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ABSTRACTS

A cryosorption panel test arrangement was installed in the Cryogenic Forevacuum (CF) Subsystem of the Active Gas Handling System (AGHS) at JET. The pump panels were of ITER relevant design in terms of geometry and dimension, coating and sorbent material. The central objective of this investigation was to study, for the first time in such an in-depth and parametric way, the interaction of tritium and tritiated gas mixtures with the panel and the influence on pumping performance and regeneration characteristics. This paper describes how the pump was implemented in the system and summarizes the major experimental results obtained in a two-staged programme: First, the test set-up was used to pump process gases under the Trace Tritium Campaign at JET; secondly, a dedicated test campaign was performed with defined external supply of tritium via a U-bed. It is highlighted that the ITER cryosorption pumping concept achieves highest pumping speeds for tritium. No show-stoppers have been identified.

1. INTRODUCTION AND MOTIVATION

The reference design of the ITER torus exhaust high vacuum system is based on eight cryosorption pumps located in the divertor ducts [1]. To pump helium, which cannot be condensed at the available 4.2K supercritical helium cooling conditions, and to assist pumping hydrogens, the cryopanels are on both sides coated with activated charcoal granules [2]. The primary pumping system is not only designed to pump the exhaust gases from the plasma, but is also needed during fine leak-testing of the torus, for wall conditioning and bake-out and to provide ultimate vacuum in the torus. This means that a broad spectrum of gases including all the different isotopic hydrogen species will have to be pumped.

To investigate experimentally the pump characteristics, a near ITER scale model pump has been manufactured and tested over the last years in the TIMO test bed (Test Facility for ITER Model Pump) at Forschungszentrum Karlsruhe (FZK) [3, 4]. The pump has been validated in all aspects of operation except the performance under tritium, which is not possible to do in TIMO. For the qualification programme there, which involved a series of different ITER-relevant exhaust gas mixture compositions, the tritium fractions have been replaced by deuterium. Tritium performance is the last remaining issue which has not been covered yet on the level of a technical scale device. Extrapolation from non-active hydrogens may be dubious due to the potential influence of ß particles on the energy distribution across the charcoal surface. Moreover, the tritium compatibility of the cryopanel set-up (bare panel sheet, inorganic bonding agent, charcoal type coating) which is common to all large cryosorption vacuum systems on ITER (torus pumping, NBI pumping, cryostat pumping) has only been checked on small scale samples so far [4].

In preparation of ITER, it is essential to assess the pumping and regeneration behaviour of a technical scale pump and to demonstrate the applicability of the cryopanel design for pumping tritiated gases. It is foreseen to ship the cryopanels after testing to tritium labs (TLK Karlsruhe, Germany and CEA Cadarache, France) for further investigations with respect to detritiation methods and determination of residual inventory.

2. DESCRIPTION OF THE TEST SET-UP

A Prototype Cryosorption Pump (PCP) was designed, manufactured and finally installed for testing in JET-AGHS [5]. It has an overall height of 3.2m and a diameter in the lower cylindrical tube of 185 mm, see Figure 1. The cryosorption panel test arrangement is of ITER relevant design in terms of dimension, coating, bonding and sorbent material. Different from the ITER operation which involves supercritical helium cooling at 4.2K, the PCP is based on cooling with boiling liquid helium supplied via a 2000 l dewar system. The total panel surface of 0.4 m^2 (both sides counted) corresponds to one ITER panel, 28 of which are installed in each ITER torus exhaust pump. The PCP panel arrangement comprises three sub-panels welded in series. This is to reduce the cutting steps of the then contaminated panel arrangement after the experiment.

The cryopanels were equipped with resistance heaters, one on each side, and electrolytically copper plated (≈400 μm thick) to achieve a homogeneous surface temperature distribution. The heaters allow to perform the pump regeneration under controlled conditions rather than just by normal warm-up due to heat in-leaks. The ITER reference regeneration temperatures are about 100K to release the hydrogens, room temperature to release any air-like impurities, and 450K to release water-likes and for conditioning purposes. The panels are equipped with 11 temperature sensors (Si diodes) on both sides for monitoring and control. The cold ends of the heaters (each 3 m long), and the cryogenic wiring of the temperature sensors are connected to UHV feedthroughs in the upper head of the device. The head also provides connections for a set of pressure gauges and for the gas supply. The LHe is supplied via insulated transfer lines from outside and carried in a simple pipe inside.

3. IMPLEMENTATION AT JET

The PCP was installed in CF Module 5 of AGHS, replacing one accumulation cryopump [6]. The existing cryosupply was upgraded for higher flowrates of liquid helium (LHe). To achieve ITER relevant temperatures of 4.2K, a separate transfer line from a LHe dewar was installed, different from the normal JET cryosupply conditions with sub-atmospheric LHe at about 3.4K. This temperature difference is very relevant since too low temperatures may completely change the pumping mechanism from sorption (at higher temperatures) to condensation (at lower temperatures).

For regeneration, the pump is being heated and the released gas is pumped out by the turbomolecular pump system or by a transfer cryopump.

The pressure inside the pump was monitored by four vacuum gauges overlapping in range, namely a cold cathode Penning gauge, a Pirani gauge, and two calibrated capacitance gauges (1 Torr maximum pressure; 2.5 bara maximum pressure). They were connected to the PCP interior volume via a 1765 mm long connection pipe (4.5mm inner diameter) which was present from the former ACP pump. The influences on the pressure reading resulting from the relatively long connection pipe are not negligible, especially not in the high vacuum range during pumping, and were considered by means of a conductance calculation and included in the evaluation of the data.

The gas species dependence for Pirani and Penning gauges were considered by the typical factors, as given by the companies.

In the first experimental stage, during the Trace Tritium Campaign (TTE) at JET, the PCP was directly connected to the torus (Torus and Neutral Beam Injector (NIB) matrix lines) via a DN 100 pipe. After TTE completion, the pump was thoroughly air purged to reduce the tritium inventory. Following this, the connection line was breached to prepare the second experimental stage with direct gas supply from a reservoir vessel via a $^3/_4$ in. diameter pipe. The reservoir volume could be fed with standard gases and with tritium from the U-beds.

The maximum tritium inventory was limited to 5g in the system. This corresponds to a filling pressure of 200 mbar in the 100 l reservoir (at room temperature). To have a defined flowrate from the reservoir into the PCP, a JET certified tritium compatible valve equipped with a defined orifice was installed in the dosage line. An orifice diameter of 0.3mm was found to be sufficient to ensure choked flow conditions (which means throughput becoming directly proportional to the reservoir pressure) and to generate cryopanel surface related flowrates in the range comparable with the ones in ITER. The final set-up (valve+orifice+filter) was calibrated at FZK prior to the experiments.

4. EXPERIMENTAL PROGRAMME

The central objective of this task is to study the interaction of tritium and tritiated gas mixtures with the panel, in terms of pumping performance and desorption characteristics. The existing knowledge in this field is limited to qualitative results gained in other fusion devices and only one small scale phenomenological experiment at 77K [4]. Together with the existing data for protium and deuterium, a sound assessment of any isotopic effect is aimed at.

The experimental programme was structured into two stages. The first one was direct processing of tritiated gases within TTE to pump tritium-rich gas from the neutral beam injector box and trace tritium gas from the torus. The second experimental stage was the investigation of the pump performance under a more structured and parametric variation of the influential properties.

4.1. OPERATION UNDER TTE

The PCP was installed, leak-tested, functionally checked and finally commissioned for operation during TTE [7]. Under steady-state cold conditions, (regular LHe supply rate was 0.6 l/min) the pressure in the PCP was below 10^{-4} Pa, and the temperatures were between 4.2 and 5K for the two lower panels, between 7 and 10K at the top panel. CF is typically operated in a batch-wise manner. This means, a portion of gas released from the divertor or NIB cryopumps under regeneration is rapidly expanded into the pump volume, typically over night. This causes a sudden temperature increase (up to 40K to 50K) and a pumping effect during the following cool down. Due to the presence of charcoal in the PCP, this operational procedure ensures that any pump effect is definitely caused by cryosorption and not by condensation, because adsorption starts to become active at much higher temperatures. Table I lists the operational runs with tritium containing gases, and the T_2 contents of the gases as processed with the PCP during TTE.

The PCP was running without problems and according to specification. The pump performance was very supportive of AGHS operation due to the fact that sorption pumping of hydrogens begins at much higher temperatures than condensation. The cumulative amount of pumped tritium was approximately 1 bar·l (0.3g T_2). The highest gas amount pumped in one batch was under non active conditions 140 bar·l of D2. Related to the charcoal-coated pumping surface of 4000 cm•, this yields a gas load of about 2.3 (Pa·m^3)/cm^2. This is higher than ever measured before and by a factor 10 larger than what is required for ITER.

4.2 PARAMETRIC TESTING

The tests involved two basic categories [5]:

- Pumping tests: Measurement of PCP pressure evolution under defined inflow of gas.
- Thermal Desorption Spectroscopy experiments (TDS): Measurement of PCP pressure evolution with active forepumping during regeneration heating.

4.2.1 Scaling Parameters

The idea of the parametric programme was to replicate as much as possible the ITER-relevant parameters of the torus exhaust cryopumps in order to achieve scalable results in terms of:

- throughput/pumping area,
- gas load/pumping area, and
- pumping speed/inlet cross section.

The reference values according to the current ITER design [8] are a fuelling rate of 120 (Pa·m^3)/s, a total exhaust gas rate of 153 (Pa·m^3)/s, 8 torus cryopumps in branched geometry (for long pulse scenario: 4 pumps pumping, 4 pumps regenerating), a staggering interval of 150s resulting in pumping times of 600s, and 12 m^2 coated pumping surface (front plus rear side counted together). This yields for our case a surface-related fuel flowrate of about $q = 2.5 \cdot 10^{-4}$ (Pa·m^3)/(s·cm^2), which corresponds for the PCP with a coated surface of about 4000 cm^2 to about 1 (Pa·m^3)/s. Integrated over a pumping time of 600s, this sums up to a maximum accumulated gas load of L = 600 (Pa·m^3) = 0.15 (Pa·m^3)/cm^2 = 0.26 mol. Applied to a pure tritium test, this is 1.6g T_2.

The maximum gas load per test run would thus correspond to a Δp of 6kPa in the 100 l gas reservoir (if being at room temperature). As it is well known that the flowrate has an influence on the pumping speed, it was tried to establish constant throughputs [8]. The flow characteristics of the gas inlet valve are such that always choked flow is prevailing. This is the reason why, to minimize the relative change of the flowrate during the dosage, the starting pressure in the reservoir was chosen to be close to 200mbar, corresponding to the full 5g tritium limit been transferred in the reservoir. The throughput can then be calculated via the pressure decrease in the reservoir ($q = -V_{RES} \cdot dp_{RES}/dt$).

4.2.2 Pumping Speed Characteristics

For cryopumps, the absolute numbers for the pumping speed S are not at all directly scalable to

other pumps, as being strongly dependent on the pump interior geometry. The only geometry-independent and physically relevant parameter which can be involved in scale-up estimations is the sticking coefficient, which characterises the interaction of the cryosorbent and the gas being pumped at the present conditions of pressure, temperature and gas load. The following equation shows how the pumping speed S (defined as ratio of gas throughput q and pressure p) depends on the type of gas being pumped, the temperature and the geometry:

$$S = \frac{q}{p} = K \cdot c \cdot S_{id} = K \cdot c \cdot \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M}} \cdot A \qquad (1)$$

with c being the effective capture coefficient of the pump, which depends on the geometry (the transmission probability for the molecules passing between pump inlet and cryopanel), the sticking coefficient a of the charcoal for the gas being pumped, and on the flow regime in which the pump is operated. The square-root term denotes the ideal pumping speed which is identical with the maximum flow of a gas with molecular mass M through an aperture of cross-section area A at a given temperature T. K>1 represents a correction factor for pumping at transitional flow conditions. In the PCP with a characteristic dimension of half the pump diameter, the resulting Knudsen numbers during pumping operation are between 0.5 and 5, which means that K should be close to unity. The capture coefficient under molecular flow conditions and Maxwellian velocity distribution at the gas inlet (usually ensured by a big sized inlet gas dome) can be estimated by means of Monte Carlo simulation to a good accuracy. However, these requirements could not be met because the PCP had to fit into a given housing. Therefore, to facilitate the transfer of the experimental results on other pump arrangements, the decision was taken to design the PCP such that the transmission probability is of minor influence. In this case, the capture coefficient becomes identical to the sticking coefficient. Under these assumptions, eq. (1) simplifies to

$$S\,(PCP) = \frac{q}{p} \approx \alpha \cdot S_{id} = \alpha \cdot \sqrt{\frac{R \cdot T}{2 \cdot \pi \cdot M}} \cdot A \qquad (2)$$

Consequently, the design does not include any baffle or shield in front of the pumping panels, which would reduce the pumping speeds due to their limited transmission probability. This has to be paid for by increased cryogen consumption. The sticking coefficients for the tritiated gases, which form the central result of these tests can be derived from the experiments according to eq. (2).

To have a sound data-base which allows for cross- checks with literature data, a series of non-active reference gases was started with: N_2, D_2, H_2, He and a D_2- based gas mixture (denoted D_2-base, containing 3.7% fusion typical impurities (CO, CO_2, O_2, CH_4)) with 10% He. These runs were complemented with pure tritium, an equimolar D2+T2 mixture (close to equilibrium when being pumped: 30% D_2, 40% DT, 30% T_2) and a three-component mixture with 10% He. Figure 2 illustrates the results obtained for the fusion relevant isotopes D_2, T_2 and DT as well as for He,

plotted as ratios of measured and ideal pumping speed vs. the gas load being pumped. The ratios S/Sid are equal to the sticking coefficient, if the assumptions above hold. It should be noted that the numbers named pumping speed are just the ratio of throughput over pressure, and should not be mixed with real pumping speeds measured according to the standards. The big scatter of the derived data results from insufficient smoothing of the reservoir pressure sensor signals used to calculate the throughput and the limited bandwidth in transfer of the PCP vacuum gauge output voltages. The first 100 s of each run could not be evaluated because the measured pressures were significantly falsified by the transient build-up of the steady-state pressure profile along the connection pipe to the vacuum gauge; this effect has been estimated by solution of the one-dimensional transient Fourier differential equation for the pressure propagation.

It becomes obvious that hydrogen isotopes are pumped very well with tritium being close to ideality. Moreover, tritium is the only ga which behaves almost constant over the increasing gas load. This behaviour was validated within a special long-term test with a final gas load of 0.25 ($Pa \cdot m^3$) of tritium, which is a clear indication that tritium is pumped by condensation rather than by sorption. It is known from the TIMO tests that H_2 is pumped by sorption exclusively, D_2 is pumped by combined sorption and condensation. Table II compares the measured initial sticking coefficients with literature data. For He and H_2 which are known to show a strong temperature dependency of the sticking coefficient [9], the measured values are smaller than reported elsewhere. This is probably due to the fact that the temperature of the upper cryopanel was not below 9K.

It is also revealed that the pump performance of a 10% helium in hydrogen mixture is governed by the helium content due to its low sticking coefficient. The decrease of S/Sid with increasing gas load is more pronounced than observed in other facilities [3, 11], which is attributed to the existing temperature gradients across the upper cryopanel.

The absolute values of the pumping speeds for the hydrogen isotopes (D_2, T_2, DT) were in the range of 6.5m^3/s. In this experimental campaign, the PCP has pumped an integral amount of 4.8g of T_2 and 1.3g of DT. To assess any permanent effect of tritium on the pump performance for other gases, a comparison before and after the tritium runs has been made, using the 90% D_2-base + 10% He-mixture, see Figure 3. The difference in the pumping speed curves is small and well within the experimental accuracy.

4.2.3. Regeneration Characteristics

The second central issue in performing these tests was to clarify the pumping mechanism of tritiated gases. The advantage of using a cryosorbent is that the DT fusion ash helium can be pumped effectively. Earlier investigations have shown that, under the conditions of a cryosorption pump at 4.5K, protium is predominantly pumped by sorption (as helium) in the charcoal pores, and deuterium is pumped by combined sorption and condensation, governed by sorption at small gas loads (as for the experiments described in this paper) to condensation at high gas loads. From the extrapolation of the saturation pressure curve, one would expect tritium to be pumped predominantly by condensation (formation of ice layers) on top of the charcoal. However, the decay heat and existence of β particles may change the energy distribution on the surface of the charcoal and thus lead to different results.

One goal of the test campaign is therefore to identify the pumping mechanism of tritium.

The constant sticking coefficient for tritium shown in Figure 2 was already one indication for condensation pumping. Figure 4 shows the result of a TDS experiment for the two gases D_2 and T_2, i.e. the pressure evolutioncurve when the panels get heated for regeneration. The pressure peak for tritium, which has no correspondence for deuterium, is interpreted by sublimation of condensed tritium, which is then re-adsorbed from the gaseous phase, because the sorption efficiency of charcoal is still quite high at temperatures above sublimation. After this step, all condensed particles have end up at the charcoal again, but bound at a different energy. So, in the temperature range above sublimation, thermodynamics of classical desorption are valid. The actual desorption regeneration starts quantitatively not before 40K at the charcoal.

An important consequence of condensation pumping of T_2 is the potential risk of blocking the charcoal pores by formation of an ice layer on top. In this case the pumping speed for the species which have to be pumped by sorption, especially He, may drastically diminish.

The gas release associated with desorption defines the temperatures which are needed for partial regeneration of the pump. This is the temperature level where the hydrogen isotopes are completely released. It is essential to know this temperature accurately to be able to limit the tritium inventory in the pumping systems at ITER and to design the cryoplant. Figure 5 shows the measured release curves for the hydrogen isotopes. It is revealed that temperatures between 90 and 100K are needed to achieve an effective desorption of pumped hydrogens. The release curves agree well for all the hydrogen isotopes within experimental accuracy. This corresponds to the results measured earlier in TIMO for the non active isotopes H_2, HD and D_2 [1].

CONCLUSIONS AND OUTLOOK

For the first time, a prototypical cryosorption pump in technical scale based on the design principle of the ITER cryopumping systems, has been operated and tested with tritium and tritated gases on a real tokamak fusion machine. The tests were performed at JET using the AGHS as a versatile test bed. The PCP was first used as regular pump during TTE, and then subjected to a parametric test programme. The measured pumping behaviour for tritium and an equilibrated equimolar D_2-T_2 mixture was excellent. It became obvious that the sticking coefficient for pumping tritium is close to unity, near the maximum possible. The pumping mechanism of tritium was clearly identified to be condensation. This may lead to competing pumping situations in case of tritium-helium mixtures, an issue which should be better characterized and quantified in an upcoming experimental campaign. In spite of the experimental limitations, the scientific value and output of this task fully justified the decision to implement a technical scale test unit in a tritium plant in parallel to ongoing work in the torus. It is a good example to show how JET with its unique capabilities in tritium handling can be used to prepare operation of ITER.

The ITER cryosorption pumping concept could be fully validated. No severe design weaknesses have been identified. The processing of tritium did not cause any deterioration of the pump performance. The task will be continued with in-depth detritiation studies of the cryopanels.

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Run #	Gas Origin	Gas amount (bar · l)	Tritium content (%)
1	Divertor	10	0.1
2	NB	16	5.1
3	Divertor	76	0.005
(several)	Torus cleaning	350 (integrated)	0.03 (averaged)

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TABLE I: Pumped amounts of tritium during TTE and in the cleaning phase.

α	He	H_2	D_2	T_2
This work	0.1	0.4	0.88	1.0
Lit (10)	0.15	0.6	0.90	—

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TABLE II: Comparison of initial sticking coefficients.

Figure 1: PCP (Design, manufacturing, installation).

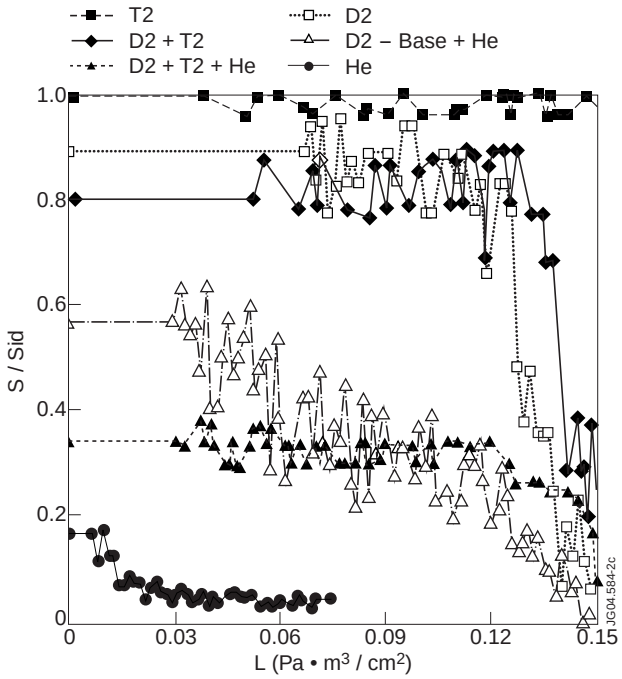

Figure 2: Measured sticking coefficients for tritiated gases.

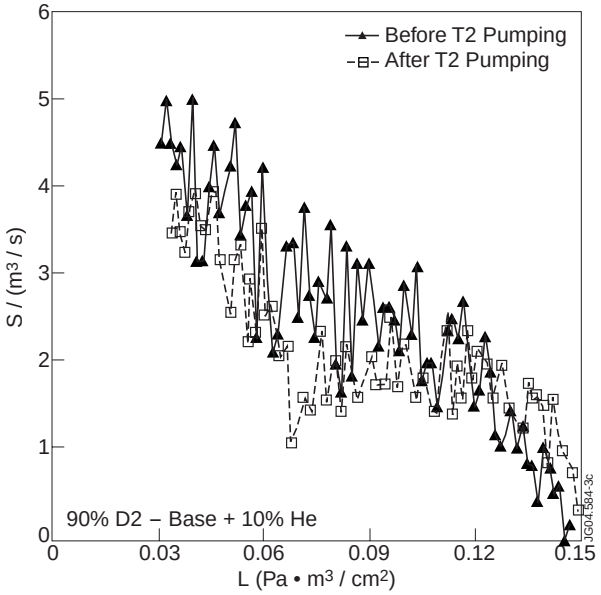

Figure 3: Comparison before and after the tritium tests.

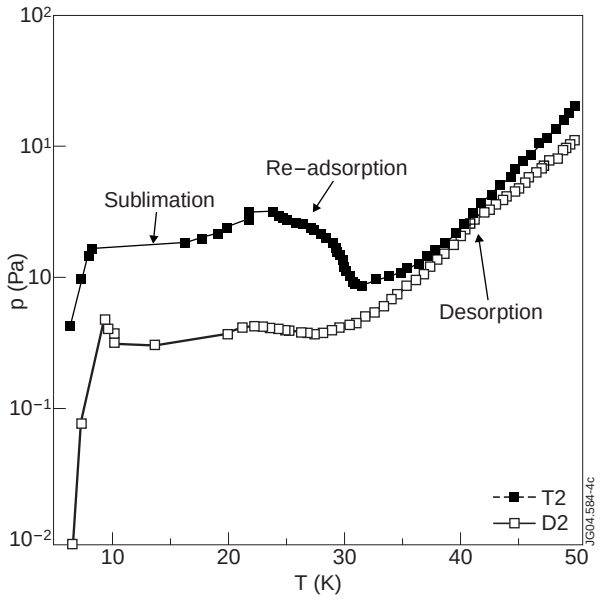

Figure 4: TDS test for condensed T2 and sorbed D2.

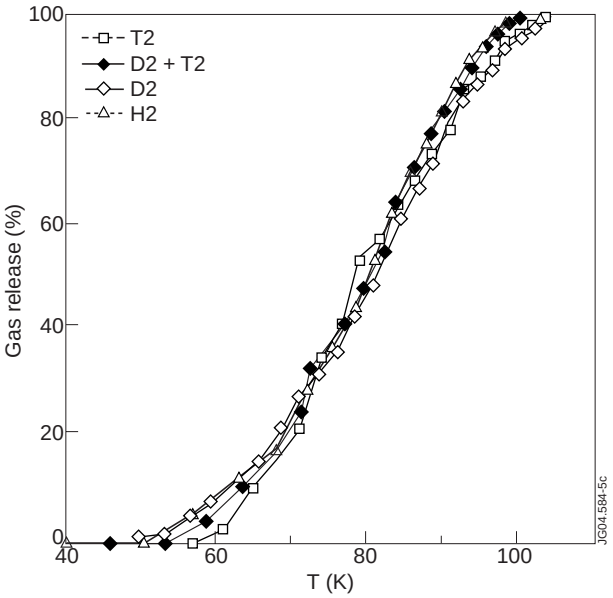

Figure 5: Hydrogen release within partial regeneration.