International Atomic Energy Agency

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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

# IAEA Advisory Group Meeting on: "Critical Assessment of Tritium Retention in Fusion Reactor Materials"

## 7-8 June 1999, IAEA Headquarters, Vienna, Austria

# SUMMARY REPORT

**Prepared by:**
R.K. Janev, G. Federici and J. Roth

July 1999

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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# Abstract

The proceedings, conclusions and recommendations of the IAEA Advisory Group Meeting on "Critical Assessment of Tritium Retention in Fusion Reactor Materials", held on June 7-8, 1999 at the IAEA Headquarters in Vienna, Austria, are briefly described. The report contains a summary of the presentations of meeting participants, a review of the data status (availability and needs) for the fusion most relevant bulk and mixed materials, and recommendations to the IAEA regarding its future activity in this data area.



Reproduced by the IAEA in Austria
July, 1999

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## 1. INTRODUCTION

The IAEA Advisory Group Meeting on "Critical Assessment of Tritium Retention in Fusion Reactor Materials" was held on June 7-8, 1999 at the IAEA Headquarters in Vienna, Austria, and was organized by the IAEA Atomic, Molecular (A+M) and Plasma-Material Interaction (PMI) Data Unit on recommendation of the Subcommittee for A+M/PMI Data of the IAEA International Fusion Research Council. The objectives of the meeting were:

a) to review the available data on hydrogen (tritium) retention in fusion reactor materials and identify priority needs for such data from a fusion reactor design point of view, and
b) to make recommendations to the IAEA regarding its activity in this area to meet the needs of international fusion programme for such data.

The meeting was attended by ten participants from the leading research laboratories in USA, Russia, Japan, Germany, UK, Canada and from EC (see Appendix 1: List of Participants). The meeting was also attended by the staff of the IAEA A+M/PMI Data Unit.

## 2. BRIEF MEETING PROCEEDINGS

After the opening remarks by the Scientific Secretary (Dr. R.K. Janev), the work of the meeting proceeded in three sessions, in accordance with the adopted agenda (see Appendix 2: Meeting Agenda). The first session was devoted to the presentation of the results of current research on tritium retention in fusion reactor materials and overviews of the status and needs for such data from the point of view of next step fusion devices design (e.g. ITER).

Dr. R.A. Causey presented a critical review of the available data on hydrogen (tritium) retention parameters (diffusivity, solubility, surface recombination, trapping (energy and density of traps)), as well as of the hydrogen implantation effects in beryllium, tungsten, carbon and (partly only) structural materials (stainless steel, vanadium). The effects of codeposition and neutron damage on hydrogen retention were also addressed. In his conclusions, Dr. Causey emphasized that the solubility of hydrogen in Be is still unknown (although suspected to be very small), that the discrepancies on hydrogen diffusivity in W are still high and a better determination of this parameter is required, and that the codeposited layer on carbon (with no apparent limit to its thickness) has high retention efficiency for tritium and appropriate techniques have to be developed for its removal.

Dr. G. Federici presented an overview of the R&D priority needs for the in-vessel tritium retention and removal in ITER. The R&D areas of highest priority include: implantation/ permeation experiments at high particle fluxes, sticking and formation of D-rich carbon-based films on cold surfaces, mixed-material effect on T-retention and removal, removal of codeposited films and recovery of retained tritium, and modeling of tritium retention effects. The specific research issues in each of the above areas were identified. It was emphasized that the tritium inventory in the in-vessel components emerged (during the ITER EDA) as one of

the most serious reactor design constrains. Codeposition (particularly on carbon) could determine the operational regime and schedule of a fusion device.

Dr. M. Mayer presented an exhaustive account of the available hydrogen retention and release data for different pure and doped carbon materials obtained mainly in his laboratory (FZ Jülich). The emphasis was given on the implantation of energetic hydrogen atoms in these materials, on the retention and release from codeposited layers and on the fluence and temperature effects on hydrogen retention. It was shown that for most carbon-based materials, no saturation of the hydrogen retention had been observed for high fluences and that codeposition decreases with the increase of substrate temperature. The wall pumping and the hydrogen gas balance in Textor were also analyzed.

Dr. T. Tanabe addressed the question of dynamic retention and hydrogen inventory in several types of materials. He first analyzed the latest experience on redeposition and hydrogen recycling and retention in the Textor W and W/C (twin) limiter, leading to the need of a more detailed analysis of the retention/release problem. The concept of dynamic hydrogen retention includes an analysis of the particle and energy balance in the incidence (beam), interaction (within the bulk material) and post-interaction (release or trapping) stages of the evolution of incident particle beam. All elastic and inelastic processes, as well as species transforming processes (reactions), have to be taken into consideration in this approach, including the processes of creation (and destruction) of excited atomic/molecular states, ionization, recombination, etc., as well as the collective processes within the bulk (diffusion, recombination, etc). Effects of the surface coverage on reflection and re-emission of hydrogen (also in excited states) were also analyzed in Dr. Tanabe's talk.

Dr. J. Roth presented a model (developed by Dr. A. von Keudell) for tritium codeposition on carbon materials in toakamak divertors. The model is based on the assumption that, at appropriate divertor plasma-substrate temperature conditions, a polymer-like C:H structure is formed as an intermediate state facilitating the conversion of $CH_x$ into $C_2$ $H_x$. The model presumes also knowledge of the radical surface loss probability (which is complement of the radical reflection coefficient) and which contains a part responsible for non-reactive volatile product production and another part responsible for film growth (co/re-deposition). With appropriately chosen values of this probability, the model reproduces the measured deposition profiles of certain $C_2$ $H_x$ hydrocarbons in a cavity. Plans were outlined for installation of two such cavities at the inner louvers in JET and measurement of surface loss probability for certain radicals.

Dr. M. Guseva reported on the recent experiments in the Kurchatov Institue on deuterium retention in tungsten under the complex action of stationary and power pulse plasmas. The experiments were done on the MKT-electrodynamical plasma accelerator (plasma density=$10^{15}$ $cm^{-3}$, energy density=0.5 $MJ/m^2$, pulse duration=60μs, number of pulses=60, max, ion energy=1keV). The results of these measurements showed that after a

stationary plasma irradiation (200 eV $D^+$ ions, dose of $10^{26}$ $m^{-2}$, W layer temperature 800K) the integral retained D concentration in W was $1.5\times10^{20}$ $m^{-2}$. After a subsequent irradiation by high power (0.5 $MJ/m^2$ pulse) pulsed deuterium plasma (10 pulses of 60μs duration) the retained D concentration in W was reduced to $2\times10^{19}$ $m^{-2}$, mainly due to the evaporation and erosion of the surface W layer. Direct irradiation of pure W with 10 pulses of high power (0.5 $MJ/m^2$ pulse) pulsed D plasma did not result in measurable amounts of retained D. The same high power pulsed plasma treatment of C-coated W led to complete destruction of the C layer (250nm) and formation of a mixed C+W layer in which the integral concentration of retained D was found to be $3\times10^{19}$ $m^{-2}$.

Dr. K. Morita presented the results of a comprehensive experimental and theoretical study of hydrogen (deuterium) retention and re-emission properties of the WC layer on graphite. The specific aim of the study was to determine the rate constants of elementary processes for retention and re-emission in the mass balance equations determining the time evolution of H(D) concentrations in materials: trapping, thermal detrapping and molecular recombination. The results of this study showed that the saturation concentration of D in WC layers was 0.36 ($1.67\times10^{22}$ $D/cm^3$), that the thermal re-emission took place in three stages (the first two appeared at lower temperatures due to re-emission from two different trapping sites, with $E_1$=0.18 eV and $E_2$=0.24 eV, and the third stage appeared at higher temperatures and was due to re-emission from carbons ($E_3$=0.31 eV) segregated in the grain boundaries of the WC layer) and that the determined rate constant for effective molecular recombination reproduced well the thermal desorption spectrum.

Dr. A. Haasz presented an overview of the results of his laboratory on D retention and re-emission for tungsten and carbon-based materials and the planned experiments on H retention and permeation. For several types of pure graphite (monocrystal, PyG, EK98, CKC-ref) all non-reflected D was found to be retained in the implantation zone until its saturation. It was also found that the fluence dependence of retention depended on the specimen structure. For doped graphites (e.g. CKS doped with B, Si, Ti, W) it was found that subsequent to reaching saturation of the implantation zone, the specimens with different dopants exhibit different fluence dependence for D retention. It was also observed that higher ion energy leads to higher retention, while higher specimen temperature leads to lower retention. The D-retention properties in pure W depend on specimen temperature. For T ~ 300K, D retention approached saturation at fluences greater than $10^{23}$ $D/m^{-2}$, and the saturation level was the same for $D^+$ ion energies of 300, 500 and 1000 eV. For T > 300K, enhanced D retention in pure W was observed. For T=500K, large scatter of D retention was observed and was attributed to the implantation history. It was also found that at high fluences, the trapped levels rise well above those for T=300K, with no sign of saturation (consistent with diffusion-limited trapping). For the W - 1% $La_2O_3$ alloy, however, saturation of D retention was observed at T=500K and high fluences. Experiments with C-implanted W (1 keV $C^+/m^2$) showed that D retention at low $D^+$ fluences (500 eV, T=300-500K) was much lower than that for pure W, while at higher $D^+$ fluences (>$10^{24}$ $D/m^{-2}$) it approached the level of the pure W

case. For $D^+$ implantation (1 keV, $10^{21}$ $C^+/m^{-2}$) in a 500K W, the D retention at 300K was found the same as in the pure W case (for all fluences), but at T=500K, the D retention level was reduced to a half of that for pure W case (for all fluences).

The re-emission results from graphite showed that below 1000K all hydrogen was re-emitted as molecules, while above 1000K atoms were also emitted (in amounts directly proportional to T). Atomic re-emission from W (also from Ta and Mo) occurred only for $T \geq$ 1200K.

Dr. G. Counsell presented results from JET (obtained by J.P. Coad et al) demonstrating evidence for impurity drift in the JET SOL from the outer to the inner SOL region. The drift was evidenced by an observed strong asymmetry in the material deposition on the inner and outer sections of JET divertor, and was related to the difference in the plasma-wall interaction processes and properties of deposited layers. The presentation demonstrated the need for a close collaboration of divertor modeling and plasma-wall interaction research communities in understanding and interpreting the divertor observations.

Dr. V. Alimov reported on his laboratory results regarding deuterium retention in W (single crystal) and its thermal desorption, depth profile measurements of D atoms in W materials, as well as on modification of the near-surface layer of W (single crystal) due to D-ion irradiation. The main conclusions of his presentation were: 1) deuterium is trapped in the near-surface layer and in the bulk in form of D atoms (no $D_2$ formation); 2) deuterium retention is governed by diffusion and the diffusion zone with trapped D is more than two orders of magnitude than the implantation zone; 3) the majority of implanted D atoms diffuse in the bulk and are captured by lattice imperfections, and probably also by gain boundaries and dislocations; 4) the trapped D inventory only slightly depends on the incident ion energy and scales with the square root of the incident fluence; 5) the fraction of trapped D in the ion stopping zone does not exceed 10%. At 300K, the maximum concentration of D trapped at a depth of the ion projected range is $1\text{-}3\times10^{21}$ $D/m^{-3}$, and at a depth beyond the implantation range it is $3\text{-}6\times10^{20}$ $D/m^{-3}$ for the materials investigated (W single crystal, hot-rolled W and CVD$W_{75}$ $C_{25}$); 6) increase of the irradiation temperature from 300K to 600K, leads to decrease of the D content in the near-surface layer by a factor 4-5 (for all samples).

In the second meeting session, the participants discussed in detail the overall data status and needs for hydrogen retention/release in the prospective fusion reactor materials (including the mixed surface layers and codeposited materials) and the result of these discussions are given in the next section of the present Report. At the third meeting session, the participants formulated the meeting conclusions and recommendation regarding the future IAEA activities in this data area. These are given in Section 4 of the present Report. The text in these two sections was prepared by Dr. G. Federici and Dr. J. Roth.

## 3. DATA STATUS AND NEEDS

Tritium retention in plasma facing materials and control of tritium in-vessel inventory have emerged as primary concerns for T-fuelled next-step fusion devices and future fusion reactors with strong implications for the in-vessel component design, materials selection, operational schedule and safety. These problems are closely interrelated with important aspects of plasma boundary physics, wall diagnostics and erosion/redeposition/transport in the Scrape-off-Layer (SOL) and core plasma.

The current status of the database for hydrogen-isotope retention and release properties was reviewed for various materials of interest both for plasma facing applications (e.g. C-based materials, Be, W, Mo, etc) and structural applications (e.g. stainless steel, Ni, etc.). Very preliminary data were also presented for H-isotope retention in, and release from, mixed-materials. These are expected to play a strong role in devices such as the International Thermonuclear Experimental Reactor (ITER), where more than one type of material is anticipated to be used.

The following tables identify for each material the areas where data are either scarce or missing for the conditions of interest. For the sake of convenience a distinction was made between two-classes of materials: 1) bulk materials; 2) codepositing materials and mixed-material surface layers. For the latter, bulk effects are expected to play a minor role.

For the bulk materials, the properties of most relevance for tritium retention are diffusivity (D), solubility (S), surface recombination ($K_r$), energy of traps ($E_{trap}$) and density of traps ($C_{trap}$). For codepositing materials the parameters determining the tritium inventory were identified to be: sputtering erosion yield (Y), the H-isotope concentration in the surface layer ($C_{sat}$) and energy of thermal release ($E_t$), together with details of the transport/sticking of hydrocarbon radical species, properties of the codeposited layers (e.g., impurity concentration, porosity, grain size, etc.) and methods of removal.

Table 1: Bulk materials (Symbols: v = reasonably good database, SA = some data are available but more experiments are needed; NA= no data are available; NI = not an issue)

| Material | D | S | $K_r$ | $E_{trap}$ | $C_{trap}$ | Special needs |
|---|---|---|---|---|---|---|
| **Be** | v_ | v_ | v enhanced re-emiss. Effects (SA) | SA | SA | • BeO;<br>• characterisation of properties in plasma sprayed morphologies;<br>• permeation at high fluxes;<br>• n-irradiation effects. |
| **Ni** | v_ | v_ | SA | v_ | v_ | • implantation and permeation at high fluxes (for calibration of theory). |
| **St.St.** | v_ | v_ | v_ | v_ | v_ | • implantation and permeation at high fluxes. |
| **Mo** | SA | SA | SA | SA | SA | • implantation and permeation at high fluxes. |
| **W and W-based alloys** | SA (*) | SA (*) | SA Probably NI | SA (**) | SA (**) | • (*) data are needed primarily at temperature <1000 C<br>• (**) trapping effects. Experiments should look into trap conc. vs. annealing temp. and structure of the material and the influence of the fabrication process;<br>• characterisation of properties in plasma sprayed morphologies;<br>• n-irradiation effects. |
| **C** | v_ | v_ | v_ | v_ | v_ | • influence of dopants on physical/chemical properties. |
| **SiC** | SA | SA | SA | SA | SA | |
| **TiC** | SA | SA | SA | SA | SA | |

Table 2: Mixed surface layers and codepositing materials.

| Material | Y | $C_{sat}$ | $E_t$ | Transport/ sticking of radicals | Properties of codeposited layers | Removal methods | Special needs |
|---|---|---|---|---|---|---|---|
| **C** | v_ | v_ | v_ | SA | SA | SA | • Migration and sticking of radicals; |
| **Si** | v_ | v_ | v_ | SA | SA | NA | • Behaviour of silanes; |
| **SiC** | v_ | SA | v_ | NA | SA | SA | |
| **WC** | v_ | SA | SA | NI | SA | NA | • Formation carbides |
| **W/Be** | NA | NA | NA | NA | NA | NA | |
| **Be** | v_ | v_ | v_ | NI | SA | NA | • Fraction of oxide; |
| **$Be_2O_3$** | v_ | vb | v_ | NI | SA | NA | • Influence of O conc. on H-release |
| **$Be_2C$** | v_ | SA | SA | NI | NA | NA | |
| **B** | v_ | v_ | v_ | SA | v_ | NI | |
| **$B_4C$** | v_ | v_ | v_ | SA | v_ | NI | |
| **Li** | v_ | SA | SA | NI | NI | NI | • Investigate Li in C |

In addition to the materials listed in the tables above, some experiments should be conducted to investigate interaction of H-isotopes with candidate braze materials for high heat flux component development.

## 4. MEETING CONCLUSIONS AND RECOMMENDATIONS

*1) Further development of theoretical models*

As the estimates of tritium retention in materials can be obtained from the collected bulk parameters only on the basis of theories and models, adequate effort should then be devoted to the development/improvement of theories and to the application of physical models to interpret the observed findings. In particular, the applicability of classical diffusion/ recombination theories often used to interpret the results need to be better assessed.

*2) Data collection and generation*

Specific proposals were made for ad-hoc experiments to be carried out to collect/ generate the missing data. There is a subset of issues which requires experiments in bench-top experiments, plasma simulators and other essential work which requires dedicated experiments (dedicated operational time and time-resolved wall diagnostics) in tokamaks. As far as modelling is concerned, there is in particular the need to provide a physically realistic explanation of the amount of deuterium/tritium retained in codeposited layers in existing tokamaks and enhance the confidence of predictions for tritium inventory in future fusion devices.

*3) Codeposition on carbon*

It was concluded that tritium retention and the control of the tritium inventory in future reactors strongly depends on the choice of plasma facing materials and their operational conditions (e.g. temperature, flux density of impinging particles), plasma edge conditions and geometry effects (e.g. gaps, non-in-line-of-sight regions etc.). As long as C-based materials are used, even in limited regions of in-vessel components, the dominant mechanism for retention will be codeposition of tritium with eroded carbon in colder regions of the divertor system. The advisory group recognises the primary importance of this problem and emphasises that, as long as C is used in any form in tokamaks, there is an urgent need to continue investigation in laboratories and demonstrate efficient techniques for removal of T in the codeposited films and recovery of the embedded tritium. Allowance for the use of oxygen and high temperature baking capabilities (=3300 C) for divertor components may be necessary. Considerations were also made on the possibility to operate specific components at higher temperatures. Also, serious consideration needs to be given to the assessment and implications of not having carbon in a next-step machine.

*4) Coordination of tritium retention and mixed-materials IAEA activities, and coordination with other fusion programmes*

An important task for this group and of the IAEA is to ensure that there is a productive synergism/communication between the plasma facing materials and

plasma physics communities, tokamak and non tokamak program etc. In particular, because of the strong interrelation of this group with the group working on mixed-material effects, it was recommended that consideration be given to have further meetings of the two groups synchronised.

*5) "Core group" experts for IAEA tritium data activity*

A strong recommendation was made by the advisory committee that this effort should be maintained under the auspices of the IAEA. A tentative list of the names of specialists in relevant fields who should be involved in this work was proposed and is provided below. It was also recommended that, in order to expedite progress, a "core group" of experts should be formed. Their main responsibilities would be to promote the R&D effort in their countries, to monitor the progress, to report and discuss (electronically) the results with the other members, and finally compile the collected data in a data compendium and to carry out other action items which will emerge in the context of this activity for the Agency.

A tentative preliminary proposal for members of the core was made at this meeting and they are indicated below with the symbol (O).

**US:**
(O) R. Causey (SNLL), (O) C. Skinner (PPPL), W. Wampler (SNLA).
**Canada:**
(O) A.A. Haasz (UTIAS) and possibly others to be selected.
**Germany:**
(O) A. Von-Keudell (IPP-Garching) , (O) M. Mayer (IPP Juelich) , R. Penzhorn (FZ Karlsruhe),
**Japan:**
(O) T. Tanabe, N. Yoshida
**UK:**
(O) J.P. Coad (JET) , G. Counsell (UKAEA)
**Sweden:**
M. Rubel
**EU Commission:**
(O) G. Federici (ITER JCT), A. Perujo (CCR Ispra -to be checked) and possibly others
**Russian Federation:**
M. Guseva (Kurchatov-Inst.), V. Alimov (IPC) or other from IPC, A. Pisarev (Moscow Univ.) (O)

**Appendix 1**

**IAEA Advisory Group Meeting on:**
**"Critical Assessment of Tritium Retention in Fusion Reactor Materials"**

7-8 June 1999, IAEA Headquarters, Vienna, Austria

## List of Participants


Dr. A.A. Haasz
Institute for Aerospace Studies
University of Toronto
4925 Dufferin St., Downsview
Ontario M3H 5T6
CANADA
Tel.: 1-416-667-7734
Fax: 1-416-667-7743
aahaasz@utias.utoronto.ca

Dr. Gianfranco Federici
ITER Joint Working Site Garching
Boltzmannstrasse 2
D-85748 Garching
GERMANY
Tel.: 49-89-3299-4228
Fax: 49-89-3299-4110
federig@ipp.mpg.de

Dr. M. Mayer
Institut für Plasmaphysik
Forschungszentrum Jülich GmbH
D-52425 Jülich
GERMANY
Tel.: 49-246-161-2183
Fax: 49-246-1612660
m.mayer@fz-juelich.de

Dr. J. Roth
Max-Planck-Institut für Plasmaphysik
Boltzmannstrasse 2
D-85748 Garching
GERMANY
Tel.: 49-89-3299-1387
Fax: 49-89-3299-1149
jor@ipp-garching.mpg.de

Dr. K. Morita
Department of Crystaline Material Science
Graduate School of Engineering
Nagoya University
Furo-cho, Chikusa-ku
Nagoya 464-8603
JAPAN
Tel.: 81-781-5111-4686
Fax: 81-527-89-3791
k-morita@mail.nucl.nagoya-u.ac.jp

Dr. T. Tanabe
Center for Integrated Research
in Science and Engineering
Nagoya University
Furo-cho, Chikusa-ku
Nagoya 464-8603
JAPAN
Tel.: 81-52-789-5177
Fax: 81-52-789-3791
tanabe@cirse.nagoya-u.ac.jp

Dr. V.Kh. Alimov
Institute of Physical Chemistry
Russian Academy of Sciences
Leninsky Prospect 31
117915 Moscow
RUSSIAN FEDERATION
Tel.: 7-095-330-2192
Fax: 7-095-334-8531
alimov@ipc.rssi.ru

Dr. M.I. Guseva
Scientific Research Centre
"Kurchatov Institute"
Ploshchad I.V. Kurchatova
Moscow D-182, 123182
RUSSIAN FEDERATION
Tel.: 7-095-196-7768
Fax: 7-095-943-0073
martyn@qq.nfi.kiae.su

*(Contd. List of Participants)*

Dr. Glenn Counsell (Observer)
UKAEA Culham Division
D3 1.76 Culham Science Centre
Abingdon, Oxfordshire, OX14 3DB
UNITED KINGDOM
Tel.: 44-123-546-
Fax: 44-123-546-4192
glenn.counsell.cc@ukaea.org.uk

Dr. Rion A. Causey
Sandia National Laboratories
Livermore, CA 94551-0969
U.S.A.
Tel.: 1-510-294-
Fax: 1-510-294-1489
causey@ca.sandia.gov

*IAEA AMDU staff*

Dr. R. K. Janev
Atomic and Molecular Data Unit
International Atomic Energy Agency
Wagramerstrasse - 5, P.O. Box 100
A-1400 Vienna, AUSTRIA
Fax: 43-1-26007
janev@ripcrs01.iaea.or.at

Dr. J. Stephens
Atomic and Molecular Data Unit
International Atomic Energy Agency
Wagramerstrasse - 5, P.O. Box 100
A-1400 Vienna, AUSTRIA
Fax: 43-1-26007
j.stephens@iaea.org

**Appendix 2**

## IAEA Advisory Group Meeting on
## "Critical Assessment of Tritium Retention in Fusion Reactor Materials"

June 7-8, 1999, IAEA Headquarters, Vienna, Austria

Tentative Meeting Agenda

Monday, June 7 **Meeting Room: A-07-42**

| | | |
|---|---|---|
| 09:30 - 10:00 | - Opening<br>- Adoption of Agenda | |
| *Session 1:* | *Review of the Data and Current Research on Tritium Retention in Fusion Reactor Materials* | |
| **Chairman:** | **A. Haasz** | |
| 10:00 - 10:30 | Causey: | An overview of tritium retention in fusion reactor materials |
| 10:30 - 11:00 | Federici: | R&D priority needs on in-vessel tritium retention and removal in ITER |
| 11:00 - 11:30 | *Coffee break* | |
| 11:30 - 12:00 | Mayer: | Hydrogen retention in carbon based materials |
| 12:00 - 12:30 | Tanabe: | Dynamic retention and hydrogen inventory |
| 12:30 - 14:00 | *Lunch* | |
| *Session 1:* | *(Continued)* | |
| **Chairman:** | **R. Causey** | |
| 14:00 - 14:30 | Roth: | Tritium co-deposition: mechanisms for the formation re-deposited layers |
| 14:30 - 15:00 | Gouseva: | Deuterium retention in tungsten under complex action of stationary and power pulse plasma |
| 15:00 - 15:40 | Morita: | Isotope effects in retention and re-emission of hydrogen implanted into WC layers deposited on graphite |
| 15:40 - 16:10 | *Coffee break* | |
| 16:10 - 16:40 | Haasz: | Hydrogen retention in carbon and tungsten |
| 16:40 - 17:10 | Counsell: | Evidence for impurity drift in the scrape-off layer of JET |
| 17:10 - 17:40 | Alimov: | Deuterium retention in tungsten implanted with D ions |

Tuesday, June 8 **Meeting Room: A-07-42**

*Session 2:* *Assessment of the Data Status and Needs for Hydrogen Retention in Fusion Reactor Materials*

**Chairman: J. Roth**

09:30 - 12:30 All participants

12:30 - 14:00 *Lunch*

*Session 3:* *Formulation of Meeting Conclusions and Recommendations Regarding the IAEA Future Activity in the Area of Hydrogen Retention in Fusion Reactor Materials*

**Chairman: T. Tanabe**

14:00 - 17:00* All participants

17:00 - *Adjournment of the Meeting*

* A 30 min Coffee Break is included in this interval

Nuclear Data Section
International Atomic Energy Agency
P.O. Box 100
A-1400 Vienna
Austria

e-mail: services@iaeand.iaea.or.at
fax: (43-1) 26007
cable: INATOM VIENNA
telex: 1-12645
telephone: (43-1) 2600-21710

Online: TELNET or FTP: iaeand.iaea.or.at
username: IAEANDS for interactive Nuclear Data Information System
usernames: ANONYMOUS for FTP file transfer;
FENDL2 for FTP file transfer of FENDL-2.0;
RIPL for FTP file transfer of RIPL;
NDSONL for FTP access to files sent to NDIS "open" area.
Web: http://www-nds.iaea.or.at