INVESTIGATION OF RADIATION INDUCED ELECTRICAL DEGRADATION IN ALUMINA UNDER ITER-RELEVANT CONDITIONS - L. L. Snead, D. P. White and S. J. Zinkle (Oak Ridge National Laboratory)

OBJECTIVE

To investigate whether radiation induced electrical degradation occurs in the IEA reference heat of alumina at irradiation conditions that are appropriate for ceramics in ITER.

SUMMARY

An in-situ experiment investigating the radiation induced electrical degradation (RIED) effect in polycrystalline alumina is described. A Wesgo AL-995 polycrystalline alumina sample has been irradiated with fission neutrons to 1.4 displacements per atom (dpa) at 340-365°C with no evidence of RIED. The implication of these and previous results are discussed in terms of their impact on the International Thermonuclear Experimental Reactor (ITER), with the conclusion that RIED will be of no consequence during the basic performance phase of the machines operation.

PROGRESS AND STATUS

1. Introduction

Ceramic materials are required in several areas of the International Thermonuclear Experimental Reactor (ITER) where design requirements call for highly resistive materials. Unlike previous tokamak machines, the core components of ITER will undergo significant nuclear heating and displacement damage, which raises new questions concerning the stability of these materials under irradiation. Table 1 lists the expected operating temperatures and neutron displacement levels for several ceramic components at the end of the basic performance phase of ITER. Three general areas of application for ceramics listed in Table 1 are 1) microwave heating windows, 2) insulating breaks, and 3) diagnostic probes. For the case of both the electron and ion cyclotron resonance heating (ECRH and ICRH) windows the displacement levels are relatively low (less than 0.1 dpa) with operating temperatures less than 200 °C. These windows are expected to be monolithic sapphire or polycrystalline alumina and are cooled in order to reduce the amount of heating caused by the transmitted microwave heating beam. Toroidal insulating breaks may be located throughout the blanket and divertor regions of ITER and will typically be operated at less than 200 °C and receive lifetime displacement levels up to 1 dpa. These components are intended to serve as protection against the large toroidal current which could be induced during a plasma disruption. At present, such current breaks are regarded as an option for ITER, mainly due to uncertainty in how the disruption current will develop. It is possible that the use of current breaks in the blanket will not be required. The ceramic components which will receive the highest neutron fluence and operating temperatures are the magnetic probes located at or near the first wall, though the ITER design has not matured to the point where the operating temperature of these coils can be clearly defined.

The leading candidate material for the components listed in Table 1 is alumina, whether in the single crystal or polycrystalline form. In general, neutron irradiation produces only moderate degradation of properties such as thermal conductivity, mechanical strength, and volumetric swelling in alumina. Therefore, relatively straightforward experiments can be made to provide the necessary engineering information for ITER. In contrast with the thermomechanical properties of alumina, the electrical properties of ceramic insulators are known to change significantly under irradiation [1], and have received the greatest amount of attention in recent years.

Alumina, as with any highly insulating material, undergoes a large instantaneous increase in electrical conductivity when subjected to ionizing radiation. This increase is transient, and returns to its original value in the absence of the ionizing field. This radiation induced conductivity (RIC) has been shown to increase the conductivity of alumina by many orders of magnitude at fusion relevant

Table 1. Summary of anticipated irradiation conditions for ceramic insulators in the ITER device.

Application	Operating Temperature	Lifetime Displacement Level (end of basic performance phase)
ECRH Window	80 K	<0.001 dpa
ICRH Window	<200°C	<0.1 dpa
Toroidal Insulating Breaks	<300°C	~1
Diagnostic Probe		
Near First Wall	>300°C	1 to 3
Rear of Blanket	<300°C	<1

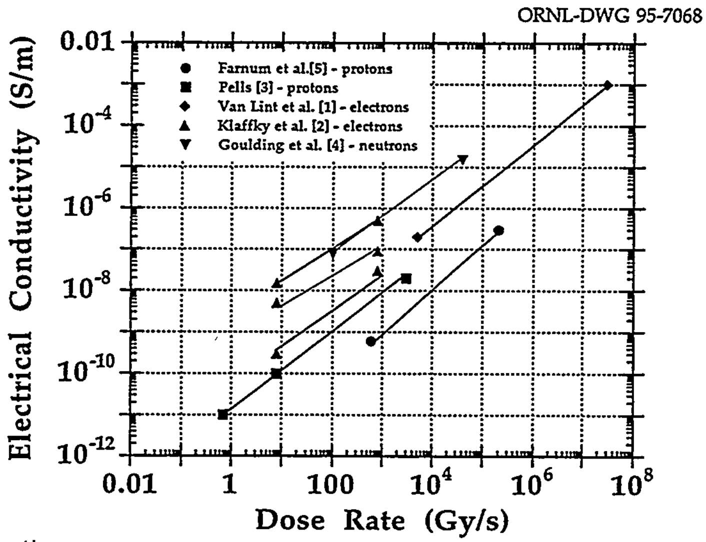

Fig. 1. Radiation induced conductivity measured in alumina during electron [1,2], proton [3,5] and fission neutron [4] irradiation.

ionizing radiation fields. Figure 1 gives a compilation of data from several studies [1-5] of RIC in alumina. As an example, it is seen that the room temperature electrical conductivity of alumina increases by more than six orders of magnitude to a value of approximately 10^{-6} (W-m)$^{-1}$ at a representative first wall dose rate of ~2000 Gy/s. While this increase in conductivity is dramatic, it is still two orders of magnitude less than the assumed limit due to joule heating concerns of ~10^{-4} (W-m)$^{-1}$ for fusion insulators [6]. It is interesting to note that there can be order of magnitude differences in the RIC not only for the different oxide ceramics but also between different grades of nominally pure polycrystalline alumina. It has also been demonstrated that the doping of single crystal alumina can significantly reduce the level of RIC, because of increased impurity trapping of conduction electrons [2].

In the past few years there have been several papers on a potentially more serious problem relating to the use of insulating ceramics in fusion systems [7-19]. Several research groups have published studies in which electrical conductivity was measured in the presence of ionizing and displacive radiation fields while an electric field was applied. The results of some of these studies indicated that in addition to the well-established increase in conductivity due to RIC, a permanent increase in conductivity occurs which greatly exceeds the RIC value after some threshold fluence is reached. As can be seen from Table 2, the observed threshold for RIED ranges from as low as 6×10^{-5} dpa [9] (1.8 MeV electron irradiation) to 0.1 dpa [12] (fission neutrons). This effect has been classified as radiation induced electrical degradation (RIED) and has to this point not exhibited an upper limit in conductivity. The potential effect of this phenomena as it relates to fusion is that critical components of future power reactors, such as microwave windows and diagnostics, would fail in a relatively short time.

While there is not yet a good explanation of the physical mechanism responsible for this effect, it is known that an applied electric field is necessary during irradiation, and there is evidence suggesting that RIED does not occur below 150°C or above 650°C [6,10,11,20]. It has been speculated [9] that radiation induced colloid formation is taking place similar to that seen in alkali-halides [21]. However, RIED has been observed in irradiated alumina specimens that did not contain any colloids [17,22]. A recent analysis [23] has shown that colloid formation is very unlikely to occur in alumina below 500°C.

Here, we present results of an experiment designed to investigate the RIED effect in Wesgo AL-995 polycrystalline alumina irradiated in a fission neutron spectrum in the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. Results from this study are compared with an earlier study by the authors and contrasted with similar studies on RIED where fission neutrons, electrons and charged particles were used. The significance of these new results, and their relation to the current design of ITER, will be presented.

2. Experimental

A schematic of the irradiation capsule used to measure the in-situ electrical conductivity of alumina during fission reactor irradiation is shown in Figure 2. The sample was sealed in a helium filled subcapsule in order to minimize the deposition of gaseous impurities (e.g. conductive hydrocarbons) on the sample surface. All components were meticulously cleaned prior to capsule assembly followed by capsule bake-out and repeated evacuation and backfilling of the capsule interior utilizing a turbomolecular vacuum pump and ultra-high purity helium. The Wesgo AL-995 polycrystalline alumina sample of 8.5 mm in diameter and 0.75 mm in thickness was vacuum brazed using a TiCuAg braze foil to an alumina platen at 1050°C for 15 minutes. This braze material covered the entire bottom surface of the sample and the top of the vanadium pin, thus serving as the rear electrode. This platen was then vacuum brazed to a vanadium heat sink (880 °C, 15 minutes). A third braze (at a lower temperature) was performed to secure the alumina cap to the heat sink, and was followed by sealing of the electrode lead penetrations in the cap under a high purity helium cover gas. The interior of the subcapsule was filled with ultra-high purity helium to 1 atmosphere at room temperature during the final sealing process. The subcapsule was helium leak checked, and then inserted into an aluminum capsule (2.8 cm outside diameter by 11 cm long, with a wall thickness of 0.27 cm). The electrical leads were fed through a 6 mm diameter aluminum tube which was connected to a helium gas bottle. The atmosphere inside of the capsule and aluminum tube underwent three cycles of evacuation and back-filling using a turbomolecular pump and ultra-high purity helium prior to insertion of the capsule into the reactor.

Platinum electrodes were sputter deposited on the alumina specimen in a guard ring configuration with a 4 mm central electrode diameter and a 1.0 mm gap between the central electrode and guard ring. A dc potential of 100 V was continuously applied during the irradiation to the brazed sample back with a Hewlett-Packard 6634A power supply, which corresponds to an applied electric field of 133 V/mm. Sample current was periodically measured from the (low-side) central electrode with a Keithley model 237 electrometer with the aid of a Keithley model 7001 high density switch system and a model 7153 high voltage matrix switching card [25]. The thermocouple potentials were measured with a Keithley 199 digital multimeter using a Keithley model 7014 themocouple multiplexer. The data acquisition and control program was written using National Instruments' LabVIEW II software. Bulk current

Table 2 . Compilation of significant RIED-related studies.

Reference	Material	Irrad. Type/ Source	Temp (°C)	RIED Threshold Dose(dpa)*	RIED Observed
Ivanov et al. [7]	Vapor deposited alumina	Fission neutrons	450	10^{-4}	Yes?
Hodgson [9]	Sapphire	1.8 MeV e^-	450	6×10^{-5}	Yes
Hodgson [26]	Sapphire	1.8 MeV e^-	330 500 530	1×10^{-3} 2×10^{-5} 3×10^{-4}	Yes Yes Yes
Pells [11]	Vitox polycrystal	18 MeV p	400 500	5×10^{-3} 7×10^{-3}	No Yes
Shikama et al. [12]	Kyocera polycrystal Sapphire	fission neutrons	500-530 330	0.1 0.03	Yes No
Zinkle & Kesternich[30]	Wesgo polycrystal	28 MeV He	500-600	4×10^{-3}	No
Möslang et al. [15]	Wesgo polycrystal	104 MeV He	450	0.015	No
	Vitox polycrystal			~0.001	Yes
Snead et al. [16]	Coors polycrystal	fission neutrons	80	0.45	No
Shikama et al.[19]	Kyocera polycrystal	fission neutrons	410	0.05	No?
Zong et al. [17]	Sapphire	1.8 MeV e^-	500	2.5×10^{-5}	Partial
Kesternich et al. [18]	Wesgo polycrystal	28 MeV He	450	2.5×10^{-3}	No
	Rubalit polycrystal		550	0.2	No
Farnum and Clinard [13]	Sapphire	Spallation neutrons	395, 615,655	0.02	No
	Wesgo polycrystal				No
Present study	Wesgo polycrystal	fission neutrons	340-365	1.4	No

* for cases where RIED was not observed, this column give the maximum dose investigated

measurements were typically recorded every 15 minutes during the ~40 day irradiation. A settling time of 4 seconds after switching from the power supply to the electrometer was found by trial and error to eliminate signal noise associated with the capacitance of the data leads. The ohmic nature of the sample was periodically checked by ramping the applied voltage from 0 to 100 V. Mineral insulated coaxial and triaxial cables were designed by ORNL and fabricated by the DeltaM Corporation [24]. High purity MgO powder insulation was used with OFHC copper for the center and guard leads. The outer sheath of the 13 meter cables was Type 304 stainless steel. The coaxial cable was 1.57 mm in diameter and supplied the high side voltage, while a triaxial cable (1.07 mm outer diameter) carried the low-side signal. The center conductor and inner shield of the triaxial cable had lead resistances of 1.5 and 6 ohms, respectively. A more complete description of the measurement technique has been reported elsewhere [16,25].

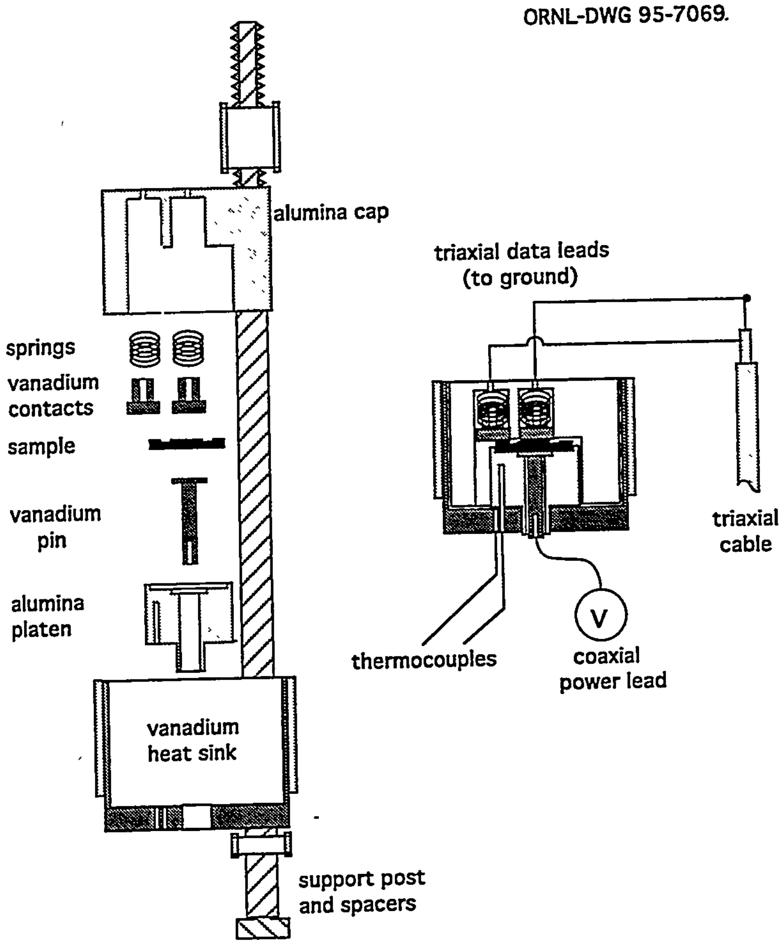

Fig. 2. Schematic of the RIED capsule.

The irradiation capsule was designed to perform a guarded electrical conductivity measurement. However a problem arose during the final brazing step causing the braze material from the rear electrode to contact the guard electrode. This shorted the guard electrode and thereby allowed surface currents to contribute to the measured specimen current. The guard ring lead was disconnected at the electronics equipment during the irradiation to avoid large leakage currents from the high side electrode along the triaxial conductor inner sheath. Due to the shorted guard ring, the measurements reported here constitute an upper limit to the bulk conductivity of the sample, the measured current being a combination of surface leakage currents and the material "bulk current" due to RIC and RIED. It should be noted that the electric field under the center electrode would be reasonably uniform (~133 V/mm) even though the guard ring was at potential, due to the 1 mm gap between the center electrode and guard ring.

The irradiation was performed in the V-16 thimble mid-core position of the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. The fast neutron flux (E>0.1 MeV) in this position is 4 x 10^{18} n/m^2-s and the sample was irradiated to a total fast neutron fluence of 1.4 x 10^{25} n/m^2 (about 1 1/2 cycles). This is approximately equivalent to 1.4 dpa in alumina assuming a sublattice-averaged displacement energy of 40 eV. The gamma heating rate for this thimble is about 6 W/g (6000 Gy/s). The sample temperature was generated by gamma heating using a 0.18 mm helium gas gap between the aluminum capsule wall and the vanadium subcapsule wall, and was continuously measured in-situ with a chromel-alumel type-K thermocouple located 1 mm from the sample. A second thermocouple was located in the base of the vanadium heat sink (cf. Fig. 2). The temperature difference between the two thermocouples was ~30°C when the reactor was at full power, due to the temperature drop over the lower 9 mm of the alumina pedestal. The actual specimen temperature is calculated to be ~3 °C above the measured thermocouple temperature in the alumina pedestal. The measured temperature in the alumina pedestal varied between 360 and 365°C during the first 100 hours of irradiation, and then the reactor was shut down for fuel reloading. When the reactor was restarted, the measured temperature slowly decreased from 345°C at the start of the new cycle to 330°C at the end of the irradiation.

3. Results and Discussion

The capsule was inserted into the HFBR core while the reactor was at full power (30 MW). The application of the electric field and the initial sample measurements occurred within approximately one hour of entry. An example of an current-voltage curve taken during full-power reactor operation (at ~0.75 dpa) is shown in Fig. 3 and demonstrates the nearly ohmic behavior of the system. This ohmic behavior was observed throughout the experiment.

The raw data for the low-side center electrode current is given in Figure 4 and represents ~4300 data points taken during the experimental run. At the beginning of the irradiation, the signal was somewhat erratic at approximately 10^{-7} amps and slowly increased to $\sim10^{-6}$ amps. The initial level of current (10^{-7} amps) would be consistent, though on the lower end of the scatter band, with the expected level of RIC as seen in Figure 1. The gradual increase from this initial value may have been due to contamination of the sample surface. The dramatic drop in current at approximately 100 hours into the irradiation corresponds to the start of the ten day reactor shutdown for refueling. Following the subsequent startup, the signal was relatively steady at approximately 8×10^{-6} amps, which corresponds to a conductivity of $\sim3.0\times10^{-6}$ S/m assuming that the effective center electrode area extends halfway between the Pt-deposited center and guard ring electrodes. Data for the sample conductivity were generated from the slope of a best linear fit to the current-voltage plots and are given as a function of displacement level in Figure 5. This figure also includes results from several previous RIED studies on alumina performed at temperatures where the RIED effect is expected to be most pronounced (450-500°C). It is seen that the present results for the Wesgo AL-995 material do not show a dramatic increase in conductivity associated with the onset of RIED as seen in some previous studies.

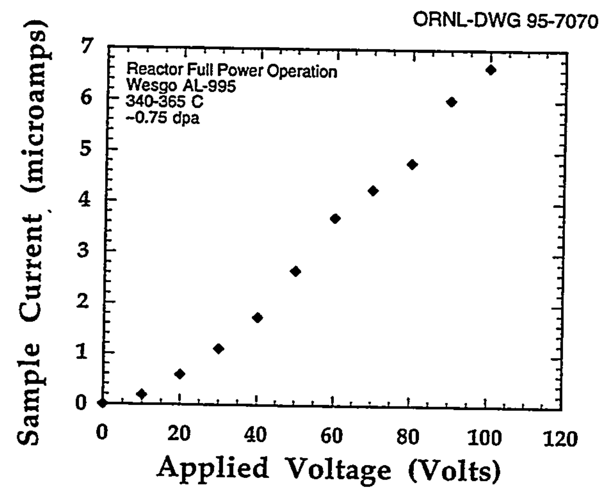

Fig. 3. Characteristic current vs. voltage curve measured during full-power irradiation.

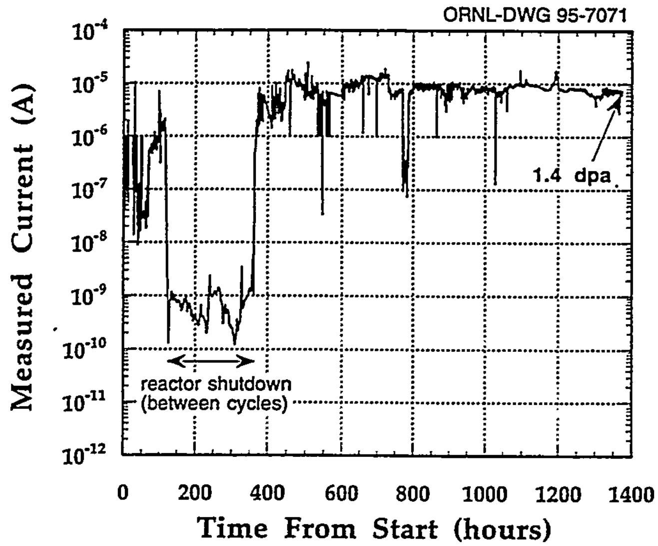

Fig. 4. Raw data of the low-side sample current during the HFBR irradiation.

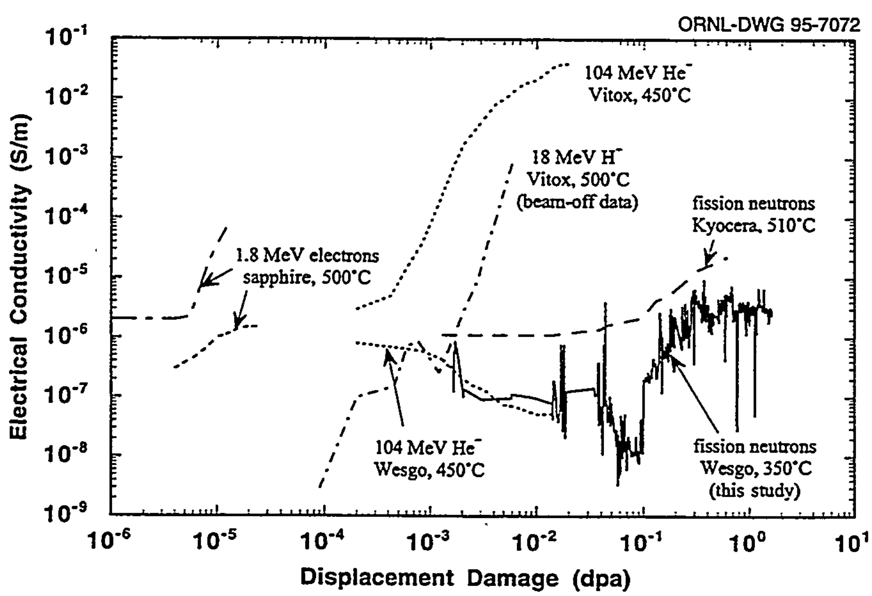

Fig. 5. Comparison of the present results at 350°C with previous RIED studies performed with electron [9,17], light ion [11,15] and fission neutron [12] irradiation sources near the peak degradation temperature of ~500°C.

The present results demonstrate that RIED is not present to any significant level in Wesgo AL-995 polycrystalline alumina irradiated near 350°C up to a dose of 1.4 dpa. Due to the nature of the low-side measurement made in this experiment, and to the fact that the sample remained ohmic throughout the measurement period, there is complete confidence regarding the integrity of the measurement. In particular, the ohmic response on the low (ground) side of the sample as the voltage was periodically ramped demonstrated that the voltage was applied to the sample and there was contact to the sample electrodes. While it is possible that some fraction of the measured signal was due to surface contamination, had the RIED-like behavior occurred as seen in previous studies, it should have produced a specimen current orders of magnitude larger than the observed value (cf. Fig. 5 and refs. 10-12,15,17). It is also worth noting that the measured conductivity was quite close to that expected from simple radiation induced conductivity (~10^{-6} S/m). It is certainly possible that some effect has taken place which has altered the base, permanent bulk conductivity of the sample, although this conductivity level would necessarily be less than the RIC (plus surface contamination) level measured here of ~10^{-6} S/m. This possibility will be examined by performing post-irradiation testing of the sample.

The results of this work are another data point in what is proving to be a difficult phenomena to study. Following the initial work by Ivanov [7], which showed a large in-reactor conductivity increase followed by a decrease to nearly the initial RIC value, several researchers have studied this effect, albeit under quite different experimental conditions. The results of these studies are quite variable. Table 2 gives a synopsis of the significant work to date on the RIED effect starting with the first published research by Ivanov [7], Hodgson [8] and Pells [11]. Both Hodgson and Pells have observed significant levels of RIED at temperatures between 300 and 600°C. Following these initial results, and the realization of their potential impact on fusion reactor design, there have been numerous studies in this area. Researchers have utilized an array of irradiation sources and types of alumina, with some observing the RIED effect and some not. Work by Kesternich and coworkers [18] has been instrumental in showing that RIED does not always occur in alumina; for example, RIED was not detected in a Rubalit grade of alumina irradiated up to 0.2 dpa at ~550°C [18] nor in Wesgo-AL995 alumina irradiated at ~500°C to 0.004 dpa [30] or 450°C to 0.0025 dpa [18]. In one particularly interesting recent study by Möslang and coworkers [15], RIED was observed to occur in Vitox alumina, but not in Wesgo AL-995, at identical irradiation conditions [15]. It is worth noting that, in published studies to date, RIED has never been observed in Wesgo AL-995 alumina [13,15,18,30].

As seen in Figure 5, there is apparently a critical dose at which the RIED conductivity appears above the RIC conductivity level, raising the question of a required threshold dose. Several studies have shown that a lower and upper temperature limit also exists [9,14,20] with a peak temperature for observing RIED of ~450°C and an apparent minimum temperature of ~150°C. Most recently, Hodgson has suggested [26] that there is an effect of displacement rate which can shift the displacement threshold towards higher values for higher dose rates. Hodgson also showed that the form of material, i.e. polycrystalline alumina as compared to sapphire, may affect the onset of RIED. Furthermore, it can be speculated based on the work of Möslang et al. [15] that the grade of polycrystalline alumina chosen will affect the results.

It has been suggested by some researchers [18,23,27] that, due to the intrinsically difficult nature of making these measurements, the RIED effect may actually be due to experimental error rather than a bulk material effect. In particular, it has been shown [18,27] that an apparent RIED effect could be produced as a result of surface contamination during the in-beam experiments. Other plausible explanations include sample cracking which could lead to conduction through the sample simply due to crack-surface conduction or from diffusion of electrode material [22] along internal cracks. Such cracking could either be a radiation induced phenomena or simply be in response to stress which develops during the pre-irradiation processing (e.g. brazing). Other design related issues such as degradation of mineral insulated cables (in the case of in-reactor irradiations) are also potential experimental problems. Evidently, the real significance of RIED on ceramic component performance remains unclear at this point. Because of the large number of variables elucidated above, a fully comprehensive experimental investigation of the RIED phenomenon will be lengthy, complex and expensive. However, the data reported here, along with our previously reported data [16] (80°C fission neutron irradiation) allow us to definitively address whether RIED will be a design issue for fusion reactor ceramic components of near-term fusion reactors, ITER in particular.

Referring to Table 1, it is seen that, with the possible exception of diagnostic coils located near the first wall, the expected operating temperatures for all ITER ceramic components are 300°C or below. The displacement levels which are expected at the end of the basic performance phase of ITER will vary due to component location in the machine and will be highest for the diagnostic probes located near the first wall (1 to 3 dpa), and generally less than 1 dpa for other probes and the toroidal insulating breaks. Due to the extreme sensitivity of alumina windows to radiation induced changes in both the thermal conductivity and the dielectric loss, these components will be positioned to limit their dose to < 0.1 dpa for ICRH, and <0.001 dpa for ECRH windows [28]. The allowable dose limits to these components may be reduced even further as more information becomes available on the effect of low temperature neutron irradiation on the loss tangent.

It is very plausible that the threshold for the observance of RIED is not simply dictated by the irradiation temperature, material and total dose. Other variables such as irradiation spectrum, applied field and dose rate could affect the incubation dose for RIED, or whether the degradation occurs at all. Assuming that RIED is a bulk material effect, however, arguments can be made that RIED is of no concern for ITER, given the appropriate choice of material. This is based on the absence of RIED in polycrystalline Wesgo AL-995 alumina irradiated in this study (~350 °C to 1.4 dpa) and a previous lower temperature neutron irradiation on a Coors AD-998 polycrystalline alumina (80 °C to 0.45 dpa) [16]. It should be noted that the displacement dose of this previous study has been corrected from our originally published value of 0.11 dpa due to a recent clarification on the E>0.11 to E>1 MeV neutron flux ratio of the HFBR.

From the conditions of these experiments it can be argued that all the possible variables influencing a shift in the incubation dose for RIED have been satisfactorily addressed. Specifically, the neutron spectrum in these experiments was a water moderated fission neutron spectrum which, while somewhat lower in average energy than the blanket spectrum of a fusion reactor, is not fundamentally different in its spectrum-integrated damage characteristics. The temperatures of the two studies under consideration are directly relevant, or slightly higher than the expected operating temperatures in ITER. Assuming there is a temperature threshold for RIED (for the Wesgo AL-995 irradiated with neutrons) it would be expected to be higher than the ~ 350 °C temperature of this study, therefore above the operating temperature for ITER. In both the present work and the lower temperature irradiation [16] , the applied field was 133 V/mm, which is higher than the field which would be experienced by ceramic insulators in ITER and is therefore conservative.

Finally, a comparison of the dose and dose rate of this experiment and the proposed ITER parameters needs to be addressed. As can be seen from Table 1, the dose of 1.4 dpa from this experiment is above the proposed range any ITER ceramic component would undergo during the basic performance phase, with the possible exception of the near-wall diagnostic probes. However, the fast neutron dose rate for the HFBR (~ 4×10^{18} n/m^2-s, E>0.1 MeV) can be significantly different from these encountered by ITER ceramic components. The fast neutron flux at the first wall of ITER will be comparable with this (~1.5×10^{18} n/m^2-s) [29], but the displacement rate decreases rapidly with distance from the first wall. For example, the dose rate has been calculated to be a factor ~1000 less at the vacuum vessel of the ITER machine [29].

The effect which this difference in dose rate will have on RIED is unknown, again due to the lack of knowledge of the physical mechanism responsible for this phenomenon. However, if aluminum colloid formation [9] is assumed to be the triggering mechanism, it would be reasonable to expect the main effect of a change in dose rate would be to induce a shift in the temperature dependence of RIED. Temperature shifts due to changes in irradiation dose rate have been commonly applied to studies of colloid formation in alkali-halides [21] and the formation of voids in metals [31]. While experimental verification of the dose rate effect has not been sufficiently demonstrated for the formation of sodium colloids [21], the effect of displacement rate on the temperature dependence of voids in metals under irradiation has been experimentally verified. In its simplest form the effective temperature shift can be calculated from chemical rate theory to be :

$$T_2 - T_1 = \frac{\dfrac{kT_2^{\,2}}{E_m^{Al}} \ln\left(\dfrac{D_2}{D_1}\right)}{1 - \dfrac{kT_2}{E_m^{Al}} \ln\left(\dfrac{D_2}{D_1}\right)} \tag{1}$$

where D_1 and T_1 are the assumed dose rate and temperature for ITER, D_2 and T_2 are the dose rate and temperature of the present work, k is Boltzmann's constant and E_m^{Al} is the migration energy for aluminum vacancies, assumed here to be 3.9 eV [32]

As mentioned earlier, the flux expected in ITER near the first wall is very close to the HFBR flux of this study and therefore is directly relevant, i.e. no temperature shift is required to correct for dose rate effects. However, if one assumes a thousand-fold reduction in fast neutron flux over the HFBR flux, which is expected near the ITER vacuum vessel [29], equation (1) yields a temperature shift of 64°C. Thus the present (high dose rate) results at ~350°C are equivalent to that expected at the ITER vacuum vessel (low dose rate) irradiated to the same dose at ~290°C. The consequences of this temperature shift would be to move the "effective" temperature of the present work into a more ITER-relevant range (Table 1). The preceding calculation ignores ionization enhanced diffusion effects, which may cause a reduction in the vacancy migration energy in insulators. However, even if the migration energy were reduced by a factor of two, the corresponding temperature shift would be only 139 degrees and the present study would still be ITER-relevant.

It should be noted that a slightly different analysis of the effect of dose rate on the displacement threshold for ITER has been developed by Hodgson [26] based on the formation of aluminum colloids. In his analysis, Hodgson has developed curves which predict the threshold displacement dose required to produce RIED (in this case for neutron irradiated polycrystalline alumina) as a function of dose rate and temperature. Following his analysis, however, the onset of RIED at 350°C should have occurred at ~ 0.05 dpa for the HFBR dose rate of ~ 4 x 10^{-7} dpa/s, significantly less than the 1.4 dpa of the present study. Furthermore, even if RIED would have occurred at (just greater than) 1.4 dpa for the HFBR Wesgo AL995 material, and Hodgson's analysis was applied to predict when RIED would occur at appropriate blanket dose rates, Hodgson's theory predicts that RIED would not occur in the basic performance phase of ITER. For example, extrapolation of a 1.4 dpa HFBR incubation dose to the mid-blanket ITER dose rate of 3 x 10^{-9} dpa/s predicts RIED would occur at 0.18 dpa compared to the expected dose of 0.045 dpa at the end of the basic performance phase.

In any event, the ~350°C HFBR results indicate that the Wesgo AL-995 alumina should not suffer significant RIED in ITER components during the basic performance phase. It then appears that if RIED did exist as a bulk effect in some grades of alumina, RIED could be avoided in ITER by the appropriate selection of alumina grade. The obvious choice of material at this point would be to select a material such as Wesgo AL-995 which has been shown in this and previous studies [13,15,18,30] not to be susceptible to RIED, as opposed to Vitox alumina which has demonstrated RIED in studies by Pells [11] and Möslang [15].

A second consideration for ceramic insulators in ITER is surface contamination [13,18,27], which is a very real possibility for certain tokamak components such as current breaks and microwave windows. For the case of microwave windows this contamination problem would have no significant effect on the loss tangent and therefore is not a great concern other than any possible optical problems associated with the contaminating layer. For current breaks, however, an increase in conductivity, whether it be bulk RIED in the insulator or simply surface contamination, would increase the magnitude of the disruption currents and would therefore need to be kept below some minimum value. For the case of the diagnostic probes in which the alumina is used as an insulator in a coaxial cable, there would obviously be no problem associated with surface contamination.

The final piece of the RIED puzzle which needs to be addressed for ITER is a problem which has been categorized as both a bulk phenomenon and an artifact. The possibility of irradiation induced cracking [22] appears to be a plausible explanation for RIED and will require some investigation. However, this would be a very design dependent phenomenon and would require proof testing once the engineering design of ITER has matured to the point where temperatures and stresses on its ceramic components can be defined.

CONCLUSIONS

The results of the study reported here indicate that Wesgo AL-995 polycrystalline alumina does not exhibit catastrophic radiation induced electrical degradation (RIED) during irradiation up to a neutron dose level of 1.4 dpa in the temperature range of 340-365 °C. Given these results, in combination with the results of several other published studies, RIED appears not to pose a problem for ceramic insulator components in the basic performance phase of ITER, with the possible exception of diagnostic mineral insulated cables due to the very high dose, high temperature conditions these cables must withstand.

However, considering the puzzling, diverse behavior observed in different RIED studies, it is also clear that the phenomenon of RIED is poorly understood and that many questions remain as to its cause and extent. A continuing study of RIED is necessary in order to fully understand this effect.

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