PREFACE

LAYERED AND DOPED MATERIALS FOR PLASMA-FACING COMPONENTS

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Forschungszentrum Jülich (KFA) invited researchers from the fields of plasma physics, solid-state physics, surface physics, physical chemistry, materials sciences, and engineering to participate in the 5th Workshop on Carbon Materials for Fusion Applications held May 17–18, 1990, in order to discuss problems related to layered and doped materials for plasma-facing components. The Carbon Workshops bring together scientists from research laboratories and industry in order to define problems and present solutions regarding the performance of plasma-facing components in operating fusion devices and to build up a data base to guide engineers in designing plasma-facing components for fusion devices of the future. Because most fusion devices use graphite as shielding for the vacuum vessel and for delicate equipment such as antennas and the in-vessel components of diagnostic systems and because KFA has acquired a data base on graphites for nuclear application from the work related to the high-temperature fission reactor (20 years in operation at a core temperature up to 950°C), graphite has always been the focus of these workshops in the past.

The performance of tokamaks under normal operating conditions, however, has indicated problems associated with the use of graphite and amorphous hydrogenated carbon (a-C:H) films produced *in situ* by carbonization. These include unwanted release of oxygen and carbon into the plasma core and difficulties in controlling the plasma density in the boundary layer for entering into the supershot regime and the hot-ion mode, i.e., regimes where the rate of fusion reactions became substantial. Boron and beryllium have been introduced to overcome these problems. Boron-carbon systems such as doped graphites, boron carbide (B_4C) coat mix materials, plasma-sprayed B_4C graphites, and amorphous boron-containing hydrogenated carbon (a-C/B:H) films produced *in situ* by boronization are under investigation today, and some of these have performed quite well in tokamaks. The same holds true for beryllium, which is introduced into the tokamak by evaporation techniques or as tiles. When not all plasma-facing parts of a fusion device are made out of solid tiles or bricks of the same material, plasma-facing components are layered because the plasma takes care of the distribution of the different materials by erosion and redeposition, covering all plasma-facing components with a mixture of all the materials in direct contact with the plasma and with atomic hydrogen if the material is chemically reactive and of low vapor pressure at a given wall temperature.

Tokamaks operating now in the range of 5 to 10 s and longer require actively cooled shielding. In some devices, such as Tore Supra, this shielding is directly bonded to a copper cooling structure by brazing techniques, another facet of the problems of layered structures in plasma-facing components. Tokamaks under off-normal conditions require the use of fiber-reinforced materials such as carbon-fiber composite (CFC), which shows superior performance under extreme heat loads in terms of mechanical stability.

Therefore, it became obvious that the Carbon Workshop should be extended to materials other than graphite and that the peculiarities of doped and layered components exposed to a hot hydrogen plasma should be addressed.

The requirements and design concepts for plasma-facing components and operational limitations of materials for Next European Torus/International Thermonuclear Experimental Reactor (NET/ITER) were presented by G. Vieiders and C. Wu (NET/ITER

Team). The results of modeling carbon transport in the plasma boundary layer and the redeposition rate using a Monte Carlo code were presented by D. Reiter (KFA). J. Dietz (Culham Laboratory), E. Dylla (Princeton University), and J. Winter (KFA) presented results on plasma performance using novel plasma-facing components in the Joint European Torus (JET), the Tokamak Fusion Test Reactor (TFTR), and Tokamak Experiment for Technology Oriented Research (TEXTOR), respectively. Beryllium was used in JET and a-C/B:H films in TFTR and TEXTOR. The results were encouraging in terms of oxygen, carbon, and hydrogen density control. JET reproducibly reached the hot-ion mode, and TFTR and TEXTOR the supershot regime without much extra work in conditioning the plasma-facing components before the discharge.

The performance of brazed graphite and CFC-TZM materials for actively cooled structures in qualification tests was presented by I. Šmid (Österreichisches Forschungszentrum) and under plasma loads in Tore Supra by M. Lipa (Centre d'Etudes Nucléaire Cadarache). From the experience of graphite tiles mechanically attached to a cooling structure in TFTR, M. Ulrickson (Princeton University) deduced criteria for materials and mechanical alignment of plasma-facing components in a tokamak close to breakeven, i.e., at temperatures of 30 keV and central densities $>10^{20}$ particle/m^3.

The fabrication of carbon-boron and carbon-beryllium materials and the results of qualification tests were presented by M. Coulon (Carbone Lorraine), followed by a description of thick carbon deposition by D. C. Schram (Eindhoven). The quality of deposited carbon was tested, and measurements of the lattice structure were reported.

The performance of boron-doped graphites in the PISCES plasma simulator was presented by Y. Hirooka (University of California–Los Angeles), and under laser, electron, and hydrogen beam loads and for plasma-sprayed B_4C and for a-C/B:H films by J. Linke and E. Vietzke (KFA). Performance of CFC and pyrolitic graphite under short and intense heat loads was reported for laser beam exposure by J. G. van der Laan (ECN-Petten) and for electron beams by H. Bolt (NET). Special diagnostics for such experiments were addressed by M. A. Scheindlin (Moscow).

Special emphasis was given to the problem of sputtering of doped materials. Experimental results of physical and chemical sputtering of multicomponent solids were presented by W. Eckstein (Garching), and metal sputtering in metal-carbon composite materials was discussed by K. Morita (Nagoya University). The latter paper also addressed the question of hydrogen retention as did the earlier paper by Hirooka.

Changes in the physical and chemical properties of graphite caused by neutron irradiation was discussed particularly for changes in the surface structure by T. Tanabe (Osaka University). Already 0.5 dpa was found experimentally to amorphize the surface. This value is much lower than that for producing bulk damage in graphite.

The use of beryllium as an alternative material for plasma-facing components was discussed by R. Nygren (Sandia National Laboratories), who listed the pros and cons of high-*Z* and low-*Z* carbon-based materials and of beryllium in terms of plasma confinement, component lifetime, and safety issues.

Test facilities were used to expose larger areas (50 to 500 cm^2) of plasma-facing components to 10-s ion beams at power densities of up to 100 MW/m^2 [M. Lochter (KFA)] and to dc at power densities of 3 MW/m^2 by a plasma [J. Lingertat (Zentralinstitut für Elektronenphysik)].

Doped and layered materials for plasma-facing components showed encouraging performance in current tokamaks under negligible neutron loads in which the hydrogen inventory matters only as far as the density control and the isotopic composition in the boundary layer are concerned. The latter is sensitive to ion cyclotron resonance minority heating. Long-pulse or dc performance under reactor-relevant neutron loads at minimized tritium inventory is left to future meetings.

The Carbon Workshop at Jülich retains the characteristics of a workshop and is not a formalized meeting. There is plenty of room for discussion, and the participants can report work published previously. The expected cross-fertilization between the different areas in science and engineering allows for a free exchange of information, not all of which can be published because of proprietary features. *Fusion Technology* is, however, giving those authors who contributed new work the opportunity to publish their findings. Some submitted extended abstracts, others full papers; both are given in this special issue on carbon materials.