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Metal Foil Pump Performance Aspects in View of the Implementation of Direct Internal Recycling for Future Fusion Fuel Cycles

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The current design baseline for the EU DEMO implements the KALPUREX process for the tritium fuel cycle. This process aims to reduce the tritium inventory of the fuel cycle by separating hydrogen from other gases within the tokamak building and feeding it back to the matter injection system. Thus, systems with high tritium inventory are close to the torus and have small residence time. The systems with smaller inventories are allowed to have longer residence times. The best candidate for the hydrogen separation unit close to the torus is a metal foil pump that relies on the effect of superpermeation. This effect is studied at a dedicated setup at KIT.

In this paper the impact of DIR on the fuel cycle of a fusion device is quantified. This is done by introducing dimensionless numbers for the tritium stream reduction, the tritium conversion rate improvement and the mean tritium processing time.

Additionally, experiments showing hydrogen permeation on an iron foil are shown. Superpermeability and surface limited permeation is demonstrated with an iron foil.

Keywords: Direct Internal Recycling (DIR), Superpermeation, Metal foil pump (MFP)

1. Introduction

If the current fuel cycle of ITER is to be scaled up without changes towards DEMO it will become prohibitively large. This includes both, the different process units as well as the total tritium inventory. To tackle this problem a revised fuel cycle architecture was suggested [1]. While for ITER, as a solely experimental machine, it is necessary to have a versatile setup; DEMO can be optimized towards a single operational point. For the EU DEMO a fuel cycle with Direct Internal Recycling (DIR) was chosen as a baseline design [2]. This DIR requires a process unit capable of separating large amounts of hydrogen close to the torus. A Metal Foil Pump is capable of doing so. It is planned to be installed before the main torus pumping system. A Metal Foil Pump is based on the principle of superpermeation, which selectively pumps hydrogen. This process step thus separates hydrogen species close to the torus from other gases and allows reinjecting them after a very brief processing time.

2. Fuel Cycle

The DIR concept splits the previously single loop for tritium processing into at least two loops. Fig. 1 shows a simplified scheme of an inner fuel cycle of a fusion machine. The process steps of the DIR are shown in the middle, being separated by the dashed box from the rest of the fuel cycle. On the left side the torus and matter injection side are displayed, on the right the pumping and the tritium plant are shown. Above the DIR the process unit for the gas distribution and control is shown, which will have a more demanding task in a multi loop fuel cycle than in a single loop design. First the effect of the DIR is analyzed from the point of view of the tritium plant, as it dominates the tritium inventory of the inner fuel cycle. Second, the view from the torus is accessed.

The fusion reaction rate Φ_{Fus} directly depends on the flow of tritium fueling $\dot{Q}_f$, the fueling efficiency η_f and the burnup fraction f_b. For the steady state

$$\frac{\Phi_{Fus}}{\dot{Q}_f} = \eta_f f_b \qquad (1)$$

describes this relationship. As the tritium burnup fraction and the fueling efficiency always appear together in this paper, their product is called tritium conversion rate in the following. In the case of a fuel cycle without DIR the amount of tritium fueling is equal to the tritium stream coming from the tritium plant $\dot{Q}_{TP}$. In a fuel cycle containing a DIR, this is reduced by the ratio

$$\frac{\dot{Q}_{TP}}{\dot{Q}_f} = 1 - \eta_{MFP}\left(1 - \eta_f f_b\right), \qquad (2)$$

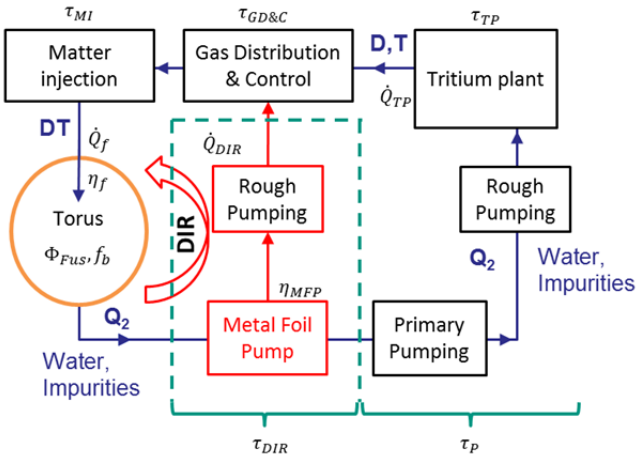

Fig. 1. Simplified scheme of a fusion fuel cycle.

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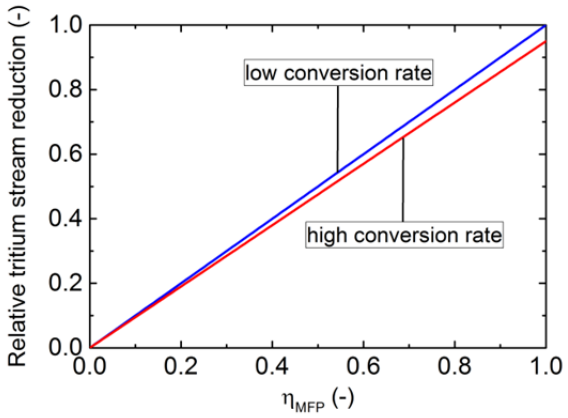

Fig. 2. Tritium stream reduction from single fuel cycle loop to fuel cycle including DIR vs. the tritium separating efficiency of the Metal Foil Pump.

where η_{MFP} is the fraction of tritium that is separated in the Metal Foil Pump and thus contributes to the tritium stream of the DIR $\dot{Q}_{DIR}$.

Fig. 2. shows the tritium stream reduction relative to a fuel cycle without a DIR. Two cases are displayed. The case "high conversion rate" overestimates the values for the fueling efficiency ($\eta_f = 0.5$) and the burnup fraction ($f_b = 0.1$). The other case "low conversion rate" underestimates the fueling efficiency ($\eta_f = 0.1$) and the burnup fraction ($f_b = 0.001$).

The term fueling efficiency is used quite differently in literature. Here the ratio between the tritium input stream into the torus and the tritium arriving in the plasma core is meant. In the process treatment of this paper possible tritium losses or inefficiencies between the input stream of the matter injection system and the tritium stream entering the torus are neglected. It is noteworthy to mention that the plasma physics demands a certain tritium density in the scrape of layer (SOL) of the fusion plasma. This can only be fulfilled by a fraction of tritium that goes through the torus, without entering the plasma core, which means that there is an upper achievable limit for the fueling efficiency less than unity. The value of $\eta_f = 0.5$ was taken from [3].

It can be seen that the DIR can have a tremendous impact on the amount of tritium that needs to be supplied by the tritium plant. It can also be seen, that the reduction of the needed tritium stream is nearly independent of the conversion rate. This shows that the benefit of a DIR is clearly more dominant than the one of advances in the conversion rate.

This benefit can also be expressed in a different way. In the perspective of the tritium plant (right side, Fig. 1) there is one tritium stream entering the plant and one leaving the plant. The conversion rate determines the tritium flow needed, eq. (1). As the DIR decreases the tritium stream needed from the tritium plant, it seems to increase the conversion rate from the perspective of the tritium plant. So instead of the fueling rate $\dot{Q}_f$, the rate of tritium coming from the tritium plant $\dot{Q}_{TP}$ has to be used, yielding

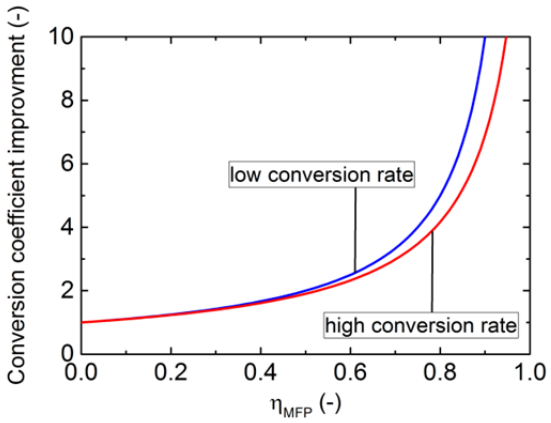

Fig. 3. Improvement factor of the conversion rate as given by the difference between eq. (1) and (3).

$$\frac{\Phi_{Fus}}{\dot{Q}_{TP}} = \frac{1}{1-\eta_{MFP}\left(1-\eta_f f_b\right)}\,\eta_f f_b. \qquad (3)$$

The difference between eq. (1) and (3) is the prefactor before the conversion rate on the right side of the equation. This "improvement factor" of the conversion rate is plotted in Fig. 3 against the separation fraction of the metal foil pump.

Although even small separation fractions of the metal foil pump improve the conversion rate, the biggest influence can be seen for high separation fractions. As the metal foil pump is planned to be installed in the divertor region of the torus, it operates at similar pressures. Thus it can be assumed, that its separation capability is limited by the gas arriving on the metal foil pump. First vacuum flow calculations suggest, that a separation fraction above 0.9 is realistic.

The previous numbers considered the decrease of the tritium flow that needs to be supplied by the tritium plant. The DIR has another advantageous effect: it decreases the mean processing time. This can be seen as an evaluation of the fuel cycle from the torus' perspective. The mean processing time τ_P gives an average time how long a tritium atom needs from leaving the torus to reentry. For a fuel cycle loop without a DIR it is the sum of the mean residence times of all process units:

$$\tau_P = \tau_{MI} + \tau_{GD\&C} + \tau_P + \tau_{TP}. \qquad (4)$$

Even for the fuel cycle with a DIR, the mean residence times of the matter injection systems τ_{MI} and the gas distribution and control system $\tau_{GD\&C}$ will be fully part of the mean processing time of as every tritium atom has to pass through it, whereas the mean residence times of the pumping system τ_P and the residence time in the tritium plant τ_{TP} will only partially included:

$$\tau_{P,DIR} = \eta_{MFP}\,\tau_{DIR} + (1-\eta_{MFP})\,(\tau_P + \tau_{TP}) + \tau_{GD\&C} + \tau_{MI}. \qquad (5)$$

The separation fraction of the Metal Foil Pump η_{MFP} determines how much the mean residence time of the DIR cycle τ_{DIR} and how much the mean residence time of the pumping system τ_P and the tritium plant τ_{TP} impact the processing time. It is likely that the mean

residence time in the tritium plant will dominate the processing time. It is expected to be in the order of hours [4]. In contrast to this, the mean residence time in the DIR loop is expected to be in the order of seconds. For a sensible design target of a metal foil pump separation fraction of 0.9, the mean processing time from the torus exhaust to the gas distribution and control unit is decreased by nearly an order of magnitude.

In [4] Abdou et al. presented results of a simulation of a tritium plant and its necessary start up inventory. In Fig. 4 some simulated values of this simulation are plotted. Although the numbers are only valid for the system chosen, it gives an impression of the influence of the tritium conversion rate and the mean processing time on the start-up inventory needed.

This clearly shows that the direct internal recycling concept is a tremendous improvement for future fusion machines. It is unlikely that any other physics or technology advancement has a similarly high impact on the sizing of the fuel cycle. The big disadvantage of this technology is its low technical readiness level. There is currently no metal foil pump, which is capable of working under fusion relevant conditions.

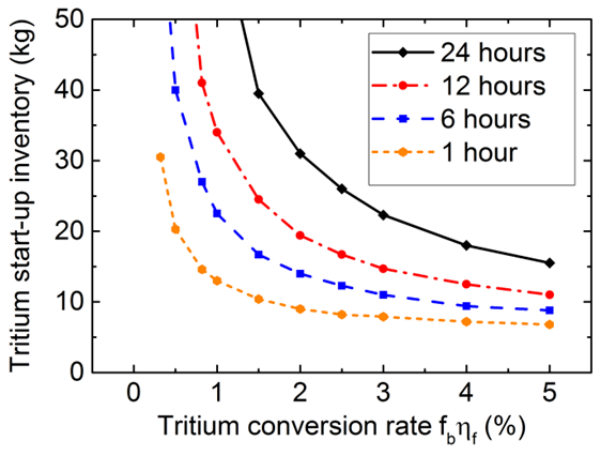

Fig. 4 Simulation data of a necessary tritium start-up inventory vs. tritium conversion rate for different mean processing times, simulation results taken from [4].

3. Superpermeation

The envisioned Metal Foil Pump bases on the effect of superpermeability. Several test stands, based on this effect have been built previously, mainly to investigate the underlying effects.

Superpermeation describes permeation that is driven by energetic hydrogen instead of gas pressure, as it is done in the classical gas-driven permeation (GDP). Hydrogen dissolves in metals in atomic form. To do so, the hydrogen molecules in the gas phase have to split up before entering the metal lattice. In GDP this occurs statistically on the metal surface in both directions, from gas into bulk and reverse. Here a high permeation rate can only be achieved if the surface is clean and the electrons of the metal catalyze the cracking of the hydrogen. Energetic hydrogen on the other hand summarizes all forms of hydrogen, where the hydrogen itself holds the energy for dissociation. This can be already split up hydrogen radicals, but also hydrogen ions or hydrogen with high kinetic energy. These forms of hydrogen can easily enter the metal bulk, the implantation depth will nevertheless be very small. In this case it is helpful if the surface does not catalyze the recombination. Otherwise it would be much more likely for the hydrogen in the bulk to recombine on the same surface where it entered. This surface barrier can be supplied for example by non-metals that bond to the metal surface.

Previous investigations focused either on group 5 metals [5], or on pure iron [6].The group 5 metal vanadium was previously investigated in the current setup at KIT [7]. In this paper iron is investigated.

The big difference between vanadium and iron is the heat of solution for hydrogen in the metal. Whereas hydrogen has a negative heat of solution in vanadium, the heat of solution in iron is positive. It is thus energetically favorable for hydrogen to be in solid solution in vanadium, but in iron many other positions in a metal foil could be preferable. These positions could be vacancies or grain boundaries.

4. Experimental setup

The HERMES setup at KIT was built for the investigation of superpermeation. It consists of two vacuum chambers that are separated by a metallic membrane. The circular membrane has a circular, active surface with a diameter of 70 mm. It is sealed by a Helicoflex seal on a flat surface. In the upstream chamber an ECR plasma source (tectra GenII) faces it. This chamber is constantly pumped by a turbomolecular pump, the pressure is regulated by a PID loop with a mass flow controller as actuator. On the downstream side of the membrane a radiation heater is mounted, this is the actuator for a PID loop controlling the membrane temperature. This temperature is measured by a K-type element pressed against the back side of the membrane. The downstream chamber is pumped by a turbomolecular pump, which can be disconnected with a gate valve. A combined penning and pirani gauge was used for the measurements below one mPa, for higher measurements capacitance manometers were used. A schematic view of the setup can be seen in Fig. 5.

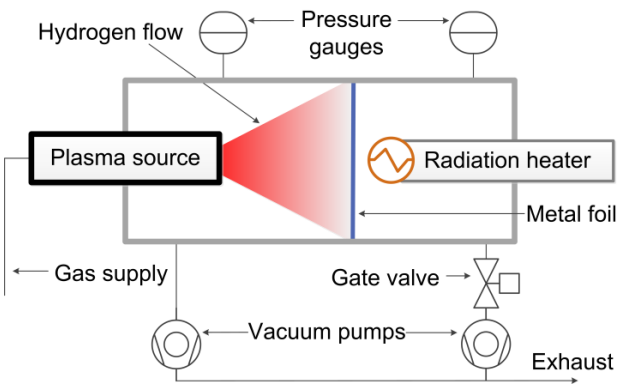

Fig. 5. The HERMES setup at KIT.

A measurement is performed by establishing a constant pressure in the upstream chamber while evacuating the downstream chamber. The measurement is started by closing the gate valve in front of the downstream turbomolecular pump, stopping the pumping of permeated gas and thus causing a pressure rise. Blind measurements with an evacuated upstream chamber led to pressure rises orders of magnitudes below the results shown. As the membrane is sealed against atmosphere and not against the other chamber, a leak from one side to the other can be excluded as influencing factor.

5. Experiments

The aim of the performed experiments was the demonstration of superpermeation with an iron foil. An essential prerequisite of this effect is surface limited permeation. Such a surface limitation can be detected in different ways. As the surface dominates the process, surface changes will also directly affect the permeation flux. The permeability of such a membrane will always be below a diffusion limited membrane. To calculate the permeability, the driving pressure difference has to be taken into account. For a diffusion limited system this will give permeability values that are independent of the driving pressure.

The GDP study was performed first, so the plasma source was not used. In general, the upstream pressure acts as a driving force and causes a pressure rise in the downstream chamber. For all GDP measurements, the pressure rise downstream was in the range of a fraction of mPa after half an hour for the measurements at 50 °C and 150 °C. In Fig. 6, the typical downstream pressure evolution is displayed on the ordinate while the measuring time is displayed on the abscissa. An upstream pressure of 100 Pa and a metal foil temperature of 150 °C were used in this case. Four successive measurements at the same conditions are carried out. After a quick initial rise (likely to be caused by the closing of the gate valve and hence not a permeation effect itself) all the pressures increase nearly linearly. But from the first measurement (lowest curve) to the last (top curve) the curves show increasing slope, although the boundary conditions have been maintained the same.

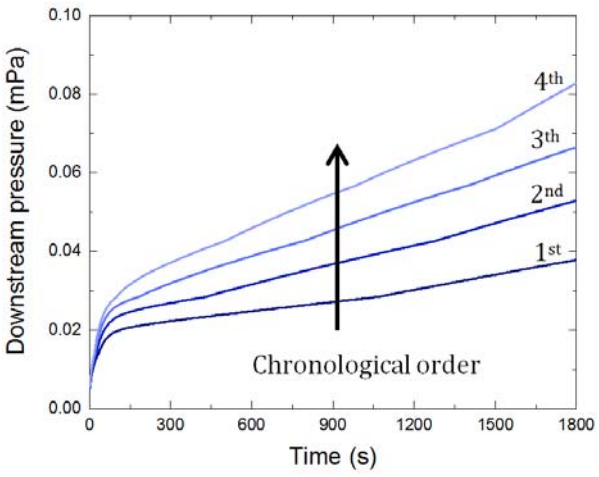

Fig. 6. Pure iron - Time evolution GDP at 150°C and upstream pressure of 100 Pa.

This kind of time evolution can be attributed to two effects. It can be attributed to insufficient saturation of the metal foil. Due to crystal defects and grain boundaries in the metal, traps are formed and filled up by diffusing hydrogen atoms first. Only after all traps are filled, the metal foil is completely saturated with hydrogen and steady state permeation is possible. Another possible reason could be a degradation of the impurity layer on the membrane surface, as it was previously suggested for a vanadium membrane [7].

Although the difference between the experiments decreased after many repetitions, the trend towards higher pressure increases continued. This led to the assumption that the foil was saturated at some point, but the surface still changed. A surface change will only cause a difference in the permeated pressure rise, if the permeation process is surface dominated. In order to find this out, gas-driven permeation experiments were performed at several foil temperatures as well as at different driving pressures. From the measured pressure rises, the permeabilities were calculated. In Fig. 7 these values are plotted.

As it can be seen in Fig. 7, the permeability values are always below the literature value [8] and different for the different driving pressures. This gives clear evidence for a surface limited permeation process.

The data of the measurement shown in Fig. 8 was one of the first plasma-driven permeation (PDP) experiments with the iron foil. Before the beginning of the experiment, the membrane temperature was set to 250 °C. A constant pressure of 0.6 Pa was established and regulated in the upstream chamber. To start the experiment (Time zero in Fig. 8), the plasma source was switched on and the gate vale was closed. One can see the drastic pressure rise. Already after half a minute the pressure in the downstream chamber exceeded the upstream pressure, a clear feature of superpermeation [7]. Additionally the temperature of the metal foil increased drastically. Comparative experiments with other gases (Ar, N_2, He) did not show a similar

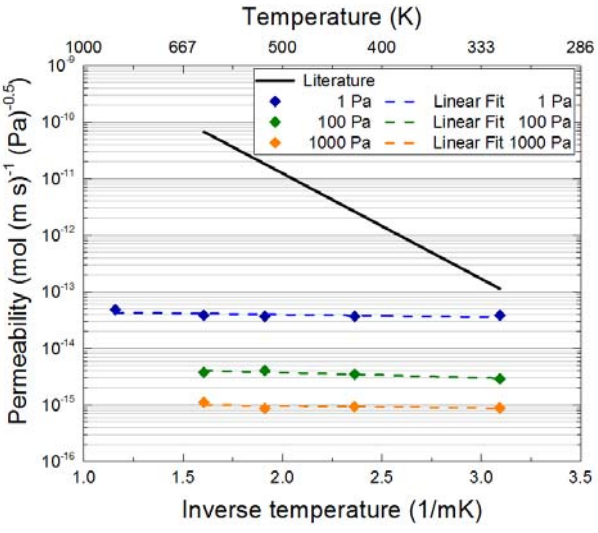

Fig. 7. Permeability P of iron over inverse temperature at different upstream pressures (dashed) and literature (solid) [8].

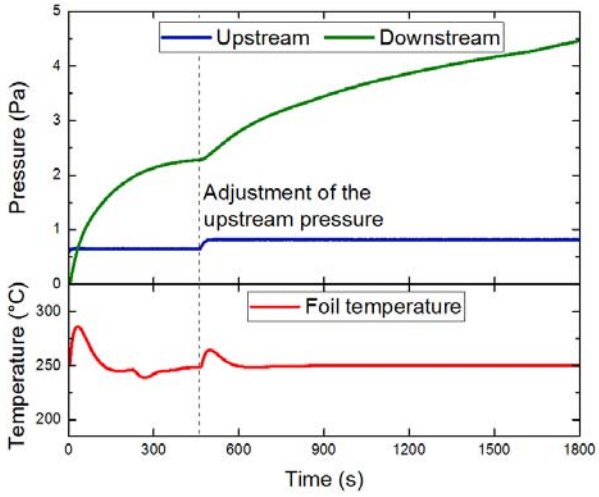

Fig. 8. Pure iron - upstream, downstream pressure, foil temperature over time.

temperature increase. Thus, it is believed that this temperature increase is caused mainly by hydrogen atom recombination. The PID loop regulating the membrane temperature counteracts this process and reestablishes the previous set temperature of 250°C.

As the plasma source was used close to its lowest operation pressure, it probably extinguished at some point, this was the reason to increase the upstream pressure a little at the displayed point. Once again, the temperature increased and the downstream pressure increase, which had become to a halt before, increased again.

This gave the opportunity to do another proof of the surface limitation. The metal foil surface was cleaned by treating the surface with argon plasma for about 2 hours. Afterwards another GDP measurement was performed. To try to reestablish the surface barrier, the upstream gas was exchanged with synthetic air over night. The result of the subsequent GDP is shown together with the measurements before and after the argon cleaning in Fig. 9.

It can be clearly observed, that the argon treatment did clean the surface and thus allowed a higher permeation flux. The surface barrier for permeation did increase

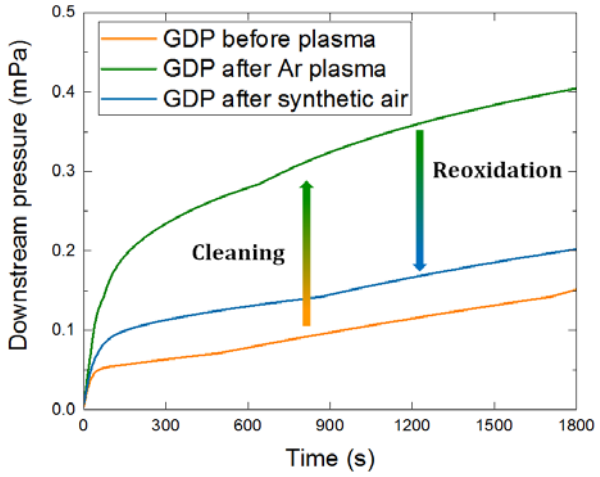

Fig. 9. Three pressure rises in the downstream chamber of the after the treatment with synthetic air, but did not reach previous values.

6. Conclusion and Outlook

It has been shown via dimensionless numbers for tritium stream reduction, the tritium conversion rate improvement and the mean tritium processing time that a DIR is a tremendous improvement for future fusion fuel cycles in terms of the size of the tritium plant as well as the start-up tritium inventory. The needed technology of a metal foil pump should thus be developed to a high technical readiness level.

The permeation studies on iron show a similar behavior as previous studies with vanadium. Superpermeation with an iron foil has been demonstrated as well as surface limited diffusion. The problem of quickly degrading surface barriers has to be addressed.

For further investigations a thorough theoretical treatment on the material choice should be performed. This should allow concentrating on fewer materials for the further development of the metal foil pump.

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