SUMMARY OF THE 9TH IEA WORKSHOP ON RADIATION EFFECTS IN CERAMIC INSULATORS — S. J. Zinkle (Oak Ridge National Laboratory), E. R. Hodgson (CIEMAT), and T. Shikama (Tohoku Univiversity)

OBJECTIVE

The objective of this report is to summarize the discussions held at the IEA workshop on Radiation Effects in Ceramic Insulators.

SUMMARY

Twenty one scientists attended an IEA workshop in Cincinnati, Ohio on May 8-9, 1997, which was mainly devoted to reviewing the current knowledge base on the phenonenon of radiation induced electrical degradation in ceramic insulators. Whereas convincing evidence for bulk RIED behavior has been observed by two research groups in sapphire after electron irradiation, definitive levels of bulk RIED have not been observed in high purity Al_2O_3 by several research groups during energetic ion or fission neutron irradiation. Possible reasons for the conflicting RIED results obtained by different research groups were discussed. It was concluded that RIED does not appear to be of immediate concern for near-term fusion devices such as ITER. However, continued research on the RIED phenomenon with particular emphasis on electron irradiations of single crystal alumina was recommended in order to determine the underlying physical mechanisms. This will allow a better determination of whether RIED might occur under any of the widely varying experimental conditions in a fusion energy device. Several critical issues which are recommended for future study were outlined by the workshop attendees.

PROGRESS AND STATUS

Introduction

Several IEA workshops have been held over the past few years to discuss the growing number of experimental studies on the intriguing phenomenon of radiation induced electrical degradation (RIED). The experimental evidence for RIED is primarily based on electron irradiation studies performed by Eric Hodgson and coworkers on single and polycrystal forms of Al_2O_3 [1-6]. Additional evidence for RIED has been reported by several research groups for electron-, light ion- and neutron-irradiated Al_2O_3 [7-11]. These studies suggest that the electrical conductivity of Al_2O_3 may exceed 10^{-5} S/m after doses as low as $\sim 10^{-3}$ displacements per atom (dpa) if an electric field >100 V/mm is applied during irradiation in the temperature range of ~200 to 550°C. On the other hand several other research groups have failed to observe catastrophic RIED in Al_2O_3 following electron [12,13], light ion [14-16], or neutron irradiation [17-20]. Some published results for electron [3,5,21] and light ion [22] irradiation have suggested that the initiation of RIED may be influenced by the purity or quality of the insulator.

Due to the difficulties associated with performing in-situ electrical conductivity measurements on irradiated insulators, considerable attention has recently been focused on measurement methods. The essential experimental techniques for accurate in-situ measurement of the electrical conductivity of ceramic insulators were discussed in detail at an IEA workshop held in Stresa, Italy in September 1993. It was concluded that the experimental techniques used by the investigators which had observed RIED were generally appropriate, but additional recommendations for future experimental studies were formulated. A round robin RIED experiment on Wesgo AL995 alumina (the IEA reference insulator) was initiated following the Stresa workshop, and the results were reported at an IEA workshop held in Obninsk, Russia in

September 1995. No evidence for bulk RIED in this material was observed by 5 different research groups using electron, light ion, and neutron irradiation sources [23].

In the past year, several new RIED irradiation experiments have been performed which have a significant impact on the understanding of the RIED phenomenon. These experiments include a HFIR neutron irradiation experiment on 12 different grades of single- and poly-crystal alumina (450°C, ~3 dpa, 200 V/mm) and several additional electron and light ion irradiation experiments. The primary objective of the IEA workshop was to review the available RIED studies on ceramic insulators. Some discussion of recent work in other areas such as loss tangent measurements, mechanical strength, etc. occurred on the final afternoon of the workshop. The workshop was held immediately after a related symposium on "Fabrication and Properties of Ceramics for Fusion Energy and Other High Radiation Environments," which was convened on May 5-7, 1997, as part of the American Ceramic Society annual meeting in Cincinnati, Ohio. Copies of the viewgraphs presented at the IEA workshop and abstracts of the presentations were collected for distribution to the attendees as a bound booklet (ORNL/M-6068).

Workshop Presentations

The agenda for the workshop is given in Table 1, and the list of attendees is given in Table 2. In the opening talk, Eric Hodgson summarized the experimental evidence generated in his laboratory for bulk RIED in ceramic insulators. A clear increase in the volume current was measured using guard ring techniques in several specimens irradiated with electrons. Small surface currents were observed in sapphire and Vitox alumina, whereas large surface and bulk currents were measured in MgO and spinel. Optically visible features could be observed in the bulk of electrically degraded sapphire specimens, which are apparently clusters of gamma alumina precipitates according to TEM analysis. He presented results which support the importance of point defect production in the degradation process, and then outlined a theoretical model which may explain the RIED process. The model assumes that the degradation is due to the formation and clustering of oxygen vacancies via the following sequence: F (oxygen vacancy with two trapped electrons) ->F^+ (one trapped electron, enhanced mobility compared to F center) ->F_2 ->colloids (Al metal precipitate due to deficiency of oxygen). The colloids are assumed to promote gamma alumina precipitation in neighboring regions, since the gamma alumina (spinel) structure can be formed by introducing cation vacancies on octahedral sites [24].

Tatsuo Shikama summarized evidence for long-term increases in the electrical conductivity of ceramic insulators irradiated in fission reactors. The presence of an offset current which has been attributed to "radiation induced electro-motive forces" (RIEMFs) was observed in essentially all cases, although the physical mechanism responsible for this offset current remains unclear. He proposed that the premature failure (electrical shorting) observed in several of the specimens irradiated in the HFIR-TRIST-ER1 experiment may be correlated with specimen type, although there was no evidence for an increase in electrical conductivity prior to the shorting. A pronounced increase in the electrical conductivity of a 0.05%Cr-doped sapphire (ruby) specimen was observed in the HFIR experiment at low doses (~0.1 dpa). The conductivity slowly decreased with increasing dose for the remainder of the irradiation.

Chiken Kinoshita presented in-situ electrical conductivity data obtained on sapphire specimens with thicknesses of 0.27 and 0.75 mm irradiated with 1 MeV electrons in an HVEM. The temperature dependence of the bulk radiation induced conductivity was found to be dependent on the specimen electrode type (vacuum deposited Ti or Au versus sputter deposited Pt). Permanent RIED was not detected for irradiation up to $\sim 9 \times 10^{-5}$ dpa at 420°C with an applied electric field of 93 V/mm. It was proposed that previous reports of RIED may be due to the effect of electrode materials and/or the measuring system.

Table 1. Agenda for IEA Workshop on Radiation Effects in Ceramic Insulators

Wednesday afternoon (May 7):

1:00 pm Introductory Comments--Workshop organizers

1:10 pm Evidence for bulk RIED in ceramics
E.R. Hodgson (CIEMAT)
T. Shikama (Tohoku Univ.)

1:50 pm Recent RIED experiments
1:50 pm Electron irradiations
C. Kinoshita (Kyushu Univ.)
T. Terai (U. Tokyo)
Y. Chen (DOE)
E.R. Hodgson (CIEMAT)

2:50 pm Ion irradiations
W. Kesternich (KFA-Jülich)
A. Möslang (Forschungszentrum Karlsruhe)
V.M. Chernov (IPPE-Obninsk)

3:50 pm Neutron irradiations
S.J. Zinkle/HFIR-TRIST-ER1 (ORNL)
T. Shikama/JMTR (Tohoku Univ.)
K. Noda/JRR (JAERI)
V.M. Chernov (IPPE-Obninsk)
E.R. Hodgson/Mol (CIEMAT)

Thursday (May 8):

8:30 am Possible explanations for conflicting results on bulk RIED
Effects of dose rate, temperature, electric field, material, and test environment
E.R. Hodgson (CIEMAT)

Electron beam straggling and implanted charge effects
A. Möslang (Forschungszentrum Karlsruhe)
S.J. Zinkle (ORNL)

Irradiation spectrum effects on F/F^+/colloid formation
S.J. Zinkle (ORNL)

1:00 pm Overview of recent work on ceramic insulators (non-RIED)
E.R. Hodgson (CIEMAT)
R. Vila (CIEMAT)
V.M. Chernov (IPPE-Obninsk)
K. Noda (JAERI)
C. Kinoshita (Kyushu Univ.)
T. Shikama (Tohoku Univ.)
S.J. Zinkle (ORNL)

3:00 pm Discussion of critical issues, workshop statement on RIED, recommendations for future work (including proposed collaborations/ round-robin experiments)

Table 2. Attendees at IEA Fusion Ceramics Workshop.

Anton Möslang, Forschunszentrum Karlsruhe, Germany

Wilto Kesternich, Forschunszentrum Jülich, Germany

Rafael Vila, CIEMAT, Spain

Eric Hodgson, CIEMAT, Spain

Tatyana Bazilevskaya, Kharkov State University, Ukraine

Vyacheslav M. Chernov, SSC RF-IPPE, Obninsk, Russia

Chusei Namba, National Institute for Fusion Science, Japan

Akira Kohyama, Kyoto University, Japan

Tatsuo Shikama, Tohoku University, Japan

Akira Hasegawa, Tohoku University, Japan

Kenichi Shiiyama, Kyushu University, Japan

Chiken Kinoshita, Kyushu University, Japan

Toyohiko Yano, Tokyo Institute of Technology, Japan

Takayuki Terai, University of Tokyo, Japan

Kenji Noda, Japan Atomic Energy Research Institute, Japan

Lance Snead, Oak Ridge National Laboratory, USA

Steve Zinkle, Oak Ridge National Laboratory, USA

Kenneth Young, Princeton Plasma Physics Laboratory, USA

Yok Chen, U.S. Department of Energy, USA

F. W. Wiffen, Office of Fusion Energy Sciences, U.S. Department of Energy, USA

J. Y. Park, Korean Atomic Energy Research Institute, Korea

Yok Chen summarized electron irradiation RIED results on unguarded sapphire specimens reported in two recent publications [10,11]. He concluded that the mechanisms leading to RIED in Al_2O_3 appear to be similar to those for thermal dielectric breakdown. In particular, a moderately high dislocation density (~$10^{12}/m^2$) was present in both irradiated and thermally degraded oxide specimens. Precipitates were not observed in the irradiated specimens. A theoretical model based on carrier injection from the electrodes was outlined which appeared to describe the main features of the RIED process in his experimental studies. RIED was observed to be inhibited when the electric field was reversed, in contrast to an earlier study by Hodgson [3]. According to the carrier injection model, the electrical conductivity should decrease immediately after the electric field is reversed.

Eric Hodgson reported his recent work on Wesgo AL995 surface/bulk conductivity. He observed that irradiation in vacuum causes severe surface degradation, but irradiation in air or He does not. In further irradiations it was observed that collimation of the electron beam to irradiate only the central electrode drastically reduces the surface degradation (i.e. the surface degradation is radiation induced or enhanced) He noted that this observation helps to explain the conflicting results of Kesternich and Möslang. Further experiments were carried out with a collimated beam to study the volume degradation in vacuum. Up to 500 kV/m no volume degradation was observed (> 200 h irradiation). However at 1 MV/m a clear volume degradation was observed. The process is complicated by radiation enhanced impurity segregation (electrolysis) at the negative electrode, which caused saturation in the observed RIED. However polishing off < 0.1 mm indicated severe volume degradation. At 1.5 MV/m (AC 50 Hz) a clear volume degradation was observed with no saturation.

Wilto Kesternich summarized RIED data obtained on several different grades of alumina, including Rubalit, Wesgo AL995 and Deranox (Vitox) irradiated with energetic protons or alpha particles. Bulk RIED was not observed in any of these specimens. In one case, specimen microcracking produced an increase in the current measured by the center electrode. After an initial increase in the measured current, the crack appeared to slowly heal (or else the surface conducting layer oxidized and became poorly conducting) with further increases in dose. He reiterated the importance of adhering to all of the measurement techniques approved at the Stresa IEA workshop in 1993, and added that the possibility of surface microcracking must be investigated (using SEM) in all specimens which show an apparent increase in bulk conductivity.

Anton Möslang presented the results of RIED studies on 104 MeV He^+ ion irradiated Al_2O_3 (Vitox/Deranox, Wesgo AL995) and AlN specimens. A previously reported [22] observation of pronounced RIED in a Vitox alumina specimen was attributed to specimen cracking effects in his presentation; a nominally identical grade of alumina (Deranox) produced by the same manufacturer did not exhibit any permanent electrical degradation following irradiation to similar conditions as the Vitox specimen. In addition, RIED was not observed in Wesgo AL995 alumina or AlN specimens. He concurred with Kesternich's conclusion that specimen cracking must be investigated in specimens which exhibit apparent bulk RIED.

Vyacheslav Chernov reported that neither RIC nor RIED was observed in alumina irradiated with 10 MeV protons at room temperature or with fission neutrons at ~580°C, 70 Gy/s. These irradiation conditions are outside of the temperature range where previous studies have reported RIED (~250-530°C). The lack of observable RIC in the neutron irradiated specimen may be attributable to the relatively high temperature and low ionizing dose rate. On the other hand, the absence of observable RIC in the proton-irradiated specimen is unexpected based on previous RIC studies near room temperature by other research groups. He also reported observation of dielectric breakdown and cracking within ~0.8 mm of the incident surface of a 2.7 mm thick sapphire specimen irradiated with 1 MeV electrons.

Steve Zinkle summarized the results of a recently completed DOE/Monbusho in-situ electrical conductivity experiment on several different grades of alumina that was performed at 450-500°C in the HFIR fission reactor. A total of 15 specimens (3 without dc bias) were irradiated to a maximum dose of ~3 dpa. The bulk conductivity measured during full-power irradiation (10-16 kGy/s) remained below 1×10^{-6} S/m in all of the pure alumina specimens. The only specimen which exhibited an apparent bulk conductivity higher than 1×10^{-6} S/m was a 0.05% Cr-doped sapphire specimen, which showed a rapid initial increase in conductivity to $\sim 2 \times 1 \times 10^{-4}$ S/m after ~0.1 dpa, followed by a gradual decrease to $<1 \times 10^{-6}$ S/m after 2 dpa. Nonohmic electrical behavior was observed in all of the specimens, and was attributed to preferential attraction of ionized electrons in the capsule gas to the unshielded low-side bare electrical leads emanating from the subcapsules. The electrical conductivity was determined from the slope of the specimen current vs. voltage curve at negative voltages, where the gas ionization effect was minimized. More than half of the coaxial cables shorted during the 3 month irradiation. Dielectric breakdown tests performed on nonirradiated coaxial cables indicated that the shorting was associated with breakdown in the glass used to seal the ends of the cables. Postirradiation measurements of the temperature-dependent electrical conductivity of all specimens are planned, along with examination of the shorted coaxial cables. Measurements made on two high purity sapphire specimens which were irradiated for the full 3 reactor cycles indicate that the electrical conductivity did not exceed the normal RIC value of $\sim 1 \times 10^{-6}$ S/m at any point during the irradiation.

Tatsuo Shikama reported results of a JMTR fission neutron experiment carried out under the US/Japan collaboration in conjuction with the recent HFIR experiment (performed under the same collaboration framework, and reported at the workshop by Steve Zinkle). He pointed out some interesting but mysterious phenomena obtained in fission reactor experiments. These results were first recognized in JMTR and clearly and confidently confirmed in HFIR. These results may infer problems associated with fusion reactor developments. He implied that they may have some correlation with a long term degradation of electrical insulation of ceramics. He proposed to continue international collaborations which focus on studying the fundamental nature of these phenomena in inexpensive and easily accessible reactors such as JMTR.

Kenji Noda described a recently completed in-situ electrical conductivity experiment on MgO and Al_2O_3 performed at 300 to 450°C in the JRR-3 reactor. The RIC values appeared to be in good agreement with previous studies. It was concluded that RIED did not occur to any significant degree up to the maximum damage level of 0.2 dpa. The session was concluded by Eric Hodgson with a brief description of a neutron irradiation experiment in the Mol reactor that is scheduled to begin in the summer of 1997.

On the second day of the workshop, the morning session was devoted to discussion of possible reasons for the apparent conflicting results regarding the presence of RIED in irradiated specimens. Eric Hodgson noted that most of the observations of RIED were obtained using electrons at low dose rates ($<10^{-9}$ dpa/s), whereas most of the ion and neutron irradiation experiments were performed at 3 orders of magnitude higher dose rate. Assuming that the incubation dose for RIED is proportional to the square root of dose rate (in analogy with void swelling and colloid processes), then RIED for typical ion and neutron conditions would become evident at doses ~10 to 100 times higher than that for the electron irradiations. However, the reported absence of RIED at doses above 0.01 to 0.1 dpa in several ion and neutron irradiation studies cannot be explained by dose rate effects. Hodgson also noted that several experiments which reported the absence of RIED were performed at temperatures outside the RIED temperature regime of ~250-530°C. The electric field threshold for initiation of RIED is expected to be material dependent, and it is possible that low-purity materials may have higher threshold electric fields than the ~50 kV/m threshold reported for high-purity sapphire. Similarly, impurities may increase the incubation dose for initiation of RIED. Hodgson also suggested that additional work is needed to understand the role of test environment (air vs. vacuum, etc.) on the electrical degradation process.

Anton Möslang and Steve Zinkle discussed aspects associated with electron irradiation which might promote the RIED process in electron-irradiated specimens compared to neutron-irradiated specimens. Both presentations pointed out that, due to the large range straggling for electrons, greater than 20% of the charge from a 1.8 MeV electron beam incident on a 1 mm-thick Al_2O_3 specimen would be deposited in the specimen. This implanted charge might produce high localized electric fields under certain circumstances, which could lead to internal dielectric breakdown (similar to the well-known Lichtenberg avalanche breakdown patterns in electron-implanted insulators). A further consideration for near-threshold irradiation sources such as electron beams is the nonstoichiometric defect production rate on the anion and cation sublattices, which may contribute to localized polarization effects. It was noted that the internal electric field is generally not related to the applied electric field in a simple manner; however, it was interesting to note that the macroscopic electric field due to the injected charge from the electron beam in a 1 mm-thick specimen was comparable to the threshold electric field for rapid RIED obtained in electron irradiation studies. Another effect worth considering is that the relatively high ionization/ displacement ratio for electron irradiation may enhance the F^+/F center ratio compared to neutron irradiations, which could have an impact on the microstructural evolution of irradiated specimens (particularly if colloid formation is responsible for the initiation of RIED).

Several additional details associated with RIED were brought up in the ensuing general discussion. Yok Chen expressed concern about F^+ center identification and recommended cathodoluminescence instead of radioluminescence/ photoluminescence. However Hodgson insisted that the optical characteristics of the F, F^+ and F_2 reported were in excellent agreement with literature values and could be adequately identified by absorption and radioluminescence.

Two preliminary models were proposed to describe the RIED process, based on charge injection form the electrodes and colloid/gamma alumina precipitation, respectively. Both models appear to successfully explain some aspects of the electrical degradation observed in electron irradiated specimens, but do not explain other aspects. For example, pronounced electrical degradation would have been predicted by the charge injection model for the long-term (2 days to 3 months) ion and neutron irradiation experiments where RIED was not detected. There also appeared to be a discrepancy between the results of two research groups [3,11] on whether RIED is suppressed when the electric field is periodically reversed during electron irradiation. Further work is clearly required to address this discrepancy.

There was general agreement by the workshop participants that, with the possible exception of ion irradiation results by Pells [7] (which might be attributable to specimen cracking similar to that observed by Möslang and Kesternich), definitive levels of bulk RIED have not been observed for ion or neutron irradiations. This raises the possibility that perhaps some aspect of electron irradiation promotes RIED more vigorously than ion or neutron irradiation sources. Even for the case of electron irradiation, several studies have failed to detect RIED under conditions where pronounced electrical degradation was found by Hodgson and coworkers and Zong et al. Therefore, the workshop participants concluded that the most fruitful research area for future RIED studies would be to develop an improved understanding of the electron irradiation conditions which enhance RIED (e.g., effect of specimen thickness, reversed electric fields, etc.). Eric Hodgson agreed to distribute virgin specimens of the Union Carbide sapphire used in his electron irradiation studies to W. Kesternich and T. Terai for a round-robin electron irradiation study.

Concerning fission reactor experiments, there was a general consensus that the recent HFIR experiment gave conclusive results in a helium environment. To confirm the results, postirradiation examination of irradiated specimens, including the temperature dependence of the conductivity of irradiated specimens and examination of the mineral insulated cables, and if possible microstructure (TEM) examination, was recommended. Eric Hodgson's planned reactor experiment in Mol will be a useful complement to the HFIR experiment, since it will provide information on the effect of environment (inert gas vs. vacuum) and dose rate dependence. Tatsuo Shikama's proposal of a JMTR experiment will enlighten fundamental aspects of electrical conductivity of ceramic insulators under fission reactor iradiation (which is the closest high-intensity approximation to the fusion irradiation environment presently available).

Brief summaries of recent non-RIED work on ceramic insulators were presented by the workshop participants in the final afternoon session. Copies of the presented viewgraphs are contained in the bound volume (ORNL/M-6068) to be distributed to the workshop participants.

<u>Workshop Summary Statement</u>

Volumetric defects (gamma-alumina and/or dislocations) and evidence for bulk RIED-like behavior have been observed in sapphire by two research groups during electron irradiation near 450°C with applied E fields >100 V/mm [5,10,11,24]. However, 2 other research groups did not observe pronounced RIED in sapphire after electron irradiation [12,13]. Evidence for bulk RIED has been found in only one new experiment [24] since the Stresa IEA workshop in September 1993, where revised standard experimental conditions were defined. However, very few electron irradiations have been performed on sapphire since that time.

Definitive levels of bulk RIED have not been observed in high purity Al_2O_3 by several research groups during energetic ion or fission neutron irradiation. All ion and neutron irradiation experiments performed since the Stresa workshop have not observed bulk RIED. Some previous reports of RIED in ion and neutron irradiated specimens are due to surface leakage currents or specimen cracking. Postirradiation examination of the HFIR-TRIST-ER1 specimens should be performed to determine if any low-level RIED (i.e., below ~$5x10^{-7}$ S/m at 450°C) exists in the irradiated specimens. To aid in the interpretation of the HFIR and other reactor experimental results, some radiation-induced phenomena such as RIEMF and non-ohmic behavior should be studied using smaller reactors. The planned BR-1 and BR-10 reactor experiments (with vacuum environment) will provide additional important information concerning RIED under fission reactor irradiation.

Two models have been proposed to explain the RIED phenomenon under electron irradiation, based on Al colloid/gamma alumina formation and electrode charge injection, respectively. Neither model fully explains all of the available electron irradiation data on RIED.

RIED does not appear to be of immediate concern for near-term fusion devices such as ITER. However, continued research on the RIED phenomenon with particular emphasis on electron irradiations of single crystal alumina is warranted in order to determine the underlying physical mechanisms. This will allow a better determination of whether RIED might occur under any of the widely varying experimental conditions in a fusion energy device. Future studies on RIED should continue to follow the Stresa IEA workshop recommendations regarding essential features of the experimental technique [23], including careful measurement of surface and contact resistances. In addition, detailed postirradiation microstructural examination (SEM for cracks and TEM for bulk defects) should be performed and reported on all specimens exhibiting apparent RIED. Research is particularly recommended in two areas: (1) effects of AC or periodically reversed DC electric fields on the RIED process, and (2) vacuum/gas environmental effects (strong effects have been reported for the surface conductivity, but it is uncertain whether any effect on the bulk conductivity may occur).

Although RIED does not appear to be an issue for near-term fusion devices such as ITER, numerous experiments have highlighted technological problems which need to be considered in the reactor design. These issues include enhanced surface conductivity, crack propagation, and issues associated with the best way to terminate mineral insulated cables. Additional work is needed to determine if acceptable engineering designs can be made to accommodate these problem areas.

CRITICAL ISSUES AND RECOMMENDED FUTURE WORK

- The priority for future RIED studies should be on electron irradiation experiments on UV-grade sapphire
  — air vs. vacuum
  — field reversal effects (flipped sample and ac electric field)
  (Eric Hodgson agreed to supply unirradiated Union Carbide sapphire specimens to W. Kesternich and T. Terai for electron irradiation studies)

- Attention should be given to the various experimental problems which have been identified in recent RIED studies (specimen cracking, surface conductivity, MI cable terminations, etc.)
  — any relation to bulk RIED?
  — significance of these problems for ITER and future devices?

- Concerning the increase in electrical conductivity due to RIC, the most recent results have a tendency to give lower values of RIC. This could be interpreted that the more improved techniques will give more appropriate and lower values of RIC. Considering that the accumulated values of RIC do not always satisfy the ITER magnetic coil critera for ceramic insulators, namely conductivity lower than 10^{-6} S/m at 10 kGy/s, confident evaluation of RIC values by the most accurate experimental technique is recommended.

- Standardized dpa calculations for ceramics are urgently needed
- R&D on blanket insulator coatings is needed, although recent results were not discussed in the workshop
- The value of IFMIF was recognized, but details regarding effective utilization of such an irradiation source were not discussed in the workshop

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