Tritium Purification, Storage and Supply in the Tritium Plant of a Fusion Reactor

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The techniques used at the JET tritium plant for separation of torus exhaust gas and impurity processing are discussed in view of the requirements for the tritium plant of a next generation fusion reactor. A chemical method to convert tritiated hydrocarbons and water with a liberation of molecular hydrogen is presented. The efficiency and safety of uranium hydride containers used at JET for pumping, storage and supply of tritium and deuterium are analyzed and the possible use of non-radioactive intermetallic alloys for metal hydride storage systems is investigated.

1. Introduction

The JET tritium plant (Active Gas Handling System, AGHS) has recently been commissioned with trace tritium - a mixture of \( \approx 30 \text{TBq} \) of tritium diluted in \( D_2 \), left over from JET's first tritium experiment in 1991 [1]. In the near future, the operating inventory will be built up in steps (up to 20g \( T_2 \) in 1996/1997) to the full operating inventory of up to 90g \( T_2 \) in 1998/1999. The JET tokamak, with its integral fuel recycling system, is expected to provide a sound database for the tritium processing requirements of ITER, operating with a burning D-T plasma.

This paper concentrates on torus exhaust gas processing which is currently a key point of the fuel cycle and on the operation and performance of JET uranium hydride containers. As an alternative, several candidate intermetallic alloys for tritium storage and supply are discussed. The paper presents results of experiments at JET, at the Russian Research Institute of Inorganic Materials and at the Karlsruhe Research Center (Germany).

2. Basic features of tritium processing on JET and ITER

The main features of the JET tritium plant is its batch mode of operation: during torus operation, deuterium, tritium and impurities are pumped by cryocondensation pumps in the torus and neutral beam injection system. These primary pumps may be regenerated at the end of each operation day. The released gas mixtures are transferred to cryocondensation panels in the AGHS Cryogenic Forevacuum (CF) system [2]. The CF system separates the pumped gases into three "clean" product streams:

- helium (which is accumulated on charcoal cryocondensation panels);
- hydrogen isotopes mixture;
- impurities.

Helium and impurities are collected in a buffer tank for further processing, hydrogen isotopes are transferred to the Intermediate Storage (IS) uranium containers (U-container) and subsequently fed to either of the two isotope separation systems (ISS), i.e. Gas Chromatography (GC) or Cryogenic Distillation (CD). Separated \( D_2 \) and \( T_2 \) are stored in Product Storage (PS) uranium containers and supplied to the torus and neutral beam injectors.

Impurities released from the torus cryopumps during daily regeneration to 77K consist mainly of methane and ethane. However, recent experience has shown that regeneration of the cryopumps to room temperature, or higher, after extended operation for one to two weeks leads to the release of substantial
amounts of higher hydrocarbons (see Fig. 1) which had been cryocondensed on the 77K baffles of the cryopump. The JET AGHS Impurity Processing (IP) system can cope with these species as well as with the previously expected methane and ethane.

![Graph showing mass spectrum of gases released from JET divertor cryopump regenerated at 200K]

**Fig.1.** Mass spectrum of gases released from JET divertor cryopump regenerated at 200K.

The tritum plant for ITER will have to process exhaust gas quasi-continuously at a flow rate of ≈200 times the throughput of JET. The ITER design [3,4] considers a once-through operation mode for torus exhaust gas separation and impurity processing. Gas separation is to be performed by a front-end palladium permeator. Most of the permeated clean D-T fuel will be directly recycled to the torus, while a bypass stream is isotopically separated to adjust isotopic balance as required for optimum plasma operation. For impurity processing, a number of advanced techniques are currently under development [3]. The once-through mode of operation presently selected for ITER impurity processing requires a substantially higher efficiency than the process used at JET, where impurity bunches can be reincirculated until the necessary detritiation factor is achieved.

### 3. Torus exhaust gas processing

To minimize releases of tritium to the environment for both JET and ITER, a gas detritiation factor (DFIP) in the order of ≈10^8 is desirable. DFIP is the product of detritiation factors of primary fuel clean-up (DFCUC), the impurity processing (DFIP) and the final exhaust detritiation system (DFED). For the currently adopted nominal composition of plasma exhaust gas (total impurity content <10%, including ≤4.5% methane and ≤0.5% water), detritiation factors DFCUC and DFIP in the order of ≈10 and ≈10^5, would be acceptable.

The primary purpose of the fuel clean-up (FCU) system is the purification of hydrogen isotopes to a purity acceptable for the isotope separation system or direct recycling to the plasma. Purification of torus exhaust gas by the ITER front-end palladium permeator should easily achieve impurity concentrations of ≤1ppm in the permeated hydrogen stream, with an impurity "waste" stream containing less than 1% hydrogen.

Tests of the JET method of cryogenic separation of gas mixtures have shown that this system separated D_2 from the methae (8.9%) and helium (2.2%) giving a D_2 purity of ≥99.95%. Final purification of hydrogen isotopes takes place in the U-containers in the IS system.

#### 3.1 Impurity processing in the current JET AGHS

Hydrocarbons and traces of molecular hydrogen are converted into water (with oxygen added as required) on a palladium catalyst at temperatures up to 770K. The water is collected in a cold trap operating at 160K. The gas mixture is recirculated until the desired DFIP is achieved. Subsequently, after stacking the detrititated waste gas through the Exhaure Detritiation (ED) system, the water from the cold trap is passed through modules filled with iron powder at ~823K. The resulting molecular hydrogen is absorbed in U-containers together with residual water not decomposed on irion. Oxidized iron can be regenerated with tritium-free H_2. Tritium
contaminated water resulting from regeneration is retained in the ED molecular sieve adsorbers for disposal as tritiated water.

The option of further reprocessing in a CECE (combined electrolysis catalytic exchange) type water decontamination system is being considered. Trace tritium commissioning with 500appm tritium concentration showed high efficiency of the recombiner/cold trap system, with residual activity of ~0.1GBq/m³ in the 2m³ buffer tank after processing a mixture of tritiated methane, hydrogen and water. The residual tritium concentration in water produced during reduction of FeOx with trace tritium hydrogen corresponds to ~0.5% of the processed tritium inventory, giving a DF[H]/Pd 200, which is acceptable for the next tritium phase of JET.

Evaluation of a new technique for impurity reprocessing in the JET tritium plant. We are presently investigating advanced techniques to improve the performance of the JET AGHS IP system, with the following desirable features:

- capability to process impurities of widely variable flow rates and composition;
- capability to process "abnormal" batches, such as the recently found higher hydrocarbons;
- long service life without component replacement;
- avoidance of cumbersome on-line and real-time chemical analysis equipment for process control.

The key point of this technique is the introduction of a palladium permeator and a new catalytic reactor.

Investigation of palladium membrane. Pd-membrane ageing caused by the accumulation of 3He, which is a product of 3H decay, and poisoning by several gases are investigated for membranes used for commercial Pd-permeators. Samples of commercial tubes of Pd-alloy (containing 15%Ag, 0.6% Pt, 0.6% Ru, 1.0% Au and 0.2% Al additionally to Pd) have been exposed [5] to D:T=1:1 mixture at temperature of 620K and gas pressure of 500-900kPa. Tensile properties, the dimension of He bubbles, crystal lattice parameters of an initial sample and samples exposed for extended periods of time have been measured. Electron microscopy, X-ray analysis and positron annihilation spectroscopy have been also used for characterization of exposed samples. Details and results of the experiments are given in [5]. Positron annihilation analysis of the samples shows a tendency for increase in concentration and size of defects of the crystal lattice with extended exposure of the membrane in tritium atmosphere. Nevertheless, no obvious effect of 3He (3He atomic concentration is calculated to be 470appm, average size and concentration of bubbles are 3nm and ~2·10¹⁶cm⁻³) on mechanical properties and crystal lattice parameters is detected after 2000 hours of exposure.

The Pd-membrane (Pd-25%Ag alloy) throughput decreased to 50% of its initial value after ~150 hours of operation at 723K with He containing from 1 to 50kPa of CH₄ and increased again up to 60% after ~30 hours of operation with mixtures containing additionally H₂O, CO, CO₂. This effect means that the efficiency of long term operation of Pd-membrane depends on the chemical composition of the gas mixture. It was found that the operation of the Pd-membrane for several months with gas mixtures containing higher hydrocarbons and at temperatures >673K can lead to irreversible chemical contamination of the membrane surface and a decrease in its permeability for hydrogen.

Possibility of HITEX reactor application in JET tritium plant. A schematic layout of HITEX operation in a batch regime is shown in Fig.2. Gas species are mixed with protium in a buffer tank (BT) and then circulated through a catalytic reactor (CR) and a palladium permeator (P). Molecular hydrogen removed from the mixture by the Pd-permeator is sent to ISS. The tritium depleted product of the ISS is returned to the catalytic reactor inlet.
The time dependence of DF obtained by the solution of a differential kinetic equation (\(V \cdot (dY/dt) = G \cdot (X_F - X_d)\)) is described [6] by:

\[
\text{DF}^{-1} = (\alpha \cdot X_d) / (\theta \cdot Y_{eq}) + \exp\left(-G \cdot q \cdot \theta / (V \cdot (\alpha + \lambda - q))\right)
\]

(1)

where \(\alpha\) is a separation coefficient between molecular hydrogen and hydrogen containing gas; \(\theta\) is an approach to isotopic equilibrium at the CR outlet; \(V\) is a number of moles of chemically bound hydrogen (in the form of impurities) in the BT; \(G\) is the flow rate of the molecular hydrogen through the CR; \(\lambda = G / L\); \(L\) is the flow rate of chemically bound hydrogen through CR; \(q\) is the part of molecular hydrogen recovered from the gas mixture by the palladium permeator (\(G-q\) is the throughput of the palladium permeator) and then replaced with protium; \(X_i\) and \(X_p\) are tritium isotopic concentrations in molecular hydrogen at the CR inlet and outlet, \(Y_i\) is the tritium isotopic concentration in chemically bound hydrogen in BT; \(Y_{eq}\) are the initial tritium isotopic concentrations in chemically bound hydrogen and in molecular hydrogen.

Equation (1) has been used for an estimation of the parameters of a HITEC reactor which could provide impurity detritiation in the JET tritium plant. Parameters \(\alpha\), \(q\), and \(\lambda\) were found to be equal to 1, 0.5 and 1.17 by fitting equation (1) to the kinetic curves obtained [7] for the detritiation of methane (mixture of 70% \(H_2\) and 30% \(CH_4\)). In the calculations \(\alpha = 1\) and \(G-q \cdot 6 \cdot 5 \cdot 10^5\) (which is the feed flow rate of JET cryogenic ISS) have been used. Results of calculations are given in Table 2.

**Detritiation of gases via their chemical conversion with molecular hydrogen formation.** The key point of the technique is the operation of a catalytic reactor. The basic impurity of torus exhaust gas is assumed [3] to be methane. The industrial method of "black carbon" production by catalytic cracking of hydrocarbons [8] is tested experimentally and is shown [9,10] to be effective for the processing of tritiated hydrocarbons. To be attractive, a technique based on hydrocarbons cracking should provide: a large carbon deposit to allow a reactor service life in excess of 1 year (reprocessing of torus exhaust gas containing \(\leq 4.5\%\) of methane [3] needs cracking of \(\leq 3 \cdot 10^2\) moles of methane during 1 year operation of a reactor of ITER's scale), very low residual pressure of tritiated hydrocarbons and water in gas to reach a high DF.

The viability of this technique for impurity processing in the JET tritium plant has been experimentally tested using an installation which could be a prototype of a future impurity processing sub-system. The main components of a system are: a palladium reactor, a palladium permeator of nominal throughput of \(150\) Nl/h as a \(H_2\) inlet pressure of 100 kPa and temperature of 670K, a 20 L buffer tank, a water vapor generator, a gas chromatograph and a humidity sensor. Gas is circulated through CR and/or Pd-permeator using a metal bellows pump, the gas flow rate is maintained constant by flow controllers. All the valves, pipe lines in the circuit and the BT can be maintained at an elevated temperature to avoid water vapor condensation. First results of experiments are given briefly below.

Several nickel catalysts had been tested in the Tritium Laboratory, Karlsruhe [11] to find the most promising candidate. Catalyst Nikki 111 containing 38% of Ni was selected for this research.
The rate of carbon deposition on Nikki 111-catalyst was measured to be 2.5w.%/h at CR temperature of 820K. The rate of volume rise of growing carbon deposit was found to be ≈5[%(volume rise)/w.%.C]. This considerable increase in the volume of Nikki 111 during carbon deposition needs a very large void in CR for the achievement of high carbon deposition.

The structure of carbon deposited on Ni was the initial composition of the catalyst and the operation conditions of hydrocarbon cracking. Highest bulk density has carbon deposited in graphite form [8]. To allow carbon to be deposited in the form of graphite, the original Nikki 111 catalyst has been modified. Several modifications of Nikki 111 were tested. Results of the tests presented in Table 1 show that there is a possibility for optimization of Ni-reactant modification.

**Table 1. Results of the test of CH₄ cracking on modified Ni-catalyst**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nikki 111</th>
<th>Modified Ni-catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.1</td>
<td>No.2</td>
</tr>
<tr>
<td>Rate of C deposit [a], w.%/h</td>
<td>2.5</td>
<td>≈20</td>
</tr>
<tr>
<td>Bulk density of C deposit [b], kg/m³(C)</td>
<td>7000</td>
<td>9000</td>
</tr>
</tbody>
</table>

[a] Rate of CH₄ cracking was measured by thermogravimetric analysis (sample of ≈0.1g, T=770K, P₀(CH₄)=100kPa). Maximum carbon depositions of 120w.%C, 360w.%C and 180w.%C are achieved experimentally for reactants of modification No.1, No.2 and No.3, respectively.

[b] Error of measurement is of ≈50% because of very small sample.

The removal of CH₄ and H₂O from gas mixtures is investigated with a Ni-reactant No.1. As an example, experimental kinetic curves are shown in Fig.3. Methane is more difficult to remove than water. The rate of H₂O removal rises with increasing of partial pressure of water vapor. The rate of CH₄ removal is found to be independent of CH₄ pressure in the range between 1 and 100kPa. Rate of carbon deposition is a function of the amount of carbon deposited on Ni. The maximum rate of 24w.%CH₄ was observed at carbon deposition of ≈400w.%C. The decrease in catalytic activity of Ni-reactant at carbon deposit >400w.% is caused by diminution of concentration of Ni-particles penetrated into the carbon deposit from the "mother" reactant [12]. The rate of the reactant volume rise is measured to be ≈0.4[%(volume rise)/w.%.C]. Efficiency (F) of impurity removal from gas mixture circulating through a CR was estimated by fitting the experimental kinetic curves to the equation:

\[
\ln(\frac{P_0}{P}) = (G-F)T/V
\]

which is a solution of differential kinetic equation:

\[
V(\frac{dP}{dt}) = -G(P_{out} - P) = G(P_0 - P_0/1-F)P
\]

(3)

(where V is the volume of BT; P₀, P are the initial and actual pressures of impurity in BT; P₀ is the pressure of impurity at the CR outlet; G is the gas flow rate).

Fig.3 shows a comparison of the kinetic curves of CH₄ removal from helium for Nikki 111 and Ni-reactant No.1. Simple calculations show that to provide the same efficiency of CH₄ removal, the amount of Ni-reactant No.1 required is ≈5 times less than that for Nikki 111.

The simulation of impurity processing for the JET tritium plant has been carried out with helium containing 50vol.% of CH₄ and 5.5vol.% of H₂O. Three different modes of IP operation are considered (see Table 2). Mode 1 presents single stage process of circulation of a gas mixture of 100kPa initial pressure through CR and Pol-permeator until DF=10^5 is achieved. Mode 2 is a double stage process with gas pressures of 100kPa in the stage I and 50kPa in the stage II which should provide DF₁=10^5 and DF₁=100. Mode 3 is a double stage (DF₁=DF₁=500) process with initial
pressures of 200kPa. In mode 3, impurities remaining after stage I are diluted by a factor ≈100 via injection of additional amounts of CH\textsubscript{4} and H\textsubscript{2}O.

It is clear from Fig.4 that a long time is required for impurities to be removed at low pressure when the driving forces of chemical reactions and hydrogen diffusion in the Pd-membrane are low. Gas compression at stage II (see mode 2 in Table 2) allows reducing duration of processing by ≈50\% but still requires operation with low residual pressure of methane and water. Injection of additional amounts of CH\textsubscript{4} and H\textsubscript{2}O at the beginning of stage II (see mode 3 in Table 2) considerably decreases duration of processing and allows avoidance of operation at impurity low pressure. The amount of hydrogen isotopes to be isotopically separated after impurity processing is increased only by 20\%. This value is much less than 1770\% for a HITEX reactor. Mode 3 of chemical impurity processing meets JET requirements and can be a choice for farther development.

4. Tritium storage, supply and pumping by metal tritides

4.1 Investigation of JET uranium containers

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**Fig. 3.** Kinetic curves of CH\textsubscript{4} and H\textsubscript{2}O removal from helium in the integral loop (initial gas pressure is 100kPa, temperature of the Pd-permeator is 720K, temperature of CR is 870K).

**Fig. 4.** Time dependence of CH\textsubscript{4} and H\textsubscript{2}O pressures in helium for mode 1 and mode 3 of IP operation.

**Table 2.** Comparison of different modes of impurity processing\textsuperscript{a,b)}.

<table>
<thead>
<tr>
<th>Parameter\textsuperscript{a,b)}</th>
<th>Chemical reactor</th>
<th>HITEX reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textsuperscript{a}} P\textsubscript{0} (Pa)</td>
<td>Mode 1 5.55×10\textsuperscript{-4}</td>
<td>Mode 2 5.55×10\textsuperscript{-4} (278)</td>
</tr>
<tr>
<td>\textsuperscript{b}} P\textsubscript{f} (Pa)</td>
<td>0.55</td>
<td>55.5 (2.8)</td>
</tr>
<tr>
<td>Duration (hours)</td>
<td>&gt;70</td>
<td>≈40</td>
</tr>
<tr>
<td>V\textsubscript{02} (mol)</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

\textsuperscript{a)} Impurities are removed from 160 moles of exhaust gas containing 4.5 mol of methane, 0.5 mol of water and 4.5 mol of inert gases need to be deuterated;
\textsuperscript{b)} P\textsubscript{0}, P\textsubscript{f} are initial and final total pressures of methane and water (values for second stage are given in brackets); V\textsubscript{02} is the amount of hydrogen isotopes generated during impurity processing as feed flow for isotope separation.
Uranium is in general use as hydride-forming material for tritium handling in tritium facilities. Uranium containers are used in the JET tritium plant for hydrogen isotope storage, supply and pumping. Modern uranium containers have secondary (evacuated) and often tertiary (vacuumed or filled with an inert gas) containment, software (SW) and hardwired (HW) interlock protection against overheating/overpressurizing; valves and interconnecting lines placed in an inert gas atmosphere box. JET uranium containers additionally have cooling systems with forced N₂ flow, large heat capacity (5.7 kJ/K), increased thermal conductivity and quick response on uranium temperature rise due to Ni-fins placed in uranium powder layers and brazed to the primary containment wall [13].

To transfer hydrogen isotopes, U-containers need to be heated to >770K to provide the required pressure of ≥120 kPa. Tritium permeation loss from the primary containment has been measured (with D₂) as 3.8sccm/h for a container operated at 770K with a gas pressure of 100kPa. This value corresponds to hydrogen permeability through SS316 of 4.2·10⁻⁶ sccm m⁻¹ kPa⁻¹/² and agrees well with known values. The pumping capacity (10l/sec) of the currently used getter pump (C500) filled with getter material ST707 allows >2000 hours of continuous pumping of hydrogen permeated from the primary containment of the U-container. The residual pressure in the secondary containment of the uranium container, continuously evacuated with a getter pump, rises from ≤10⁻⁵ Pa by ≤2 orders of magnitude when the container is operated at high temperature. The low gas conductance through the pump inlet filter at low gas pressure limits the hydrogen transport rate from the containment to the getter material. Therefore, the temperature of the secondary containment wall (in JET, the secondary containment is placed in an additional evacuated containment) rises to achieve a steady state temperature 50-70K below the temperature of the primary containment. Due to the high activation energy of hydrogen diffusion through stainless steel, tritium permeation loss from primary containment should decrease rapidly with decreasing temperature. At 570K permeation rate would be ≤3% of the value measured for 770K.

The ability of uranium containers to operate as high vacuum hydrogen pumps is limited because of exothermicity of reaction of hydrogen sorption by uranium. Time dependencies of temperature of primary containment of a JET tritium storage container filled with 4.5 moles of U and continuously cooled down with N₂ flow (110NL/min) during D₂ sorption from a 100L tank is shown in Fig.5. During the container loading, the uranium temperature increases by 70K. About 1 hour is required to pump 95NL of D₂ by a U-container of 150NL capacity. To achieve a low temperature of uranium and high vacuum, the U-container needs to be continuously cooled down with N₂ flow for several hours. To evacuate hydrogen from a volume to low residual pressure and absorb it by uranium

\[ \text{Fig. 5. Kinetic curve of D₂ absorption from 100L tank} \]

more quickly, gas could be pumped and compressed at the U-container inlet via a molecular drag pump or a small (≤15 m³/h) Normetex pump.

The vacuum isolation of the primary and secondary components of JET U-containers allow them to be maintained under quasi-adiabatic conditions for some period of time. This fact is used [14] for "in-situ"
measurement of container tritium inventory. The calibration curve, ie the time derivative of the container temperature (°K/s) versus tritium loading (g), is a linear function $y=ax$ with $a=3.98 \times 10^{-5}$ K/°s g(T2). Error of measurement decreases from ±15% to ±0.3%, with tritium loading increasing from 1 to 30g of T2.

Hydride containers for tritium handling should satisfy a criteria of inherent safety in accidental situations. Experimental investigations [15,16,17] of U-containers in air ingress accidents have been carried out with containers of low capacity and have shown contradictory results giving either high temperature rise and even partial damage of container or negligible uranium temperature rise. Analysis of the conditions and results of the experimental tests allows the conclusions: fine uranium powder can start a reaction with air (both with O2 and N2) even at room temperature; hydrogen presence in a primary containment prevents a reaction with air due to hydrogen blanketing.

Safety of a JET uranium container in accidental situations has been evaluated [18] using results of thermogravimetric analysis of the reactions of uranium powder with air and N2. Modern U-containers, as mentioned above, are very well protected against any air ingress accident. U-containers of high capacity (with a large amount of uranium placed into a primary containment of small volume) designed for a fusion tritium plant could be considered as safe even for the very unlikely event of air ingress into evacuated container (no hydrogen blanketing can take place). Argon, existing in air with 1% concentration, will start blanketing uranium powder and moderate a reaction with incoming air after absorption <100NL of air. The resulting highest temperature of uranium should not exceed the SW/HW protection temperature of the container. A high temperature rise could be expected only in an event of air flowing through uranium powder with low flow rate. Such an accident, as estimated [18], could lead to a local temperature rise up to 1400K. This value agrees well with experimental result [15].

The disadvantage of uranium as a tritium storage material is that even during normal operation of U-container its temperature can be higher than the temperature $T_{N_2}$ sufficient to sustain a self-accelerating reaction with N2, which is estimated [18] to be ≈770K. Analysis of the JET U-container in an N2 ingress accident shows [18] that the uranium temperature could not exceed the SW/HW protection temperature plus 80K.

The advantage of uranium as a hydrogen isotope pumping material, ie its low equilibrium sorption pressure, is difficult to be utilized in a fusion tritium plant. On the other hand, its high reactivity even towards N2 and the temperature of tritium thermodissociation need special precautions for hydride container operation. If other hydride-forming metals/alloys could show properties better than those of uranium, they could be considered as candidates to replace uranium in the tritium plant.

4.2 Hydride-forming alloys for tritium storage, supply and pumping
To be an alternative to uranium, a hydride-forming material should have the following desirable properties:
- $T_{des} > T_{N_2}$
- stability against hydrogen-induced disproportionation at the highest operation temperature $T_{des}$
- $T_{des} < 573K$ (to provide low tritium permeation loss from primary containment during tritium supply)
- suitable hydrogen sorption/desorption characteristics.

No hydride-forming metal meets to these requirements. The results of investigations of several hydride-forming intermetallic alloys are given briefly below. Kinetic curves of reaction of uranium and several alloys in powder form with air measured [19] by thermogravimetric analysis with a heating rate of 5K/min are presented in Fig.6. Experimental kinetic data have been fitted to different kinetic equations [20] of gas-solid
reactions. Probable mechanisms of the reactions have been estimated and kinetic parameters have been found. As an example, reaction of air with ZrCo powder (at T>673K) can be described by an equation of nucleation with two-dimensional growth with activation energy of 15kJ/mol.

![Fig. 6. Kinetic curves of uranium and alloys reactions with air, O₂ and N₂](image)

Uranium clearly shows the highest reactivity towards air. ZrCo starts reacting with air at a temperature higher than that of uranium and LaNi₅Mn₂ but reaction occurs also with high rate. The difference in pyrophoricity of the alloys ZrCo, LaNi₅Mn₂, Zr₀.₉Ti₀.₂Co found at relatively low temperatures becomes negligible [19] at T=770K because of high values of activation energy (33kJ/mol for LaNi₅Mn₂, 86 kJ/mol for ZrCo at T<673K).

For all tested alloys (see Table 3) Tₙ₂ₙ is found [18] to be > Tₐₑₛ.

The deterioration of the sorption properties of alloys via their disproportionation, ie intrinsic deconstruction of alloy into a metal hydride and a pure metal or a new alloy, leads to loss of the thermodynamic sorption/desorption properties and the ability to absorb hydrogen reversibly. Disproportionation of alloys occurs during their contact with hydrogen at a pressure higher than equilibrium pressure at an elevated temperature. Kinetic curves for disproportionation of several alloys are shown in Fig.6 for a hydrogen pressure of 100kPa and a temperature of Tₐₑₛ. ZrCo does degrade within ~1hour, LaNi₅Mn₂ disproportionates more slowly but also at a visible rate. The stability of ZrCo towards disproportionation can be improved by partial substitution of Zr with Ti. The alloy ZrCrFe demonstrates no disproportionation during long term exposure at Tₐₑₛ. Completion of the reaction needs >100 hours at temperature >300K higher than Tₐₑₛ.

![Fig. 7. Kinetic curves of intermetallic alloys disproportionation](image)

4.3 An intercomparison of tritium storage materials

Analysis of several properties of some hydride-forming alloys given in Table 3 shows that the application of some alloys can increase the safety of hydride containers for tritium handling. Alloys, like ZrCrFe, Zr₀.₉Ti₀.₂Co which show stability against disproportionation and relatively low Tₐₑₛ at pressures ≥100kPa, could be considered as materials for tritium supply. Alloys, like Zr₀.₉Ti₀.₂Co, could be also used for tritium pumping.

5. Summary

The impurity detachment sub-system of a tritium plant for a fusion reactor is currently a key point of fusion tritium technology.
Table 3. Comparison of hydride-forming metals and alloys for tritium storage, supply and pumping.

<table>
<thead>
<tr>
<th>Metal/Alloy</th>
<th>Psorp (Pa)</th>
<th>Tdes (K)</th>
<th>Reaction rate at T=Tdes</th>
<th>N2</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>6E-13</td>
<td>&gt;800</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>U</td>
<td>&lt;1E-3</td>
<td>710</td>
<td>no</td>
<td>fast</td>
<td>no</td>
</tr>
<tr>
<td>LaNi5Mn2</td>
<td>4</td>
<td>550</td>
<td>slow</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>ZrCo</td>
<td>4E-3</td>
<td>690</td>
<td>fast</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Zr80Ti20Co</td>
<td>4</td>
<td>600</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>ZrCrFe</td>
<td>11E3</td>
<td>560</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

*) Psorp is given for T=300K; Tdes is given for PH2=100kPa.

Selection and efficiency of operation of impurity processing techniques depends very much on the chemical composition of the fusion reactor exhaust gas which is an unknown variable. A technique based on the chemical conversion of gas species with the liberation of molecular hydrogen seems to be attractive because it is not very dependent on impurities composition and does not require a powerful isotope separation system. Development of this technique for the JET tritium plant will be continued after torus exhaust gas composition is further evaluated during near future JET D-T experiments.

Hydride containers filled with uranium are used successfully within the JET tritium plant for hydrogen isotope storage, pumping and supply. However, their safety could be increased if uranium is replaced with hydride-forming alloys which have more suitable properties. The selection of an appropriate alloy would require optimization for every application and is not currently being considered.

References