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PARTICLE-INDUCED AMORPHIZATION of COMPLEX CERAMICS

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FINAL REPORT (DE-FG03-93ER45498)
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PARTICLE-INDUCED AMORPHIZATION OF
COMPLEX CERAMICS

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ABSTRACT

The crystalline-to-amorphous (c-a) phase transition is of fundamental importance. The c-a transition has important technological applications because amorphous materials may have increased hardness, are more resistant to corrosion and oxidation, may be used in opto-electronic devices, have high magnetic permeabilities and electrical resistivities, and radiation-induced damage cascades can be used for flux pinning of high T_c superconductors. Additionally, in the geosciences many geochronological isotopic techniques are affected by radiation damage, and in nuclear waste management amorphization is one of the most important considerations in evaluating the long term durability of a nuclear waste form.

Particle irradiations provide an important, highly controlled means of investigating this phase transformation and the structure of the amorphous state. The interaction of heavy-particles (α -recoil nuclei, fission fragments and implanted ions) with ceramics is complex because these materials have a wide range of structure types, complex compositions, and because chemical bonding is variable (not only from structure-type to structure-type, but also within a single structure). Radiation damage and annealing can produce diverse results, but most commonly, single crystals become aperiodic (the metamict state) or break down into a polycrystalline aggregate (sometimes not the same as the original phase). We continued our studies of the transition from the periodic-to-aperiodic state in natural materials that have been damaged by α -recoil nuclei in the uranium and thorium decay series and in synthetic, analogous structures. The transition from the periodic to aperiodic state was followed by detailed x-ray diffraction analysis, *in-situ* irradiation/transmission electron microscopy, high resolution transmission electron microscopy, extended x-ray absorption fine structure spectroscopy/x-ray absorption near edge spectroscopy and other spectroscopic techniques. These studies continued to utilize ion beam irradiations completed at the HVEM- and IVEM-Tandem Facilities at Argonne National Laboratory. These studies were completed in conjunction with bulk irradiations that can be completed at Los Alamos National Laboratory or Sandia National Laboratories.

Principal questions addressed in this research program included:

- (1) What is the process at the atomic level by which a ceramic material is transformed into a disordered or aperiodic state?
- (2) What are the controlling effects of structural topology, bond-type, dose rate, and irradiation temperature on the final state of the irradiated material?
- (3) What is the structure (at the nearest-neighbor atomic scale and at the scale of fundamental structural units) of the partially- and fully-damaged material?
- (4) What are the mechanisms and kinetics for the annealing of interstitial and aggregate defects in these irradiated ceramic materials?
- (5) What general criteria may be applied to the prediction of amorphization in complex ceramics?

INTRODUCTION

During the past decade, there has been increased interest in the solid-state crystalline-to-amorphous (c-a) transition (Schwardz and Johnson, 1988; Okamoto and Meshii, 1988; Wang and Ewing, 1992a), now considered a phenomenon as fundamental as the crystallization or melting of solids (Mansur, 1991; Fecht and Johnson, 1988; Lam Okamoto, 1994; Motta, in press). Amorphous materials, especially amorphous alloys and intermetallic compounds, are often characterized by high hardness, corrosion and oxidation resistance, and high magnetic permeabilities and electrical resistivities. A more fundamental understanding of the c-a transformation in materials is needed, not only because of the consequences on materials performance, but also because of the potential for developing a basic understanding of the phase stability of crystalline materials. Indeed, pressure-induced amorphization (Hemley et al., 1988, 1989; Handa et al., 1991; Kruger et al., 1992; Tse and Klug, 1992; Guyot and Reynard, 1992) has been an area of active research because of improved, high-pressure experimental capabilities and the implications for the phase petrology of the Earth's mantle. Heavy particle irradiations provide a controlled means of studying this important phase transformation. This proposal outlines a program to study the effects of structure/bonding, cascade energy, defect accumulation and temperature on the amorphization of complex ceramic materials in order to develop a more complete view of the amorphization process.

"Complex" ceramics, for the purpose of this proposal, include materials that are generally strongly bonded (mixed ionic and covalent), refractory and frequently good insulators. They are distinguished from simple, compact ceramics (e.g., MgO and UO₂) by structural features which include: 1.) open network structures, best characterized by a consideration of the shape, size and connectivity of coordination polyhedra; 2.) generally, complex compositions which characteristically lead to multiple cation sites and lower symmetry; 3.) directional bonding; 4.) bond-type variations, from bond-to-bond, within the structures. The response of these materials to irradiation is complex, as energy may be dissipated ballistically by transfer of kinetic energy from an incident projectile or radiolytically by conversion of radiation-induced electronic excitations into atomic motion. This results in isolated Frenkel defect pairs, defect aggregates, isolated collision cascades or bulk amorphization: all may occur concurrently. The amorphization process is heterogeneous. The transition from the periodic-to-aperiodic state is not only governed by the damage process and the accumulation of isolated defects and defect aggregates (collision cascades or thermal spikes), but also by the mechanisms and kinetics of relaxation and annealing. Impurities, diffusion of defects and phase transformations may all affect the end-result of heavy-particle and ceramic interactions. Numerous reviews of radiation effects in ceramics are available (Matzke and Whitten, 1966; Wilks, 1968; Hobbs, 1979; Kelly, 1981; Matzke, 1982, 1992; Crawford and Slifkin, 1972; Weber and Roberts, 1983; Clinard and Hobbs, 1986; White et al., 1989; McHargue, 1991; Mansur, 1991; Nastasi and Mayer, 1991; Ewing, 1994; Hobbs et al., 1994). Most recently the importance of radiation effects on materials in high-radiation environments has been summarized by Weber et al. (1991a). The research of our group has focused on the systematic examination of complex ceramics as a function of ion dose and temperature (Ewing et al., 1995a).

The completed work at the University of New Mexico is particularly timely, as now there are a number of recent ideas and hypotheses that have been proposed to explain the

amorphization process (see recent summary by Motta (in press)). Most notably these include the study of topological controls on amorphization by Hobbs (1995; Hobbs et al., 1996) and a thermodynamic approach by Lam and Okamoto at Argonne National Laboratory (1994) in which solid-state amorphization is considered a process similar to melting. However, these models have not been well tested and may not be easily applied for multi-cation, complex ceramic materials. Our data can be used to test and extend these models. In our proposal, we will continue to investigate structure and bonding effects (Ewing et al., 1995a, Wang et al. 1995, Wang et al., 1996), as well as thermodynamic controls (Gong et al., 1996a, 1996b) on amorphization. We have also initiated a study of the properties of glass (as compared to the crystalline solid) in determining whether particular compositions are more susceptible to amorphization (Wang, S. et al., in press and submitted). We have also initiated a number of studies to investigate the effects of ionizing radiation on defect formation and migration during heavy-particle irradiations.

Previously, three approaches have been used in the study radiation effects and radiation-induced amorphization in ceramics. This work has been reviewed in detail by Hobbs et al., 1994 and Ewing et al. 1995 and is briefly summarized in this proposal.

(1) Mineralogists and materials scientists (Broegger, 1890; Pabst, 1952; Ewing, 1975; Ewing and Haaker, 1980; Lumpkin et al., 1986; Bhandari et al., 1971; Bursill and McLaren, 1966; Fleischer et al., 1964, 1965, 1975; Yada et al., 1981, 1987; Chakoumakos et al., 1987; Lumpkin and Ewing, 1988a; Murakami et al., 1991; Hawthorne et al., 1991; Warner and Ewing, 1993; Eby et al., 1993; Farges et al., 1993; Ewing, 1994; Ellsworth et al., 1994; Lumpkin and Ewing, 1995; Meldrum et al., 1996) have studied the effect of α -recoil nuclei and fission fragments on natural materials. In the mineralogical literature, the resulting aperiodic structure is known as the metamict state. The materials typically have complex compositions, but with structure types that are important in a wide variety of technological applications (e.g., the pyrochlore structure type which has diverse applications (Chakoumakos, 1984). Doses may reach values as high as 10^{17} α -events/mg which is equivalent to >50 displacements per atom (dpa), and there is a regular change in the structural and physical properties of the material with increasing dose (e.g. Holland and Gottfried, 1955; Murakami et al., 1986a; Lumpkin & Ewing, 1988a; Chakoumakos et al., 1989; Murakami et al., 1991; Hawthorne et al., 1991). The study of natural materials is restricted to those which contain U and Th and is limited by the number and types of samples available and the fact that samples with doses in the narrow range of interest (e.g. the crystalline-to-amorphous transformation) sometimes cannot be found. Alteration and thermal annealing complicate the interpretation of microstructures found in natural materials (Ewing et al., 1988; Lumpkin and Ewing, 1988a; Lumpkin and Chakoumakos, 1988; Ewing and Headley, 1983; Headley et al., 1981; Murakami et al., 1991; Lumpkin and Ewing, 1995).

(2) Radiation damage in materials analogous to those found in nature have been experimentally studied using actinide doping experiments (Chick et al., 1979; Wald and Offermann, 1982; Turcotte, 1981; Turcotte et al., 1982; Weber et al., 1980, 1982, 1985, 1986, 1994; Weber, 1982, 1983b, 1990, 1991, 1992; Clinard et al., 1982, 1984a, 1984b, 1986; Weber and Maupin, 1988; Weber and Gregor, 1990). The experiments which most closely produce the effects observed in natural materials reach doses as high as 10^{26} α -events/m³ ($= 10^{16}$ α -events/mg). Comparisons with observations for natural materials have been made for zirconolite (Ewing and Headley, 1983; Lumpkin et al., 1986; White et al.,

1995), pyrochlore (Lumpkin et al., 1986; Lumpkin and Ewing, 1988a) and zircon (Headley et al., 1982; Headley and Ewing, 1986; Murakami et al., 1986a, 1991; Weber and Maupin, 1988; Weber, 1990, 1991; Weber et al., 1994). Perhaps the most striking feature of the comparison of damage ingrowth (as determined by volume expansion or the reduction in x-ray diffraction intensity) is the great similarity between the curves for Pu-doped zircon and natural zircon (Weber et al., 1994). The slight differences in measured properties (i.e., density or diffraction intensity) is a result of the slightly different energies of the recoil nuclei, the method of dose calculation, and most importantly, the long-term annealing of isolated defects in the early stages of damage accumulation in the natural zircon (Weber and Maupin, 1988; Murakami et al., 1991). These data have been the basis for the performance assessment of zircon as a waste form for plutonium (Weber et al., 1996).

(3) The crystalline-to-amorphous transition in complex oxides has also been studied by an array of irradiation techniques, including heavy-ion bombardment (Cartz and Fournelle, 1979; Cartz et al., 1980, 1981a, 1981b; Karioris et al., 1981; Bursill and Braunshausen, 1990; Eby et al. 1992; Wang et al. 1991-1995; Weber and Wang, 1994), ion implantation (Dran et al., 1980, 1981; Headley et al., 1982; Petit et al., 1987; White et al., 1989; Weber et al., 1992); fast neutron irradiation (Crawford and Wittels, 1956; Reeve and Woolfrey, 1980); thermal neutrons, that is radiation effects due to (n, α) reactions (Vance et al., 1982); fission fragment damage (Krishnaswami et al., 1974; Vance and Boland, 1975; Vance and Pillay, 1980).

There has been great interest in the formation of the aperiodic state in intermetallics and ceramics as a result of ion beam interactions (Naguib and Kelly, 1975; Kelly, 1981; Matzke, 1982; Arnold and Borders, 1984; Mazzoldi and Arnold, 1987; Okamoto et al., 1988; White et al., 1989; Birtcher and Wang, 1991; Nastasi and Mayer, 1991; Wang and Ewing, 1992a, b, c; Lam and Okamoto, 1994). This work is summarized by McHargue et al. (1986) in the proceedings volume of a Symposium on Irradiation Effects Associated with Ion Implantation (Andersen and Picraux, 1986). The most thorough review of ion implantation effects for oxides is given by White and co-workers (1989) and for intermetallic compounds by Nastasi and Mayer (1991). Walter Brown (1988) has summarized very eloquently "the many faces" of such interactions in insulating materials, and the implications for technological applications in thin film devices are profound.

One of the striking features of these reviews is the limited number of oxide structure types that have been studied by ion implantation/irradiation. Most of the previous work has concentrated on Al_2O_3 , ABO_3 structure-types, MgO and ZnO . Although there has been considerable work on the complex ceramic, spinel - MgAl_2O_4 , because of its radiation "resistance" (Zinkle et al., 1990; Kinoshita et al., 1995; Sickafus et al., 1995), it is possible to introduce disorder and even amorphize spinel (Yu et al., 1994; Bordes et al., 1995a, b; Devanathan et al., 1995).

Still, for most other complex ceramics, many of the systematic studies of their behavior as a function of bond-type, structure type, and temperature (Wang et al., 1991; Weber et al., 1991; Eby et al., 1992; Wang and Ewing, 1992; Wang et al., 1993; Wang et al., 1994a; Ewing et al., 1995; Wang et al., 1995) have been completed at the University of New Mexico. Ion implantation of these phases shows very clearly the potential application of ion implantation combined with Rutherford backscattering-channeling experiments (McHargue et al., 1986) and analytical electron microscopy (Bentley, 1986) to more

complex phases. Chakoumakos et al. (1989) have shown a striking similarity between the effect of α -recoil damage in natural zircons and Pb-implanted synthetic zircons; and Murakami et al. (1991) have demonstrated the similarity between damage effects observed in natural zircon and Pu-doped zircon (Weber et al., 1994). These studies are a first step in understanding damage effects caused by a variety of irradiations (e.g. natural radioactive decay, actinide-doping experiments and ion irradiation).

RESEARCH PROGRAM RESULTS (1993-1997)

The presently funded three-year research program, supported by the Division of Materials Sciences of the Office of Basic Energy Sciences, was initiated on August 1, 1993; during the period in which the grant will have been active, \$249,561 of support have been provided to date with an additional \$79,723 to be spent during the third, final year (ending July 30, 1996). Additionally, we will complete the first year (\$107,000) of a three year program (initiated on August 1, 1996) at the University of New Mexico. The subsequent years (this proposal) will be completed at the University of Michigan. The primary purpose of the program is to develop an understanding of heavy-particle radiation effects -- α -recoil nuclei, fission fragments, ion-irradiations -- on ceramic materials and the thermal annealing mechanisms by which crystallinity might be restored. During the past two years, we have completed major studies on zircon (ZrSiO_4), olivine (Mg_2SiO_4 and ten other compositions), spinel (MgAl_2O_4 and four other compositions), and silica polymorphs (quartz, coesite and stishovite), as well as berlinite (AlPO_4) which is isomorphous with quartz. During the past year we have initiated studies of phases in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ and a wide variety of phases with the monazite and zircon structure-types.

The work on zircon was particularly important in that we established the efficacy of actinide-doping and heavy-ion beam irradiations as techniques to simulate long-term damage (over hundreds of millions of years) of complex ceramics (Weber et al., 1994). Zircon is probably the most useful naturally occurring phase for such studies. Based on this fundamental research program, we (Ewing et al., 1995) proposed the use of zircon as a host phase of the immobilization of the plutonium that results from the dismantlement of nuclear weapons. The University of New Mexico and PNNL have received a patent for this idea (August 13, 1996). This proposal generated considerable interest, particularly abroad, where zircon and monazite (CePO_4) are candidate materials for inert fuel matrices for the "burning" of actinides separated during reprocessing of nuclear fuel. Our proposal was cited by BES/DOE as having a "Significant Implication for Department of Energy Related Technologies" in the Metallurgy and Ceramics category of the 1995 Materials Science Research Competition. It was gratifying to see basic research find an important application. We are presently pursuing the applied aspects of this work with support from Los Alamos National Laboratory. The basic research will continue but with a focus on monazite, probably the only other naturally occurring phase for which such study is practical. This is the basis of the Ph.D. dissertation of Al Meldrum.

The work on olivine (HCP derivative structure) and spinel (CCP structure) was in large part completed and a major manuscript has been prepared (Wang et al., submitted). Preliminary results were summarized in Ewing et al. (1995). The very close structural relation between these phases, as well as the wide compositional variety of these phases, allowed us to examine structural and bonding controls on radiation-induced amorphization. One important finding of this study is that the dose required for amorphization of a particular crystal structure may vary greatly with the changing composition. For compositions with the same structure-type, parameters such as bond ionicity, melting temperature, Debye temperature and free energy of formation may all be used as criteria for predicting the relative susceptibility for amorphization to a great extent. However, these criteria fail when comparing different structure-types. In close collaboration with LANL,

we have made the observation that MgAl_2O_4 can be amorphized at low temperatures by a disordering process (Bordes et al., 1995b) after very high doses. The most interesting and important result was that irradiation "resistant" structure types, such as spinel, can be easily amorphized by changing the composition. This was determined on an Fe-Si-spinel which is thermodynamically unstable under normal pressure condition (Wang et al., 1995). The results mean that thermodynamic stability, bonding type and strength, in addition to topological stability, play important roles in determining the "irradiation resistance" of a material. The success of this approach will serve as a basis for the systematic study of silicates, phosphates and vanadates of the tetragonal zircon and the monoclinic monazite structure-types by Al Meldrum. Universal criteria for amorphization, which may be a combination of several material parameters, can only be determined when more data from this type of systematic study become available.

In addition to these major studies, we continued work on a variety of complex ceramics: 1.) pyrochlores (Lumpkin and Ewing, 1995); 2.) zirconolite (Farges et al., 1993; White et al., 1995); samarskite (Warner and Ewing, 1993); vesuvianite (Eby et al., 1993); berlinite (Bordes and Ewing, 1995); monazite (Meldrum et al., 1995); TI-type high temperature superconductors (Wang et al., 1994b; Newcomer et al., 1996). Additionally, we have sought to apply our results to other fields, such as geochronology (Onstott et al., 1995) and nuclear waste disposal (Weber and Ewing, 1995). Some of these results are high-lighted in this proposal, and selected publications are included in the Appendix.

The analytical techniques used in the research program have involved: (1) detailed x-ray diffraction analysis, XRD, (2) high resolution transmission electron microscopy, HRTEM, (3) extended x-ray absorption fine structure spectroscopy, EXAFS, (4) x-ray absorption near edge structure, XANES, (5) complete electron microprobe analysis, EMPA, (6) scanning electron microscopy, SEM, (7) differential thermal analysis and differential scanning calorimetry, DTA/DSC, (8) thermal gravimetric analysis, TGA, (9) instrumental neutron activation analysis, INAA and (10) *in situ* TEM analysis during ion irradiations. It is important to note that the HVEM- and IVEM- Tandem Facility at Argonne National Laboratory has become an essential facility for our research program.

As part of this research program, Professor Ewing was a co-organizer of the Materials Research Society symposium, "Scientific Basis for Nuclear Waste Management XVIII", held in Kyoto, Japan in October of 1994, a member of the program committee for the 1996 meeting in Boston, and a member of the program committee for the 1997 meeting to be held in Davos, Switzerland. Ewing was a co-organizer of the symposium "Radiation Effects in Ceramics" of the Minerals Metals Materials Society Meeting held in Las Vegas in February of 1995, a member of the program committee for IBMM-96 held in Albuquerque in September of 1996, a member of the program committee for the "Plutonium Futures -- The Science" meeting to be held in Santa Fe, New Mexico in August of 1997 and a member of the program committee for REI-9 to be held in Knoxville, Tennessee in 1997.

During 1996, the most important activities included organization of the following meetings:

"Radiation Effects in Glasses Used for Immobilization of High-Level Waste and Plutonium Disposition" (co-chair with W.J. Weber): A panel convened by the Council on Materials Science, Department of Energy, February 25-29, 1996.

ion irradiated Tl-type high temperature superconductors. *Physica C, Superconductivity*, vol. 267, 243-253.

Hj. Matzke and L.M. Wang (1996) High-resolution transmission electron microscopy of ion irradiated UO_2 , *Journal of Nuclear Materials*, vol. 231, 155-161.

W.L. Gong, L.M. Wang, R.C. Ewing and J. Zhang (1996) Electron and ion beam-induced amorphization of coesite, *Physical Review B*, vol. 54(6), pages 3800-3808.

S.X. Wang*, L.M. Wang, R.C. Ewing and R.H. Doremus (in press) Ion irradiation-induced amorphization in the $\text{Al}_2\text{O}_3\text{-SiO}_2$ system: A comparison with glass formation, *Journal of Applied Physics*.

W.L. Gong, L.M. Wang and R.C. Ewing (in press) Interface-mediated amorphization of coesite by 200 keV electrons, *J. Applied Physics*.

A. Meldrum*, L.A. Boatner, L.M. Wang and R.C. Ewing (in press) Ion-beam-induced-amorphization of LaPO_4 and ScPO_4 , *Nuclear Instruments and Methods in Physics Research B*.

S.X. Wang*, L.M. Wang, and R.C. Ewing (in press) Amorphization of Al_2SiO_5 polymorphs under ion beam irradiation, *Nuclear Instruments and Methods in Physics Research B*.

Y.X. Guo, L.M. Wang, and R.C. Ewing (in press) Ion-beam-irradiation induced structure transformation in $\alpha\text{-AlMnSi}$, *Nuclear Instruments and Methods in Physics Research B*.

L.F. Chen, L.M. Wang, and R.C. Ewing (in press) Ion irradiation of Al-Cu-Co-Ge alloy: a decagonal quasicrystal, *Nuclear Instruments and Methods in Physics Research B*.

A. Meldrum*, L.M. Wang, Y.X. Guo and R.C. Ewing (submitted) Electron irradiation-induced phase segregation in crystalline and amorphous fluorapatite, *American Mineralogist*.

S.X. Wang*, L.M. Wang, R.C. Ewing and R.H. Doremus, Ion-beam-induced amorphization and glass formation, a case study of Al-Mg-Si oxide system—Part I: Experimental (submitted) *Journal of Noncrystalline Solid*.

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A. Meldrum*, L.A. Boatner and R.C. Ewing (submitted) Electron-irradiation-induced nucleation and growth in amorphous LaPO₄, ScPO₄ and zircon. *Journal of Materials Research*.

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R.C. Ewing and J. Akimoto (1995) "The Metamict State" in Higher Mineralogy. A.S. Marfunin, Ed., Springer-Verlag, Germany.

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Rodney C. Ewing and W. Lutze [guest editors] (1994) Special Issue on Nuclear Waste Disposal. *Materials Research Society Bulletin*, vol. XIX, no. 12, 72 pages.

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Abstracts

(over 70 abstracts were published during the period 1993 to present)

Invited Presentations

- "The Future of Mineralogy: The Role of Materials Science" (R.C. Ewing): Aarhus University, Denmark, March 1, 1993.
- "Radiation Effects in Minerals and Ceramics: The Centennial" (R.C. Ewing): Aarhus University, Denmark, March 3, 1993.
- "Radiation-Induced Amorphization of Materials" (R.C. Ewing): Princeton Materials Institute symposium on "Materials Under Extreme Conditions", Princeton University, May 17, 1993.
- "Radiation Effects in Nuclear Waste Forms" (R.C. Ewing): International Summer School on the Fundamentals of Radiation Damage, University of Illinois at Urbana Champaign, August 4, 1993.
- "The Metamict State: 1993 - The Centennial" (R.C. Ewing): Radiation Effects in Insulators - 7, Nagoya, Japan, September 6, 1993.
- "Radiation-Induced Amorphization of Zircon" (R.C. Ewing): Department of Geological Sciences, University of Texas, Austin, October 14, 1993.
- "Crystalline Ceramics: Future Uses as Radioactive Waste Forms: A Review and Comparison" (R.C. Ewing): symposium on Emerging Technologies in Hazardous Waste Management VI sponsored by the American Chemical Society, I&EC Division, Atlanta, Georgia, September 20, 1994.
- "Radioactive Waste Forms: A Review and Comparison" (R.C. Ewing): seminar on Radioactive Waste Management Practices and Issues in Developing Countries sponsored by the International Atomic Energy Agency, Beijing, China, October 13, 1994.
- "The Development of Ceramic Nuclear Waste Forms" (R.C. Ewing): seminar presented at the Beijing Institute for Nuclear Engineering, Beijing, China, October 17, 1994.
- "Amorphization of Complex Ceramics by Heavy-Particle Irradiations" (R.C. Ewing): symposium on the Microstructure of Irradiated Materials, MRS, Boston, MA, November 30, 1994.
- "Amorphization of Coesite Induced by Electron- and Ion-Beam Irradiation" (W.L. Gong): symposium on Radiation Effects in Nonmetals, TMS 1996 Annual Meeting, Las Vegas, NV, February 13, 1995.
- "Digital Analysis of HRTEM Images of Ion-Beam Damaged Ceramic Materials" (L.M. Wang): symposium on Radiation Effects in Nonmetals, TMS 1996 Annual Meeting, Las Vegas, NV, February 13, 1995.
- "Zircon: A Host-Phase for the Disposal of Weapons Plutonium" (R.C. Ewing): workshop on the Elimination of Weapons Plutonium, sponsored by the German-American Academic Council Foundation and the U.S. National Academy of Sciences, Bonn, Germany, March 22, 1995.
- "Radiation-Induced Amorphization in Ceramics" (R.C. Ewing): research conference on Kinetic Processes in Minerals and Ceramics, sponsored by the European Research Conferences, Blankenberge, Belgium, March 25, 1995.
- "Zircon: A Host-Phase for the Disposal of Weapons Plutonium" (R.C. Ewing): seminar at Plutonium Facility, Los Alamos National Laboratory, April 12, 1995.
- "Crystalline Ceramics: Alternative Waste Forms for the Disposal of Plutonium" (R.C. Ewing): NATO Advanced Research Workshop on "Disposal of Weapons Plutonium - Approaches and Prospects", St. Petersburg, Russia, May 15, 1995.
- "Radiation-Induced Amorphization in Nuclear Waste Forms" (R.C. Ewing): Annual meeting of the American Crystallographic Association, Montréal, Canada, March 29, 1995.

- "Radiation Effects in Nuclear Waste Forms" (R.C. Ewing): IVEM Workshop on Major Issues in Irradiation Effects Research organized by the Electron Microscopy Center for Materials Science at Argonne National Laboratory, October 25, 1995.
- "Where Is the Materials Science in Radioactive Waste Disposal?" (R.C. Ewing): Symposium X, "Frontiers in Materials Science", Fall meeting, Materials Research Society, Boston, MA, November 29, 1995.
- "The Role of Waste Forms in the Performance Assessment of Nuclear Waste Repositories" (R.C. Ewing): Advisory Committee on Nuclear Waste of the Nuclear Regulatory Commission, Washington, D.C., January 26, 1996.
- "Role of Materials Science in Radioactive Waste Disposal and Performance Assessment" (R.C. Ewing): DOE Council on Materials Sciences Workshop on "Radiation Effects in Glasses for the Immobilization and Disposal of High-Level Radioactive Wastes and Excess Weapons Plutonium", Santa Fe, New Mexico, February 26, 1996.
- "The Role of Mineralogy in Designing Nuclear Waste Forms" (4 lectures) (R.C. Ewing): Institute of Geology, Aarhus University, Denmark, March 11-15, 1996.
- "Regulatory Time of Compliance for Radioactive Waste Disposal: Insights Gained From Natural Analogue Studies" (R.C. Ewing): Advisory Committee on Nuclear Waste, Nuclear Regulatory Commission, Washington, D.C., March 27, 1996.
- "Immobilization of Excess Weapons Plutonium in Ceramics" (R.C. Ewing): Department of Nuclear Engineering and Radiological Protection, University of Michigan, Ann Arbor, MI, March 29, 1996.
- "Natural Glasses and the Verification of the Long-Term Durability of Nuclear Waste Glasses" (R.C. Ewing): National Academy of Sciences workshop, "Glass as a Waste Form and Vitrification Technology", Washington, D.C., May 14, 1996.
- "Zircon: A Host-Phase for the Disposal of Weapons Plutonium" (R.C. Ewing): 5th International Congress on Applied Mineralogy, Warsaw, Poland, June 5, 1996.
- "Where is the Materials Science in Radioactive Waste Disposal?" (R.C. Ewing): CEA Saclay, Service de Chimie Moléculaire, France, November 19, 1996.
- "TEM Study of 1.5 MeV Xe Irradiation of ZrO₂" (R.C. Ewing): Workshop on Inert Matrix for Plutonium and Actinide Incineration, Paul Scherrer Institut, Villigen, Switzerland, November 21, 1996.
- "Where is the Materials Science in Radioactive Waste Disposal?" (R.C. Ewing): Paul Scherrer Institut, Villigen, Switzerland, November 22, 1996.
- "Where is the Materials Science in Radioactive Waste Disposal?" (R.C. Ewing): Office of Basic Energy Sciences, Department of Energy, Germantown, Maryland, December 6, 1996.

COLLABORATIVE INTERACTIONS

A number of collaborative efforts have resulted from this BES supported program (1993-1997). We expect that many of the following collaborations will continue:

G. Arnold	SNL	ion implantation of silicate structure types; member of Ph.D. committee for A. Meldrum
C.W. Allen R.C. Birtcher	ANL	use of the HVEM-Tandem Facility at ANL;
L. A. Boatner	ORNL	ion implantation and Rutherford backscattering-channeling studies. member of Ph.D. committee for A. Meldrum
G. Brown F. Farges	Stanford U.	EXAFS study of metamict zirconolite
M. Cameron	NSF	HRTEM study of fission tracks in apatite
F. Clinard (retired)	LANL	radiation effects in nuclear waste forms
R. Doreums	RPI	amorphization of ceramics (spent 95-96 academic year at UNM on sabbatical)
K. Sickafus	LANL	ion beam implantation studies at LANL
Y. Eyal	Technion U. Israel	irradiation studies of glass; bubble formation
F. C. Hawthorne	U. Manitoba	analysis of structural distortion as a result of radiation damage
L.W. Hobbs	MIT	irradiation study of berlinite
Hj. Matzke	TUI/Karlsruhe	ion implantation of UO ₂
B. Morosin J.C. Barbour	SNL	radiation damage & flux pinning in TI-type high temperature superconductors
T. Murakami	U. Tokyo	HRTEM and XRD study of metamict zircons
Alex. Navrotsky	Princeton U. T.C. Onstott	high temperature calorimetric studies of partially damaged zircon and zirconolite and radiation effects on ⁴⁰ Ar/ ³⁹ Ar dating
E. Salje	Cambridge U.	low angle scattering studies of defect annealing in metamict zircon
W.J. Weber	PNNL	radiation effects in complex silicates; member of Ph.D. committee for A. Meldrum

T.J. White

U. South
Australia

ion beam irradiation study of zirconolite

STUDENTS & POST-DOCTORAL FELLOWS SUPPORTED BY THE BES PROGRAM

During the period 1993 to 1997, a number of students, post-doctoral fellows, research staff and visiting scholars have been funded by or associated with this BES program. They are listed below with their present employment.

Robert H. Doremus	Visiting scholar	RPI
Al Meldrum	Ph.D. candidate	University of New Mexico
Mark Miller	Research scientist	University of New Mexico
Nicole Bordes	Post-doctoral fellow shared with LANL	Microscopy Unit, University of Sydney
Peter Burns	Post-doctoral fellow NSERC Fellowship	University of New Mexico
LiFan Chin	Visiting scholar	University of New Mexico
W.L. Gong	Visiting Scholar Chinese Academy Sc.	University of New Mexico
Yongxiang Guo	Research technologist	University of New Mexico
T.J. White	Fulbright Fellow	University of South Australia
Paula Newcomer	M.S., 1995	Sandia National Laboratories
Shixin Wang	Ph.D. candidate	University of New Mexico
Al Meldrum	Ph.D. candidate	University of New Mexico