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Tritium Inventory in Fusion Reactors

Summary Report of the final Research Coordination Meeting

IAEA Headquarters, Vienna, Austria

25 – 27 September 2006

Prepared by

R.E.H. Clark

November 2007

IAEA Nuclear Data Section, Wagramer Strasse 5, A-1400 Vienna, Austria

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Abstract

Detailed discussions were held during the final Research Coordination Meeting (RCM) at IAEA Headquarters on 25-27 September 2006, with the aim of reviewing the work accomplished by the Coordinated Research Project (CRP) on "Tritium Inventory in Fusion Reactors". Participants summarized the specific results obtained during the final phase of the CRP, and considered the impact of the data generated on the design of fusion devices. Conclusions were formulated and several specific recommendations for future fusion machines were agreed. The discussions, conclusions and recommendations of the RCM are briefly described in this report.

November 2007

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Introduction

The final Research Coordination Meeting of the Coordinated Research Project (CRP) on “Tritium inventory in fusion reactors” was held on 25-27 September 2006 at IAEA Headquarters, Vienna, Austria. Both the aims and accomplishments of the CRP were reviewed, conclusions were formulated, and recommendations agreed regarding the issues identified with tritium inventories.

Twelve participants reported on the results of their research (Appendix 1). Considerable discussion took place during the course of these presentations, as summarized below.

Meeting Proceedings

A. Nichols (Section Head, Nuclear Data Section) welcomed the participants on behalf of the International Atomic Energy Agency (IAEA). He noted the excellent progress already reported from the previous Research Coordination Meetings, and expressed gratification to the participants for their hard work on this important topic. R. Clark (Scientific Secretary) reviewed the proposed agenda, which was accepted without change (see Appendix 2).

Each participant gave a detailed presentation of their research activities during the final phase of the CRP, and provided short written summaries (see Appendix 3). These presentations have been collected together electronically and distributed on CD; only brief summaries are given below. Overall conclusions of the CRP were formulated, as well as a list of specific recommendations relating to the evolving issues identified with tritium inventories.

N. Bekris described experiments on tritiated flakes received from the JET fusion machine. Measurements of tritium release were undertaken, and the influence of gamma-ray bombardment was assessed.

P. Coad reported on ion studies of tritium retention in JET and de-tritiation techniques. Analysis of tiles removed from JET was summarized, and new diagnostics techniques were described. Further developments on photon cleaning methods were also discussed.

C. Skinner presented some recent results involving dynamic retention and dust issues. The results from quartz crystal microbalances to determine material gains and losses were presented. Dust represents a potential hazard in ITER type devices, and methods were described to control the dust inventory.

A. Pisarev discussed tritium-related investigations of hydrogen behaviour in fusion-based materials. Studies of thermal desorption, permeation, parasitic discharges as an erosion mechanism, isotopic effects, and the impact of surface release and protection barriers on gas-driven permeation were summarized.

T. Tanabe presented an overview of the retention of hydrogen isotopes and carbon erosion/deposition in the JT-60U machine. Deposition of hydrogen isotopes from different processes was analyzed, as well as retention in redeposition processes.

S. Artemov reported on studies of the tritium content in materials proposed for fusion reactors. Improvements to the Neutron-induced Elastic Recoil Detection (NERD) method and appropriate applications were reviewed.

M. Mayer reported on a study of ion-driven permeation of deuterium through tungsten. Tungsten foils were bombarded with deuterium ions and the rate of permeation measured. Permeation fluxes were calibrated through D_2 leaks.

R. Causey presented work on tritium retention and permeation in beryllium. Existing data were examined to determine a range for permeation coefficients, which were subsequently used in the DIFFUSE code to predict the permeation of tritium into the coolant.

A.A. Haasz summarized hydrogen isotopic effects on the chemical erosion of carbon. Measurements were made of erosion from H and D and the relative erosion rates were determined. The results were fully consistent with the square root of mass dependence proposed for the modelling of chemical erosion.

R. Doerner discussed PISCES-B mixed material experiments designed to quantify the behaviour of plasma-created mixed Be/C and Be/W surfaces. The inclusion of only a small fraction (~ 0.1%) of beryllium impurity has been shown to suppress dramatically the erosion of plasma-exposed carbon samples.

J. Roth presented work on deuterium retention in carbon fibre composite (CFC) irradiated with low energy D ions. CFC materials are presently used in a number of fusion machines, and have been proposed for some parts of ITER. Studies included quantification of retention at different energies and temperatures from ion beam and thermal plasma sources.

V.Kh. Alimov reported on deuterium retention in tungsten exposed to low-energy and high-flux clean and carbon-contaminated deuterium plasmas. Experiments were performed at a range of temperatures and depth profiles of the trapped deuterium were measured to a depth of 7 μm.

Following the presentation of the impressive results achieved during the course of the CRP, discussions focused on the formulation of a comprehensive summary of the work accomplished, as well as recommendations for the future. All participants will provide journal style articles for inclusion in a volume of the A+M Unit journal *Atomic and Plasma-Material Interaction Data for Fusion (APID)*. In addition, participants agreed to work together on a single article summarizing the work that will be submitted for publication in a suitable refereed journal.

Recommendations and Conclusion

The main recommendations directed towards the fusion community are as follows:

1. Focus more R&D on determining the effectiveness of tritium removal techniques from Be and BeO co-deposits with carbon and tungsten impurities.
2. Need the capability within the design to change materials in the first wall, due to concerns that unacceptably high tritium inventories may occur with current PFC materials.
3. ITER should explore the possibility of using a high temperature (400°C or more) for tritium removal and for reduction of the tritium inventory.
4. Design a cooled (room temperature) co-deposit collector in the divertor, which is heatable to > 700°C for subsequent hydrogen release and removal.

Any increase of stored energy and pulse duration in ITER coupled with the lack of experience in contemporary tokamaks with respect to the plasma-facing materials proposed for ITER make the choice of these materials arguably the highest risk factor for ITER. The tritium inventory is a major source term in accident scenarios, and erosion and tritium retention are decisive factors in the selection of the most appropriate plasma-facing materials.

The main conclusions of the CRP can be summarized as follows:

- Of the proposed ITER wall materials, tungsten demonstrates the lowest tritium inventory risk.
- Carbon presents the greatest risk in terms of tritium inventory - removal techniques will have to be applied if carbon-based materials are adopted.
- Beryllium presents major retention risk through co-deposits in the presence of oxygen - tritium removal techniques need to be developed and applied for beryllium.
- Limited understanding of possible mixed material effects increases tritium inventory risks.

Final IAEA Research Co-ordination Meeting on "Tritium Inventory in Fusion Reactors"

25-27 September 2006, IAEA Headquarters, Vienna, Austria

Scientific Secretary: R.E.H. Clark

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Appendix 2

Final IAEA Research Co-ordination Meeting on "Tritium Inventory in Fusion Reactors"

25-27 September 2006, IAEA Headquarters, Vienna, Austria

Scientific Secretary: R.E.H. Clark

Meeting Agenda

Monday 25 September **Meeting Room: A-0478**

09:30 – 10:00 Opening, Adoption of Agenda, A. Nichols, R. Clark

Session 1: Current research

Chairman: T. Tanabe

10:00 – 10:40 N. Bekris
Gamma irradiation of flakes retrieved from the JET fusion machine

10:40 – 11:10 *Coffee Break*

11:10 – 11:50 P. Coad
Studies of tritium retention in JET and of de-tritiation techniques

11:50 – 12:30 C. Skinner
Recent results in dynamic retention and dust

12:30 – 14:00 *Lunch*

Session 2: Current research continued

Chairman: N. Bekris

14:00 – 14:40 A. Pisarev
Tritium related investigations of hydrogen behavior in fusion materials

14:40 – 15:20 T. Tanabe
Overview of retention of hydrogen isotopes (H, D, T) and carbon erosion/ deposition in JT-60U

15:20 – 15:50 *Coffee Break*

15:50 – 16:30 S. Artemov
Study of the tritium content in materials of fusion reactors

16:30 – 17:10 M. Mayer
Study Ion-Driven Permeation of Deuterium through Tungsten

Tuesday 26 September

Session 3: Current research continued

Chairman: A.A. Haasz

09:30 – 10:10	R. Causey Tritium retention and permeation in beryllium
10:00 – 10:40	*Coffee Break*
10:40 – 11:20	A.A. Haasz Hydrogen isotopic effects on the chemical erosion of carbon
11:20 – 12:00	R. Doerner PISCES-B mixed-material experiments
12:00 – 13:30	*Lunch*

Session 4: Current research continued

Chairman: R. Causey

13:30 – 14:10	J. Roth Deuterium retention in carbon fibre composite irradiated with low-energy D ions
14:10 – 14:50	V.Kh. Alimov Deuterium retention in tungsten exposed to low-energy and high-flux clean and carbon-contaminated deuterium plasmas
14:50 – 15:20	*Coffee Break*
15:20 – 17:00	All Summary of current research

Wednesday 27 September

Session 5: Summary of CRP Results

Chairman: A. Pisarev

09:30 – 11:00	All Discussion
11:00 – 11:30	Coffee Break
11:30 – 12:30	All Discussion
12:30 – 14:00	*Lunch*

Session 6: Recommendations from CRP

Chairman: R. Clark

14:00 – 15:00	All Discussion
15:00 – 15:30	*Coffee Break*
15:30 – 16:30	All Discussion

Final IAEA Research Co-ordination Meeting on “Tritium Inventory in Fusion Reactors”

25-27 September 2006, IAEA Headquarters, Vienna, Austria

Scientific Secretary: R.E.H. Clark

SUMMARIES OF THE WORK PERFORMED

Deuterium retention in tungsten exposed to low-energy and high-flux clean and carbon-contaminated deuterium plasmas

V.Kh. Alimov[1], J. Roth[2], R. Causey[3], D.A. Komarov[1], S. Lindig[2], Ch. Linsmeier[2]

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Depth profiles of deuterium trapped in polycrystalline W exposed to low energy (~200 eV D^{-1}) and high ion flux (~10^{21} m^{-2} s^{-1}) "clean"[1] and carbon-contaminated D plasmas at a fluence of about 2×10^{24} D/m^2 and temperatures from 313 to 853 K have been measured up to a depth of 7 μm using the $D(^3He,p)^4He$ nuclear reaction in a resonance-like technique[2].

The "clean" D plasma was generated in a planar dc magnetron, operated with D_2 gas. The W samples placed on the cathode surface and covered with a tantalum mask with an aperture of 5 mm in diameter were bombarded with plasma ions accelerated in the cathode sheath of the magnetron discharge with a discharge voltage of 450 V. To generate the carbon-contaminated D plasma, pieces of graphite were placed on a sputter-dominated area of the cathode surface at distance of about 20 cm from the W sample. During plasma exposure, the sample temperature was controlled by a chromel-alumel thermocouple welded to the front surface of the sample outside the irradiation area.

After exposure to "clean" and carbon-contaminated plasmas the integrated deuterium retention in the bulk (> 0.3 μm) is a factor of about 10 higher than that in the near surface layers. In the case of the "clean" D plasma exposure, the total deuterium retention increases with the exposure temperature reaching its maximum value of 5×10^{20} D m^{-2} at about 500 K, and then decreases as the temperature grows further. An addition of carbon impurities (hydrocarbon molecules) into the D plasma doubles the maximum D retention and shifts the temperature, at which the D retention peaks its maximum, to about 600 K. It can be assumed that a tungsten carbide film formed on the W sample under the carbon-contaminated D plasma exposure serves as a barrier layer and prevents the outward transport of deuterium thus increasing the D retention in the bulk.

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[1] We use the term "clean" in quotation marks having in mind the impossibility to obtain absolutely clean plasma. In our case the conception "clean" D plasma means the plasma without specially introduced carbon impurities.
[2] V. Kh. Alimov, M. Mayer, J. Roth, Nucl. Instrum. Methods B234 (2005) 169.

Study of the tritium content in materials of fusion reactors

S.V. Artemov

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The goal of our project has been to upgrade the NERD (Neutron-induced Elastic Recoil Detection) method, which was developed for the study of hydrogen isotope content and concentration profiles in materials. It is supposed that the NERD method will be used for diagnostics on areas of tritium concentration in fusion devices in the framework of the IAEA Coordinated Research Project “Tritium Inventory in Fusion Reactors”.

The NERD method was developed in the Institute of Nuclear Physics of Academy of Sciences (Uzbekistan). The method obtains information on the depth and concentration of hydrogen in a sample by analysis of the energy spectrum of H-ions knocked out by monochromatic fast neutrons. This allows one to measure the concentration of all hydrogen isotopes simultaneously through the thickness of the sample.

During the reporting period we have improved the neutron method for determination of tritium content and concentration profiles in various materials.

The following tasks have been completed during the Project period:

1. **The sensitivity of the method was increased.** Achieved in three ways:

   i). By reduction of the background of charged particles (including tritons). This was achieved by using materials which do not generate tritons under the effect of fast (14 MeV) neutrons for the box of the $\Delta E - E$ detecting system.
   ii). By decreasing the background of random coincidences of pulses from ΔE and E –detectors of the detecting system Random coincidences arise from the large intensity of the gamma-quanta generated by the interaction of fast neutrons with material of the neutron-producing TiT-target of the Neutron Generator. For this purpose some fast electronics were used. The fast gate, coincidence scheme and time delay circuits have been designed and manufactured. They provide for the quick selection ($T = 0.3$ μsec) of the analysed signal. The corresponding variant of the spectrometer was assembled, and the adjustment of all blocks was carried out.
   iii). By subtracting the background energy spectrum of tritons which arise in the interaction of fast neutrons with the nuclei of the matrix of the analysed specimen. For this purpose a special program has been developed which is based on Monte-Carlo simulation of the background spectrum.

2. **The speed of the analysis was increased** through the utilization of the above mentioned fast electronics because this allows one to use a more intensive neutron flux.

3. **The depth resolution was improved** due to a more monochromatic neutron flux irradiating the analyzed specimen. This was achieved by developing and manufacturing some new units in which a large amount of metal along the neutron trajectories from the neutron source to the specimen was excluded. As a result the “geometric” energy resolution and hence the depth resolution was improved.

4. **The reliability of the results of analysis was increased** due to the procedure of comparing the experimental energy spectra of the recoiled tritium nuclei with simulated ones which are calculated via the modified program of spectra simulation (DRIN_M). This possibility is especially useful for the cases of non-uniform distribution of hydrogen in the analyzed specimen.

5. Some improvements in methods were made to expand the applications of the method and to raise the efficiency: better geometrical resolution of the detector telescopes and the electronic circuit of summation of spectrometric pulses for using two E-detectors.

The characteristics of the upgraded NERD installation were checked using the test samples. The typical energy resolution of the spectrometer is 300 – 400 keV. These values result in the following depths resolutions:

for depths profile of hydrogen ~ 60 μm;
of deuterium ~ 20 μm;
of tritium ~ 10 μm (up to 5 μm using Monte-Carlo simulation).
The depth of analysis (for example, in silicon) is
1200 μm for hydrogen;
500 μm for deuterium;
260 μm for tritium.

The sensitivity of the analysis is limited mainly by the preventing nuclear reactions (n,p), (n,d) and (n,t) on the nuclei of the analyzed materials. It varies for various materials over a wide range: from ~ 0.1 at. % to 1 at. % for deuterium and tritium isotopes and from ~ 1 at. % to 10 at. % for hydrogen (protium) isotope. Time of analysis is a few hours for small concentrations (close to the sensitivity) and ~ tens minutes for concentrations of ~ 100 at. %.

Some realistic samples with implanted hydrogen and deuterium have been analyzed and the concentration profiles of hydrogen isotopes were obtained.

The improved NERD installation and analogues can be successful used for diagnostic of "first wall" materials of tokamaks and other materials of nuclear technology.

Results have been presented at international conferences and in publications:

1. G.A. Radyuk, S.V. Artemov, A.Kh. Abdurakhmanov, V.P. Yakushev, E.A. Zaparov, "Improvement of the Neutron-Induced Elastic Recoil Detection Spectrometer on Base of Neutron Generator NG-150". Abstract Book of Int. Conf. "NUCLEUS-2004", Belgorod, Russia, June 2004, pp. 284.

2. G.A. Radyuk, S.V. Artemov, A.H. Abdurakhmanov, A.A. Karakhodzhaev, L.I. Slusarenko, V.V. Tokarevsky, V.P. Yakushev, E.A. Zaparov, "Modified NERD Spectrometer for H –Isotopes Profiling in Various Materials", Third Eurasian Conference "Nuclear Science and its Application", Tashkent, Uzbekistan, 5 – 8 October 2004, Abstract book, pp.69-70.

3. S.V. Artemov, M.A. Kayumov, G.A. Radyuk, V.P. Yakushev, "Procedure of Account of the Background Reactions in the NERD Method for Definition of Concentration Profiles of Hydrogen Isotopes", 5th Int. Conf. "Nuclear & Radiation Physics", Almaty, Kazakhstan, 26 – 29 September 2005.

4. S.V. Artemov, Ya.S. Abdullaeva, A.H. Abdurakhmanov, A.A. Karakhodzhaev, G.A. Radyuk, V.P. Yakushev, E.A. Zaparov, "NERD-method to study profiles of tritium concentration in interior elements of a fusion reactor", Summary Report of Second IAEA Research Co-ordination Meeting, Tritium Inventory in Fusion Reactors, IAEA Headquarters, Vienna, Austria, 18 – 19 October 2004.

Gamma irradiation of flakes retrieved from the JET fusion machine

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The use of carbon and especially carbon fibre composite (CFC) as a first wall and divertor plate protection material in a D-T fusion device is attractive due to the low-Z and excellent thermal shock resistance. However, due its high porosity connected to its high hydrogen affinity, carbon fixes large amounts of tritium, increasing the in-vessel tritium inventory which could be a critical problem for the safe operation of a fusion machine like ITER.

As an example we consider the Joint European Torus (JET) where 35g tritium were injected into the torus and 11.5g were retained by the first wall materials after the last tritium fuelled pulse of the Deuterium Tritium Experiment (DTE1) campaign.

Even though calculations estimate that for ITER the tritium co-deposition on the first wall of the machine will be smaller (4g/pulse) than what was observed in machines like JET, it is still quite substantial and will reach the safety imposed in-vessel tritium co-deposition limits (350g tritium) after less than 88 pulses. Therefore, efficient *in-situ* tritium removal techniques, need to be developed to keep the in vessel tritium inventory at low levels, not only for the limits imposed by safety but also for fuel supply economic reasons.

In this respect, the gamma irradiation of the hydro-carbonaceous co-deposited layer, build-up in such carbon based fusion machine, was tested during this Coordinated Research Project (CRP) and results will be presented during the RCM.

The physical and chemical properties of such radioactive material (flakes) collected at JET after the DTE1 campaign will be described as well as the tritium release rates measured under air or inert atmosphere. Moreover, a presentation of the gaseous analysis of the off-gassing species released by the sample will be given, both before and after having placed the flake sample under a strong gamma field.

Tritium retention and permeation in beryllium

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This report examines the literature on both tritium retention and permeation in beryllium. While past experiments prove rather conclusively that tritium retention in beryllium will not be a driver on overall inventory for ITER, no real examination of permeation has been performed. Past experimental data is examined to determine a range for permeation coefficients. These are then used in the DIFFUSE code to predict the permeation of tritium into the coolant.

Studies of tritium retention in JET and of de-tritiation techniques

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A full poloidal set of divertor tiles was removed in the 2004 shutdown after operations from 2001-2004. The tiles were analysed to compare the erosion /deposition pattern with previous campaigns with different divertor configurations. Deposits on inner divertor tiles removed in 2001 had shown a change in the rate of carbon sputtering during the latter part of the preceding campaign that was tentatively attributed to a change in vessel temperature. However, the latest data show that operating with He plasmas was most probably the reason for the change. H-isotope retention has also been assessed (including tritium from the 2003 trace tritium experiment). ^{13}C was puffed into the outer divertor in the form of ^{13}C-labelled methane on the last day of operations prior to the shutdown, and the distribution of the ^{13}C found in the torus is being ascertained, and is being modelled to study transport mechanisms.

A number of extra diagnostics have been installed in JET to monitor erosion/deposition and H-isotope retention including more quartz micro-balances, rotating collectors, smart tiles and mirror test units.

Further developments in photon cleaning have led to the removal of up to 90 microns from deposited films on tiles from the JET divertor. Laser cleaning has also been applied to divertor tiles in the beryllium handling facility, and total removal of the deposited film on a tile 170x150 mm was achieved in ~20 minutes.

PISCES-B mixed-material experiments

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A beryllium-seeded deuterium plasma is created in PISCES-B to investigate mixed-material erosion and redeposition properties of ITER relevant divertor materials. The beryllium containing plasma simulates the erosion of first wall material into the ITER sol plasma and its subsequent flow toward the tungsten baffle region and the carbon divertor plates. The experiments are designed to quantify the behavior of plasma-created mixed Be/C and Be/W surfaces. The inclusion of only a small fraction (~0.1%) of beryllium impurity has been shown to dramatically suppress the erosion of plasma exposed carbon samples. The temporal evolution of the plasma interactions with mixed Be/C surfaces is examined to better understand the fundamental mechanisms in play at the surface and to allow scaling of these results to the conditions expected in the ITER divertor. Codeposited material is also collected during these plasma exposures to address the issue of composition and tritium content of codeposits that might be expected in ITER. Beryllium containing plasma interactions with tungsten targets have also been investigated with the goal of understanding the formation conditions and growth rates of tungsten beryllide alloys. W targets are exposed to high flux deuterium plasmas ($\sim 3\times 10^{18}$ $cm^{-3}s^{-1}$) with beryllium fractions in the range $0.001< f_{Be} <0.01$. Target temperature, f_{Be} and ion impact energy have all been found to influence the formation of these alloys on targets. A new periodic heat pulse deposition system is installed on PISCES-B to simulate the transient temperature excursions of surfaces expected to occur in the ITER divertor during ELMs and other off-normal events. These periodically applied heat pulses allow us to study the effects of transient power loading on the formation, stability and tritium content of mixed-material surfaces that are created during the experiments.

Hydrogen isotopic effects on the chemical erosion of carbon

A.A. Haasz, J.W. Davis

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Chemical erosion studies of graphite due to H^+ and D^+ impact show evidence of some isotopic effect – with the deuterium yield being larger. The isotopic yield ratios (D-yield/H-yield) observed in almost all of the chemical erosion measurements, including ion-beams, laboratory plasma devices, and tokamaks, lie between 1 and 2. The recently measured chemical erosion yields due to tritium ions also fall in this range. (The notable exceptions are the mass-loss studies at the Max-Planck Institut für Plasmaphysik, Garching, where for energies <100 eV, the isotopic yield ratio was seen to increase from 4 to 6-7 with decreasing energy.) A nominal value of 1.5 ± 0.5 is suggested as the most appropriate value for the D/H yield ratio. This is fully consistent with the square root of mass dependence proposed for the modelling of chemical erosion.

Ion-driven permeation of deuterium through tungsten

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The permeation of deuterium through 50 and 300 µm thick tungsten foils was measured in the temperature range from 800 to 1000 K. The tungsten foils were bombarded from the front side with a mass-separated beam of 200 and 3000 eV D ions, the permeation signal at the back side was determined with a quadrupole mass spectrometer. The permeating flux was absolutely calibrated with calibrated D2-leaks. The back side of the foil could be cleaned by Ar-sputtering, which resulted in an increase of the permeation signal and better reproducibility of the results. The lag time between the start of the bombardment and the onset of the permeation signal allows one to estimate the diffusion coefficients, which are in rough agreement with the data obtained by Frauenfelder.

Tritium related investigations of hydrogen behavior in fusion materials

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An overview of activities on the investigation of hydrogen behavior in fusion materials during 2005-2006 is given. The following topics are discussed:

1. Experiments on thermal desorption from tungsten implanted with deuterium ions
2. Experiments on thermal desorption from MPG graphite and CFC after deuterium plasma implantation
3. Experiments on permeation of deuterium through graphite
4. Experiments on parasitic high frequency discharges as a mechanism of erosion and deposition in gaps
5. SEM characterization of T-10 limiter tiles after long D-D campaign
6. Modeling of isotopic effects in recombination and co-permeation
7. Modeling of influence of surface relief on gas driven permeation
8. Modeling of influence of protection barriers on gas driven permeation

Deuterium retention in carbon fibre composite irradiated with low-energy D ions

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CFC carbon materials are presently being used as facing components (Tore Supra, JET, ASDEX Upgrade) and foreseen for ITER (NB31 CFC). Therefore, deuterium retention in different CFC materials was studied by irradiation with 30 to 200 eV D ions, both from ion beam (High Flux Ion Source, IPP) and plasma devices (PISCES-A, Magnetron Plasma Device), using methods of the thermal desorption spectrometry and $D(^3He,p)^4He$ nuclear reaction in a resonance-like technique.
It is found that at target temperatures from 323 to 723 K the amount of deuterium trapped in the CFC materials increases with ion fluence, Φ. No saturation was reached as observed in pyrolytic graphite HPG and fine grain graphite. At temperatures close to room temperature and high fluences the deuterium retention proceeds proportional to $\Phi^{0.5}$.
Depth profiles show that saturation occurs only within a near surface layer equivalent to the ion range. The increase in total retention is accompanied by an increasing long profile tail extending beyond 14 μm with D concentrations above 10^{-1} at.% at fluences above 10^{24} D/m^2. The tails of the depth profiles can be approximated by an error function as predicted by deuterium diffusion. The diffusivity of deuterium as derived from the depth profiles depends only weakly on the irradiation temperature and lies between 5×10^{-17} and 5×10^{-15} m^2 s^{-1} for irradiation temperatures in the range of 323 to 723 K.
The hydrogen isotope retention due to implantation and diffusion into CFC materials at an ion energy of 200 eV, temperature of 473 K, and a fluence of $5x10^{24}$ D/m^2 amounts to $6x10^{21}$ D/m^2. This inventory appears relevant in the explanation of the high amount of deuterium retained in Tore Supra during long pulses. In ASDEX Upgrade a direct comparison of CFC and fine grain graphite as outer divertor target clearly confirms the increased retention in CFC.

Recent results in dynamic retention and dust

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Three quartz crystal microbalances have been deployed in NSTX to measure deposition/erosion in plasma shadowed areas at the upper & lower divertor and outboard midplane. These show a complex pattern of material gain and loss. At the time of a plasma discharge a transient increase in mass of order ~0.1 µg cm-2 is observed that decays in the interpulse period to a level either higher, lower or similar to that prior to the discharge. The first discharge of the day always shows a long term step-up in mass. Some correlations of mass gain with plasma duration, stored energy, and change in the plasma shape are observed. Following a days plasma operations, a slow decay in mass is observed. The results are interpreted in terms of dynamic retention and erosion/deposition.

Methods to measure the inventory of dust particles and to remove dust if it approaches safety limits will be required in next-step tokamaks. A novel electrostatic dust detector, based on a fine grid of interlocking circuit traces, biased to 30 or 50 V, has been developed for the detection of dust on remote surfaces in air and vacuum environments. Impinging dust particles are detected when they create a short circuit between the traces, however this short circuit is temporary suggesting the device may be useful for the removal of dust from specific areas. The fate of the dust particles has been tracked by measurements of mass gain / loss. Heating by the current pulse caused up to 90% of the particles to be ejected from the grid or vaporized, the removal efficiency depending on the experimental geometry. We also report the first attempt at real-time dust detection in NSTX.

Overview of retention of hydrogen isotopes (H, D, T) and carbon erosion/deposition in JT-60U

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Recent studies on retention of hydrogen isotopes (H, D, and T) and erosion/deposition in plasma facing carbon materials as well as dust sampling in JT-60U are summarized. In D-D discharge machines like JT-60U, tritium produced by D-D reaction does not fully loose its initial energy of 1 MeV and is implanted into plasma facing wall at depths greater than 1μm. Hence the tritium retention profile is separate from carbon deposition profiles. On the other hand, in JT-60U, H+D retention profiles in the divertor region were well correlated with the carbon deposition profiles and the deposition-dominated inner divertor tiles showed high retention, while the erosion-dominated outer divertor tiles showed low retention. Nevertheless the retained amount in the re-deposited layers was smaller than those observed in JET, which is attributed to temperature rise of the re-deposited layers, probably owing to their poor thermal contact to the substrate. Carbon deposition on the plasma shadowed areas and on remote areas like pumping ducts was very small and only a small amount of dust was collected. Low deposition in the remote areas in JT-60U could be attributed to the precise alignment of divertor tiles both toroidally and poloidally. This suggests that divertor geometry could have rather strong effects on carbon deposition or carbon transport.

However, hydrogen concentration in the re-deposited layers at the plasma shadowed areas was appreciably higher than that of the plasma facing surface, probably because their temperature remained low compared with the appreciable temperature rise of the plasma facing surfaces.

Most of the plasma facing surface of the main chamber was eroded and, hence, its hydrogen retention in unit area was smaller than that of the divertor area. However, rather high deuterium retention was observed within a few μm from the top surface of the eroded first wall, which is attributed to implantation of high energy deuterium originating from NBI. Actually, deuterium retention profiles on the first wall were very similar to those of tritium supporting the implantation mechanism. Large toroidal ripples of the magnetic field of JT-60U very likely enhanced such high energy deuterium implantation by a ripple-loss mechanism. Nevertheless, this finding suggests that significant amounts of tritium produced by DD reaction in a DT reactor could be retained in the first wall at significant depth from the surface and would be difficult to be removed.

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