ELSEVIER

Journal of Nuclear Materials 271&272 (1999) 560–568

journal of nuclear materials

15.6. Ceramics
(Session Organizers: C. Kinoshita, S.J. Zinkle and E.R. Hodgson)

Irradiation effects in ceramics for fusion reactor applications

Tatsuo Shikama [a], Kazuhiro Yasuda [b], Shin Yamamoto [c], Chiken Kinoshita [b], Steven J. Zinkle [d], Eric R. Hodgson [e]

[a] *Oarai Branch, Institute of Materials Research, Tohoku University, Oarai, Ibaraki 311-1313, Japan*
[b] *Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Hakozaki, Fukuoka 812-8581, Japan*
[c] *ITER JCT, Garching near Munich 85748, Germany*
[d] *Oak Ridge National Laboratory, Oak Ridge, TN 37831-6376, USA*
[e] *Euratom/CIEMAT Fusion Association, 28040 Madrid, Spain*

Abstract

A review is given on the status of R&D of ceramics for fusion reactor applications. Emphasis is placed on the engineering design activity of fusion reactor, the International Thermonuclear Experimental Reactor, Engineering Design Activities (ITER-EDA) as well as related research of electrical, dielectric and mechanical properties, and fundamental aspects of defects. The paper is based mainly on the presentations and discussion, including a keynote lecture and several short presentations by invited panelists, at the discussion session of 'Ceramic Insulators for Fusion Energy Applications' at ICFRM-8, on 30th October 1997 in Sendai, Japan. This report illustrates how the ITER-EDA and other related international activities have functioned not only to coordinate, but also to promote international collaborations and to mobilize the limited research resources effectively. A database which is necessary for reliable design of diagnostic components in ITER is included in the review. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

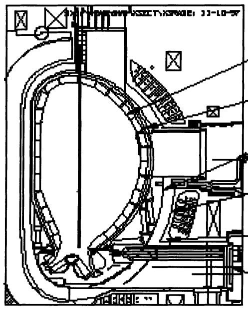
Research and development of fusion reactor ceramic materials (hereafter denoted as fusion ceramics) has in recent years made steady progress, and has been particularly stimulated by specific demands from the detailed designs of the proposed fusion reactor known as International Thermonuclear Experimental Reactor (ITER) [1,2]. The Engineering Design Activity for ITER (ITER-EDA) has elucidated detailed roles of specific ceramics in major components such as plasma diagnostics [3,4]. Quantitative data on radiation effects in ceramics have been accumulated and gathered in a comprehensive database. The research and development of fusion ceramics has provided an example of effective interdisciplinary interaction of materials science and engineering with fusion reactor design and development, contributing to the appreciation of fusion reactor material studies. The achievements in fusion ceramics through domestic as well as internationally collaborative efforts are remarkable, despite the fact that earlier fusion materials programs seriously underrated the roles and importance of fusion ceramics. Such an under-evaluation of fusion ceramics is regretfully but equivocally reflected in the program of the present conference, ICFRM-8, only a half of one small session being allocated to the fusion ceramics.

This paper reviews recent progress of fusion ceramics, with emphasis on the ITER-EDA and earlier research of electrical, dielectric and mechanical properties and fundamental aspects of defects. The contents in this paper are mainly based on the presentations and remarks at the discussion session of 'Ceramic Insulators for Fusion Energy Applications' at ICFRM-8.

2. Status of ITER-EDA

Fusion reactors will be the first theater where nonfissile ceramics are used in heavy irradiation environments. Fig. 1 shows the irradiation environments where ceramics are proposed to be used in ITER [3,4]. Components are

PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 8 7 2 - 1



	n/m²/s	n/m²/s	Gy/s
First wall	8.10^{17}	3.10^{18}	3.10^{3}
At first wall	1	1	1
At back plate (plasma side)	$6.9.10^{-4}$	$4.8.10^{-3}$	$4.0.10^{-3}$
At vac. vessel (plasma side)¥	$1.8.10^{-4}$	$1.5.10^{-3}$	$1.2.10^{-3}$
At vac. vessel (TFC side)	$6.7.10^{-7}$	$4.3.10^{-6}$	$4.0.10^{-6}$

The maximum flux and fluence to surfaces of the plasma side of each in-vessel component

Maintenance Classification	**Example**	**Required lifetime** **Numbers of full power discharges with 1000 sec**	**Flux** **[n/m²/s]** **(>0.1 MeV)**	**Fluence** **[n/m²]** **(>0.1 MeV)**	**dpa in ceramics**
Class 3	Back plate	10^5	$2x10^{16}$	$2x10^{24}$	$2x10^{-1}$
Class 2	Blanket module	10^4	$3x10^{18}$	$3x10^{25}$	3
Class 1	Divertor cassettes Diagnostic plug (Horizontal and Vertical)	$3x10^3$	$3x10^{18}$	$9x10^{24}$	$9x10^{-1}$

Fig. 1. Irradiation environments of ITER, where ceramic materials will be used [3].

categorized into three classes, depending on their required lifetime and irradiation flux. Although the required lifetime irradiation dose is not excessively large, reaching at most only a few dpa (displacement per atom), the dynamic irradiation effects must be taken into consideration from the onset of irradiation in the case of ceramics.

Table 1 shows the crucial radiation effects on plasma diagnostic components whose major constituents are ceramics [3,4]. The contents of this table formed the starting point and basis for the concluding discussions in the ITER-EDA R&D task T246 on 'Radiation Effects in Diagnostic Components'. Not only a clear but also a quantitative understanding of the unique features of irradiation effects in ceramics is essential for ensuring appropriate operation and lifetime of the numerous diagnostic systems. For this, a comprehensive database of irradiation effects on some of the physical properties of ceramics is absolutely necessary in order to develop reliable design. International collaboration through the T246 of ITER-EDA and related activity through the International Energy Agency (IEA) has played a crucial role in mobilizing and focussing the limited international research resources on fusion ceramics studies to establish an extensive reliable database for designing diagnostic components.

Table 2 shows primary candidate ceramics for diagnostics, which were proposed and/or irradiated in the course of the ITER-EDA T246 activity. Table 3 summarizes the available results of irradiation tests, evaluating the irradiation flux and fluence limits for each materials. Nearing the end of the first stage of ITER-EDA, the international research community is summarizing presently highlighted topics of research and development of ceramic materials [3–5]. These can be itemized as follows.

1. Dynamic irradiation effects are important and in situ measurements are essential (electronic properties, optical properties, etc.).
2. New phenomena, which may be caused through complicated interactions among multiple irradiation parameters, must be assessed especially in conjunction with their roles in mechanisms in property deterioration in fusion irradiation environments.
3. The role of electronic excitation is of fundamental importance, in contrast with irradiation effects in metallic materials.
4. Development of innovative ceramics is indispensable for successful development of future fusion reactors.

The status of the R&D of fusion ceramics will be presented with reference to the above four items, mainly based on a keynote lecture and prepared presentations at the discussion session of ICFRM-8.

3. Present status of studies of fusion ceramic materials

3.1. Dynamic irradiation effects

Dynamic effects of irradiation together with the concurrent influence of external factors such as applied

Table 1
Important components in plasma diagnostic system in ITER whose major constituents are ceramics and expected degradation processes [3]

Diagnostic components	Physical and mechanical properties	Properties to be examined
Ceramics	Electrical (insulation)	RIED, RIC
	Optical (see windows)	
	Thermal	Thermal conductivity
	Mechanical	Subcritical crack growth
	Dimensional stability	Swelling
	Others	Tritium diffusion and retention
Windows	Optical	Permanent absorption
		Transient absorption
		Radio luminescence
	Thermal	Thermal conductivity
	Mechanical	(High power laser damage to window)
	Dimensional stability	Swelling
	Others	(Window metal joint/subcritical crack growth)
Optical fibers	Optical	Permanent absorption
		Transient absorption
		Radio luminescence
	Mechanical	Stability of metal jacket
	Others	(Joint solder)
Mirrors/reflectors	Optical	Reflection
	Thermal	(High power laser damage of mirrors)
	Mechanical	Adhesion of coated metal (flaking, peeling)
	Dimensional stability	Swelling of bulk materials
	Others	(Distortion due to radiation heating)
Wires/cables	Electrical	RIED, RIC, RIEMF (MI cables)
	Mechanical	Stability of coated ceramics
	Others	(Termination of the cable)

electric field or mechanical stress have recently been attracting strong interest and concern especially in the field of plasma diagnostics [3,4]. For such studies it is essential that in situ experiments are performed. Extensive international collaboration has been carried out and an invaluable database has been set up, not only concerning engineering aspects but also fundamental aspects. The properties of particular concern which have so far been examined include electrical conductivity, optical transmission and emission, and mechanical strength.

The phenomenon of radiation induced electrical degradation (RIED), which manifests itself as a permanent increase in electrical conductivity, is potentially one of the most crucial problems of insulating ceramics. In the course of extensive studies of RIED, international round-robin tests were proposed for reliable measurements of electrical conductivity under irradiation [6,7]. Extensive experiments have been carried out successfully, using a standardized measuring technique that was established by a group of active researchers [8]. The available knowledge on RIED was summarized at the ninth IEA workshop in Cincinnati in 1997 [5], leading to a conclusion that bulk RIED can be produced in Al_2O_3 during electron irradiation [9,10]. However, a definite evidence of RIED has not been observed in Al_2O_3 during numerous ion or fission neutron irradiation to damage levels much higher than those achieved in the electron irradiation studies, including international collaborations between the USA and Germany [11], and between the USA and Japan through the JUPITER project [12,13]. Further, RIED has not been observed in Al_2O_3 under recent reactor irradiation studies of JRR-3 [14] and JMTR [15] in Japan Atomic Energy Research Institute (JAERI), and in High Flux Beam Reactor (HFBR) in Brookheaven National Laboratory (BNL) [16]. The recently completed in-reactor RIED experiment in High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) reported at the IEA Workshop [5] also indicated no significant increase in electrical conductivity for the 12 different samples. However further analysis has revealed moderate to substantial electrical degradation in some of the sapphire samples [17]. Clearly material type is an important parameter, and the high purity material (sapphire) appears to be more susceptible to degradation. It should be noted here that reactor irradiation experiments were carried out in helium atmosphere, while charged particles

Table 2
List of candidate ceramics for each component and materials irradiated in the course of T246 of ITER-EDA [3]

Diagnostic components	Primary candidate materials	Irradiated materials
Ceramics for insulator	• Alumina (Al_2O_3) • High purity silica glass	Alumina, silica glass, BeO, AlN, Si_3N_4, $MgAl_2O_4$, MgO, pyrolitic BN
Windows-1 (300–1200 nm)	• High purity quartz and fused silica (SiO_2) • Single crystal alumina (sapphire)	Sapphire, quartz, fused silica glass KU quartz[a]
Windows-2 (2000–5000 nm)	• High purity quartz and fused silica (SiO_2), same as shorter wavelength	Single crystal alumina (sapphire), fused silica
Window-3 (10 mm)	• ZnSe	
Window-4 (100–10 mm)		Diamond, silica
Fiber optics UV to IR (300 nm to 5 mm)	• Low OH, pure silica core, F-doped cladding, aluminum jacket	Quartz, core(pure silica)/clad (F-doped silica) • Improved type, core (pure SiO_2)/clad(F-doped SiO_2), low OH-content (from 1 to 100 ppm), 2 samples, Al jacket or High OH-content (300 ppm) polymer or Al jacket,
	• Fluorine-doped core fiber	• F-doped SiO_2 core
	• Hydrogen-treated fibers	• Gamma hardened fibers
	• Gamma hardened fiber	• Single crystal fibers
Mirrors/reflectors-2 Secondary mirror (UV/visible/infrared)	Aluminum-coated spinel ($MgAl_2O_4$)	
Mirrors/reflectors-3 High-power laser mirror (laser mirror and collection systems) (UV/visible/infrared)	• HfO_2/fused silica • TiO_2/fused silica	High-power laser mirror (laser mirror and collection systems)
Mirrors/reflectors-4 (X-rays 1–500 Å)	• Various diffraction crystals • Layered synthetic microstructure (LSM)	LSM
Mineral-insulated cables	• MgO, stainless steel sheath, nickel or copper center with diameter from 0.3 to 2.3 mm OD	• Al_2O_3, MgO, MgO-insulation; Ni, NiCr, SS-wire; SS-shield
	• Other insulator	• Ten different improved MI cables
Ceramic coated wire		• $70MgAl_2O_4 + 30Al_2O_3$, plasma spraying insulation, Ni-wire

[a] KU1 (round-robin materials).

irradiations were performed in vacuum. However, the present data indicate that the long-term volume degradation of electrical insulating ability should not impose serious technological problems at least in the short and middle term development of fusion devises such as ITER. Additional problems which have been identified such as surface conductivity [18,19], insulator cracking [20,21], mineral-insulated cable termination issues [22,23] and electric charging effects [24] require further investigation to determine the physical mechanisms responsible for associated RIED-like electrical degradation, and to assess their possible influence on the insulator performance and lifetime.

Reliable extensive data on radiation induced conductivity (RIC) have also been accumulated. One example for Al_2O_3 under 14 MeV neutron irradiation using Fusion Neutron Source (FNS) at JAERI [25] was presented at the discussion session. The measured RIC was proportional to the electronic excitation dose rate, and fell within the scatter band of the RIC-dose rate relation obtained during X-ray, γ-ray, electron, ion and fission neutron irradiation.

Concerning optical properties, work in Japan, and in Russia/USA and Russia/EU has yielded a quantitative database on radiation effects in optical ceramics [3,4]. It is important to note the key role played by the ITER Project in promoting these coordinated efforts and international collaborations. Plasma diagnostics in the Thermonuclear Fusion Test Reactor (TFTR) burning plasma device in Princeton revealed drastic dynamic irradiation effects in optical fibers [3,4,26], and work has been carried out within the ITER framework to assess and quantify this and related problems [3,4]. The ITER design study of a plasma diagnostic system using a laser probe beam (LIDAR) indicates that small dynamic irradiation effects may have disastrous consequences for

Table 3
Materials recommended for constituents of diagnostic components and their irradiation limit [3]

Diagnostic components	Recommended materials	Accumulated effects	Dynamic effects
Ceramics (electical insulators)	Single crystal sapphire and polycrystal alumina (Al_2O_3)	3 dpa in helium (RIED: No catastrophic degradation)	10^4 Gy/s (RIC: $<10^{-6}$ S/m)
Wires/cables	MI-cables: SUS, Inconel (sheath)/MgO, Al_2O_3 (insulator)/Cu, Ni (centre conductor)	1.8 dpa (RIED: No catastropic degradation)	10^4 Gy/s (RIC: $<10^{-6}$ S/m)
Windows	Fused silica/quartz (400–1200 nm)	10^{-3} dpa (Transmission; 5% degradation: 8 mm^t)	Radioluminescence: 10^7 photons/Gy A sr cm^3
	Sapphire(800–5000 nm)	0.4 dpa (Transmission; No degradation: 1 mm^t)	Radioluminescence: 10^{10} photons/Gy A s cm^3 at 410 nm
Optical fibers	Pure silica (core)/F-doped (clad)/Al jacket (visible region)	10^7 Gy (Transmission: 2–2.5 dB/m) 6×10^{-6} dpa (Transmission: 10 dB/m)	Radioluminescence
	Pure silica (core)/F-doped (clad)/Al jacket (IR region)	1 dpa(Transmission: 10 dB/m)	Radioluminescence
Mirrors/reflectors	First mirrors: Metal (Cu, W, Mo, SS, Al)	40 dpa (Cu) (reflectivity: no degradation)	
	First mirrors for LIDAR: single coated (Rh/V)?		
	Dielectric mirrors: (HfO_2/SiO_2, TiO_2/SiO_2)?	$<10^{-2}$ dpa (flaking, blistering)	
	LSMs: (Mo/Si, W/B_4C and W/C)?	$<10^{-2}$ dpa (the shift of the peak reflectivity to shorter wavelength)	
	X-ray crystals: (Ge, Si, SiO_2, Graphite)	10^{-2} dpa	

the diagnostic window [3,4]. Here a 0.5 dB increase of optical absorption will cause serious heating and resultant damage in the window due to thermally induced stress.

Dynamic irradiation effects on thermal properties of ceramics are still theoretically studied and a comprehensive in situ type experiment is proposed in a high flux fission reactor such as HFIR in ORNL [27]. One of the presentations at the ICFRM-8 fusion ceramics discussion session emphasized the need to correctly analyze the thermal conductivity data by monitoring the radiation induced increase in the thermal resistance (reciprocal of the conductivity) as a function of irradiation dose, as opposed to the more commonly used parameters of the ratio of irradiated to unirradiated conductivity, etc. [27]. The radiation-induced increase in thermal resistance is proportional to the concentration of radiation defects (dislocation loops, isolated vacancies, etc.), and can be a sensitive monitor of defect production and annealing processes in ceramics.

A completely new demonstration of dynamic irradiation effects has been presented for the mechanical properties of alumina [28,29]. Subcritical crack growth (SCCG) of two grades of polycrystalline alumina, Deranox 975 and 995 (97.5% and 99.5% respectively), was measured under constant load with or without exposure to γ-radiation at 1.5 Gy/s. The time to failure for a given ratio of applied stress to critical stress was found to increase by a factor of about 9 compared to unirradiated samples for 97.5% alumina, but the same radiation reduced the time to failure of the 99.5% alumina by a factor of about 2. A much high population of short cracks were observed in γ-irradiated 97.5% alumina. The conflicting dependence of SCCG on ionizing radiation was considered to be related to the presence or absence of silica-rich grain boundary phases in different grades of alumina.

3.2. New phenomena potentially causing deterioration of properties of ceramics

Electrical conductivity and optical transmission/luminescence are receiving much attention. Radiation induced defects in dielectric ceramic materials, which affect electrical and optical properties, may strongly interact with internal and external electrical fields. For this reason the roles of electric and magnetic fields in radiation effects in ceramics have been attracting strong interest. One aspect of radiation damage, unique to dielectric materials is radiolysis, i.e., the conversion of electronic defects into structural and permanent defects by purely ionizing radiation [9,10,30]. For insulators in general, radiation fields deposit far more energy in the materials through electronic excitation process than through an atomic displacement process. Hence if radiolysis takes place efficiently, permanent structural changes will proceed far more quickly than in the case where radiolysis is absent. Radiolysis is a well-established phenomenon in alkali halide ceramics and in several other ceramics including quartz (SiO_2).

There is a general consensus that most of candidate ceramic insulators in fusion reactors, such as alumina, will not be susceptible to radiolysis. However, it is conceivable that some form of radiolysis may take place under conditions where some unique interactions take place among irradiation parameters. One proposed mechanism for RIED is an electric-field induced radiolysis. An evaluation of the electric field was made by measurements of radiation induced luminescence (RIL) with a corresponding theoretical approach [24]. A large amount of excess positive charge, $\sim 10^4$ Q/m^3, was estimated in Al_2O_3 and Cr-doped Al_2O_3 irradiated with 8 MeV proton ions. This electric charging was estimated to produce an electric field of 10^6 V/m using a model based on inhomogeneously distributed electric charging. Such an electric field would be introduced dynamically through charge redistribution among different atoms under irradiation.

Recently, the effects of radiation induced electromotive force (RIEMF) have been highlighted for plasma diagnostic components such as the magnetic probes [3,4,31]. A large RIEMF was observed under irradiation in several metal/ceramic systems. Some of the RIEMF may be generated at the boundary between metal and ceramic [13,24,32]. Fig. 2 shows measured electrical current between the center lead and the sheath in a 0.5 m long and 1.6 mm outer diameter mineral insulting cable [31] during JMTR irradiation at about 570 K. An electrical current of more than 10 μA was observed in an alumina/metal system under HFIR irradiation at about 770 K [13]. Causes of RIEMF are not well understood yet and further studies are urgently required.

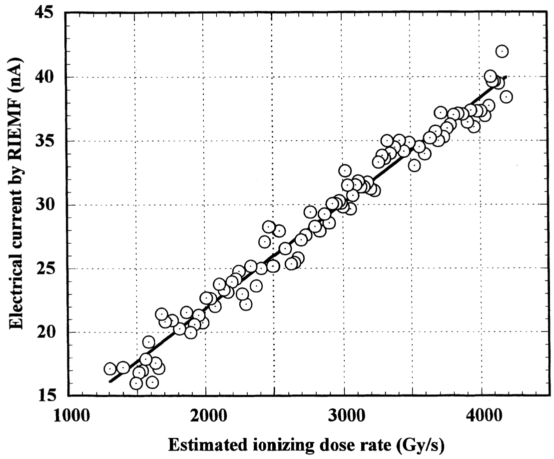


Fig. 2. Observed RIEMF in Mi-cable under JMTR irradiation [31].

3.3. Fundamental aspects of radiation effects

It is important to note that radiation processes in dielectric ceramics are far more complicated than those in metallic materials. Atomic displacement models similar to those of metallic materials can be applied in some ionic ceramics [33,34]. However, the multi-atomic nature of most typical ceramics makes the model more complicated than in metals. For example, in the case of covalently bonded materials such as silica, the atomic displacement model developed in metallic materials cannot be applied simply. Furthermore, fundamental parameters, such as threshold energies of displacements, and migration energies of vacancies and interstitials, are not quantitatively evaluated yet for many ceramics. The present understanding of these fundamental parameters is summarized in a recent review paper for a limited number of ceramics [35]. For example, rate-controlling (slowest) interstitial migration enthalpies in $MgAl_2O_4$ and Al_2O_3 were evaluated by measurements of the width of the denuded zone of dislocation loops adjusted to grain boundaries [36]. The derived rate controlling interstitial migration enthalpies were 0.2 and 0.6 eV for $MgAl_2O_4$ and Al_2O_3, respectively. The surprisingly low interstitial migration energy in $MgAl_2O_4$ might be some contribution of ionization-induced diffusion (IID), which can produce low migration energy or even athermal point defect diffusion in some ceramics [36].

It is also worthwhile to emphasize here the irradiation spectrum effects, which affect the stability and the migration of radiation induced defects in ceramics [36–39]. The irradiation spectrum effects include two main components: (1) effects of recoil energy spectrum of primary knock-on atoms (PKAs) and (2) effects of non-displacive collisions (ionization and subthreshold displacement collisions). Effects of non-displacement have been observed recently in some ceramics. For example, intense ionizing radiation has been found to retard formation of dislocation loops and enhances their growth in some oxide ceramics, especially in $MgAl_2O_4$ [37,38]. The ratio of ionizing stopping power (S_e) to displacive stopping power (S_n), S_e/S_n, was considered as convenience parameter to describe the suppression of dislocation loop nucleation [37,38]. Another approach on the irradiation spectrum effects has been investigated by using transmission electron microscopes interfaced with ion accelerators [39–42]. Concurrent irradiation with focused electrons and homogeneously distributed ions enables one to change the ratio of S_e/S_n and to observe the dynamic formation process of defect clusters. Suppression of dislocation loop formation and preferential bubble formation are seen under the concurrent irradiation, depending on the ion mass and electron energy [41,42]. Lower energy electrons are found to be more effective for the above microstructure evolution, indicating an important role of ionization induced diffusion (IID) and/or radiation induced diffusion (RID). The S_e/S_n is found not to be sufficient to describe fully the microstructural evolution under concurrent irradiation, especially under higher ionizing radiation [38,41,42]. A competitive process between the production of dislocation loops with ion irradiation and the stability of dislocation loops under electron irradiation was proposed as an explanation for the concurrent irradiation effects [40,42].

Fundamental studies are strongly recommended to establish comprehensive models of basic processes of radiation effects and to have reliable parameters describing radiation processes. In particular, further work is needed to elucidate the role of ionizing radiation on the evolution of defect clusters in irradiated ceramics.

3.4. Development of innovative materials

An improvement of physical properties in certain types of ceramics has resulted in remarkable advancements in designs of facilities in fusion reactors. Dielectric materials for transmission windows with lower dielectric loss and higher thermal conductivity have been developed to replace the previous reference materials which were single crystal of alumina (sapphire) and fused silica [3,4]. The newly developed materials are CVD diamond [43,44], synthetic quartz [45] and high resistivity silicon (HS) [46–48]. Irradiation experiments on these materials with neutrons, ions, electrons and X-rays have shown that they possess lower loss tangent even under high temperature irradiation. One disadvantage is that quartz and silicon are not resistant to ionizing radiation [47,48]. This has been overcome by introducing electron–hole recombination centers into the materials, for example Au doping of HS [46]. The higher thermal conductivity of these materials is expected to eliminate the need for cryogenic cooling.

Development of low transmission loss optical fibers will simplify optical instrumentation and reduce the cost [3,4,26,49]. Radiation resistant silica core optical fibers are being developed in conjunction with the ITER-EDA. These materials maintain low transmission loss up to more than 10^{24} n/m^2 fast neutron fluence in the infrared region. Recently developed fibers such as KU-1 and KS-4V in Russia [3,4] and an F-doped (fluorine-doped) fiber in Japan [3,4,49] showed good radiation resistance in a visible wavelength range up to 10^{23} n/m^2 fast neutron fluence.

4. Near term prospect

Studies of fusion ceramics have made steady progress. Related international activities, such as the ITER-EDA and the IEA activities, have worked as effective coordinators to construct a material database needed for the design of components such as burning plasma diagnostics. Crucial phenomena are analyzed based on the constructed database as indicated in Table 3. Fig. 3 shows schematic structures of a prospective cable termination and optical window, where expected degradation phenomena are indicated [3,4]. The impact of each expected degradation processes could be evaluated quantitatively by using the accumulated database.

Studies of materials performance in actual components will be the next step for the development of reliable components using ceramic materials. For example, there will be many metal/ceramic interfaces in components as shown in Fig. 3. An improved understanding of the mechanism of RIEMF is essential, though little is currently known concerning the behavior of metal/ceramic interfaces under irradiation.

Also, unexpected synergistic effects may cause significant degradation. A differential swelling in a temperature gradient region may cause unexpected internal stress and result in premature cracking of ceramic materials. In general, irradiated ceramics have low thermal conductivity, and therefore large temperature gradients may be generated under bulk heating by ionizing irradiation. The differential swelling will be enhanced by radiation enhanced diffusion and preferential precipitations of transmutation gas atoms along a temperature gradient. Constraint of brittle ceramic materials at a metal/ceramics interface may cause a premature crack growth in ceramic materials under irradiation. It should be noted that some of observed electrical degradation (RIED-like behavior) could be attributed to the cracking of ceramics at the ceramic/metal–electrode interface and subsequent diffusion of metal atoms along the generated cracks.

Studies of irradiation effects in components are resource-consuming enterprises, and they tend to produce complicated results that cannot be easily analyzed into elementary and fundamental processes. For the effective analysis, well-designed irradiation tests are essential. International collaboration guided by coordinating organizations such as the ITER-EDA and the IEA will play an indispensable role there.

Further investigations on effects of impurities and electric field were encouraged at the discussion session.

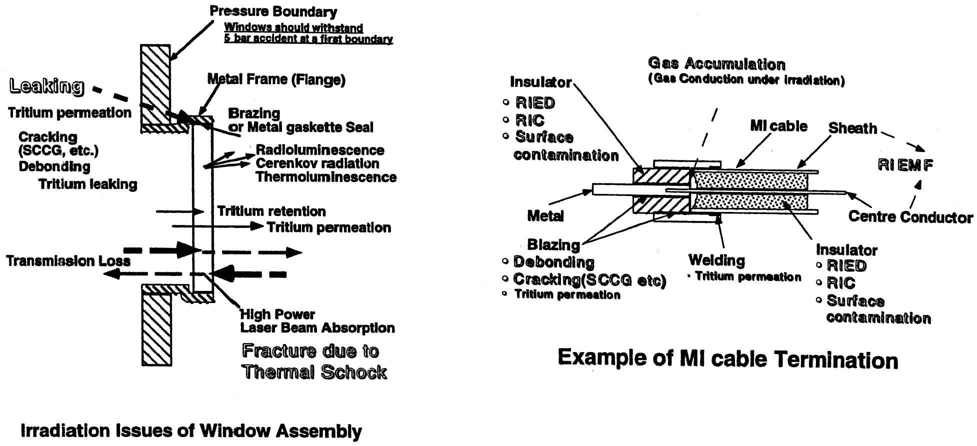


Fig. 3. Structures of window assembly and MI-cable termination and expected deterioration processes [3].

Especially, hydrogen (or OH^- ions) and vapor water were pointed out to be investigated, as these can change the nature of defects and defect aggregation in ceramics. Only a few limited observations are, however, available in a small number of ceramics, such as graphite [50] and MgO [51,52]. For example, OH^- ions in MgO have been found to retard the formation of dislocation loops or to enhance the formation of surface etch-pits under electron or ion irradiation. Structural vacancies, which are introduced to compensate the charge neutrality in the crystal, are considered to play a role for the increase of recombination rates of point defects. Similarly, retardation of dislocation loop formation is seen in single crystals of Al_2O_3 doped with V or Ni ions under concurrent irradiation with ions and electrons [53]. This result may also indicate that structural vacancies introduced by aliovalent solutes serve as recombination sites for interstitials and vacancies, suggesting a possibility for the positive control of the nature of point defects by using selected, controlled impurities. Electric fields in fusion devices may change (probably increase) the mobility and the recombination rates of point defects, and lead to changes of physical properties of ceramics. Studies of electrical field effects from the stand point of microstructure are strongly recommended.

5. Summary

The ITER engineering design activities are currently summarizing the work performed over the past five years and are producing qualified and quantified databases of ceramics for the ITER application [3]. An examination of the performed research highlights important topics, which should be studied cooperatively under international collaborations. Examples are:

1. Behavior of electrical conductivity in ceramics should be examined in details to understand fundamental processes of electrical conductivity under high dose rate irradiation. Charge redistribution and resultant spatial charge-up and electromotive force between different materials, non-ohmic behavior (which may be caused by interfaces between different materials), etc. should be examined.
2. Roles of electronic excitation and atomic displacement should be examined further. The process of radiolysis claimed to be a possible cause of the permanent electrical degradation in ceramic insulators is not clearly understood yet. The radiolysis is thought to play important roles in radiation effects in glass–ceramics and covalently bonded ceramics.
3. A robust model of fundamental processes of radiation effects is not well established especially in the case of covalently bonded ceramics. Therefore, fundamental concepts such as threshold energy for atomic displacement should be re-examined and geometric models of fundamental irradiation induced defects should be assessed.
4. The development of a detailed quantitative database is essential to promote application of ceramic materials in fusion reactors. Also, extensive efforts should be devoted to the development of radiation resistant ceramics.

References

[1] T. Matoba, in: Proceedings of the ITER Workshop on Radiation Effects on Diagnostic Components, October 1991, St. Petersburg, USSR.

[2] E.H. Farnum, in: Proceedings of the Radiation Effects in Materials for Fusion Diagnostic Systems, Planning Workshop, March 1991, Princeton, USA.

[3] S. Yamarnoto, Design Description Document of ITER-EDA, WBS 5.5.M, Radiation Effects, ITER-JCT Garching, Germany.
[4] S. Yamamoto et al, in: P.E. Stott et al. (Eds.), Diagnostics for Experimental Thermonuclear Fusion Reactors 2, Plenum Press, New York, 1998, pp. 269–278.
[5] S.J. Zinkle, in: Proceedings of the Ninth IEA Workshop on Radiation Effects in Ceramic Insulators, May 1997, Cincinnati, USA, ORNL/M-6068, 1997.
[6] S.J. Zinkle (chair), in: Proceedings of the Seventh IEA Workshop on Radiation Effects in Ceramic Insulators, Stresa, Italy, September l993; S.J. Zinkle, G.P. Pells, F.W. Clinard Jr., Fusion Materials Semiannual Progress Report for Period ending 30 September 1993, DOE/ER-0313/15, 1993, p. 417.
[7] F. Wedig, Berichte des Forschungszentrums Julich, Jul-3334, December 1996.
[8] S.J. Zinkle et al., Fusion Materials Semiannual Progress Report for Period ending 30 June 1997, DOE/ER-0313/22, 1997, p. 179.
[9] E.R. Hodgson, J. Nucl. Mater. 179–181 (1991) 383.
[10] E.R. Hodgson, J. Nucl. Mater. 212–215 (1994) 1123.
[11] W. Kesternich et al., J. Nucl. Mater. 206 (1993) 68.
[12] S.J. Zinkle et al., Fusion Materials Semiannual Progress Report for Period ending 30 June 1996, DOE/ER-03 13/20, 1996, p. 257.
[13] T. Shikama, S.J. Zinkle, J. Nucl. Mater. 258–263 (1998) 1861.
[14] K. Noda, presented at the discussion session, in: T. Tanifuji, Y. Katano, T. Nakazawa, K. Noda, J. Nucl. Mater. 253 (1998) 156.
[15] T. Shikama, M. Narui, H. Kayano, T. Sagawa, J. Nucl. Mater. 212–215 (1994) 1133.
[16] D.P. White, L.L. Snead, S.J. Zinkle, J. Appl. Phys. 83 (1998) 1924.
[17] T. Shikama, S.J. Zinkle, et al., J. Nucl. Mater. 258–263 (1998) 1867.
[18] W. Kesternich, F. Sceuermann, S.J. Zinkle, J. Nucl. Mater. 219 (1995) 190.
[19] M.M.R. Howlader, C. Kinoshita, T. Izu, K. Shiiyama, M. Kutsuwada, J. Nucl. Mater. 239 (1996) 245.
[20] W. Kesternich, J. Nucl. Mater. 253 (1998) 167.
[21] S.J. Zinkle, J.D. Hunn, R.E. Stoller, Mater. Res. Soc. Symp. Proc. 373 (1995) 299.
[22] E.H. Farnum, T. Shikama, M. Narui, T. Sagawa, K. Scarborough, J. Nucl. Mater. 228 (1996) 117.
[23] S.J. Zinkle, W.S. Eatherly, L.L. Snead, T. Shikama, K. Shiiyama, Fusion Materials Semiannual Progress Report for Period ending 30 June 1996, DOE/ER–313/22, 1997, p. 188.
[24] O.A. Plaksin, V.M. Chernov, presented at the discussion session; O.A. Plaksin, V.A. Belyakov, V.M. Chernov, P.A. Stepanov, V.A. Stepanov, presented at the discussion session.
[25] K. Noda, T. Nakazawa, Y. Oyama, H. Maekawa, J. Kaneda, C. Kinoshita, Fusion. Eng. Des. 29 (1995) 448.
[26] K.M. Young, A.T. Ramsey, private communication and in Ref. [3].
[27] L.L. Snead, presented at the discussion session; L.L. Snead, S.J. Zinkle, D.P. White, to be published.
[28] E.R. Hodgson, presented at the present discussion session.
[29] G.P. Pelles, R.M. Boothby, J. Nucl. Mater. 256 (1998) 25.
[30] A.E. Hughes, A.B. Lidiard, AERE Rl 3319, AERE Harwell, UK, 1989.
[31] T. Shikama, M. Narui, T. Sagawa, Nucl. Instrum. and Meth. B 122 (1997) 650.
[32] K. Shiiyama, M.M.R. Howlader, S.J. Zinkle, T. Shikama, M. Kutsuwada, S. Matsumura, C. Kinoshita, J. Nucl. Mater. 258–263 (1998) 1848.
[33] C. Kinoshita, K. Hayashi, S. Kitajima, Nucl. Instrum. and Meth. B 1 (1984) 209.
[34] C. Kinoshita, K. Hayashi, T.E. Mitchell, Advances in Ceramics 10, Structure and Properties of MgO and Al_2O_3 Ceramics, ACeS, 1985, p. 490.
[35] S.J. Zinkle, C. Kinoshita, J. Nucl. Mater. (1997) 200.
[36] S.J. Zinkle, presented at the discussion session, Mater. Res. Soc. Symp. Proc. 439 (1997) 667.
[37] S.J. Zinkle, Nucl. Instrum. and Meth. B 91 (1994) 307.
[38] S.J. Zinkle, J. Nucl. Mater. 219 (1995) 113.
[39] C. Kinoshita, H. Abe, S. Maeda, K. Fukumoto, J. Nucl. Mater. 219 (1995) 152.
[40] K. Yasuda, presented at the discussion session.
[41] K. Yasuda, C. Kinoshita, R. Morisaki, H. Abe, H. Naramoto, in: Proceedings of the Seventh International Symposium on Advanced Nuclear Energy Research, edited by Japan Atomic Energy Research Institute, 1997, p. 384.
[42] K. Yasuda, C. Kinoshita, R. Morisaki, H. Abe, Philos. Mag. A 78 (1998) 583.
[43] R. Heidinger, presented at the present discussion session; R. Heidinger, A. Ibarra, J. Molla, J. Nucl. Mater. 258–263 (1998) 1822.
[44] R. Heidinger, in: Digest 19th International Conference on Infrared and Millimeter Waves, Sendai, Japan, JSAP Cat Nr. AP941228, 1994, p. 277.
[45] R. Heidinger, G. Link, Fusion Technol. 1 (1995) 509.
[46] A. Ibarra, presented at the discussion session; J. Molla, R. Vila, R. Heidinger, A. Ibarra, J. Nucl. Mater. 258–263 (1998) 1884.
[47] R. Heidinger, A. Kumlin, A. Ibarra, J. Molla, in: Proceedings of the 16th International Conference on Infrared and Millimeter Waves, SPIE1576, 1991, p. 452.
[48] R. Heidinger, A. Kumlin, in: Proceedings of the 16th International Conference on Infrared and Millimeter Waves, SPIE1576, 1991, p. 450.
[49] T. Kakuta, K. Sakasai, T. Shikama, M. Narui, T. Sagawa, J. Nucl. Mater. 258–263 (1998) 1893.
[50] T. Tanabe, Physica Scripta. T 64 (1996) 7.
[51] T. Sonoda, H. Abe, C. Kinoshita, H. Naramoto, Nucl. Instrum. and Meth. B 127&128 (1997) 176.
[52] C. Konoshita, T. Sonoda, A. Manabe, Philos. Mag. A 78 (1998) 657.
[53] K. Yasuda, C. Kinoshita, M. Ohmura, H. Abe, presented at ICFRM-8.