1 of 1

ANL/MSD/CP - 88610
QW-930703 - 32

TENSILE AND SHEAR FRACTURE BEHAVIOR OF FIBER REINFORCED PLASTICS AT 77K IRRADIATED BY VARIOUS RADIATION SOURCES*

Karl Humer¹, Harald W. Weber¹, Elmar K. Tschegg², Shigenori Egusa³,
Robert C. Birtcher⁴, and Heiko Gerstenberg⁵

¹Atominstitut der Österreichischen Universitäten, A-1020 Wien, Austria

²Institut für Angewandte und Technische Physik, TU Wien, Austria

³Japan Atomic Energy Research Institute, Takasaki Radiation Chemistry
Research Establishment, Takasaki-shi, Japan

⁴Materials Science Division, Argonne National Laboratory, Argonne, IL

⁵Fakultät für Physik, E 21, TU München, D-8046 Garching, Germany

August 1993

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

SEP 07 1993
OSTI

Submitted to ICMC Albuquerque, Adv. Cryog. Eng. 40, Albuquerque, NM,
July 13-16, 1993.

*Work supported in part by the U. S. Department of Energy, BES-Materials Sciences, under Contract W-31-109-Eng-38 and the Federal Ministry of Science and Research, Vienna, Austria, under contract #77.800/2-25/92.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

87E

**TENSILE AND SHEAR FRACTURE BEHAVIOR
OF FIBER REINFORCED PLASTICS AT 77K
IRRADIATED BY VARIOUS RADIATION SOURCES**

Karl Humer,¹ Harald W. Weber,¹ Elmar K. Tschegg,² Shigenori Egusa,³
Robert C. Birtcher,⁴ and Heiko Gerstenberg⁵

¹Atominstitut der Österreichischen Universitäten, A-1020 Wien, Austria

²Institut für Angewandte und Technische Physik, TU Wien,
A-1040 Wien, Austria

³Japan Atomic Energy Research Institute, Takasaki Radiation Chemistry
Research Establishment, Takasaki-shi, Gunma 370-12, Japan

⁴Materials Science Division, Argonne National Laboratory,
Argonne, IL 60439, USA

⁵Fakultät für Physik, E 21, TU München, D-8046 Garching, Germany

ABSTRACT

The influence of radiation damage (gamma and neutrons) on the mechanical properties of fiber reinforced plastics (FRPs) has been investigated. Different types of FRPs (two or three dimensional E-, S- or T-glass fiber reinforcement, epoxy or bismaleimide resin) have been irradiated at room temperature with 2 MeV electrons and ⁶⁰Co γ-rays up to 1.8×10^8 Gy as well as with different reactor spectra up to a fast neutron fluence of $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$). Tensile and intralaminar shear tests were carried out on the irradiated samples at 77 K. Some samples were irradiated at 5 K and tested at 77 K with and without an annealing cycle to room temperature. The results on the influence of these radiation conditions and of the warm-up cycles on the mechanical properties of all FRPs are compared and discussed.

INTRODUCTION

In view of applications of fiber reinforced plastics (FRPs) as insulating materials for the windings of superconducting magnets in fusion reactors¹⁻³, the mechanical properties of these materials have to be tested both at low temperatures and under various loading conditions (e.g. tension and shear) as well as in a radiation environment expected at the

magnet location (γ -rays and neutrons up to doses of 10^3 - 10^9 Gy). It is well known that γ -rays and neutrons lead to different damage processes in polymer matrix composites^{4,5}. Hence, studies of the degradation behavior under pure γ - as well as under combined γ - and neutron irradiation are important. Several investigations of radiation damage in FRPs have been reported on previously⁶⁻¹⁷.

Some of the most important aspects¹⁸ of irradiation experiments on organic insulating materials should be emphasized. Firstly, the usual testing procedures, i.e. material irradiations in research (fission) reactors, do not provide us with the "right mixture" of radiation. Therefore, different reactor spectra should be investigated, in order to approximate the irradiation conditions of the FRPs in real fusion magnets as closely as possible. Secondly, the radiation damage will be introduced into the materials at the operating temperature of the magnet, i.e. at ≈ 5 K, and several thermal cycles to room temperature will occur over the life time of the magnet. Thirdly, because of space limitations in existing (low) temperature irradiation facilities, all of the mechanical tests have to be done on samples which are smaller than those of the established standards.

In view of this situation, a series of irradiation experiments has been initiated, the first results of which are reported on in the present paper. Different types of FRPs (two or three dimensional E-, S- or T-glass fiber reinforcement, epoxy or bismaleimide resin) have been irradiated at room temperature by 2MeV electrons and ^{60}Co -gamma rays up to 1.8×10^4 Gy and by different gamma and neutron fission spectra up to neutron fluences of $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1$ MeV) and γ -dose levels of $\approx 2 \times 10^8$ Gy. Mechanical tests in tensile and intralaminar shear (mode II) were carried out on the irradiated samples at 77 K, in order to investigate the influence of these different radiation environments on the mechanical properties. After 5K irradiation, some tensile samples were tested at 77 K with and without annealing cycles to room temperature.

SPECIMEN GEOMETRIES AND TEST PROCEDURES

As mentioned above, due to space limitations in existing (low temperature) irradiation facilities, all of the mechanical tests have to be done on small specimens, which can lead to serious problems. Whenever inhomogeneous materials (e.g. concrete) are tested, "size-effects" have to be investigated in much detail¹⁹. Earlier studies²⁰⁻²⁴ on various FRPs have shown that specific sample dimensions can indeed influence the measured mechanical quantities. Therefore, extensive scaling experiments were made at room temperature on tensile^{22,23} and intralaminar shear²⁵ samples, in order to select small specimen geometries for low temperature experiments on irradiated samples. These tests have shown only small variations (10-20%) of the ultimate tensile strength and of the specific fracture energy with sample dimensions and have, therefore, led to satisfactory results.

The geometry and the dimensions of both the tensile (smallest sample geometry in Ref.^{22,23}) and the rectangular mode II²¹ specimen, which is double-notched on both sides, have been presented elsewhere. For the selection of the mode II sample geometry, FEM calculations (for isotropic materials) have been employed. The results show that mostly shear conditions prevail ($\approx 95\%$) when the specimen is loaded²¹.

All mechanical tests were carried out at 77 K using a stiff tensile testing machine. In addition, a force-reversal arrangement was used for the mode II tests. The crosshead speed was kept constant at 0.5 mm min^{-1} throughout all experiments. During the tensile measurements, both the force and the sample elongation were recorded on an XY recorder.

The loading arrangement for the intralaminar shear test with a specimen in the test position has been shown and discussed in previous work^{21,25} as well. In this case, the specimen is placed onto a compressive plate and the load is applied vertically through a specially shaped stamp. During the measurements, the load-displacement curves are

recorded. The specific fracture energy as well as the specific fracture energy for crack initiation can be calculated based on the fracture energy concept. Details on the application of the fracture energy concept as well as the evaluation procedure are presented elsewhere^{21,25,26}. It should be pointed out that the recorded load-displacement curves represent the main test results, which contain all the information needed for the fracture mechanical characterization of FRPs (characteristic material parameters), if combined with FEM²⁵⁻²⁷.

MATERIALS

For the present experiments, both the tensile and the mode II specimens were cut from plates of the following FRPs: Two-dimensional woven S-glass fabric/epoxy ISOVAL 10/S (Isovolta AG, Wiener Neudorf, Austria) and CTD-101 (Composite Technology Development Inc., Boulder, USA); two-dimensional E-glass fabric/epoxy ORLITHERM N (Asea Brown Boveri Ltd., Zürich, Switzerland) and EPO-HGW (Elin Energieanwendung GesmbH., Weiz, Austria) as well as the three-dimensional T-glass fabric/epoxy and bismaleimide triazine resin ZI-003 and ZI-005 (Shikibo Ltd., Yokaichi-shi, Shiga, Japan).

In order to load the anisotropic FRPs in mode II in their weakest direction, the fiber orientation with the lower fiber content was chosen to be perpendicular to the notches of the specimens. Before testing a sample, the notches were sharpened with a razor blade. For the tensile tests, the samples were cut with their lengths parallel to the direction of the fiber orientation with the higher fiber content.

Whereas the sample thickness was 2 mm for all the mode II specimens, different sample thicknesses were used for the tensile tests (1 mm for CTD-101, ZI-003 and ZI-005; 2 mm for ISOVAL 10/S, ORLITHERM N and EPO-HGW). Two samples were measured for each data point.

TENSILE TESTS - VARIOUS RADIATION SOURCES

In order to obtain a first overview of the radiation response of all materials, 2 MeV electron irradiation (JAERI, Takasaki) was carried out at room temperature up to a dose of 1.8×10^8 Gy.

The results on the ultimate tensile strength (UTS) as a function of absorbed dose are summarized in Fig.1. Beginning with the three-dimensional fiber reinforced plastics (3DFRPs), we note that ZI-005 shows a higher radiation resistance than ZI-003. Whereas for the bismaleimide first degradations in the UTS (about 20%) are observed in the range from 1.4 to 1.8×10^8 Gy, significant degradation takes place in the epoxy already at 2.0 - 8.0×10^7 Gy. At higher dose levels, the epoxy is destroyed completely and the measured UTS results from the glass fibers, which are oriented in the direction of the tensile load. Hence, no further reduction of the UTS is observed at higher dose levels up to 1.8×10^8 Gy. The results on the 2DFRPs (all epoxies) demonstrate the influence of different compositions of the composite compounds (glass fibers and epoxies). CTD-101 shows the best values of the UTS at all doses and the final reduction amounts to about 35% at 1.8×10^8 Gy. Furthermore, different epoxy compositions lead to significantly different strength values (ORLITHERM N - EPO-HGW). For these FRPs, the reduction of the UTS amounts to about 70% and leads to unacceptable strength values at high doses. Finally, a comparison of the dose dependence reveals that the radiation resistance increases in the order EPO-HGW $\rightarrow$ ORLITHERM N $\rightarrow$ CTD-101 $\rightarrow$ ZI-003 $\rightarrow$ ZI-005.

Based on these results, the influence of different reactor spectra (gamma rays and neutrons) on the UTS was investigated for the "best" three FRPs. In this case, all samples

Figure 1. Ultimate tensile strength of ZI-005, ZI-003, CTD-101, ORLITHERM N and EPO-HGW as a function of the absorbed dose following room temperature irradiation with 2 MeV electrons and fracture at 77K.

were irradiated at room temperature at different radiation sources as follows: Up to neutron fluences of 1×10^{21} , 1×10^{22} and $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$) in the TRIGA Mark II reactor Vienna (γ -dose rate: $\approx 10^6 \text{ Gyh}^{-1}$), up to 1.5×10^{21} , 2.3×10^{21} and $7.8 \times 10^{21} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$) at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (γ -dose rate: $\approx 2 \times 10^4 \text{ Gyh}^{-1}$). Furthermore, pure ^{60}Co γ -irradiation was done (JAERI, Takasaki) up to absorbed doses of 3.6 and $36 \times 10^6 \text{ Gy}$ ($\approx 1.35 \text{ Mr h}^{-1}$). The dose dependence of the UTS measured on ZI-005, ZI-003 and CTD-101 under these conditions is shown in Fig.2. We note increasing radiation damage in the order of 2 MeV electrons $\rightarrow$ ^{60}Co γ -rays $\rightarrow$ TRIGA Vienna $\rightarrow$ IPNS Argonne for all composites investigated. However, the differences in the dose dependence are very small and the overall effects are in the range from 20% (CTD-101) to 40% (ZI-003). Again the bismaleimide resin shows better radiation resistance than the epoxies.

This remarkable agreement between different radiation environments can be attributed to the following two facts. Firstly, all of the reactor irradiation experiments made so far, were carried out on materials containing boron-free glass. Hence, the specific damage process related to the boron n, α -reaction did not contribute to the degradation of the tensile properties, even in the case of neutron irradiation. This aspect of the radiation environment is currently being investigated in a separate program. Secondly, due to the availability of detailed information on the neutron spectra of each irradiation source²⁸, the energy deposited by the neutrons in the resins could be assessed accurately through the computer code SPECTER²⁹. The corresponding procedure can be illustrated in the following way. For a resin with a composition of 15 wt% H, 75 wt% C, 3 wt% N, and 7 wt% O, irradiated in the TRIGA reactor to a fast neutron fluence of $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$), the energy deposited by the neutrons is calculated by the computer code for each constituent

Figure 2. Ultimate tensile strength of ZI-005, ZI-003 and CTD-101 as a function of the total absorbed dose following room temperature irradiation with different spectra and fracture at 77K. UTS_0 is the ultimate tensile strength prior to irradiation.

individually and then added up. The results for the above resin and fluence (which corresponds to a *total* fluence of $1.38 \times 10^{23} \text{ m}^{-2}$) are as follows: H - $1.7 \times 10^8 \text{ Gy}$, C - $1.3 \times 10^7 \text{ Gy}$, N - $1.9 \times 10^6 \text{ Gy}$, O - $1.1 \times 10^5 \text{ Gy}$, i.e. a total of $1.85 \times 10^8 \text{ Gy}$. In addition, during the irradiation time of 183 hours needed to achieve the above fluence of neutrons, a gamma dose of $1.83 \times 10^8 \text{ Gy}$ was accumulated, i.e. the total dose (gamma and neutrons) amounts to $3.68 \times 10^8 \text{ Gy}$. For this radiation source and for this particular composition of the test material, both kinds of radiation contribute $\approx 50\%$ to the total dose. For another material, e.g. one with 5 wt% H, 73 wt% C, 10 wt% N, and 12 wt% O, the relative contributions are significantly different and amount to $0.76 \times 10^8 \text{ Gy}$ (neutrons 30%) and to $1.82 \times 10^8 \text{ Gy}$ (gammas 70%), i.e. a total of $2.58 \times 10^8 \text{ Gy}$ under exactly the same irradiation conditions.

5 K IRRADIATION AND ANNEALING EFFECTS

Irradiation experiments employing low temperature irradiation and testing at 77 K with and without an annealing cycle to room temperature were done as well. Some tensile samples (ZI-005, ZI-003 and CTD-101) were irradiated at the 5 K-irradiation facility of the FRM Munich up to neutron fluences of 1×10^{21} , 1×10^{22} and $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1 \text{ MeV}$, γ -dose rate $2.8 \times 10^6 \text{ Gyh}^{-1}$). After 5 K irradiation, some of the samples were subjected to a warm-up cycle ($\approx 1 \text{ h}$ at room temperature) before testing at 77 K. The results are summarized in Fig.3. No systematic influence of the annealing cycle could be detected. In addition, the degradation of the ultimate tensile strength is almost identical to the one observed upon room temperature irradiation of the same materials.

SHEAR TESTS - FIRST RESULTS

Shear specimens made of ZI-005, ZI-003, CTD-101 and ISOVAL 10/S were irradiated at room temperature in the TRIGA reactor Vienna under the same conditions as described above for the tensile tests. The mechanical tests were carried out at 77 K and the values of the specific fracture energy for crack initiation were calculated from the measured load-displacement curves. The results are shown in Fig.4. No significant difference in the dose dependence of the specific fracture energy is observed between all the materials investigated. In comparison to the tensile test results, a considerably stronger degradation behavior is noticed and the decrease of the specific fracture energy amounts to about 70% at a dose level $\leq 10^8 \text{ Gy}$. Evaluations of the specific fracture energy in terms of the shear strength are currently under way.

SUMMARY

Radiation effects in glass fiber reinforced plastics have been identified as an area of concern for the long-term operation of superconducting magnets in fusion reactors. A successful material characterization program for this particular application must take into account the specific radiation environment expected at the magnet location, the dose level expected over the whole plant lifetime ($\approx 5 \times 10^{22} \text{ m}^{-2}$, $E > 0.1 \text{ MeV}$; $\approx 5 \times 10^8 \text{ Gy}$ total), the fact that the damaging process occurs at low temperatures and finally the fact that the magnet will have to be warmed up to room temperature several times during the plant lifetime. In addition, because of the very large variety of materials (type of reinforcement and resin system), a broad spectrum of composites has to be investigated for material selection purposes.

In view of this situation, a series of irradiation experiments has been started, the first

Figure 3. Ultimate tensile strength of ZI-005, ZI-003 and CTD-101 as a function of the total absorbed dose following 5K irradiation (neutrons and γ -rays) with and without a warm-up cycle to room temperature before testing at 77K.

Figure 4. Specific fracture energy for crack initiation G_F of ZI-005, ZI-003, CTD-101 and ISOVAL 10/S as a function of the total absorbed dose following room temperature irradiation with neutrons and γ -rays (TRIGA reactor, Vienna) and fracture at 77K. G_{F0} is the fracture energy for crack initiation prior to irradiation.

results of which may be summarized as follows. Different types of FRPs (two or three dimensional E-, S- or T-glass fiber reinforcement, epoxy or bismaleimide resin) were irradiated at room temperature with 2 MeV electrons and ^{60}Co γ -rays up to 1.8×10^8 Gy and with different reactor spectra up to fast neutron fluences of $5 \times 10^{22} \text{ m}^{-2}$ ($E > 0.1$ MeV). Tensile and intralaminar shear tests were carried out on the irradiated samples at 77 K.

The main results of these irradiation experiments are the following:

1. With regard to material selection, the three-dimensional fiber reinforcement and the bismaleimide resin show higher radiation resistance than the two-dimensional reinforcement and the epoxies under tensile loading conditions. The decrease of the ultimate tensile strength varies between 35 % and 70 %.
2. With regard to the influence of the radiation spectrum (electrons, neutrons and/or γ -rays) on the ultimate tensile strength, no significant difference in the dose dependence is observed and the overall effects are between 20 and 40% in the "best" materials.

3. This "scaling" of the ultimate tensile strength data with absorbed dose is attributed to a correct assessment of the energy deposited by the neutrons and to the absence of boron in the reinforcing glass.
4. Tensile tests made after 5 K irradiation do not differ significantly from the results obtained after room temperature irradiation. This holds for "cold-transfer" tests (5K → 77K) as well as for tests including an annealing cycle to room temperature (5K → 293K → 77K).
5. The intralaminar shear tests have shown no significant difference in the dose dependence of the specific fracture energy in all the materials investigated. In comparison to the tensile test results, a considerably stronger degradation behavior is found and the decrease of the specific fracture energy amounts to about 70% at the highest dose.

In conclusion, the enormous degradation observed in the *intralaminar* shear tests at comparatively low doses are believed to emphasize the importance of additional work on the fracture behavior in mode I and mode II, which should be complemented by experiments on the *interlaminar* shear behavior.

ACKNOWLEDGEMENTS

The authors are greatly indebted to Asea Brown Boveri Ltd., Zürich, Switzerland (ORLITHERM N); Composite Technology Development Inc., Boulder, Colorado, USA (CTD-101); Elin Energieanwendung GesmbH., Weiz, Austria, (EPO-HGW); Isovolta AG, Wiener Neudorf, Austria, (ISOVAL 10/S); and Shikibo Ltd., Yokaichi-shi, Shiga, Japan (ZI-003 and ZI-005), for providing us with the test materials. Technical support by Mr. H. Niedermaier and Mr. E. Tischler is acknowledged. This work is supported in part by the Federal Ministry of Science and Research, Vienna, Austria, under contract # 77.800/2-25/92.

REFERENCES

1. B.S. Brown, Radiation effects in superconducting fusion-magnet materials, *J. Nucl. Mat.* 97:1 (1981).
2. "Insulators for Fusion Applications", IAEA-TECDOC-417, IAEA, Vienna (1987).
3. R.R. Coltman, jr., Organic insulators and the copper stabilizer for fusion reactor magnets, *J. Nucl. Mat.* 108&109:559 (1982).
4. S. Egusa, M.A. Kirk, and R.C. Birtcher, Effects of neutron irradiation on polymer matrix composites at 5K and at room temperature, I. Absorbed dose calculation, *J. Nucl. Mat.* 148:43 (1987).
5. S. Egusa, M.A. Kirk, and R.C. Birtcher, Effects of neutron irradiation on polymer matrix composites at 5K and at room temperature, II. Degradation of mechanical properties, *J. Nucl. Mat.* 148:43 (1987).
6. S. Egusa and M. Hagiwara, Mechanical properties of polymer matrix composites at 77 K and at room temperature after irradiation with ⁶⁰Co γ-rays, *Cryogenics* 26:417 (1986).
7. G.F. Hurley and R.R. Coltman, jr., Organic materials for fusion reactor applications, *J. Nucl. Mat.* 122&123:1327 (1984).
8. S. Nishijima, T. Okada, T. Hirokawa, J. Yasuda, and Y. Iwasaki, Radiation damage of organic composite material for fusion magnet, *Cryogenics* 31:273 (1991).
9. S. Egusa, Anisotropy of radiation-induced degradation in mechanical properties of fabric-reinforced polymer-matrix composites, *J. Mat. Sci.* 25:1863 (1990).
10. R.R. Coltman, jr. and C.E. Klabunde, Mechanical strength of low-temperature-irradiated polyimides: A five-to-tenfold improvement in dose resistance over epoxies, *J. Nucl. Mat.* 103&104:7 (1981).
11. S. Egusa, Effects of neutrons and gamma-rays on polymer matrix composites as low-temperature materials, *Radiat. Phys. Chem.* 37:147 (1991).
12. S. Egusa, M.A. Kirk, R.C. Birtcher, and M. Hagiwara, Annealing effects on the mechanical properties of organic composite materials irradiated with gamma-rays, *J. Nucl. Mat.* 127:146 (1985).

13. S. Nishijima and T. Okada, Low temperature irradiation effects on mechanical properties of epoxy used in superconducting magnets, *Cryogenics* 18:215 (1978).
14. S. Egusa, Radiation resistance of polymer composites at 77K: Effects of reinforcing fabric type, specimen thickness, radiation type and irradiation atmosphere, *Cryogenics* 31:7 (1991).
15. H.W. Weber, E. Kubasta, W. Steiner, H. Benz, and K. Nylund, Low temperature neutron and gamma irradiation of glass fiber reinforced epoxies, *J. Nucl. Mat.* 115:11 (1983).
16. R.E. Fornes, J.D. Memory, and N. Naranong, Effect of 1.33 MeV γ - radiation and 0.5 MeV electrons on the mechanical properties of graphite fiber composites, *J. Appl. Poly. Sci.* 26:2061 (1981).
17. S. Egusa, M.A. Kirk, R.C. Birtcher, and M. Hagiwara, Neutron and γ -ray irradiation effects in composite organic insulators, *J. Nucl. Mat.* 133&134:795 (1985).
18. H.W. Weber, and E.K. Tschegg, Test program for mechanical strength measurements on fiber reinforced plastics exposed to radiation environments, *Adv. Cryog. Eng.* 36:863 (1990).
19. P. Zdenek, and P. Bazant, Size effect in blunt fracture-concrete, rock, metal, *J. Eng. Mech.* 110:518 (1984).
20. E.K. Tschegg, K. Humer, and H.W. Weber, Fracture-mechanical characterization of fiber reinforced plastics in the crack-opening-mode (mode I), *Adv. Cryog. Eng.* 38A:387 (1992).
21. E.K. Tschegg, K. Humer, and H.W. Weber, Shear fracture tests (mode II) on fiber reinforced plastics at room and cryogenic temperatures, *Adv. Cryog. Eng.* 38A:355 (1992).
22. E.K. Tschegg, K. Humer, and H.W. Weber, Influence of test geometry on tensile strength of fiber reinforced plastics at cryogenic temperatures, *Cryogenics* 31:312 (1991).
23. K. Humer, E.K. Tschegg, H.W. Weber, K. Noma, J. Yasuda, and Y. Iwasaki, Specimen size effect on tensile strength of three-dimensionally glass-fabric reinforced plastics at room and cryogenic temperatures, *Cryogenics* 33:162 (1993).
24. K. Humer, E.K. Tschegg, and H.W. Weber, Specimen size effect and fracture mechanical behavior of fiber reinforced plastics in the crack opening mode (mode I), *Cryogenics (ICMC Supplement)* 32:14 (1992).
25. E.K. Tschegg, K. Humer, and H.W. Weber, Fracture tests in mode II on fiber reinforced plastics, *J. Mat. Sci.*, to be published
26. E.K. Tschegg, K. Humer, and H.W. Weber, Fracture tests in mode I on fibre reinforced plastics, *J. Mat. Sci.* 28:2471 (1993).
27. K. Humer, E.K. Tschegg, and H.W. Weber, Small specimens and new testing techniques for fiber reinforced plastics in the crack opening mode (mode I) and in the shear mode (mode II), *Adv. Cryog. Eng.* to be published
28. H.W. Weber, H. Böck, and E. Unfried, Neutron dosimetry and damage calculations for the TRIGA Mark-II reactor in Vienna, *J. Nucl. Mat.* 137:236 (1986).
29. L.R. Greenwood and R.K. Smither, SPECTER: Neutron damage calculations for materials irradiations, ANL/FPP/TM-197 (1985).

**DATE
FILMED**

11 / 5 / 93

END