so much throughout the summer. Finally, my fellow students were instrumental in motivating me and I was very impressed by the work they presented at the end of the program.

VIII. References

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