International Atomic Energy Agency

INDC(NDS)-283

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

2nd IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials"

14-16 June 1993, Vienna Austria

SUMMARY REPORT

Prepared by R.K. Janev

September 1993

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

INDC(NDS)-283

2nd IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials"

14-16 June 1993, Vienna Austria

SUMMARY REPORT

Prepared by R.K. Janev

September 1993

Abstract

The proceedings and the results of the 2nd IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials", held on June 14-16, 1993 at the IAEA Headquarters in Vienna, are briefly described. The present report includes the summary of the data status and needs assessment for the erosion rates of candidate reactor plasma facing materials performed at the Meeting, a summary of the CRP accomplishments, and a set of recommendations regarding the future work. The final reports of the participants on their work done within the present CRP are given in the Appendix to this Report.

Reproduced by the IAEA in Austria
September 1993

93-03389

Table of Contents

Appendices

1. INTRODUCTION

The 2nd Research Co-ordination Meeting (RCM) on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials" (June 14-16, 1993, IAEA Headquarters, Vienna) was organized as part of the activity within the IAEA Co-ordinated Research Programme (CRP) on the same subject which was carried out during the period July 1990 - July 1993. The objectives of the Meeting were to review the work performed within the CRP in the period since the last RCM (May 15-17, 1991), assess the present status of erosion data for the candidate fusion reactor plasma facing materials and identify the further needs for such data, summarize the overall achievments of the present CRP and discuss the possible continuation of the co-ordinated research effort to meet the erosion data needs of next step fusion devices, such as ITER.

The Meeting was attended by eight (out of nine) chief scientific investigators of the CRP constituting projects, one project team member and the staff of the IAEA Atomic and Molecular (A+M) Data Unit. The List of Meeting Participants is given in Appendix 1.

After the opening remarks by the Meeting Scientific Secretary, the Meeting proceeded in the following sessions (see Appendix 2: Meeting Agenda):

1) Particle reflection and sputtering,
2) Chemical and other erosion mechanisms,
3) Erosion under high heat flux conditions,
4) Assessment of data status and needs for erosion rates of fusion reactor materials,
5) Meeting conclusions and recommendations.

A brief account of the presentations at the meeting (sessions 1-3) is given in the next section. The findings of the discussions on the erosion data status and needs for the currently operating next step devices (ITER) are summarized in Section 3. The Meeting conclusions and recommendations are given in Section 4 of this report. A full account of the erosion data status and needs analysis, prepared by the Meeting participants, along with a detailed summary of the accomplishment of present CRP effort, is given in Appendix 3. The progress and/or final reports on the work done within the individual projects of the CRP are given in Appendix 4.

2. BRIEF MEETING PROCEEDINGS

In the first Meeting session on physical sputtering Dr. Luo Zhengming reported on the recent development of his bi-partition model for describing the multiple scattering and collision cascade processes (backscattering and sputtering) associated with the bombardment of solids by energetic ions. The improvements in the PANDA-U 90 code have resulted in a better description of the backscattering process for collision pairs with projectile/target mass ratio greater than 0.1. The first results of the sputtering code based on the bi-partition model (collision pairs: H,D,T,He - Ni,C) were shown. Dr. Luo's study of scaling properties of the ion transport processes in solids indicates that a modified transport cross section is a good scaling parameter for the particle and energy reflection coefficients and for the ionization, induced damage and ion range distributions. Dr. W. Eckstein presented a modification of the well-known Bohdansky formula for the sputtering yield for normal ion incidence which significantly improves the description of sputtering data in the threshold region. He presented new recommended fits of the sputtering data which contain essentially, only one fitting parameter. In a separate presentation at the meeting, Dr. Eckstein discussed the important question of threshold behaviour of the sputtering yield in relation with the angle of ion incidence and other parameters of the problem, and the question of theoretical determination of the threshold energy.

In the session on chemical erosion and other erosion mechanisms, Dr. A.A. Haasz gave a comprehensive and in-depth analysis of the mechanisms determining the chemical erosion of graphites, including the mechanisms of sub-surface methane formation, synergistic chemical erosion and the erosion of doped graphites. Besides of providing a microscopic and transparent physical picture of the mechanisms governing the chemical erosion of graphites, Dr. Haasz has also presented a large amount of new experimental data on the erosion properties of these materials. Dr. E. Vietzke presented the results of a systematic experimental study of thermal sublimation and radiation enhanced sublimation (RES) properties of B-, Ti- and Si-doped carbon materials, including their thermal stability, impurity behaviour at high temperatures and dopand release. Dr. Vietzke demonstrated that while the sublimation of B, Si and Ti from doped carbon is reduced compared to pure B, Si and Ti, RES of carbon is not completely supressed (although there is a shift of the onset to higher temperature values in the case of B/C).

Dr. K. Morita described the results of an important study of the contribution of hydrocarbon emission to the thermal re-emission of hydrogen implanted into graphite. The problem was considered in terms of mass balance equations and supplemented with experimental measurements to determine the branching factor for hydrocarbon emission. It was found that the ratio of the rate constants for hydrocarbon molecule formation and trapping increases linearly with the implantation fluence and eventually saturates. Dr. M. Guseva presented a detailed comparative analysis of the erosion and thermo-mechanical properties of several boron containing graphites (USB-15, RECBOR, RGT-B, UAM-B, MPG-8, POCO-AXF-5Q). The main conclusions of this study are: the boronized graphites exhibit reduced chemical erosion with respect to pure graphites, a shift of the onset of radiation enhanced sublimation to higher temperatures, substantial reduction of the hydrogen isotope retention in a wide temperature range, and reduction of thermal conductivity. A theoretical model was offered for explanation of the observed properties of boronized graphites. Dr. Guseva also presented the results of a number of experiments on the behaviour of boronized graphites under high heat loads (including plasma disruption simulation). Dr. Yu. Martynenko described the results of a theoretical research on plasma disruption erosion modeling with inclusion of the shielding effects of evaporated (eroded) material. This selfconsistent approach to the description of disruption erosion, when applied to graphites, includes also a specific brittle destruction model as the most significant erosion mechanism in this case. The preliminary disruption erosion modeling results were presented indicating that the vapor shielding factor may be about 0.25-0.3.

In the session on erosion under high heat flux conditions, Dr. K. Morita described the results of his studies of erosion properties of a TiC layer deposited on graphite under bombardment with particle fluxes of the order of 10^{17} cm^{-2} s^{-1} in the temperature range up to 1500 °C, the particle energy being 40-300 eV. The Ti sputtering yield from the TiC layer shows a gradual increase with increasing the material temperature, and abrupt decrease at ~ 1000 °C with deep minimum at 1200 °C, and a new increase at higher temperatures. This temperature behaviour of the Ti sputtering yield was explained by a self-sustaining segregation model of TiC at the graphite surface. During the same session, Dr. E. Vietzke gave an extensive review of the results of his studies on the behaviour of B-, Si-, and Ti-doped carbon and high-Z (W and Mo) materials under high heat loads in TEXTOR tokamak.

Aspects such as mechanical and thermal stability, erosion and redeposition of bulk doped C and high-Z materials were addressed, including the effects of high material temperatures (above 1200 °C) on RES, thermal sublimation and impurity release. A "hot spot" model for the thermal electron emission at high carbon temperatures was described which successfully explains the observations.

In a very informative presentation Dr. E. Gauthier described the erosion and thermo-mechanical properties of plasma-sprayed boron carbide as a plasma facing material. The results were obtained on the Tore-Supra tokamak where B_4C was used as coating on the in-vessel components (limiters, plates, tubes, rods, RF antennae), i.e. on base materials such as Copper OFHC, Glidcop, Cu-Cr-Zr, Stainless steel, TZM (Molybdenum), Graphite and Aluminum. Except for its low thermal conductivity (< 10W/m.K), plasma sprayed B_4C has demonstrated superior erosion and thermo-mechanical properties in comparison with graphite and other candidate plasma facing materials. (The plasma spraying, as a joining method, has also numerous advantages over the other joining methods). Dr. Y. Hirooka described in detail the resent research on PISCES-B addressing a wide spectrum of issues related to the properties of plasma facing materials: net erosion rates, impurity erosion effects, outgassing rates, hydride formation, characterization of redeposited material, etc. The experimental studies included both low-Z (graphite, C-C composites, boronized graphites and C-C, beryllium, beryllium carbide) and high-Z materials (W, Nb alloys, Ta, Mo). The obtained information is compared with the results on other systems. Because the conditions in PISCES-B are close to those expected in the divertors of next step devices (including ITER), the obtained information has a direct relevance for their design.

3. DATA STATUS AND NEEDS ASSESSMENT

After the presentations of the reports on the work performed within the individual CRP projects, the Meeting during its 4th session discussed in detail the present status of the data for all relevant erosion processes of the plasma facing materials in currently operating tokamak devices (or their planned upgrades) and for the candidate materials of next step reactors such as ITER, NET, FER, BPX, etc. The shifts in the views during the post-ITER CDA discussions regarding the first options for the ITER EDA plasma facing materials have also been included in the analysis. The most important in these shifts are inclusion of

beryllium among the first options for the first wall materials, high-Z materials (W, Mo) as divertor plasma facing materials and vanadium as first wall structural material. The data status analysis covered the following processes: physical sputtering, chemical erosion, radiation enhanced sublimation (for carbon based materials) and thermal sublimation. Disruption erosion was also discussed but the lack of systematic experimental information and adequate expertise in the forum (with exception of two or three meeting participants) prevented to formulate specific conclusions on the database for this erosion mechanism. In view of its importance in the current fusion experiments and eventually in the reactor design, the Meeting formulated specific recommendations to the Agency for necessary actions to be taken for better characterization of the processes (see next section). The materials included in the analysis of the data under normal, quiescent plasma operating conditions were classified in three categories: low-Z materials (Li, Be, Carbon-based materials, including doped versions and carbides), medium-Z materials (stainless steels, V-alloys) and high-Z materials (W,Mo). For each of these material categories the data status and needs were discussed in detail and the findings are summarized in Appendix 3. Generally speaking, the database for physical sputtering for all material categories is satisfactory, mainly due to the successful numerical simulations which have been performed by the TRIM.SP code. It was felt that more accurate experimental information is needed for all considered materials (except for carbon-based materials) particularly at low energies, grazing angles and for self-sputtering. The radiation enhanced sublimation (observed only for carbon based materials but not for carbides) is less well documented, especially at high particle fluxes and for the doped carbon materials. Although the underlying physical mechanism of the process is basically understood, there are still considerable differences between the model predictions and experimental data in some cases. The chemical erosion of graphite and carbon-fibre-composites (CFCs) is fairly well documented, except for doped graphite and doped CFSs, and for high flux conditions. For other categories of materials of interest, the information on the effects of impurities (such as He,C,O) is rather scarce and urgently needed. Finally, the database for thermal sublimation for all three material categories considered is in fairly good shape, but needs updating and extension to multicomponent materials.

A significant part of the existing database for the erosion processes has been compiled, evaluated and generated by the CRP participant during the last three years. Particularly

important accomplishments were made in the areas of physical sputtering and the chemical erosion and RES of carbon based materials (including their doped versions). Beryllium, vanadium and high-Z materials (W,Mo) were not considered as first option candidate plasma facing materials during the ITER CDA and, accordingly, they have not received a high priority in the research within the present CRP. Nevertheless, some work on Be and W erosion properties has been performed in a few of the CRP participating laboratories, and other laboratories are in the final stage of their preparations to initiate such research.

4. MEETING CONCLUSIONS AND RECOMMENDATIONS

The analysis of the data status on erosion properties of candidate fusion reactor plasma facing materials with regard to the needs of presently operating large tokamaks and the next step devices (such as ITER) can be summarized by the following set of conclusions:

1) The erosion properties of carbon based materials, including doped versions, are relatively well understood and characterized under the normal plasma operating conditions typical for the present generation of large tokamaks. In view of the high particle fluxes and fluences expected in the next generation of plasma experiments, further extension of the erosion information for this type of materials is needed regarding the flux dependence of RES, erosion properties of codeposited layers and improvement in the characterization and understanding of low energy phenomena (including sputtering threshold law, surface chemistry, effects of He, C and O impurities, etc).

2) For the new high priority options for plasma facing materials, such as Li, Be, V and W (Mo), the erosion mechanisms are reduced to physical sputtering and thermal sublimation (excluding disruption erosion). The available evaporation data base for V, W and Mo needs updating, while the information on self-sputtering of Li and Be comes only from theoretical computations. Refinements of the low-energy sputtering data for V, W and Mo, including the effects of surface roughness, are necessary to establish a highly accurate threshold and gradient of the sputtering yield and to determine the edge plasma parameters which ensure minimum (or zero) erosion of the high-Z materials. Characterization of redeposition processes and erosion properties of codeposited layers also needs further research efforts.

3) Disruption erosion is a major localized erosion mechanism under off-normal conditions which has still not been adequately characterized. Vapor shielding effects may significantly reduce the energy deposited into the material during the disruption event and thereby reduce the erosion yield. Both theoretical studies of the disruption dynamics and shielding properties of the near-surface vapor, and experimental characterization of disruption erosion are urgently needed for reactor design purposes.

Specific recommendations to the IAEA:

(i) To ensure an effective support to the ITER EDA in determination of the effects of plasma facing materials erosion on the plasma performance and in the design of plasma facing components, it is strongly recommended that the present CRP continues its work for additional two years. The research should be focussed on completion of database for carbon based, doped materials and on establishing a similarly complete data base for Be, W, Mo and possibly V-alloys. The extended CRP could also provide the necessary response in data generation and compilation (evaluations) if further shifts in the material selection process take place during the first stage of the ITER EDA.

(ii) It is strongly recommended that the IAEA initiates a separate CRP on the theoretical modeling and experimental characterization of disruption erosion for candidate reactor plasma facing materials. A specific objective of this CRP could be establishment of a comprehensive package of computer codes for disruption simulation (including the vapor shielding effects), provided with all the necessary experimental information on the relevant atomic and material properties to ensure sufficiently realistic code predictions.

Appendix 1

2nd IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials"

14-16 June 1993, IAEA Headquarters, Vienna, Austria

LIST OF PARTICIPANTS

Dr. A.A. Haasz	Institute for Aerospace Studies, University of Toronto, 4925 Dufferin St., Downsview, Ontario, CANADA, M3H 5T6
Dr. Luo Zhengming	Institute of Nuclear Science and Technology, Sichuan University, Chengdu, CHINA
Dr. E. Gauthier	Dept. de Recherches sur la Fusion Controlée, Association EURATOM-CEA, Centre d'Etudes Nucleaires de Cadarache, B.P. No. 1, F-13108 Saint-Paul-Lez-Durance, FRANCE
Dr. W. Eckstein	Max-Planck-Institut für Plasmaphysik, Boltzmann Strasse 2, D-W-85748 Garching bei München, GERMANY
Dr. E. Vietzke	Forschungszentrum Jülich G.m.b.H, Postfach 1913, D-W-52425 Jülich, GERMANY
Dr. K. Morita	Department of Crystaline Material Science, Faculty of Engineering, Nagoya University, Furo-cho, Chigusa-ku, Nagoya 464-01, JAPAN
Dr. M. Guseva	Scientific Research Centre "Kurchatov Institute", Ploshchad I.V. Kurchatova, Moscow D-182, 123182, RUSSIAN FEDERATION
Dr. Yu.V. Martynenko	Scientific Research Centre "Kurchatov Institute", Ploshchad I.V. Kurchatova, Moscow D-182, 123182, RUSSIAN FEDERATION
Dr. Y. Hirooka	Institute of Plasma Physics and Fusion Research, University of California, Los Angeles, CA 90024, U.S.A.

IAEA

Dr. R.K. Janev	IAEA Atomic and Molecular Data Unit, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, AUSTRIA
Dr. R.A. Langley	IAEA Atomic and Molecular Data Unit, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, AUSTRIA
Dr. J. Botero	IAEA Atomic and Molecular Data Unit, Wagramerstrasse 5, P.O. Box 100, A-1400 Vienna, AUSTRIA

Appendix 2

2nd IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials"

14-16 June 1993, IAEA Headquarters, Vienna, Austria

MEETING AGENDA

Monday, June 14

09:30 - 09:45 :	- Opening - Adoption of Agenda	**Room: C-07-IV**
Session 1.	**Particle Reflection and Sputtering**	
Chairman:	**E. Vietzke**	
09:45 - 10:30 :	**Luo Zhengming:** On the scaling properties in ion transport	
10:30 - 11:15 :	**W. Eckstein:** Revised sputtering formulae	
11:15 - 11:30 :	**Coffee break**	
11:30 - 12:15 :	**W. Eckstein:** Threshold behaviour of sputtering	
12:15 - 14:00 :	**Lunch**	
Session 2.	**Chemical and Other Erosion Mechanisms**	
Chairman:	**Y. Hirooka**	
14:00 - 14:45 :	**A. Haasz:**	Chemical erosion of graphite
14:45 - 15:30 :	**W. Vietzke:**	Thermal sublimation of B-, Si-, and Ti-doped carbon materials
15:30 - 15:45 :	**Coffee break**	
15:45 - 16:30 :	**K. Morita:**	Contribution of hydrocarbon emission to thermal re-emission of hydrogen implanted into graphite
16:30 - 17:15 :	**M. Guseva:**	Peculiarities of ion and plasma flow interactions with graphites containing boron
17:15 - 18:00 :	**Yu. Martynenko:**	Erosion of materials during plasma disruption in tokamaks

Tuesday, June 15

Session 3. **Erosion Under High Heat Flux Conditions**

Chairman: **A. Haasz**

09:00 - 09:45 : **K. Morita:** Erosion of metal-carbide deposited graphite induced by high heat flux plasma irradiation at high temperatures

09:45 - 10:30 : **E. Vietzke:** Behaviour of B-, Si-, and Ti-doped carbon limiters under high heat load in TEXTOR

10:30 - 10:45 : **Coffee break**

10:45 - 11:30 : **E. Gauthier:** Use of plasma sprayed boron carbide as plasma facing component

11:30 - 12:15 : **Y. Hirooka:** Present status of PFC technology development programmes at UCLA

12:15 - 14:00 : **Lunch**

Session 4. **Assessment of the Data Status and Needs for Erosion Rates of Fusion Reactor Materials**

Chairman: **R. Langley**

14:00 - 15:30 : Detailed discussion on the current data status and further data needs for erosion rates of fusion reactor plasma facing materials

15:30 - 16:00 : **Coffee break**

16:00 - 18:00 : Discussion on erosion data status and needs

Wednesday, June 16

Session 4.	**Continuation**
09:00 - 10:15 :	Preparation of a summary report on the status of erosion data and the accomplishments of present CRP
10:15 - 10:30 :	**Coffee break**
10:30 - 12:00 :	Preparation of the CRP summary report
12:00 - 14:00 :	**Lunch**
Session 5.	**Meeting Conclusions and Recommendations**
Chairman:	**R.K. Janev**
14:00 - 16:00 :	- Discussion and adoption of CRP summary report - Discussion on final CRP documents - Formulation of Meeting conclusions and recommendations
16:00 - :	**Adjourn of the Meeting**

Appendix 3

Summary Report on the IAEA Co-ordinated Research Programme on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials"

Period: July 1990 - July 1993

Contents:

1. Introduction

The IAEA CRP on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials" was initiated in December 1989 on recommendation by the International Fusion Research Council, the Subcommittee on Atomic and Molecular Data for Fusion. The Agency Contractual Committee on Scientific Services approved the Programme at its 198th session on March 12, 1990. All invited laboratories and institutions to participate in the co-ordinated research programme have accepted the invitation, and the majority of the Research Contracts and Agreements have been finalized by July 1990. The Programme commencement date was taken as July 15, 1990.

The organization of the IAEA CRP on this subject was motivated by the appreciation of the critical role of erosion processes in reactor level fusion devices and their impact on the overall reactor plasma performance and fusion reactor engineering. The compilation of available information on erosion processes, its critical evaluation, and the enhancement of generation rate of new erosion data (e.g. for new materials, or in new domains of plasma-wall interaction conditions) on a time scale compatible with the dynamics of fusion research and reactor design needs was deemed possible only through a joint, co-ordinated and well focussed international effort.

The objectives of the CRP were, therefore,

- generation of experimental and theoretical data for all plasma-wall interaction processes contributing to the erosion of candidate plasma facing fusion reactor materials;
- compilation and critical assessment of existing data on plasma-wall interaction erosion processes; and
- preparation of recommended sets of erosion data for candidate fusion reactor materials.

2. CRP Participants

Ten laboratories and institutions with high expertise in the field were selected to participate in the Programme. Two participating institutions were granted IAEA research contracts (label RB below), and with the other institutions research agreements (label CF) were signed. The CRP participating institutions and the project chief scientific investigators are given below.

	Institute and Country	Chief Scientific Investigator	Contract or Agreement No.	Date of entry into Programme
1)	University of Toronto, Institute for Aerospace Studies, North York, Ontario, **CANADA**	Prof. A.A. Haasz	6092/CF	15.07.1990
2)	Max-Planck-Institute for Plasma Physics, Garching, **GERMANY**	Dr. W. Eckstein	6093/CF	15.07.1990
3)	Faculty of Engineering, Nagoya University, Nagoya, **JAPAN**	Prof. K. Morita	6094/CF	15.07.1990
4)	Oak Ridge National Lab., Oak Ridge, Tennessee, **U.S.A.**	Dr. R.A. Langley	6095/CF	15.07.1990
5)	Sichuan University, Institute of Nucl. Science and Technology, Chengdu, **P.R. CHINA**	Prof. Luo Zhengming	5738/RB	15.07.1990
6)	Forschungszentrum Jülich, Institute for Plasma Physics, Jülich, **GERMANY**	Dr. E. Vietzke	6237/CF	15.10.1990
7)	Kurchatov Institute of Atomic Energy, Moscow, **RUSSIAN FED.**	Dr. M. Guseva	6238/CF	15.10.1990
8)	University of California, Institute of Plasma and Fusion Research, **U.S.A.**	Dr. Y. Hirooka	6239/CF	15.10.1990
9)	Boris Kidrich Institute of Nuclear Sciences, Atomic Physics Laboratory, Belgrade, **YUGOSLAVIA**	Dr. T. Nenadovic	6240/RB	15.11.1990
10)	Centre for Nucl. Studies, Department of Controlled Fusion Research, Cadarache, **FRANCE**	Dr. E. Gauthier	6347/CF	15.12.1990

3. CRP Accomplishments

A substantial amount of experimental and theoretical data on erosion processes has been generated by the CRP participants during the reporting period. The specific yield of various erosion mechanisms (physical sputtering, chemical erosion, radiation enhanced sublimation, thermal sublimation) has been measured or calculated for most of the fusion relevant materials under a wide range of particle-surface and plasma-material interaction conditions. Net erosion (i.e. including the effects of redeposition) measurements have also been performed for a number of materials under reactor relevant plasma-wall interaction conditions. The generated amount of experimental information on erosion processes is particularly large for the carbon based materials, including B, Ti and Si doped versions.

The data generation effort was paralleled by physical studies of the plasma-material interaction phenomena. As a result of these studies, significant advancements in the understanding of the physics of erosion processes have been made. Significant progress has been made also in the development of theoretical methods for description of erosion processes and for computation of their yields.

Extensive data compilations and critical evaluations have been done for physical sputtering and chemical erosion. A comprehensive recommended data base for physical sputtering of all fusion relevant ion-material interaction systems has been produced.
The most important results achieved during this CRP can be summarized as follows:

1) More than 100 articles published in scientific journals;
2) An evaluated data compendium (including physical sputtering, chemical erosion and backscattering)
   (published as vol. 1 of the Nucl. Fusion Suppl. Series " Atomic and Plasma-Material Interaction Data for Fusion", 1991);
3) Three review articles in the book "Atomic and Plasma-Material Processes in Controlled Thermonuclear Fusion" (Elsevier Sci. Publ., Amsterdam, 1993; eds: R.K. Janev, H.W. Drawin)
4) A comprehensive database of evaluated data for physical sputtering (Max-Planck-Inst. of Plasma Phys., IPP Rep. No. 9/82 (1993));
5) An ALADDIN formatted sputtering database (IAEA).

4. Current Data Status and Further Needs (prepared by A.A. Haasz and E. Vietzke)

Here we only consider erosion processes occuring during normal operating conditions. Off-normal processes like disruptions, arcing or blistering could also greatly affect erosion, and the members of the CRP recommended that such processes be assessed by another group.

The information database summarized at the First IAEA Research Co-ordination Meeting on "Plasma-Interaction Induced Erosion of Fusion Reactor Materials" (held in Vienna, Austria, May 1991) was reviewed and updated. The selection of first wall and divertor/limiter materials was based on use in present-day fusion devices as well as future fusion reactors, with attention paid to the ITER design. The recommended set of materials includes:

- low Z (Be and Li)
- carbon-based materials (pure and doped graphites and CFC's, carbides)
- mid Z (steels and V-alloys)
- high Z (W,Mo)

Although the PMI database associated with these materials is a necessary first step in the overall characterization of plasma-facing materials, it is recognized that the actual material interacting with the plasma will be in a form modified by plasma exposure. Surface composition changes will occur due to preferential sputtering, diffusion and segregation. Wall erosion and impurity transport will lead to redeposition. Thus, more data are needed for the erosion behaviour of properly characterized redeposited and plasma-modified reactor materials. It is noted that the critical erosion parameter for fusion plasma-facing components is the net erosion, i.e., the net result of the erosion/redeposition process.

The focus of this CRP is on the following erosion processes:

- physical sputtering,
- chemical erosion,
- radiation-enhanced sublimation (RES) - applicable to carbon-based materials,
- thermal sublimation.

The current status of these erosion processes for the selected set of plasma-facing materials is summarized in Table 1. It is noted that various other processes will affect the conditions and parameters (both material and plasma) for erosion. For example, thermal e-

emission will change the sheath potential, i.e., change the ion energy and heat transmission factor ("hot spots"); photon-induced impurity production of CO and CO_2. The current assessment of the database and future needs is in reasonably good agreement with the findings of the Working Group on 'Plasma-Surface Interaction Data: Status and Requirements', IAEA Technical Committee Meeting on "Atomic and Molecular Data for Fusion Reactor Technology", Cadarache, France, October 1992 (see IAEA Report INDC(NDS)-277, May 1993).

5. Final CRP Document

In anticipation that this CRP will be continued for additional two years, the present Summary Report, together with the accompanying Progress Reports on the work carried out within the individual CRP projects, can be considered as an Interim report for the CRP. It is planned that at the end of the extended CRP period (1995/96), a more comprehensive publication is produced, which will contain both a thorough presentation of the subject and appropriately formatted recommended sets of erosion data.

Table 1. Status of Information on Erosion Processes during Plasma-Materials Interaction for a Select Group of Fusion Reactor-Relevant Materials

Materials	Application		Physical Sputtering		RES	Chemical Sputtering	Thermal Evaporation
	First Wall	Diverton/ Limiter	Calculations*	Experiment			
Li		X	S	- need data on self-sputtering	N/A	- data needed for effect of impurities (He ash, C, O)	S
Be	X	X	S	- need data on self-sputtering	N/A	- data needed for effect of impurities (He, C, O)	S
Carbon-based materials (pure/ doped graphites and CFC's)	X	X	S	S	- basic under-standing, but disagreement between model and experiment - data needed for high flux - data needed for new doped materials	- incomplete understanding - satisfactory database for pure graphites/CFC's - need data for new doped graphites/CFC's - data needed for high fluxes, energy of released molecules - data needed for impurities - (He, O, C) (some data available for pure graphites)	- need updating of evaporation rates for multi-component materials
Carbides	X	X	S	- incomplete	- not observed	- available for B_4C and TiC - data needed for impurities (He, O, C)	- need updating of evaporation rates for multi-component materials
Mid Z (steels, V-alloys	X		S	- need data for V - need data for grazing angles vs. roughness	N/A	- data needed for effect of impurities (He, C, O)	- need updating of evaporation rates for alloys
High Z (W, Mo)	X	X	S	- need data for grazing angles vs. roughness	N/A	- data needed for effect of impurities (He, C, O) (some data available for W	S

S - satisfactory database
N/A - not applicable
* - Review available (IPP/Garching)

A.A. Haasz and E. Vietzke
June 30, 1993

Appendix 4

PROGRESS REPORTS ON INDIVIDUAL CRP PROJECTS

Summary Report 1993

W.Eckstein
Max-Planck-Institut für Plasmaphysik, Garching, FRG

The main topics investigated are the processes of kinetic reflection and sputtering. The centre of the studies was devoted to sputtering. The two fields are discussed separately.

Reflection

The problem of helium ash accumulation in burning fusion plasmas asked for an extension of the reflection dataset already available for H and D on C and Fe. In collaboration with *Reiter* from KFA Jülich the following datasets have been calculated with the Monte Carlo program TRIM : T on C and Fe, He on C and Fe, and D and He on W [1]. These datasets are stored at the computer centre in Jülich and can be used as input to plasma edge codes. (Warning: the values for He on W at the lowest energy are wrong !).

Particle reflection coefficients are provided for W bombardment with T assuming monoenergetic projectiles at normal incidence and an incidence angle 65° and for a Maxwellian incidence distribution with a sheath potential (3 kT) and without a sheath [2]. For the same incidence conditions particle reflection coefficients are calculated for the cases D, T on Li, Ga, and In and for selfbombardment [3].

Another investigation dealt with the reflected energy. The experiments were performed by Winters et al. and the corresponding calculations by Eckstein [4,5]. Targets of C, Si, Cu, Ag, and Au were bombarded with the noble gas ions He, Ar, and Xe in the energy range from 8.5 to 4000 eV. Although not all of these data are fusion relevant the good agreement between experimental and calculated data gives another example for the reliability of data calculated with the Monte Carlo program TRIM.SP.

There exist a large number of reflection data at Garching which have been gained as a by-product during the determination of sputtering data. These calculated data have not

been collected and published as in the case of sputtering due to limited man power.

At the moment reflection measurements are performed for D bombardment of C at low energies from 30 to 1000 eV and oblique incidence angles. Energy distributions are determined by a time-of-flight technique and particle reflection coefficients by the trapping method. The experiments are accompanied by calculations. First experimental results on different kind of carbon material as EK98 and HOPG show that surface roughness is an important factor at low energies and oblique angles of incidence.

Sputtering

Over the last 14 years since a 1979 report a large number of experimental and calculated values of sputtering yields has accumulated at IPP. Finally, with the help of several students it was possible to publish these data in a new report [6]. This report gives sputtering yield data for elemental and compound targets for normal and oblique incidence. The data are fitted by a revised *Bohdansky* formula for normal incidence and by the *Yamamura* formula for oblique incidence. The difference to the old *Bohdansky* formula is a new nuclear stopping formula based on the Kr-C interaction potential (used in the simulations) which gives a more realistic behaviour at low energies. The large number of data in the report allowed us to generate formulae for the fit parameters Q (yield parameter) and E_{th} (threshold energy for sputtering) in the *Bohdansky* formula. The individual values of Q and E_{th} given in the plots should be preferred compared to the mean values determined by the fit formulae. The new *Bohdansky* formula shows a better agreement with the data than the old formula. Even the new formula exhibit too high threshold energies compared with calculated data. Therefore yield values below some value are not taken into account for the fitting with the new *Bohdansky* formula. The reason for the discrepancies is that the analytic threshold behaviour in the *Bohdansky* formula is not correct.
The many examples in [6] show that the *Yamamura* formula is only applicable for large mass ratios (target mass to projectile mass). The factorization of the formula into the yield at normal incidence and into a incidence angle dependent term is not applicable for heavy projectiles because the threshold energy for sputtering depends on the angle of incidence.

The report gives fit values for f and α_{opt} for different mass ratios outside the threshold region. Often the fit with the *Yamamura* formula is not very convincing.
Both formulae by *Bohdansky* and *Yamamura* can possibly be improved. Preliminary trials finding better formulae were not successful so far.

The sputtering of Be and BeO by O was investigated in a collaboration with Hechtl (TU München) and Wu (NET) [7]. The experimental yields agree well with calculated values for O on BeO at normal incidence in the energy range from 100 eV to 10 keV. Calculated angular dependences for projectile energies between 200 and 1000 eV show that a yield of unity is reached at about 300 eV and an incidence angle 60°.

The energy and angular dependence of the sputtering yield of B and B_4C due to the bombardment with D and B is studied experimentally and by computer simulation. The selfsputtering of B at normal incidence never exceeds unity. Discrepancies between measured and calculated yields, larger measured yields at normal incidence and lower measured yields at oblique angles, are probably due surface roughness [8].

A comparison of the sputtering yields of low Z materials for D bombardment at normal incidence show the highest yields for Be and the lowest yields for BeO at low incidence energies. At high incidence energies the yields are similar in a factor of 3. Furthermore, it is measured that surface roughness has the tendency to increase sputtering yield values at normal incidence, but reducing the yield at large oblique incidence angles (up to a factor of 5) [9].

The sputtering of heavy target materials with high surface binding energies like W [2,10,11] and Mo [2] was investigated experimentally in collaboration with Hechtl (TU München) and with Wu (NET) and by computer simulation. Experimental and calculated yield values for tungsten selfsputtering in the energy range from 0.1 to 10 keV and at normal incidence show good agreement; only at 100 eV the measured value is larger by a factor of 3. Calculated angular dependences for projectile energies between 350 and 2500 eV show that a yield of unity is reached at about 400 eV and an incidence angle 55° [10].
The sputtering of W with O and OH was studied in the energy range from 150 eV and 10 kev between room temperature and 1900 K at normal incidence. High O concentrations develop at low bombarding energies and low target temperatures. At 1900 K sputtering of pure tungsten prevails. The yield reduction due to oxygen built up in the surface layers

agrees well with computer calculations for the sputtering of stoichiometric WO_3 [10].
A calculational study was performed for the sputtering of Mo and W with D, T, and self-ions. The energy dependence of the sputtering yield was investigated for monoenergetic bombardment at normal incidence and at 65° and for a incident Maxwellian distribution with a sheath potential (3 and 9 kT) and without a sheath. The results demonstrate that the plasma edge temperature has to be kept as low as about 25 eV to avoid Mo or W sputtering by the hydrogen isotopes. For some projectile energies the angular dependence of the selfsputtering yield is provided [2].

A similar investigation as for Mo and W is performed for Li, Ga, and In, materials which may serve as a liquid coating at the first wall. A figure of merit which takes hydrogen and selfssputtering as well as radiation and dilution limits into account shows that Li should be preferred compared to Ga and In (at least at higher ion temperatures). It can further be concluded that Mo and W become worse in a small temperature range, whereas Li, Be, and C become better at increasing ion temperature [3].

The energy distributions of C sputtered with 5 keV He, Ne, Ar, and Kr at angles of incidence 65° and 70° are measured. The strong peaking of the energy distributions at high energies may be of importance for the penetration of these fast direct recoils into the discharge. Good agreement is found between measured and calculated distributions [12].

Bombardment of a multicomponent target or a monocomponent target with a non-volatile projectile will lead to a change in composition in the depth range of the projectiles. Two such examples have been investigated, namely 1 and 3 keV C on Be [13] and 1 and 6 keV C on W [14] as a function of angle of incidence. Both cases are studied experimentally and by a dynamic Monte Carlo program (TRIDYN). The calculations show that for W a C layer forms for incidence angles below about 40° whereas this angle is about 45° for Be. For larger angles of incidence a layer with a mixed composition occurs. In the case of W the calculated weight change is in good agreement with the measured values, whereas carbon seems to diffuse strongly in Be.

A comparative study of the erosion yield of different B doped graphites for 1 keV D ions at three temperatures, 300 K, 800 K, and 1470 K shows that, besides B_4C, USB15 is one of the most promising materials. B doping of graphite suppresses its chemical reactivity towards hydrogen isotopes, most probably due to an influence of the substitutional B

atoms on the C-H binding. In order to ensure a high substitutional B content the thermal treatment of B doped graphite is of great importance. RES can also be reduced or its onset can be shifted to higher temperatures by addition of boron [15,16]. TDS measurements with USB15 demonstrate the reduced formation of CD_4 but an increased desorption of D_2 compared to pyrolytic graphite [17].

Further investigations currently performed are a study of the dependence of the physical sputtering yield on the target temperature via a temperature dependence of the surface binding energy [18], a theoretical study on the threshold energy of sputtering [19], a thorough experimental study on Ti doped graphite (RG-TI) [20], investigations on the surface composition changes of boronated graphite due to ion bombardment [21] and Ni selfsputtering at oblique angles of incidence in collaboration with Hechtl (TU München) [22].

References

1 D.Reiter, W.Eckstein, G.Giesen, H.J.Belitz: *Database for recycling and penetration of neutral helium atoms in the boundary of a fusion plasma, Institut für Plasmaphysik, Forschungszentrum Jülich, Jül-2605* (1992)

2 W.Eckstein, J.László: J. Nucl. Mater. **183**, 19 (1991)

3 J.László, W.Eckstein: J. Nucl. Mater. **184**, 22 (1991)

4 H.Coufal, H.F.Winters, H.L.Bay, W.Eckstein: Phys. Rev. B 44, 4747 (1991)

5 H.L.Bay, H.F.Winters, H.J.Coufal, W.Eckstein: Appl. Phys. A 44, 4747 (1991)

6 W.Eckstein, C.Garcia-Rosales, J.Roth, W.Ottenberger: *Sputtering Data, Max-Planck-Institut für Plasmaphysik, Garching, Report IPP 9/82* (1993)

7 C.H.Wu, E.Hechtl, H.R.Yang, W.Eckstein: J. Nucl. Mater. **176&177**, 845 (1990)

8 E.Hechtl, A.Mazanec, W.Eckstein, J.Roth, C.Garcia-Rosales: J. Nucl. Mater. **196 – 198**, 713 (1992)

9 J.Roth, W.Eckstein, E.Gauthier, J.László: J. Nucl. Mater. **179 – 181**, 34 (1991)

10 E.Hechtl, H.R.Yang, C.H.Wu, W.Eckstein: J. Nucl. Mater. **176&177**, 874 (1990)

11 E.Hechtl, W.Eckstein, J.Roth, J.László: J. Nucl. Mater. **179 – 181**, 290 (1991)

12 W.Eckstein, E.S.Mashkova: Nucl. Instrum. Methods B **62**, 438 (1992)

13 W.Eckstein, J.Roth, E.Gauthier, J.László: Fusion Technol. **19**, 2076 (1991)

14 W.Eckstein, J.Roth: Nucl. Instrum. Methods B **53**, 279 (1991)

15 C.Garcia-Rosales, E.Gauthier, J. Roth, R.Schwörer, W.Eckstein: J. Nucl. Mater. **189**, 1 (1992)

16 J.Roth, C.Garcia-Rosales, R.Behrisch, W.Eckstein: J. Nucl. Mater. **191 – 194**, 45 (1992)

17 C.Garcia-Rosales, J.Roth: J. Nucl. Mater. **196 – 198**, 573 (1992)

18 R.Behrisch, W.Eckstein: Nucl. Instrum. Methods B , accepted for publication (1993)

19 W.Eckstein, C.Garcia-Rosales, J.Roth, J.László: Nucl. Instrum. Methods B , accepted for publication (1993)

20 C.Garcia-Rosales, J.Roth, R.Behrisch: J. Nucl. Mater. , to be published (1994)

21 R.Schwörer, C.Garcia-Rosales, J.Roth: J. Nucl. Mater. , to be published (1994)

22 E.Hechtl, W.Eckstein, J.Roth: Nucl. Instrum. Methods B , to be published (1994)

THE SUMMARY REPORT FOR RESEARCH CONTRACT NO.5738 / R2 / RB

Title: Application of Improved Bipartition Model of Ion Transport to Calculate Light Ion Reflection and Radiation Damage for Fusion Technology

Part of Coordinated Programme: Plasma–Interaction Induced Erosion of Fusion Reactor Materials

Research Institute:

Center for Radiation Physics
Institute of Nuclear Science and Technology
Sichuan University

Chief Scientific Investigator: Prof. LUO Zheng–ming

Period: from Jan., 1990 to Jun., 1993.

1. A Brief Summary of Previous Works

Our group has participated in CRP since 1990. At first our research work is the calculations of reflection coefficients of H, He and their isotopes by using bipartition model. Before we took part in CRP, the bipartition model had shown its large potential of describing ion transport by winning great successes in the calculations of electron transport and preliminary successes in the calculations of light–ion transport. Aiding financially by IAEA, we have made considerable headway in light–ion transport research since 1990. In the initial stage (1990–1991), we improved the original bipartition model for light–ion transport by using accurate elastic scattering cross section and electronic stopping cross section to take the place of power function approximation to these cross sections, then increased the calculational precision of light–ion transport. During this period, we worked out PANDA–U90 code and used it to calculate the particle reflection coefficients, energy reflection coefficients and reflected spectra for H, D, T, ^{3}He, ^{4}He ions with energies from 0.01 keV to 100 keV on Be, B, C, Al, Si, Ti, Ni, Fe, Cu,Mo, W, Au at incident angles as 0°, 15°, 30°, 45°, 60°, 75°. These data have been submitted to CRP, IAEA. During the period from 1991 to 1992, we modified PANDA–U90 code to consider the influence of surface barrier upon ion transport (including reflection), and gave out the particle and energy reflection coefficients, on which the influence of surface barrier has been considered, in aboved–metioned parameter range. These data have also been submitted to A+M Unit, IAEA, as an achievement of CRP project. According to the systematic comparisons between our results and relevant experimental or Monte Carlo simulation data, which were made by us, as well as by Thomas, Janev and Smith of IAEA, we may obtain the following conclusions: 1). When $\mu = M_1 / M_2 < 0.1$, the ion transport behaviour may be described very well by CSDA, and the bipartition model based on CSDA can calculate reflection coefficient and other transport quantities with considerable reliability and high computational efficiency. 2). When $\mu = M_1 / M_2 > 0.1$, the validity of CSDA decrease with the increase of μ. In this condition, the correlation between energy transfer and scattering angle must be cosidered. This is our research content during 1992–1993.

An important progress of our research work in 1992 is the application of characteristic line method to solve the Pn–approximation equations for diffusion ions. The characterestic line method may be proved to be equivalent

to Lax–Wendroff scheme with second precision under CSDA, but it can deal with the angular correlation of energy transfer in elastic scattering events, while the Lax– Wendroff scheme can not. Now we have finished the programming work for solving the Pn–approximation equations by using characterstic line method. Therefore, We can extend the reflection calculation to the case of multicomponent target of low Z and give out the particle and energy reflection coefficients for H, D, T, He on Be, B, C, Al, Ti, SiC and TiC. The comparison of our recent calculations with existing data claering shows that bipartition model can be successfully used to the case of $M_1 / M_2 < 1$ due to consideration of the angular correlation of ion energy transfer by means of characteristic line method.

Another important result of our group in last year is to complete the framework of the programm PANDA–SP which used for calculation of sputtering. According to the contract(RB / 5738 / R2) submitted to IAEA, three years are needed for the theoretical and programming works of sputtering induced by ions from solid surfaces. In the first year(1992), on the basis of bipartition model, we have worked out a sputtering theory within the frame of CSDA. As a middle stage of final theory, it can give fair good sputtering yields by considering the transport of cascade atoms and slightly modifying the previous program. The calculational results show that the new theory possesses potential to be a quantitative theory of sputtering. Its shortcoming is that the CSDA will lead large error when $\mu = M_1 / M_2 > 1$. In this case the large–angle scattering ions will loss larger energy, then the CSDA is not very suitable. In the next year, we plan to completely resolve this problem. As a prelimilary result, we give out the sputtering yields for H, D, T, He bombarding Ni and C. A systematic calculation will be carried out after finishing all the programming work.

2. The Future Program

1). Because our theory for ion transport is rather ripe and our sputtering theory is basically successful, we plan to make a general detail calculation of ion reflection and sputtering based on checking input data and code by using the newest theory and refined numerical method, and submit the reflection and sputtering data to IAEA as our recommended data.
2). We shall make a systematic study on the scaling property of ion transport (including reflection and sputtering).
3). We will apply bipartition model to the investigation of the phenomenon of secondary electron emission.
4). We will also study the change of first wall composition and the evolution of light–ion reflection and sputtering induced by D and T bombarding the first wall for a long–time.

3. Publications

1). LUO Zheng–ming, JIANG Bin and HOU Qing, Plasma Phys. Control. Fusion, 1993, to be published.
2). LUO Zheng–ming and HOU Qing, Acta Physica Sinica, 1993, to be published (in Chinese).
3). LUO Zheng–ming and LI Tai–hua, Acta Physica Sinica, 1993, to be published (in Chinese).
4). LUO Zheng–ming and HOU Qing, J. Appl. Phys., 1993, to be published.
5). LUO Zheng–ming, WU Wen–feng and HOU Qing, submitted to Phys. Rev. B.

COORDINATED RESEARCH PROGRAM ON "PLASMA-INTERACTION INDUCED EROSION OF FUSION REACTOR MATERIALS"

(International Atomic Energy Agency)

Progress Report

A. A. Haasz, University of Toronto, Canada
June 1993

1. INTRODUCTION

Our research has been focussed on the interaction of plasma-facing materials with plasma particles characteristic of the fusion reactor environment. From an application standpoint, our goal is to develop — in collaboration with industry — erosion-resistant materials for plasma-facing components for next-generation fusion devices, such as ITER. To date, the emphasis of our work has been on the understanding of the mechanisms related to hydrogen transport, trapping, recombination, physical sputtering, radiation-enhanced sublimation and the formation of hydrocarbon molecules when graphite is exposed to plasma particles. In some cases the effect of dopant elements on these processes was also studied. Our investigation also includes thermal conductivity measurements, due to the importance of this parameter for high heat flux components in future reactors. Future work will concentrate on the study of graphites doped with a wide range of dopants, including low-Z, mid-Z and high-Z elements, produced by a Canadian ceramics company.

2. CURRENT RESEARCH FOCUS

- Erosion of First-Wall Materials (Emphasis on Carbon-Based Materials)
  - — physical sputtering
  - — chemical erosion of carbon-based materials
  - — synergistic effects in chemical erosion
  - — radiation-enhanced sublimation of carbon-based materials

- Hydrogen Transport/Reemission/Retention
  - — hydrogen diffusion in graphite and doped graphite
  - — hydrogen reemission from graphite
  - — hydrogen retention
  - — hydrogen transport in metals (e.g., Pd, Cu, Fe, W)

3. RESEARCH FACILITIES

- Low-Energy, High-Flux Accelerators
  - — mass-analyzed single-beam accelerator (~100 eV to 10 keV) (H^+, D^+, He^+, C^+, O^+, Ar^+)
  - — dual-beam accelerator (~100 eV to 10 keV) (two independently controlled mass-analyzed beams of combinations of above ion species; also C_xH_y radicals)
  - — SIMS for surface analysis of multicomponent materials (e.g., doped graphites)

- Hydrogen Permeation Facility
  - — studies of H diffusivity, H recombination coefficient on surfaces
  - — *in situ* surface analysis using Auger Electron Spectroscopy

- Laser-Induced Thermal Desorption Spectrometry (TDS)
  - — outgassing and inherent gas content analysis using quadrupole mass-spectrometry

- High-Temperature Vacuum Furnace (to 2500 K)
  - — laser flash method for thermal diffusivity measurements (40 J pulsed laser)

- UHV Tritium Facility
  - — uhv system with ~10 Ci tritium
  - — mass-analyzed ion gun (T^+ ion beam)
  - — studies of isotopic effects on erosion and T-retention of fusion materials (exposure to H^+, D^+, T^+)

4. RECENT RESULTS ON EROSION

4.1 Mechanistic Study of Chemical Erosion

To date, the emphasis of our erosion studies has been focussed on the understanding of the mechanisms related to the formation of hydrocarbon molecules. The effect of microstructure was studied by using different graphites (monocrystal, pyrolytic, fine grain isographite). Our dual-beam ion accelerator enabled us to bombard specimens with mixed species hydrogen (H^+ and D^+) simultaneously, with independently controlled ion energies, and thus different depth distributions. By monitoring the reemitted CH_xD_y molecules, information was obtained on the mechanisms and spatial origin of the methane formation process. By changing the depth distribution of the two impacting species (H and D) from "complete overlap" to "total separation" the amount of mixed CH_xD_y molecules was found to decrease [1], supporting the end of range methane molecule formation hypothesis [Vietzke et al, J. Nucl. Mater., 128/129 (1984) 545; Roth and Bohdansky, Appl. Phys. Lett. 51 (1987) 964]. Furthermore, the transient behaviour of the methane RGA signal indicates the possible breakup of methane molecules as they diffuse to the surface to be released [2].

4.2 Synergistic Chemical Erosion of Graphite

Previous chemical erosion studies, using one energetic species (e.g., H^+, Ar^+) in combination with thermal H^0 have shown the existence of a synergistic effect, leading to an enhancement in methane formation [Vietzke et al, J. Nucl. Mater. 111/112 (1982) 763; Haasz et al, J. Nucl. Mater. 128/129 (1984) 593; Haasz, Vietzke et al, J. Nucl. Mater. 145-147 (1987) 412]. An obvious reactor-relevant extension to this study was to use energetic C^+ (plasma impurity) and H^0 and H^+ (fuel atoms/ions). For the case of C^+/H^0, we have found that thermal H^0, in combination with energetic C^+, results in chemically enhanced self-sputtering of carbon in the 600-900 K temperature range [3]. Experiments with H^+ and C^+ were undertaken to study the effect of H^+ ion energy on the erosion enhancement. We found that the addition of C^+ ions (1-3 keV) to H^+ ions with >300 eV energy does not appear to enhance the erosion yield above the level obtained for H^+ alone [4], indicating that ion-induced damage to the near-surface layer [5] has been saturated by the H^+ ions. The additional damage by

the C^+ ions does not appear to lead to significantly more hydrocarbon formation due to the limited supply of H. The erosion yield due to 300 eV H^+ is already near its maximum level, with about 40% of the incident H being reemitted in the form of hydrocarbons at 800 K [5]. When in combination with 100 eV H^+ ions, C^+ ions are able to enhance the hydrocarbon formation yield through the production of additional surface damage, which the 100 eV H^+ ions do not complete [4]. Thus the erosion yield due to H^+ ions with energy <300 eV may be increased to the level corresponding to ~300 eV.

To investigate the effect of energy deposition into the near-surface layer of graphite, we have also studied combined exposures of H^+/He^+ [4], H^+/Ar^+ and H^+/Ne^+ [6]. The addition of He^+, Ne^+ and Ar^+ to H^+ is also of interest from a fusion reactor point of view. The He, being the ash of fusion reaction, will be present in the plasma edge together with the H fuel. Introduction of neon and argon into the edge plasma, on the other hand, has been considered in order to reduce the plasma temperature and thus reduce wall erosion; of course one must also consider the erosion enhancement due to the presence of these species. It appears that in all cases the energy deposition due to the non-hydrogenic species will enhance the erosion yield of 100 eV H^+ ions to that of 300 eV H^+ .

4.3 Chemical Erosion of B and Si-Doped Carbon/Carbon Composites

We have studied the chemical erosion of some B and Si-doped carbon/carbon specimens. Chemical erosion was reduced significantly, especially at temperatures above ~800 K; the observed reduction is much larger than that expected on the basis of the dopant-containing fraction of the specimens [7]. Since only the matrix was doped, we attribute the residual reactivity to the undoped fibres. Chemical erosion yields of undoped carbon/carbon composites were found to be similar to those of pyrolytic graphite [7, 8]. Possible causes for the large reductions in the erosion yields of the doped C/C might be: (i) preferential sputtering of the pure carbon fibres leading to large near-surface concentrations of dopants, (ii) migration of dopant atoms to the near-surface, or (iii) competing chemical activity (i.e., H recombination) due to the dopant atoms, leading to a reduction of hydrocarbon formation. Various surface analysis techniques (Auger, X-ray, RBS) were used, but no conclusive correlation between dopant concentrations and changes in the erosion yields could be made. Further experiments will be performed with doped bulk graphites (without fibres) to study the mechanisms responsible for the reduction of chemical erosion.

5. RECENT RESULTS ON HYDROGEN TRANSPORT

5.1 Mechanistic Study of H Diffusion and Recombination

In addition to the hydrocarbon formation studies, we have also investigated the mechanisms related to hydrogen transport, trapping, recombination and reemission. Again, different graphites were used to study the effect of microstructure on these processes. Using our dual-beam accelerator, specimens were bombarded simultaneously with H^+ and D^+, with independently controlled energies. In contrast to our findings with CH_xD_y formation, we found that the reemitted mixed HD was independent of the implantation range separation. This leads to the conclusion that during steady state hydrogen bombardment, hydrogen diffuses in the form of atoms in the implantation region in graphite [9]. This is in disagreement with Moller and Scherzer's [Appl. Phys. Lett., 50 (1987) 1870] conclusion that hydrogen moves in the form of molecules. In fact, Moller and Scherzer's thermal

desorption spectroscopy (TDS) results are in agreement with our TDS results [10] which behave differently from our steady-state dynamic reemission results. The transient behaviour of the reemitted HD, however, depends on the microstructure of graphite. For example, for a monocrystal graphite specimen bombarded perpendicular to the a-b plane, with separated implant zones, a relatively long time is needed for the reemitted HD to reach its steady-state level. On the other hand, if the beam direction is parallel to the a-b plane, steady-state is reached relatively fast for similar beam energies. Polycrystalline pyrolytic graphite and fine-grain isographite were found to be somewhere between the two monocrystal cases. Predamaging the test specimens had the effect of speeding up the achievement of steady-state HD reemission. Based on our results we propose the hypothesis that hydrogen diffuses in the implantation zone in the form of atoms on crystallite surfaces, grain boundaries or inherent porosity [11]. In the case of the monocrystal, atom diffusion between planes is also possible. With increasing ion fluence, crystallites are broken down [Gotoh, J. Nucl. Mater. 162-164 (1989) 851] and intercrystalline paths are formed, leading to increased H-D mixing.

5.2 H/D Retention in Graphite

Hydrogen retention in first wall materials can affect tritium inventory and hydrogen recycling. In previous experiments [12], using TDS, we have shown that the amount of hydrogen retained in graphite increases with increasing H^+/D^+ fluence. Also, the amount retained was found to depend on microstructure. We proposed the hypothesis that subsequent to saturation of H in the ion implantation zone, mobile hydrogen atoms diffuse into the graphite bulk beyond the implantation zone along inherent crystallite and grain boundaries. This model is consistent with our findings that the amount of retained hydrogen is largest for fine grain graphite and smallest for pseudo-monocrystal graphite. Some concern remained, however, since we did not expect to see an increase in retention with fluence for the pseudo-monocrystal.

These earlier experiments were performed with an ion beam having a quasi-Gaussian spatial profile. In order to check whether the "wings" of the Gaussian profile might have affected the fluence dependence measurements, new experiments have been performed, using a modified technique where only the central region of the beam is allowed to impact on the test specimens [13]. The new results confirm the increasing retention with increasing incident H+/D+ fluence, for the polycrystalline fine grain and pyrolytic graphites, and also the dependence on microstructure. The major difference in the two sets of results is that in the latter case the retained hydrogen in the monocrystal did not increase with fluence, consistent with the proposed hypothesis.

5.3 Reemission of H/D from Graphites

We also studied the reemission of hydrogen from pure and B-doped bulk graphites as a function of temperature [14-16]. We found that for $T < 1000$ K the reemitted hydrogen is in the form of H_2 molecules, and as the temperature is increased above 1000 K, an increasing fraction of the reemitted hydrogen is in the form of H atoms [15]. In this study the effect of the dopants did not appear to be significant. The importance of this finding is the form of the reemitted hydrogen, i.e., dominated by H^0 at high temperatures; this could affect H-recycling and transport in the tokamak edge plasma.

6. FUTURE WORK

Future research will focus on the study of graphites doped with low-Z, mid-Z and high-Z elements vis-à-vis erosion, hydrogen transport, thermal conductivity and thermal stability. Emphasis will be on both the understanding of these processes and the characterization of doped graphite under ion beam exposure.

6.1 Erosion During Plasma Exposure

Experiments to be performed with the doped specimens will focus on chemical erosion in the 600-900 K temperature range and RES for T > 1300 K. In order to obtain a comparison of the erosion behaviour as a function of dopant type and concentration, most of the erosion studies will involve single species H^+ impact. For a selected set of specimens, however, H^+ combined with He^+, O^+ or C^+ (reactor relevant impurities) will be used to investigate synergistic effects. Some specimens will also be exposed to T^+ ions to study isotopic effects.

To study the effect of dope elements — and dopant concentrations — on the hydrocarbon formation process, we will use the dual beam accelerator to simultaneously implant H^+ and D^+ and monitor the emission of mixed species hydrocarbons (as well as H_2, HD and D_2) as a function of range separation. The technique to be used is similar to that used with undoped graphites of different microstructures. Based on previous results we know that dopants do lead to a reduction of chemical reactivity, but the mechanisms responsible for this have not been identified. In the proposed experiments we will look for characteristics in the hydrocarbon emission signal — both transient and steady-state — that might indicate whether the controlling mechanism is related to the precursor formation or the final step in the formation of the volatile molecules. These results will be assessed in conjunction with the H/D reemission measurements.

6.2 Hydrogen Retention/Diffusion

Using the TDS technique, we will study the effect of dopants (species and concentration) on the fluence dependence of H retention due to H^+ impact. The basic question is whether the dopants act as catalytic sites for increasing H_2 recombination, which in turn could lead to an increase in the H_2 reemission and a decrease in the amount of hydrogen trapped beyond the implantation zone. To gain some insight into the recombination process, H^+/D^+ implantation experiments with the dual-beam will also be performed, as discussed above for the hydrocarbon formation process.

6.3 Thermal Diffusivity

From a fusion reactor application perspective, materials used for plasma-facing components must have sufficiently high thermal conductivities to handle high heat fluxes. This requirement has become more focussed with ITER. Therefore, in addition to the erosion and H-retention behaviour of the doped graphite specimens, we will also perform a comparative study of the thermal diffusivities. For this purpose the laser flash technique will be used. The technique involves the deposition of heat via the laser on one face of a thin disc sample and the monitoring of the temperature rise on the other face. Using an appropriate selection of sample thickness and laser energy (per pulse),

thermal diffusivity can be derived from the time dependence of the measured temperature rise. The experiments will be performed using a 40 J Nd-glass laser.

7. PUBLICATIONS

1. Chiu, S., and Haasz, A. A., "Subsurface Methane Formation in Graphite due to Exposure to H^+ and D+," J. Nucl. Mater. (submitted).
2. Chiu, S., Haasz, A. A., and Franzen, P., "Methane Molecule Breakup During H^+-Graphite Interactions" (to be published).
3. Davis, J. W., and Haasz, A. A., "Chemically Enhanced Self-Sputtering of Carbon," Appl. Phys. Lett. 57 (1990) 1976.
4. Davis, J. W., Haasz, A. A., and Wu, C. H., "Synergistic Erosion of Graphite due to Simultaneous Bombardment by C^+ and H^+," J. Nucl. Mater. 196-198 (1992) 581.
5. Haasz, A. A., and Davis, J. W., "Synergistic Methane Formation Kinetics for Hydrogen Impact on Carbon," J. Chem. Phys. 85 (1986) 3293.
6. Haasz, A. A., and Davis, J. W., "Synergistic Chemical Erosion of Graphite due to Simultaneous Exposure to H^+ and Low-Z Ions Using a Dual-Beam Accelerator," J. Nucl. Instrum. Meth. (in press).
7. Davis, J. W., and Haasz, A. A., "Chemical Erosion of Carbon/Carbon Composites Doped with Boron and Silicon," J. Nucl. Mater. 195 (1992) 166.
8. Haasz, A. A., and Davis, J. W., "Comparison of the Chemical Erosion of Carbon/Carbon Composites and Pyrolytic Graphite," J. Nucl. Mater. 175 (1990) 84.
9. Chiu, S., and Haasz, A. A., "Molecule Formation due to Sequential and Simultaneous Exposure of Graphite to H^+ and D^+," J. Nucl. Mater. 196-198 (1992) 972.
10. Chiu, S., and Haasz, A. A., "Thermal Desorption of Sequentially and Simultaneously Implanted H^+ and D^+ in Graphite" (to be published).
11. Haasz, A. A., Chiu, S., and Davis, J. W., "Hydrogen Transport in Graphite," Proc. IAEA Technical Committee Meeting on "Atomic and Molecular Data for Fusion Reactor Technology," Cadarache, France, Oct. 12-16, 1992.
12. Davis, J. W., Haasz, A. A., and Walsh, D. S., "Flux and Fluence Dependence of H^+ Trapping in Graphite," J. Nucl. Mater. 176/177 (1990) 992.
13. Haasz, A. A., and Davis, J. W., "Effect of Microstructure on the Fluence Dependence of H-Retention due to H^+ Exposure of Graphite" (to be published).
14. Davis, J. W., and Haasz, A. A., "Reemission of Hydrogen and Deuterium from Graphite for Temperatures Between 1000 and 1600K," J. Nucl. Mater. 183 (1991) 229.
15. Franzen, P., Vietzke, E., Haasz, A. A., Davis, J. W., and Philipps, V., "Atomic Reemission of Hydrogen from Pure and Boronized Graphites at Temperatures Above 1000K," J. Nucl. Mater. 196-198 (1992) 967.
16. Vietzke, E., Franzen, P., Haasz, A. A., Davis, J. W., Philipps, V., and Reiter, D., "Atomic Reemission of Hydrogen from Pure and Boronized Graphites at Temperatures Above 1,000K," Proc. IAEA Technical Committee Meeting on "Atomic and Molecular Data for Fusion Reactor Technology," Cadarache, France, Oct. 12-16, 1992.

FORSCHUNGSZENTRUM JÜLICH GmbH KFA

Dr. E. Vietzke INSTITUT FÜR PLASMAPHYSIK D-52425 Jülich, Germany

Progress Report on the work of the research agreement No. 6237/CF IAEA-KFA Jülich
concerning the research project
"Chemical sputtering and radiation-enhanced sublimation
of fusion reactor materials"

Our activities in this project were mainly concentrated on the following subjects:

Chemical impurity production under boronized wall conditions in TEXTOR:

The TEXTOR SNIFFER probe has been used to analyse the chemical impurity production under various plasma and boronized wall conditions. Methane formation has been observed to 0.6-1 x 10^{-2} CH_4/H at room temperature,increasing slightly with increasing density in the SOL. The hydrocarbon formation yields increase from R.T. to the maximum at about 500°C by a factor of 1.5-2.5. Increasing the impact energy by biasing the graphite plate lead to a decrease of the hydrocarbon yield at room temperature but to an increase at 500°C. Chemical CO formation due interaction of oxygen impurities with the graphite reaches ratios between 0.5 and 3 x 10^{-2} CO/H,D increasing with increasing distance to the limiter edge.

High temperature behaviour of B-, Si- and Ti-doped carbon:

The thermal sublimation and radiation-enhanced sublimation (RES, using 3 keV D_3^+ and Ar^+ ions) of boron-doped carbon material (3.8% B, Carbonne Loraine S 1122, silicon/carbon (SiC30, Schunke), titanium/carbon (RGTi) has been studied. The summary of these result is:
The **B, Si, Ti sublimation** from doped carbon is reduced compared to pure B, Si or Ti and similar to the correspondent carbids, except one component of SiC30 is similar to pure Si (possibly the free Si component of 5%). After a heat treatment at 2000°C it is again similar to SiC.
The **impurities** desorb at characteristic temperatures in comparable large amounts. Heat treatment seems to be a possible way of reducing the impurity content (for example Fe, Al and Si in RGTi).
Radiation-enhanced sublimation (RES) is not supressed. Solely, in the case of B/C a shift of the onset temperature to higher values is observed.
By applying these result for the **release of particles under TEXTOR limiter conditions** the following statement can be made: Below 2000°C the release of partides is dominated by physical sputtering and RES, except for the impurity release and the release of free Si from SiC30.

Limiter test experiments in TEXTOR:

Test-limiters experiments in TEXTOR have been performed by using different low-Z materials: EK98 as reference, 20% B-doped carbon [Toyo Tanso], B_4C coat-mixed, SiC coat-mixed [both fabricated in KFA Jülich] and SiC30 [Schunk]. The test limiters have been exposed in TEXTOR to high heat loads up to about 30 MW/m^2. Maximum surface temperatures up to 3000°C have been reached. It has been found that the dopands sublime as expected from normal thermal simulation.
The present analysis shows that in the range between 1200 and 1900 °C the RES-induced carbon emission is much smaller than present beam and plasma simulation experiments predicts for the condition in TEXTOR. For pure carbon a sudden acceleration of the rise of the surface temperature has been found at about 2400°C: hot spot formation. The developement of the hot spot is explained by the break down of the sheath potential due to thermal electron emisssion.

Developing of a new technique for in-situ erosion and redeposition measurements:

Based on the very different refractive constants of quartz substrates (~1.5) and of amorphous deposits (>1.7) collected in the SOL of TEXTOR, in-situ reflectometry has been developed in order to determine the growth rate. After the laboratory experiments, this method has now been sucessfully tested at TEXTOR. The determined growth rate in the limiter shadow in the order of 5 nm/sec agrees well with those determined by collector probes.

Publications:

[1] E.Vietzke, V.Philipps, K.Flaskamp, J.Winter, S.Veprek
"Radiation enhanced sublimation of Boron containing Carbon Materials", J. Nucl. Mat. 176-177, 481-485(1990)

[2] A.Pospieszczyk, V.Philipps, L.Könen, U.Samm,
"High temperature erosion of graphite during extreme limiter loads in TEXTOR",
J. Nucl. Mat 176/177 (199o) 180-185

[3] A.A. Haasz, E.Vietzke, J.W.Davis, V.Philipps
"Carbon Erosion due to simultaneous H^+ and e^- impact"
J. Nucl. Mat. 176-177(1990)841-844V.

[4] V.Philipps, E.Vietzke, H.Trinkaus
"Radiation Enhanced Sublimation of Carbon and Carbon Related Materials"
J. Nucl. Mat. 179-181, 25-33(1991)

[5] V.Philipps, E.Vietzke, H.Trinkaus
"Radiation Enhanced Sublimation of Carbon and Carbon Related Materials"
J. Nucl. Mat. 179-181, 25-33(1991)

[6] E.Vietzke, V.Philipps, K.Flaskamp, P.Koidl. C.H. Wild
The reaction of atomic hydrogen with a-c:H and diamond films
Surface and Coatings Technology 47(1991) 156-161

[7] E.Vietzke, V.Philipps, K.Flaskamp, J.Winter, S.Veprek, P.Koidl "The reaction of H^0 with a-C:H, a-C/B:H and diamond films", Proc. 10^{th} Int. Symposium on Plasma Chemistry, Bochum, Germany

[8] V.Philipps, J.Ehrenberg , J.Winter, H.G.Esser, E.Vietzke
"Helium wall pumping and outgassing with carbon and boron walls in TEXTOR and beryllium walls in JET" Int. Workshop on Helium Transport and Exhaust, Gatlinburg USA 1991, Proc. ITER/US/91/PH-13-01,485-501

[9] V.Philipps, J.Ehrenberg , H.G.Esser, M.Erdweg, E.Vietzke
"Analysis of Hydrogen and impurity outgassing under Carbon, Boron and Beryllium first wall conditions,Europhysics Conference Abstracts Volume 15C,1991,Part III,49-52

[10] J.Linke, E.Vietzke "Behaviour of boron-doped graphites, plasma-sprayed B_4C and a-C/B:H as plasma-facing materials" in J.Winter (Ed.) Carbon Materials Notes, Fusion Technology 20, 228-231 (1991)

[11] J.Roth, E.Vietzke, A.A.Haasz
"Erosion of graphite due to particle impact"
Supplement to Nucl. Fusion, Vol. 1, 1991, 63-78

[12] P.Franzen , E.Vietzke, A.A.Haasz , J.W. Davis , V. Philipps
"Atomic reemission of hydrogen from pure and boronized graphites at temperature above 1000 K", J. Nucl. Mat. 196-198 (1992) 967-971

[13] J.Winter, H.G.Esser, V.Philipps, T.Rose, J. von Seggern, E.Vietzke, P.Wienhold
"Surface treatment of first wall in fusion devices (carbonization, boronization and related surface chemistry)", Vacuum 43 (1992) 413-417

[14] V.Philipps et al.,"Chemical impurity production under boronized wall conditions in TEXTOR", 19th EPS Innsbruck 1992, Proc. Vol.II(1992)827.

[15] E.Vietzke et al.,"High temperature erosion of boron/carbon materials" J.Nucl.Mat. 196-198(1992)1106.

[16] V.Philipps et al.,"Behaviour of carbon and boron/carbon materials at high temperatures in TEXTOR", J.Nucl.Mat. 196-198(1992)1106.

[17] F. Weschenfelder et al.,"A new technique for in-situ measurements of erosion and redeposition in a single discharge" J.Nucl.Mat. 196.198(1992)1101, Thesis 1993

[18] V.Phillipps et al. "Evidence of hot spot formation on carbon limiters due to thermal electron emission", To be published in Nucl. Fusion, preprint included.

Sputtering and Hydrogen Recycling in Metal-Carbide Composite Materials

Kenji MORITA
Department of Crystalline Materials, School of Engineering,
Nagoya University, Furo-cho, Chigusa-ku, Nagoya 464-01,JAPAN

OBJECTIVES of this project are understanding of erosion process of metal-carbon composite materials including redeposition and establishment of the data base and the simulation model for prediction of the erosion rate and also understanding of re-emission processes of hydrogen isotopes(H and D) in carbon and carbon-metal composite materials and establishment of the data base and the simulation model for prediction of hydrogen recycling rate and hydrogen inventory.

SO FAR, it has been shown by the present group,concerning the erosion, that ion-bombardment induced sputtering of metal from the metal carbide layer deposited on graphite at high temperatures is substantially suppressed by self-sustaining coverage of the surface with segregated carbon atoms, which are supplied via diffusion from the graphite substrate, below certain critical ion flux, for instance, $1x10^{15}$ 1keV $H^+cm^{-2}s^{-1}$ for TiC/graphite at 900 C.

It has been also shown,concerning the hydrogen retention, that the steady state depth profiles of hydrogen isotopes implanted into graphite are excellently well reproduced by the solution of the mass balance equations for both freely diffusing hydrogen andtrapped one, which various elementary processes; diffusion,recession of the surface, implantation source, trapping (or retrapping), thermal and ion-induced detrapping, local molecular recombination both between activated(free) hydrogen atoms and between an activated hydrogen atom and a trapped one and hydrocarbon formation are taken into account and by best fitting of the solution to the experimental data the diffusion constant and the rate constant of local molecular recombination between an activated hydrogen atom and a trapped one are determined as a function of inverse temperature.

IN THE LAST three(1990,1991,1992) years, we have perfomed following two tasks concern this project:(1) high temperature sputtering of metal from carbon-metal composite materials and (2) re-emission of hydrogen isotopes from graphite.

(1) High Temperature Sputtering of Metal from Carbon-Metal Composite Materials

In the experiments on WC layers(of 3000 A in thickness) bombarded with 5 keV Ar^+ion beam, it has been found that the sputtering yield of W from the WC layer at 1550 C decreases down to zero at a critical ion flux of $4.6x10^{13}cm^{-2}s^{-1}$ with decreasing the ion flux and that the sputtering yield of W at $6x10^{13}cm^{-2}s^{-1}$ also decreases down to zero at a critical temperature of 1600 C with increasing the temperature. It is determined from analysis of the latter data that the activation energy of the dissolution rate of carbon atoms at the surface is 2.0 eV, which is a key parameter for predicting the critical flux and temperature under different conditions.

The critical ion flux of $6.0 \times 10^{18} cm^{-2} s^{-1}$ for 5 keV Ar^+ at 1600C is estimated to correspond to $1.1 \times 10^{16} cm^{-2} s^{-1}$ for 100 eV H^+, which is a peak particle load at the first wall of ITER.

In the experiments with TiC coating on graphite bombarded with high heat flux plasma(NAGDIS-I plasma) at $1 \times 10^{17} cm^{-2} s^{-1}$, it has been found in the temperature up to 1600C that as the temperature increases the Ti sputtering yield increases gradually, decreases abruptly at 1000C and again increases through a deep minimum at 1200C. The sputtering behavior is reasonably explained in terms of the self-sustaining coverage of the TiC surface with segregated carbon layers. It is found in the data analysis that the most preferable performance of the plasma facing components can realized by radiation-induced multilayer segregation.

(2) Re-emission of Hydrogen Isotopes from Graphite

In order to confirm in detail the validity of the mass balance equations and to determine the rate constants of the elementary processes for re-emission included in them, the ion-induced and isothermal re-emission of hydrogen isotopes implanted into graphite has been studied by means of the ERD technique.

In the experiment on the ion-induced re-emission with 1.5 MeV He^+ ion beam, it has been found that the re-emission profiles of H and D are excellently well reproduced by the solution of the mass balance equations,in which local molecular recombination between an activated hydrogen and a trapped one plays a major role in the re-emission process. From the data analysis the ratios of the rate constants of local molecular recombination to trapping and the ion-induced detrapping cross-section have been determined. It has been also found that there exists a strong isotope effect in the ratios of the rate constants.

In the experiments on the isothermal re-emission of hydrogen isotopes implanted up to saturation, it has been found that the re-emission profiles of H and D are also well reproduced by the solution of the mass balance equations,which local molecular recombination between activated hydrogen atoms plays a major role in the re-emission process in this case. From the data analysis the thermal detrapping rate, the effective recombination rate and the branching ratio of hydrocarbon emission to hydrogen molecule emission have been determined as function of inverse temperature. It has also been found that there exsits a strong isotope effect in the effective recombination rates for H and D.

In the experiments on the isothermal re-emission of hydrogen implanted at several under-saturation levels, it has been found that the re-emission rate becomes smaller as the initial implantation concentration decreases,which is ascribed to retapping effect of thermally activated hydrogen atoms at available open traps. From the data analysis, the rate constant of hydrocarbon molecule formation has been determined as function of inverse temperature.

Finally, in order to correspond the data on the elementary processes obtained by direct measurement of hydrogen retained in the specimen to those obtained by measurement of emitted hydrogen molecule, the thermal desorption spectrum has been calculated from the theoretical re-emission profile(solution of the mass balance equation). It has been shown that the calculated thermal desorption spectrum shows good agreement with the experimental one.

Publications List(after 1990)

1)K.Morita and Y.Hasebe, A New Model for Release of Hydrogen Isotopes from Graphite, J. Nucl. Mater. 176/177, 213(1990)
2)K.Morita, Metal Sputtering and Hydrogen Retention in Metal-Carbon Composite layer Materials, Fusion Technol.19,2083(1991)
3)Y.Muto and K.Morita,Isothermal Re-emission of Hydrogen Implanted into Isotropic Graphite, J. Nucl. Sci. Technol. 29, 859(1992)
4)Y.Hasebe, M.Sonobe and K.Morita, Isotopic Effect in Ion Induced Re-emission of Hydrogen Implanted into Graphite, J. Nucl. Sci. Technol. 29,980(1992)
5)K.Morita and Y.Muto,Isotopic Effect in Isothermal Re-emission of Hydrogen Implanted into Graphite, j. Nucl. Mater. 196-198, 963(1992)
6)R.Jimbou, M.Saidoh, N.Ogihara, T.Ando, Y.Muto and K.Morita, Retention of Deuterium Implanted into B_4C-Overlaid Isotropic Graphite and Hot-Pressed B_4C, J. Nucl. Mater. 196-198, 958 (1992)
7)K.Morita, K.Mori and Y.Muto, Flux Dependence of Metal Sputtering Yield from Metal-Carbon Composite Materials at the High Temperature Regime, J. Nucl. Mater. 196-198,564(1992)
8)K.Morita,(Review Paper)Dynamic Behavior of Hydrogen Isotopes Implanted into Graphite Studied by Means of the Ion Beam Analysis Technique, Memoirs Fac. Eng. Nagoya Univ. 45,(1993) in print.
9)Y.Hasebe and K.Morita, Energy Dependence of Depthe Profiles and Peak Concentrations of Hydrogen Retained by Implantation into Graphite, J. Nucl. Mater. to be submitted.
10)S.Ikeda, S.Takamura, K.Mori and K.Morita, Sputtering of Metal-Carbide Overlaid Graphite Induced by high Heat Flux Plasma Irradiation at High Temperatures, J. Nucl. Mater. to be submitted.
11)Y.Muto and K.Morita, Contribution of Hydrocarbon Emission to Thermal Re-emission of Hydrogen Implanted into Graphite, J. Nucl. Mater. to be published.
12)B.Tsuchiya and K.Morita, Energy Dependence of MeV He Ion Induced Detrapping Cross-Section of Hydrogen Isotopes Trapped in Graphite, Proc. 9th Int. Conf. SIMS, Yokohama, Japan, 1993.

A summary of UCLA efforts on the coordinated research program on the plasma-interaction induced erosion of fusion reactor materials

Yoshi Hirooka

PISCES Plasma-Surface Interactions Research Laboratory
Institute of Plasma and Fusion Research
University of California, Los Angeles

Synopsis

Since the last CRP meeting in 1991, the emphasis in the PMI research at UCLA has been shifted from carbon-based materials to high-Z materials in order to develop divertor plate materials in ITER to be used during the technology phase. In this report, the data from recent tungsten erosion experiments will be reviewed. Also, a new beryllium handling facility is currently under construction and the details of this safety facility will be described.

1. Introduction

It is widely recognized that the conditions under which plasma-facing components are exposed to the plasma in ITER will be extremely severe. Currently, only three classes of materials are considered as candidates for the ITER divertor plate application [1]. These candidates are carbon, beryllium, and tungsten. Fusion-related properties of these materials are listed in Table 1. Their compounds such as beryllium carbide may also be considered as candidates.

Among these candidates, carbon materials have widely been used in existing magnetic fusion devices such as TFTR, JT-60, and JET. In the PISCES program, extensive characterization and evaluation experiments have been carried out for carbon-based materials. In fact, bulk-boronized graphite has been developed as the product of these experiments [2] and is currently used for the main limiter in the Wenderstein Stellarator [3].

Because of their wide application, the carbon-based materials data base is relatively well established. Although the data base is still incomplete, beryllium has been used successfully in the first DT fusion experiments in JET [4]. Based on these experiences, carbon and beryllium are the primary candidates for the ITER divertor plate during the physics phase operation. By contrast, very little is known about the performance of tungsten and its coatings as a plasma-facing material. Nonetheless, because of its high erosion resistance, tungsten can be a potential candidate for the technology phase operation of ITER.

In support of the PFC technology development for ITER, divertor materials evaluation and development efforts have been made as part of the PISCES program at UCLA. In this report, recent data from tungsten erosion experiments and a new beryllium handling facility will be described.

Table 1 The divertor plate material requirements and a comparison of three candidates.

Required properties	Beryllium	Carbon	Tungsten
1. Low atomic number	4	6	74
2. Low sputtering yield (by D^+ at 100 eV)	0.04	0.01	0 [1]
3. High melting point (^oC)	1283	3367 [2]	3410
4. High thermal conductivity (W/m K)	300	50-800 [3]	180
5. High heat capacity (J/g K)	2.3	1.6	1.4
6. No hydride formation/hydrogen codeposition	Yes[4]	Yes	No
7. In-situ repair by plasma spray ?	Yes	No	Yes
8. Machinable ?	Yes	Yes	No

(1) The threshold energy is higher than 100 eV for deuterium ion bombardment [5].
(2) Sublimation temperature at 1 atm.
(3) Room temperature values. Data strongly depend on the structure.
(4) Possible hydride formation in the presence of atomic hydrogen.

2. Recent tungsten erosion experiments

Regarding lifetime, tungsten is an attractive candidate because of its high threshold energies for physical sputtering (calculated E_{th} values for W are 783, 341, 213 eV for H, D, T, respectively [5]). This means that if the edge plasma temperature is controlled to a few tens of electron volts, it is possible to eliminate sputtering of the tungsten divertor plate due to DT-fuel ions although the effect of high-energy charge exchange neutrals on divertor erosion is yet-to-be explored.

One of the technical issues associated with the use of high-Z materials is the effect of impurities such as oxygen on sputtering. To explore this impurity effect, the erosion behavior of tungsten has been investigated using the PISCES-B mod facility [6,7]. Because machining and welding of tungsten is extremely difficult, it is important to investigate the possible use of its coatings for PFCs. Two different coatings techniques are employed here: chemical vapor deposition (CVD) and low pressure plasma spray (LPPS) to prepare 1mm thick coatings on molybdenum.

In PISCES-B plasmas there are unavoidable oxygen-containing impurities such as H_2O^+ and OH^+, both related to residual water vapor. However, the concentration of these impurities can be varied in the range from 0.1 % to 2 % by controlling the pumping speed and the electron temperature. More specifically, these control "knobs" are to regulate the neutral pressure of water vapor and the ionization rate. Here, one can assume that the sputtering yield of tungsten due to these impurity radicals is not too different from that due to elemental oxygen. The nominal oxygen impurity concentration predicted in the DT-plasma in ITER is about 0.1 % [8]. Therefore, the experimental conditions in PISCES-B mod are believed to be directly ITER-relevant.

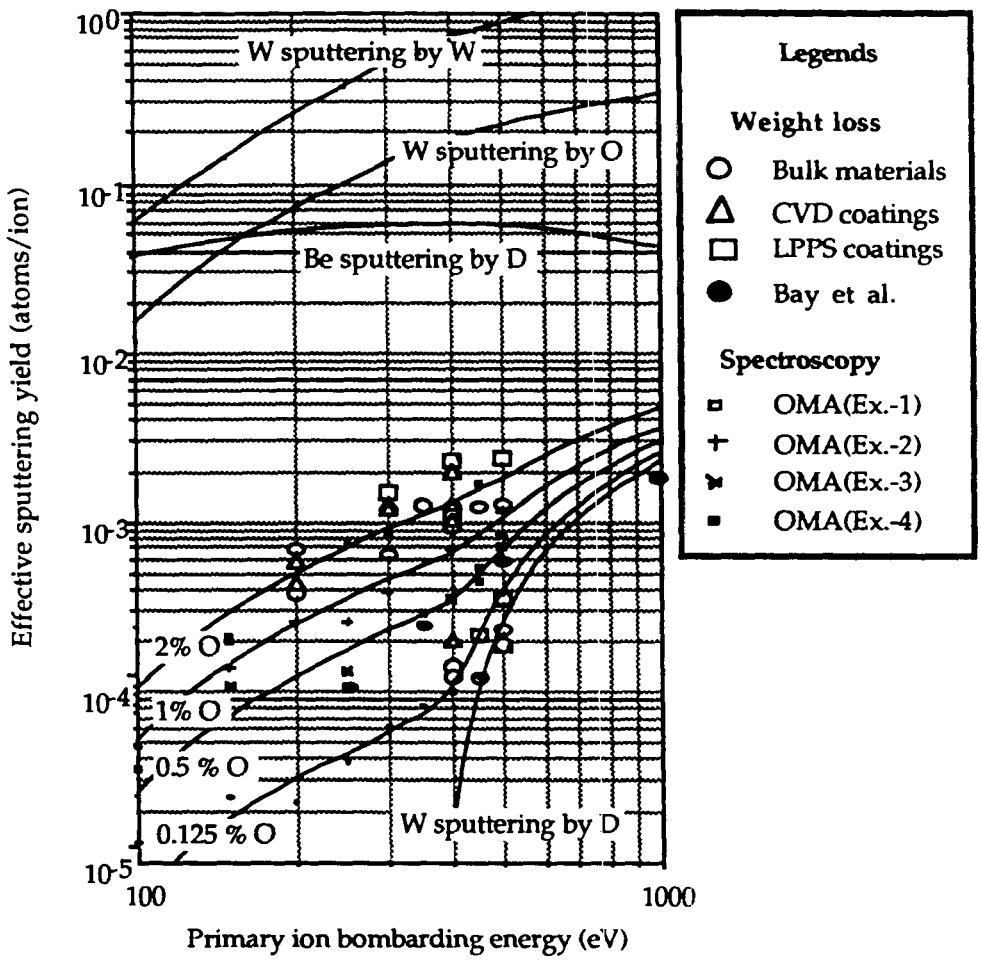

Fig. 1 Tungsten erosion under deuterium plasma bombardment with oxygen contamination in PISCES-B mod [10].

Shown in Fig. 1 are the "effective" sputtering yield data taken for tungsten and its coatings under deuterium plasma bombardment with controlled oxygen contamination at a surface temperature of 1500°C. Notice that there is no difference in the erosion behavior between bulk-tungsten and tungsten coatings, and erosion generally starts at energies below 100 eV due to the effect of oxygen contamination. The sputtering threshold of tungsten by oxygen is about 50 eV [5], which appears to be consistent with the data presented here.

Because tungsten oxides are generally volatile at temperatures above 1000°C, evaporation-enhanced sputtering was once raised as a potential issue [9]. However, tungsten oxides are predicted to be extremely unstable in the presence of atomic hydrogen, a major constituent of low temperature plasmas. Also, the estimated evaporation rate at 1500°C is found to be negligible, compared with the total erosion rate. Therefore, the effective erosion rate may be approximated by the sum of physical sputtering yields due to deuterium and oxygen [10].

As such, trace amounts of oxygen can significantly alter the overall erosion behavior of tungsten. However, this impurity effect can be minimized by lowering the electron temperature, perhaps using a new divertor concept such as gaseous divertor [11]. At electron temperatures below 10 eV, oxygen molecular dissociation does not occur rapidly and the reaction: $O_2 + e^- \Rightarrow O_2^-$ becomes more important than the reaction: $O_2 + e^- \Rightarrow O_2^+ + 2e^-$ [12]. This argument implies that at low electron temperatures, oxygen impurities may not significantly contribute to the divertor erosion.

As to the comparison of tungsten with other candidates, as shown in Table 2, even under the influence of 0.1 % oxygen impurities, the effective sputtering yield of tungsten is about 3-4 orders magnitude below those calculated for beryllium and carbon, predicted by the REDEP code [8]. At a low edge temperature of 30-40 eV, the lifetime for 5 mm thick tungsten and beryllium divertor plates is estimated to be 7 years and 2 weeks, respectively. It follows immediately from these arguments that tungsten is an important option if the lifetime is critical for the operation of ITER.

Table 2 Lifetime calculated with the REDEP code for a 5 mm thick divertor plate [8].

Material	Conditions[1)]	Duty factor[2)]	Lifetime[3)]
Carbon	T_e=30 eV, physical sputtering only	100 %	11 days
		2 %	1.5 yr
Beryllium	T_e=30 eV	100 %	4 days
		2 %	0.5 yr
Tungsten	T_e=40 eV	100 %	7 yr
		2 %	350 yr

(1) No x-point sweep assumed.
(2) Burn time per calendar time.
(3) Based on peak net erosion rates due to DT-plasma with 0.1% oxygen contamination.
Valued in this table are rearranged from Tables II and III in reference 8.

3. Near-future work on beryllium

In the PISCES program, erosion and redeposition experiments are planned for beryllium and its compounds in the near future. However, beryllium can be a deadly substance if its oxides at certain particle sizes (0.1-10 μm in diameter) are inhaled and accumulated in the human lung. Beryllium-induced symptoms, referred to as berylliosis, can be found years after exposure. The biological susceptibility to beryllium is quite individual and can not be standardized. Furthermore, unlike radioactive materials, it is not possible to monitor real-time the amount of airborne beryllium oxide particles. Therefore, the handling of beryllium

must be done with maximum caution. Presumably due to this safety issue, JET is the only operating device using beryllium for PFCs. In fact, the in-vessel work in JET is done by workers in "astronautical" full-cover pressurized suits and respirators with air supply.

Although, as shown in Table 2, beryllium can not make a long lifetime divertor plate, there are several attractive features (see Table 1) to allow us to predict successful operation of ITER. One major advantage is that beryllium has the lowest-Z number among the three candidates. There are several technical issues on the use of beryllium: (1) the low melting point of 1287°C, limiting the operational temperature; (2) high sputtering yield, limiting the duty factor of reactor operation (3) possible formation of hydrides (BeH_2) at the presence of atomic hydrogen, leading to a large tritium inventory; (4) the effect of helium bubbles to be formed due to the (n, 2n) transmutation reaction, leading to a degradation of mechanical properties (5) limited knowledge about redeposited beryllium.

In the PISCES program, a beryllium handling facility shown in Fig. 2 is being constructed and will be operational in 1994. This facility is basically an air-tight enclosure to cover the PISCES-B mod facility. Major features are: (1) ultra-clean condition with an airborne beryllium concentration below 0.01 $\mu g/m^3$; (2) high-rate ventilation with a HEPA-filtered exhaust system at a flow rate of 4000 CFM; (3) negative pressure maintained to prevent outflows of beryllium-contaminated air; (4) double-door with a key entry system to control the access. In addition, the standard operation procedure in this facility requires workers to wear safety suits equivalent to those used at JET [13].

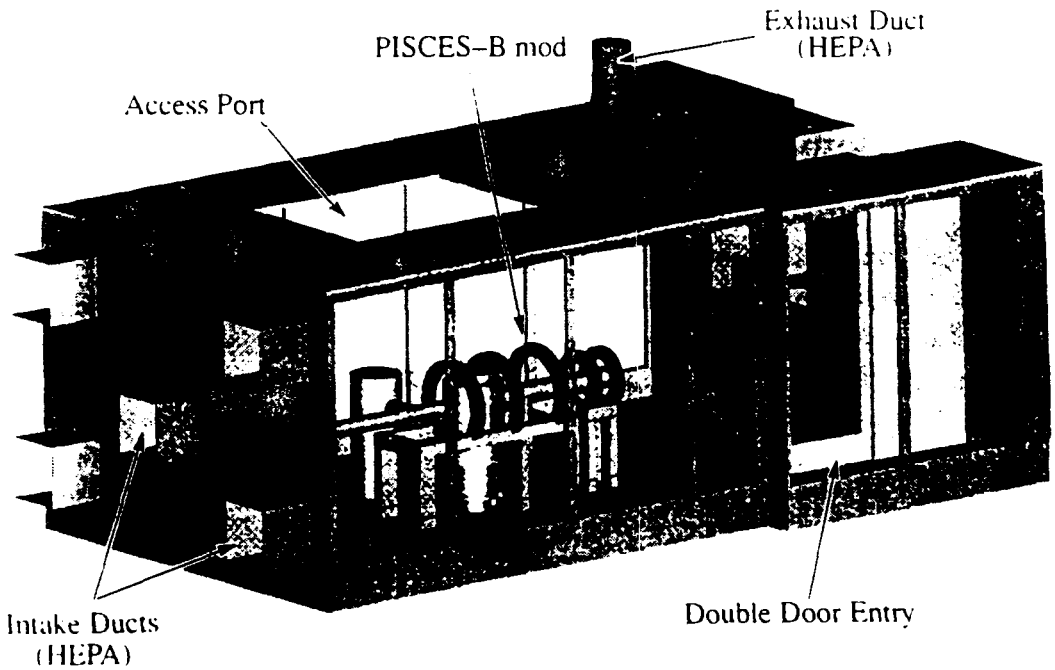

Fig. 2 The beryllium handling facility for PISCES-B mod (and PISCES-Upgrade) is currently under construction and will be operational in 1994.

References

[1] T. Kuroda et al., "ITER Plasma Facing Components", ITER Documentation Series #30, IAEA, Vienna (1991).
[2] Y. Hirooka et al., J. Nucl. Mater. 176&177(1990)473.
[3] R. Brakel, et al., J. Nucl. Mater. 196-198(1992)431.
[4] The JET team, J. Nucl. Mater. 196-198(1992)3.
[5] N. Matsunami et al., At. Data Nucl. Data Tables 31(1984)1.
[6] Y. Hirooka et al., J. Vac. Sci. & Technol. A8(1990)1790.
[7] Y. Hirooka (ed.), PISCES Program, Progress Report for 1991-1992 on Plasma-Materials Interactions and Edge-Plasma Physics Research, UCLA Report #PPG-1440, July, 1992.
[8] J. Brooks, Fusion Technol. 18(1990)239.
[9] C. Wu, J. Nucl. Mater. 145-147(1987)448.
[10] Y. Hirooka et al., J. Nucl. Mater. 196-198(1992)149.
[11] L.Schmitz et al., J. Nucl. Mater. 176&177(1990)522.
[12] G. R. Musium, J. Vac. Sci. Technol. A8(1990)1642.
[13] JET-Doc., Code of practice for the safe use of beryllium at JET, July, 1989.

A Summary Report on the Contribution of the Institute of Nuclear Fusion PRC Kurchatov Institute to the IAEA CRP on Plasma-Interaction Induced Erosion of Fusion Reactor Materials

Maria Guseva

1. Introduction

The boron containing carbon/graphite materials are characterized by a number of unique properties from the viewpoint of their perspective as ITER plasma facing components. They are:

- low atomic number of doping impurity,
- low chemical sputtering,
- shift in the radiation-enhanced-sublimation (RES) process threshold to higher temperatures and reduced high-temperature erosion,
- reduction in the hydrogen isotopes inventory.

1. The high resistance of boron containing graphites to chemical and high-temperature erosion by hydrogen ions was demonstrated for the first time on the USB-15 graphite [1-6]. However, a serious drawback USB-15, as well as of other boronized graphites, is its low thermal conductivity.

   In this connection, a high heat load test of boron containing carbon graphites materials would be of great interest.

   In co-operation with TRINITI (Troitsk) we have performed the following experiments and tests:

- plasma disruption simulation experiments by pulsed high power plasma-U,
- test of the Tokamak T-10 rail limiter, consisting of several tiles made of USB-15, B_4C and, for comparison, also of pure graphite MPG-8.

2. The physical basis of the unique properties of boron containing materials is not clear. In this connection we have performed studies of the USB-15 chemical composition after irradiation by ion and plasma hydrogen fluxes at different temperatures, and studies on the effects of simultaneous and successive irradation by $H^+ + O^+$, $H^+ + C^+$ ions on the hydrogen distribution profiles in USB-15.

3. The temperature dependences of the sputtering yield for a number boron containing carbon/graphite materials and CFCs doped with B, Si and Ti was also studied.

2. Experiment

1. Parameters of pulsed plasma

- Power flux intensity - 2.10^3 MW/m^2
- Energy flux density - 0.12 MJ/m^2
- Pulse duration - 0.06 ms
- Energy of hydrogen ions - 1 keV
- Number of pulses - up to 100

The tested materials were USB-15, Recbor (4%B), POCO-AXF-5Q, pyrolytic graphite.

The faciltiy used was - MK-200 coaxial accelerator.

2. Plasma parameters at the T-10 limiter were: n_e = 0.5x10^{12} - 10^{13} cm^{-3}; T_e = 20-50 eV, plasma flux F=5x10^{18} - 2x10^{19} cm^{-2} s^{-1}; the power load was up to 5 MW/m^2 in ohmic discharges and up to 20 MW/m^2 in discharges with ECR heating; the pulse duration was 0.5-1s, and during, ECR-heating 0,1-0,4s. The total fluence for approximate 2500 operating shots, including some hundreds of shots with disruptions, was 10^{21}-10^{22} at /cm^2. The tested materials were USB-15 coating (100-300 μm) on MPG-8 graphite, B_4C coating (100 μm) on MPG-8 graphite and on pyrolytic graphite, MPG-8 graphite.

3. Materials tested by the temperature dependences of sputtering yields: B_4C, graphite RGTi, RGTi+1%B and the CFC composites: K4P VM (Si, Ti), КП-5415 (Si, TiB) UAM, UAM+1%B.

3. Results

1. The erosion yields of graphite Recbor and USB-15, irradiated by pulsed hydrogen plasma fluxes under the same operating conditions, are the same and close to the erosion of the POCO-AXF-5Q graphite. The reason is: the same value of Kindgery's criterion, which determines the thermal strength of materials.

2. On the USB-15 and Recbor surfaces, irradiated by hydrogen plasmoids, bulges caused by the melting of B_4C-phase were observed, but no cracks: Cracks were observed on the POCO surfaces.

3. No cracks or flakes, which are typical for pure graphites (POCO, MPG-8), on the T-10 boron containing (USB-15, B_4C) limiter tiles on the ion-side were observed.

4. A significant change of the structure of B_4C coating on MPG-8 was observed on the electron side: melting of the layer surface with followed recrystallization. The melting of B_4C covering on the pyrolytic graphite had a single island character. The structure of USB-covering after exposure has practically not changed.

5. Traces of unipolar arcs on the ion side were observed on all tiles and their intensity was larger for the B_4C coverings.

6. The phase and chemical composition of the B_4C covering have not changed. The boron concentration in the surface layer of USB-15 covering increased from ~ 15 at % up to 21 at %.

7. All features observed by ion beam interactions with boron containing graphites can be explained in terms of the interaction of boron impurity atoms with the radiation defects, (such as brocken bonds among carbon atoms), which are responsible for the capture of hydrogen. Saturation of the torn bonds by boron assists in moderation of hydrocarbon production and in a reduction in hydrogen accumulation in boron containing materials. The reduction of RES erosion in boron containing graphite can be explained by production of complexes: interstitial carbon atom - boron which decelerate the diffusion of interstitial carbon atoms towards the surface.

8. In all the boron-containing carbon graphite materials the chemical sputtering is lower than that in the pure graphites. The chemical sputtering is suppressed to the highest degree in B_4C and in USB-15, which also differ from other materials by a lower erosion in the high temperature range.

We are planning the following research in the near future:

1. Study of the energy and temperature dependences of beryllium sputtering yields by Be^+-ions.

2. Study of the microstructural changes and chemcial composition of Be irradiated by neutrons before and after plasma irradiation.

3. Study of the Be-redeposited layer.

4. Study of the redeposited carbon/graphite materials produced in interaction of ions and high heat power plasmoids with graphite.

5. The effect of boron on chemical sputtering and RES erosion of CFCs under intense hydrogen flows.

References

1. Busharov, N.P., Gusev, V.M., Guseva, M.I. et al., Atomic Energy (in Russian) **42**, 486, 1977.
2. The Fusion News in Russia (in Russian) 1, 23, 1978.
3. Gusev, V.M., Guseva, M.I., Proc. V Conf. on Solid State Atom Interaction (in Russian), Minsk, 1978, p.3.
4. Vorobyev, A.V., Mirnov, S.V., Plasma Physics (in Russian) 1978, p.982.
5. Guseva, M.I., Contribution to the Phase II INTOR Workshop (1982).
6. Begramhenov, L.B., Guseva, M.I., Pleshivtsev, N.V. et al., IAE-4026/8, M. 1984, p.40.

WORK PERFORMED WITHIN THE CRP FOR THE PERIOD MAY 1991 - MAY 1993

1. Guseva, M.I., Gordeeva, G.V., Gureev, M. et al., "Interaction of the high power plasma flow with carbon based materials". The surface-Ion implantation, 10 Sov. Union Conference, Moscow, 1991, p.

2. Seki, M., Guseva, M., Vieder, G., Whitley, J., "ITER related R&D low-Z plasma-facing materials for divertor and first wall".
J. Nucl. Mater., **179-191**, p. 1189-1192, 1991.

3. Gueseva, M.I., Ionova, E.S., Isakov, M.G., et al., Effects of nitriding on sputtering and radiation blistering of surface for ferritic-martensitic steel by H and He ions irradiation. Poverchnost.
Physica, Chimica, Mechanica. **N7**, p. 140, 1991.

4. Guseva, M.I., Gureev, V.M., Gordeeva, G.V. et al., "Temperature dependence of the sputtering yield by H and Ar ions of dopes C-C composite.
Atomnaja Energia, **v.71**, p. 229, 1991.

5. Guseva, M.I., Gordeeva, G.V., Neumoin V.E. et al, Investigation of the sputtering of amorphous metallic alloys.
Atomnaja Energia, **v.70**, p. 156, 1991.

6. Vasilliev, V.I., Gahe, J.M., Guseva, M.I., McDonald, J.M., Simulation studies of plasma disruption effects on erosion of POCO-AXF-5Q and ATJ graphites.
Voprosi atomnoi nauki i techniki Nuclear Syntese 1993 (to be published)

7. Barsuk, V.A., Buzhinsky, O.I., Guseva, M.I. et al.
J. Nucl. Mater., **191-194**, 1417, 1992.

8. Barsuk, V.A., Buzhinsky, O.I., Verschkov, V.A., et al., Test of the boron containing coating of the graphite limiter in the Tokamak.
J. Nucl. Mat., **191-194**, 1417, 1992.

9. Gahe, J.M., Guseva, M.I., Dc Donald, J.M., Barabash, V., Zakharov, A., Tserevitinov, S., Heat load material studies: simulated tokamak disruptions.
J. Nucl. Mat., **191-194**, 454, 1992.

10. Gomozov, L.I., Guseva, M.I., Mansurova, A.N., "Surface radiation damage of β - Ti alloy under He, H, Ar ions bombardment".
1st Russian-Chinese symposium, Moscow-Tomsk, Actual problems of modern materials science, 1992, p. 146.

11. Gomozov, L.I., Guseva, M.I., Ionova, E.S., Mansurova, A.N., Nikolski, Yu.V., Surface radiation damage of Ti-V-Cr alloy, under He ion bombardment".
Proceeding of conference "Constructional materials for thermo-nuclear reactors", Moscow, Nauka, 1993, p. 83-87.

Progress Report on the Research of Kurchatov Institute on Disruption Erosion

Yu. Martynenko
(Addendum to the Report of Prof. M. Guseva)

Disruption erosion is one of the most important mechanisms of erosion in tokamaks; nevertheless, this mechanism has been investigated very little. The research on disruption erosion in the Kurchatov Institute (KI) started in 1990. The main attention was paid to the problems of vapor shielding and the mechanisms of surface erosion.

The work on the problem of surface shielding by vapor was done in colaboration with the Federal Russian Nuclear Centre (FRNC) in Chelyabinsk-70, where the computer codes for plasma dynamics with radiation transport were developed. There are 1-D and 2-D codes for solving the hydrodynamic equations with heat conductivity and radiation transport (including line radiation). These codes were adapted to the problem of surface shielding by vapor which can be considered as a plasma with ionization degree depending on electron temperature. The contact of the shielding plasma with the surface determines the boundary conditions. These are: the power flux from the plasma to the surface, the flux of evaporated particles from the surface to the plasma and the velocities of these particles.

The power flux to the surface determines the surface temperature, which can be obtained from the heat conductivity equation. The surface temperature determines the surface erosion rate. Usually the mechanism of surface erosion is evaporation from the surface, but, as was shown at KI, in the case of graphite and other brittle materials, the main surface erosion mechanism is cracking as a result of thermal stress and particle emission. The model of brittle material erosion under thermal shock was developed at KI. It assumes that cracking occurs at first between crystal blocks with different orientation and/or different temperatures. The erosion rate as a function of the surface temperature and the gradient of the temperature near the surface was obtained. The surface erosion rate is to be included in the boundary conditions both for the problem of shielding plasma and for the problem of heat conductivity in a material. Thus, the problems of the shielding plasma and the material heating and erosion are treated in a self-consistent manner.

The first results of the calculations of graphite erosion due to hydrogen plasma flow with $q=10$ MW/cm^2 were obtained by the FRNC computer code. They show that after short time of shielding plasma formation the energy of primary plasma flow is released within a relatively thin layer near the front edge of the shielding plasma and then is transported to the surface due to the shielding plasma heat conductivity. But the expansion velocity of shielding plasma is higher than that of heat flow. Hence the temperature of the shielding plasma near the surface gradually decreases, the erosion rate, consequently, also decreases and after a few microseconds it rapidly stops. The total erosion depth is some hundred nm. If the pulse duration is 0.1 ms only ~ 1% of the primary plasma flow energy is spent on vapor heating, ionization and expansion. For carbon only 5% of energy is back irradiated.

The above result for carbon was, however obtained without taking into account the magnetic field. As expected, the magnetic field prevents the shielding plasma expansion, increases its density and may increase the radiation. The input of radiation is also higher for higher Z materials.

This result was obtained for laminar plasma expansion. However, there are some reasons for turbulence to occur in the shielding plasma. The analytical model with turbulence mixed plasma was considered at KI. This model gives the best energy transport from the front edge of shielding plasma to the surface and gives the upper limit of surface erosion. The shielding factor obtained by this model is ¼ ÷ ⅓.

Our future research plans include:

1. Accurate computation of disruption induced graphite and beryllium erosion.

2. Research of shielding plasma behavior with taking into account the magnetic field effects and the geometry of divertor plates and first wall.

3. Research of melting materials erosion. The liquid layer of melted material contacting with plasma is unstable and may be sprayed.

List of Publications

1. Yu.V. Martynenko and P.G. Moskovkin, "About the erosion of tokamak walls under plasma disruption", Voprosy atomnoi nauki i techniki, termojadernyi sintez, 1991, 4, pp 17-21.

2. Yu.V. Martynenko and P.G. Moskovkin, "Destruction of brittle materials under plasma disruption in tokamaks", prepared for publication.

3. Report of FRNC.

Use of plasma-sprayed boron carbide as plasma facing component in Tore-Supra

E. Gauthier
Association Euratom-CEA sur la Fusion Contrôlée
CEN Cadarache
F 13108 Saint Paul lez Durance

Tore-Supra is a large size tokamak (R=2.35 m, a=0.80 m) with supraconductive toroidal coils (4.5 T on axis). The permanent toroidal field and the implementation of actively cooled plasma facing components permit to obtain long duration discharges in a steady state regime. To extend the discharge duration beyond the transformer limit a non inductive current drive generation is used by means of low hybrid waves (LH) at 3.7 GHz. The maximum LH power coupled is equal to 6 MW.

Steady state discharges as long as 1 minute on the flat top have been obtained with 2.5 MW of LH corresponding to 170 MJ injected in the plasma. The average power deposition on the inner wall in this case is about 0.3 MW/m^2. Even with such a low flux, with an infrared camera view of the inner wall some hot spots can be seen, whose surface temperature larger than 2000°C. Those hot spots never induced a carbon bloom as noticed on JET, nevertheless, carbon impurity increase as fonction of the total input energy.

Due to the technical difficulties encountered in brazing carbon on any metallic substrates (stainless steel, copper, molybdenum...), a new technic using a low Z-material without brazing is investigated for components exposed to a medium flux : Plasma sprayed boron carbide.

Plasma sprayed boron carbide techniques have been developped and patented by the CEA. It is now used on an industrial base by SNMI, a company located in Avignon. The boron carbide powder is introduced in a plasma torch where it melts and is projected to the substrate. The plasma gas is a mixture of argon and hydrogene and the coating is done in a chamber filled with argon at athospheric pressure. During the coating, the substrate temperature is kept constante (<80 °C) by using a cryogenic cooling (liquid argon). Prior to the coating a surface preparation of the substrate must be done. The substrate is sand blasted to obtain an average surface roughness of about 5μm to increase the bonding of the coating with the substrate. The tensile strength of B_4C coating on stainless steel is 20 MPa. B_4C coating have been deposited onto OFHC copper, copper alloys (glidcop Al25, CuCrZr), stainless steel, molybdenum (TZM), graphite, CFC and alumina. The thickness of the B_4C coating we used in Tore-Supra is between 100 and 200μm. Of course, the life time of the B_4C layer depends of its thickness and of the erosion yield. As the surface

temperature in the tokamak is kept lower than 1000°C, erosion is mainly due to physical sputtering of B_4C by deuterium ions. This sputtering yield was measured and is comparable to that measured on sintered boron carbide. Chemical sputtering with oxygen ions showed a reduction by a factor 3 compared with that of carbon material.

The thermal behaviour of B_4C coating was investigated by using the FE200 electron gun. These tests were achieved on a 200μm B_4C layer has been deposited on a glidcop mock-up actively cooled with a water loop. The size of the mock-up is 17x200 mm, the water tube is 10 mm o.d. with a swirl inserted in it ; the distance between the water and the glidcop surface is 2.5 mm. The mock-up was exposed to heat fluxes up to 10 MW/m² in a steady state regime, the surface temperature reached 1000°C. Then fatigue tests were performed at a level of 6 MW/m². 1000 cycles of 10 seconds were done without showing any damage on the B_4C coating. Analysis of the thermal behaviour as fonction of the heat flux was done using the code Castem 2000. The calculated values fitted very well the experimental values for thermocouples inserted at different location in the glicop anf for a B_4C layer's thermal conductivity equal to 4 W/m.K. This low value, compared with that of bulk boron carbide, is in good agreement with those obtained from laboratory measurements by our group and also the value measured with flash laser experiment by Van der Laan et al.

Plasma sprayed boron carbide has been used in Tore-Supra as low Z materials protection on the ICRH Faraday screen. The B_4C covered the frame of the screen and half part of the tubes exposed to the plasma. In vacuum, the antenna with new Faraday screen shows a reduction of the RF losses by a factor of 6 compared to the antenna with the old Faraday screen (with carbon tiles). In plasma operation, the two antennae behave similarly except for the radiated power which was 20% lower during the RF pulse with the new screen due to a strong reduction of the heavy impirities content (Ni, Fe...). After one year of operation, visual inspection of the Faraday screen was done, without showing any damage.

In the future, plasma sprayed boron carbide will be used more extensively in Tore-Supra ; two Low-Hybride waves launchers are already protected at the edge in contact with the plasma to avoid copper impurity generation during LH pulse and one of the three ICRH antennae is equiped with a boron carbide-copper limiter. In this case, the erosion of the layer will be a critical point due to the higher flux of particules which is expected on this antenna limiter. Without taking into account any redeposition process, the life time of this limiter should be about 10^4s, which is more than the total ICRH discharge duration integrated over one year.

In the next two years, a program to improve the thermomechanical properties of the plasma sprayed boron carbide coating and especialy to increase the thermal conductivity of the B_4C layer to 10W/m.K is undertaken ; this is necessary to allow to increase the thickness of the layer up to 1 mm so as to be adequate for Tore-Supra and potential ITER applications.

publications

I.Vastra, H.Viallet, Note interne P/CO-92-18

S.Joyeux, P.Chappuis, Note interne TS 51-93-02

M.Ducos, G.Schnedecker, P.Deschamps, E.Gauthier, Congrés Powder Mettalurgy, 6-8 April 92, SF2M, Paris

V.Fernandez, J.Bardon, E.Gauthier, C.Grisolia, J.Nucl. Mat.,196-198 (1992) 1022

C. Garcia-Rosalès, E. Gauthier, J.Roth, R.Schörer, W.Eckstein, J.Nucl. Mat., 189(1992)1

M.Ducos, G.Schnedecker, P.Deschamps, E.Gauthier, to be published in Surface Engineering