RADIATION DAMAGE IN SOLIDS AND REACTOR MATERIALS

Hardly considered a separate area of science some 20 to 25 years ago, solid state physics has now become a vigorous and rapidly growing discipline. The reason for its great stimulation is that modern technology has placed increasingly drastic demands on materials. Nowhere perhaps is this trend more evident than in nuclear technology, where the novel demands for certain optimum combinations of physical properties have necessitated an almost complete re-examination of materials and their associated properties from both fundamental and technological points of view. One of the most important requirements imposed by this new application is an entirely new one, viz. radiation stability. In order for a material to be useful within a nuclear reactor it must be able to withstand not only high temperatures but also high fluxes of energetic nuclear radiation for prolonged periods.

Nuclear particles passing through reactor materials transfer part of their energy to the atoms of these materials and eject some of them from their normal positions in the materials. The cumulative result is manifested in significant modifications of the physical properties of irradiated materials. These properties include physical dimensions, strength and hardness, conductivity of heat and electricity, magnetism, resistance to corrosion, and many others. Because of these modifications it is necessary to know the service-life of any material considered for use in nuclear technology, and this can be done only through research on radiation damage.

In view of the important role that knowledge of the mechanisms of radiation damage plays in nuclear technology, the International Atomic Energy Agency held a Symposium on Radiation Damage in Solids and Reactor Materials from 7 to 11 May 1962 in Venice, Italy.

Over 200 scientists from Austria, Belgium, Canada, Czechoslovakia, Denmark, France, Germany, Greece, Hungary, Italy, Japan, the Netherlands, Norway, Pakistan, Poland, Portugal, Romania, South Africa, Spain, Sweden, Switzerland, the Soviet Union, the United Kingdom, the United States and Yugoslavia and from EURATOM attended the symposium. Of some 90 papers submitted, 38 were presented individually and the others considered in panel discussions. The papers covered the following fields of radiation damage research: General Theory; Pure Metals; Metallic and Ceramic Nuclear Fuel; Graphite and Beryllium Oxide; Moderator Materials; Radiation Damage in Semiconductors, Ionic and other Non-Metallic Crystals and Special Techniques.

General Theory: Radiation Damage in Metals and Alloys

At the first session of the symposium, theoretical physicists discussed the basic processes of radiation damage and its effects in solids and other materials. The discussions showed that good progress had been made in recent years in understanding the effects of interatomic collisions in solids, though more theoretical work was needed to understand fully the nature and mechanism of these effects.

Presenting a paper on analogies between radiation effects on solids caused by nuclear radiation and by a flux of slow charged particles, S. V. Starodubtsev (USSR) pointed out that at present problems connected with changes in the physical properties of various materials under irradiation acquired more and more importance. He described some experiments to show that many phenomena in radiation physics and cathode electronics are related. On the basis of his experiments, Professor Starodubtsev suggested a programme for model studies of the effects of reactor radiations on materials.

J.R. Beeler and D.G. Besco (USA) presented a paper in which they described the use of an IBM computer in radiation damage studies, while a paper by J. Lindhard and P.V. Thomsen (Denmark) discussed radiation effects caused by electrons and other nuclear particles.

Three more papers presented by scientists from Belgium, Romania and the USA dealt with certain other aspects of the general theory of radiation damage.

Two sessions of the symposium were devoted to radiation damage in pure metals and one session to that in alloys.

Discussing the nature of radiation damage in metals, A. Seeger (Federal Republic of Germany) said that work done during the past three years supported the picture of the radiation damage by fast neutrons given by him at the second International Conference on the Peaceful Uses of Atomic Energy in 1958. More information on radiation damage had been obtained by electron transmission microscopy and by ferromagnetic measurements. Considerable work had recently been done on radiation hardening and on the plastic deformation of radiation hardened single crystals. Professor Seeger then discussed some aspects of radiation damage in the noble metals and nickel, caused by electron and fast neutron irradiation.

R.O. Simmons, J.S. Koehler and R.W. Balluffi (USA) stated in a paper that bombardment of pure metals by energetic particles produced various defects and, because most of these defects were of atomic dimensions, their study by direct observation had so far been very limited. The presence of such atomic defects in a metal altered many physical properties of a solid, such as electrical resistivity, density, stored energy and elastic and inelastic properties. In general, the authors said, two types of experiments had been used to learn something about the defects produced by irradiation and therefore about the atomic mechanisms responsible for phenomena observed in irradiated metals. Firstly, the rate and type of defects estimated by theory for a given kind of irradiation could be compared to measured changes in physical properties. This method had been most useful in the case of electron irradiation. Secondly, thermal annealing (very slow regulated cooling) of a metal subsequent to irradiation could be carried out to measure the physical property changes occurring in different temperature ranges. This method had been most useful at the lowest temperatures. The authors pointed out that numerous investigations had been made of radiation damage to the crystal structure of metals and many attempts had been made to identify the atomic defects and mechanisms responsible. While theory had been able to furnish a rough guide to interpretation, many explanations had unfortunately been of an ad hoc character. Many of the difficulties would be resolved only when more precise knowledge concerning the simplest defects in metals became available.

A.A. Johnson (United Kingdom), Mrs. N. Milasin (Yugoslavia) and F.N. Zein (UAR), in a joint paper on the embrittlement of metals by neutron irradiation, pointed out that experiments in this field had so far been of three main types. First, attempts had been made to observe the radiation damage directly by electron microscopy. This method had been applied to iron and molybdenum but it had been found that in these metals the damage was on too fine a scale to be resolved in the microscope. Secondly, attempts had been made to deduce the nature of the damage from the changes in mechanical properties which it produced. This approach had been extensively used, but was limited by incomplete understanding of the mechanical properties of irradiated metals. Finally, changes in physical properties, such as electrical resistivity, had been measured and their recovery followed when the irradiated metal was warmed above the irradiation temperature. This technique, the authors stated, was particularly useful in studying defects left in the crystal structure by irradiation. They reviewed and correlated the published results of these three types of experiment and described a set of measurements in which all three methods had been applied to the study of the behaviour of irradiated molybdenum when it was warmed in a temperature range of approximately 100° to $300^{\circ}C$.

Other papers, presented by scientists from Belgium, France, Germany, Romania, the USSR, the United Kingdom and the United States, were devoted to different aspects of radiation damage in pure metals.

At the opening session of the Venice symposium, from left to right: Dr. Henry Seligman, IAEA Deputy Director General in charge of Research and Isotopes; Dr. Vittorio Branca, from Fondazione Cini; Mr. Manfredo De Bernart, Prefect of Venice; Dr. Sigvard Eklund, Director General of IAEA; Mr. Favaretto Fisco, Mayor of Venice; and Prof. Arkadij Rylov, IAEA Deputy Director General in charge of Training and Technical Information

Discussing radiation damage in alloys, A.C. Damask (USA) pointed out that control over the type and distribution of the defects was particularly important in alloys, because any given thermodynamic state of an alloy was characterized by a positional relationship of the atoms. Mr. Damask discussed the ways in which this relationship could be altered by heavy particle bombardment.

Presenting a paper on radiation damage in zirconium, zircaloy-2 and stainless steel, L.M. Howe (Canada) said that the most suitable materials for fuel sheathing and pressure tubes were zirconium alloys because they combined the best available properties of strength, corrosion resistance, neutron economy and ease of fabrication. He said that the Canadian reactors NPD (Nuclear Power Demonstration) and CANDU (Canadian Deuterium Uranium) would use zircaloy-2, a zirconium alloy containing tin and iron, nickel and chromium combined. In these reactors the pressure tubes would be operating near the temperature of the pressurized coolant flowing within them and therefore must have sufficient strength to contain the coolant and must maintain this strength under the conditions of high temperature and neutron irradiation over long periods of time. To increase the mechanical properties of zircaloy-2 a series of irradiation experiments had been carried out. The results showed that in some cases such properties of the alloy as tensile and yield strengths were improved. An additional purpose of the experiments was to obtain information on the mechanism of radiation hardening in zircaloy-2 and zirconium.

M.S. Wechsler and R.H. Kernohan (USA) reviewed the work at the Oak Ridge National Laboratory on the effects of radiation on copper-base alloys. These studies indicated that some reactions in the alloys were enhanced as a result of exposure to neutron, electron and gamma-ray bombardment. They also indicated the conditions under which irradiated alloys might be unstable, thus influencing the use of structural materials in radiation environments.

Some of the papers presented on radiation damage in alloys by scientists from Austria, France, Italy, the USSR and the USA reported on experimental work done on different kinds of steel, where radiation effects on the mechanical properties are of technological importance, because of the wide use of steel as structural or pressure vessel material.

Fissionable Materials, Moderator Materials, Semiconductors

The symposium next reviewed the state of current knowledge of radiation effects in materials most important for the construction of reactors: the nuclear fuels themselves in the form of metallic uranium or ceramic compounds of uranium with carbon and oxygen. This was done in the form of a panel discussion, at which A. Herpin (France) surveyed nine papers submitted by participants from India, France, the USSR, the United Kingdom and the USA. The most important phenomena reviewed were uranium cracking and uranium swelling under irradiation and the study of diffusion and precipitation of rare gases in non-irradiated and irradiated fissionable metals.

At another panel discussion, W.E. Roake (USA) presented a survey paper on radiation damage in ceramic nuclear fuel.

Irradiation behaviour of uranium-carbide fuels at low and high burn-up levels and the low temperature irradiation defects in cast uranium carbide were discussed on the basis of recent research work reported in seven papers submitted by scientists from France, the Netherlands, the United Kingdom and the USA.

Another important problem discussed at the symposium was radiation damage in moderators, like graphite and beryllium oxide. The panel discussion on this subject, with a survey of graphite presented by J.H.W. Simmons (United Kingdom), showed that in the last few years great progress had been made in understanding the phenomena of radiation damage in graphite.

G.W. Keilboltz, J.E. Lee Jr., R.P. Shields and W.E. Browning Jr. (USA), in a paper on radiation damage in beryllium oxide, said that the attractive nuclear properties of beryllium oxide and its excellence as a high-temperature ceramic recommended its consideration as a moderator or reflector for a variety of power reactors in the USA and in other countries. Satisfactory and economical use of beryllium oxide required that the material withstand very high integrated neutron doses. The authors described experiments now in progress to determine specific mechanisms of the observed damages and to establish optimum parameters for fabrication and successful operation of beryllium oxide-moderated reactors.

Although appreciable effects in metals are produced by radiation of relatively short time in reactors, the effects are still more apparent in other materials, particularly in semiconductors, such as germanium.

At a special session of the symposium, P. Baruch (France) read a survey paper on radiation damage in semiconductors, which was followed by a panel discussion based on eight papers from France, Greece, Poland, Romania and the USA.

J.W. MacKay and E.E. Klontz (USA) said that the efficiency for the production of defects in semiconductors was strongly dependent on the temperature during irradiation. This was shown by experiments carried out by the authors to study the radiation damage mechanism in germanium.

P. Baruch and J.C. Pfister (France) presented a detailed report on experiments to study the effects of radiations on the diffusion of impurities (such as gallium, boron and phosphorus) in semiconductors.

At another panel discussion, which took place during the same session, E. L. Andronikashvili (USSR) presented a survey of seven papers on radiation damage in ionic and other non-metallic crystals, which were submitted by participants from the Federal Republic of Germany, Italy, Japan, Poland, Romania and the USSR.

One of these papers, submitted by K. Heine, G.B. Schmidt and W. Herr (Germany), showed that chemical aspects were also important in explaining radiation damage in ionic crystals.

In a paper on the effects of neutron irradiation on magnetic materials for nuclear techniques, E. Labusca, N. Andreescu and C. Motoc (Romania) described a number of experiments which helped them to establish the conditions in which some magnetic materials could be used in devices working in radiation fields.

Special techniques

At the last session of the symposium, scientists from France, Japan, Romania, the USSR, the United Kingdom and the USA presented seven papers on special techniques and methods in studying radiation damage.

R.R. Coltman (USA) described the use for radiation damage studies at the very low temperatures of liquid helium, in a special device called a "helium cryostat" installed near the centre of the Oak Ridge Graphite Reactor. With the help of this device, studies were made of electrical resistivity, stored energy release, length change, yield stress and other properties. Mr. Coltman said that the use of various reactor fuel configurations around the cryostat and of a movable shield around the specimens made it possible to examine the damage caused by thermal neutrons, reactor fast neutrons and fission neutrons quite independently. He discussed particularly the damage caused by gamma rays emitted by the specimens themselves as a result of capture of thermal neutrons. He also discussed the importance of these types of measurement in understanding the basic mechanisms of radiation damage.

V.E.Goldansky (USSR) described what is known as the nuclear spot welding method and some of its applications. He said that the emission of heavy charged particles in some nuclear reactions causes intense heating within the microvolumes at the particle tracks. The introduction of lithium or boron, which undergo such reactions, into the surface layer dividing any two materials and the subsequent irradiation of these materials by thermal neutrons causes heating of a large number of such microvolumes at the surface of contact and results in the so-called "nuclear spot welding" - a very strong binding of these materials with a relatively weak radiation-chemical effect. Mr. Goldansky said that the possibilities of this method were first demonstrated when a number of polymeric and other materials were bound together. Later this method had been used to increase the strength of binding rubber surfaces with certain fabrics. The results showed that the binding strength was up to four times greater than that reached by other methods.

The participants also had informal meetings to assess the most important current problems in the field and to discuss the experimental and theoretical methods by which they might be tackled. This helped in defining a number of directions in which research programmes could be planned and conducted.

The following scientists acted as chairmen of the scientific sessions or as leaders of panel discussions: Professor A. Seeger (Germany), Dr. H.G. Van Bueren (Netherlands), Professor S.V. Starodubtsev (USSR), Professor E.W.J. Mitchell (United Kingdom), Dr. E. Nagy (Hungary), Dr. A. Herpin (France), Dr. W.E. Roake (USA), Dr. J.H.W. Simmons (United Kingdom), Dr. W. Kosiba (EURATOM), Professor P. Baruch (France), Professor E. Andronikashvili (USSR) and Dr. L. Giulotto (Italy).

REPORTS FROM IAEA FELLOWS

Training in various branches of nuclear science and technology is one of the most important ways in which IAEA has been endeavouring to promote the peaceful uses of atomic energy throughout the world, and by the end of last year more than 500 trainees had completed their studies under the Agency's fellowship programme. In an attempt to assess the value of this programme, the Agency requests the fellows themselves, after they have completed their training and returned to their home countries, to send brief reports on their training and the use being made of it in their work.

Summaries of a few of these reports were carried in the last issue of this Bulletin; a few more are summarized here.

Raul Brenner, a Brazilian scientist, who has been in charge of the Electronics Department of the Atomic Energy Institute in São Paulo since 1958, was awarded an IAEA fellowship for studies and practical training at the Brookhaven National Laboratory, USA. Apart from designing electronic circuits and servicing electronic instruments at the Institute in São Paulo, he has also been teaching electronics as part of a course in nuclear engineering given at the Institute. On the value of his training, he says it gave him "an invaluable introduction to the new and extraordinary field of semiconductor devices which are becoming so important in electronic instrumentation".

Alfonso E. Leon Guim, of Ecuador, received nine months' training in the Radiotherapy Department of the Queen Elizabeth Hospital, Birmingham, UK. He says that during the period of his training he was able to gain wide experience in radiotherapy, including the treatment of patients by radium, X-rays and radioisotopes. He also attended a course at the Harwell Isotope School and a medical course at the Christie Hospital and Holt Radium Institute in Manchester. After returning home and at the time of writing his report, he was working as honorary assistant in the General Hospital in Guayaquil City and as a private practitioner. He says: "The experience I have had during my training in England has given me a new opportunity to work on the diagnosis and treatment of cancer with patients in the General Hospital and in my private office."

Laodamas Sklavenitis, a Greek scientist, received a year's training at the Technische Hochschule in Munich, Germany, and at Harwell, England. He had practical training in Munich, followed by a three-month general course at Harwell on radiation protection. After his return to Greece, he has been head of the Health and Safety Division of the Greek Atomic Energy Commission, his duties including the organization of the Health and Safety Division of the Commission and of the Health Physics Section of the Democritus Nuclear Centre. He has also been en-