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Key problems that more physicists could help with include embrittlement of pressure vessels in water reactors, swelling of fuel elements in fast breeders and plasma contamination and wall erosion in fusion reactors.

Frederick L. Vook

The United States is conducting an intensive search for more—and lower cost—energy. Because of its relatively low cost, nuclear energy is rapidly becoming an important energy source. However, there are still unsolved technological problems in the present and projected nuclear industry; many of these arise from the interaction of nuclear particles with the solid materials in the reactor.

This article briefly reviews the conclusions and recommendations of the report[1] of a summer study on radiation effects on materials, sponsored by The American Physical Society as one of a series on physics problems relating to energy technologies. The goal of this summer study was to survey the state of research and development in this area so as to identify the basic scientific problems that limit progress in energy applications; problems that could be investigated by physical scientists, especially those who are in the universities.

In 1974, 6% of the electricity generated in this country was provided by nuclear reactors, up from 3% in 1973 and 1% in 1972. In some areas, such as New England and Chicago, more than one fourth of the electric power is now provided by nuclear reactors. The recently increased costs for fossil fuels have made the operating costs of nuclear power plants significantly lower than the present alternatives. According to the *Wall Street Journal* (21 June 1974) power generated by nuclear plants now planned for completion in 1983 by the New England Electric System is estimated to cost 2.4 cents per kilowatt hour *versus* 3.8 cents and 3.4 cents, respectively, if plants were built for oil or coal. Primarily because of increased construction costs this is more than double the estimated 1 cent per kilowatt hour long-term cost of power from New England nuclear plants built in the late 1960's and early 1970's.

The radiation-effects research done in the past has been of great value in the design of the power reactors now in operation. However, it is important to realize that a considerably enhanced effort in this research will be required to provide the insight and information necessary for the solution of problems in the present light-water reactors and even more for the design of future fission and fusion reactors, because these will operate at temperatures and with particle fluxes far above those of present-day reactors.

In 1972 the AEC Division of Research sponsored two very useful meetings,[2] mostly limited to AEC contractors, on "Fusion Reactor First Wall Materials" and "Critical Questions in Fundamental Radiation Effects Research." Many of the scientific problems identified in these reports have shown limited progress but the economic urgency of increasing our understanding has greatly increased.

Although the scientific and technological research areas that warrant increased effort by the scientific community have not abated, recent years have seen a decline in funding and in the number of graduate students—indeed layoffs in government laboratories working in the materials-science area. Funding has only recently increased for this kind of research. The APS report emphasizes the need for an increased and stable funding policy.

Help from academics

Advances to ease the energy crisis will be limited by technical insight and the availability of competent scientific manpower as well as of funds. Because an important source of such manpower can be found at universities the study group recommends more cooperation between university physicists and those at industrial and government laboratories. There are many problems on which the research can be performed at universities. This can be of significant help in the proper training of graduate students and will also keep the research faculty aware of current developments. In the past, work on industrial problems was common in university physics departments; so was the temporary em-

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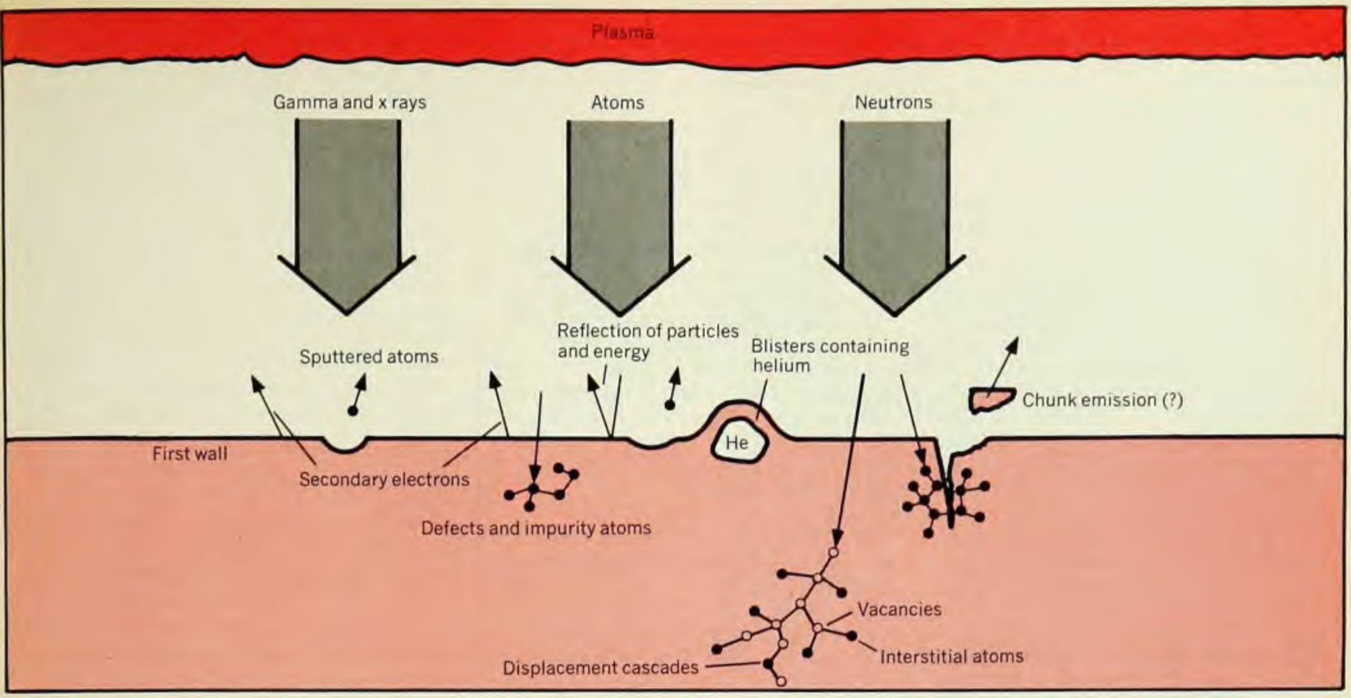


Surface processes of importance in thermonuclear reactors because of contamination of the plasma and erosion of the first wall. The lid of the helium-filled blister shown may separate in a process known as "exfoliation." The question of whether 14-MeV neutrons can cause the emission of micron-sized chunks is still controversial. Many problems on energy-related materials remain to be solved. Figure 1

ploy of graduate students and faculty at industrial laboratories. Everyone benefits from the interaction of scientific talents generated in these cooperative efforts. Such arrangements also remove, to a great extent, the manpower limitations.

The field of radiation-effects studies has applications throughout fission- and fusion-reactor technology as well as in space technology. Deficiencies in understanding the changes induced by radiation in materials used in reactors have led to costly modifications in design and operational procedures. Such induced effects are the embrittlement of materials and their swelling by the formation of voids inside them. Lack of complete knowledge of these complex processes in engineering materials requires periodic retrieval of samples from present light-water reactors for material testing; in some cases it causes operation at lower power than the design intended and leads to a need for more auxiliary equipment. There is also the possibility that the deterioration of the containing vessel may make it necessary to shut down the reactor and thus shorten its useful life. The report[1] quotes Edwin Zebroski of the Electric Power Research Institute as estimating the economic cost of these deficiencies in our knowledge at about $480 million in 1974, with an increase to over $1 billion in 1982. A breakdown of these figures is given in Table 1.

The effects mentioned here will be especially crucial in future breeder and fusion reactors, in which the neutron flux will be very high. One example is the swelling effect, which could slow down the breeding of new fuel in a breeder reactor and make it uneconomical. Another example, illustrated in figure 1, is the problem of surface processes that contaminate plasmas and erode wall surfaces in thermonuclear reactors.

Radiation-effects problems in materials other than reactor materials were also considered in the study, but to a much lesser degree. In space environments, the effects of Van Allen and solar-wind irradiations on semiconductor materials and devices such as solar cells have received extensive investigation. Of particular interest at the present time are studies of the effects of radiation on the insulating oxides and nitrides of metal-oxide semiconductor devices, which are important because of their small size and very low power consumption.

For these reasons the report urges more effort designed to obtain fundamental understanding of the basic physics of radiation effects on materials. For example, two conferences, on Fundamental Aspects of Radiation Damage in Metals and on Radiation Effects and Tritium Technology for Fusion Reactors, are to be held in October (for details see the PHYSICS TODAY calendar; the original listings were in the July 1974 and March 1975 issues). This better understanding will often lead to technological solutions to the problems or at least delineate the limits of the solutions. Further work is also necessary to relate the results of the basic research to the technological applications. It should be recognized, however, that research requires long lead times to be reduced to technological practice.

Embrittlement in light-water reactors

The commercial nuclear power plants now in service are primarily light-water reactors, either of the pressurized-water or the boiling-water type. These are thermal reactors and utilize less than one percent of the energy in naturally occurring uranium. They consume the fissionable isotope U^{235} and convert only small amounts of the more plentiful U^{238} isotope into fissionable plutonium. As a consequence their fuel supply may be limited. For this reason light-water reactors are considered a first stage in the commercial utilization of nuclear energy.

The most important radiation effects to components of light-water reactors are the results of fast-neutron damage to structural materials, especially of steels. Of special importance are the pressure vessels that contain the reactor cores and the cooling fluid. Other structures, listed in Table 1, are also exposed to enough neutrons for radiation effects to be of importance. The thermal reactors now in service could operate much more efficiently and at lower cost if the designers did not have to make allowances for the fact that the pressure vessel and the fuel cladding are subject to radiation embrittlement.

The pressure vessel for a light-water reactor is irradiated by both fast and thermal neutrons. One of the most important effects of this irradiation is to

Technological problems caused by radiation in energy sources

Thermal reactors
Improve the understanding of embrittlement in pressure-vessel steels and fuel-cladding materials.

Fast breeder reactors
Understand and reduce void swelling and radiation creep by developing resistant materials.

Controlled thermonuclear reactors
Investigate the effects of the plasma-surface interactions on contamination of the plasma and erosion of the first wall.
Gain an understanding of the effects of fusion-reactor radiation on the mechanical properties of the plasma containment vessel (first-wall) with particular emphasis on ductility, creep, stress rupture and fatigue life.

Point defects in metals
Investigate mechanisms of the interaction of point defects with themselves, with impurities, with dislocations and with strain fields.

Voids and dislocations in metals
Perform detailed experimental and theoretical studies to elucidate the mechanisms responsible for the nucleation and growth of voids in model face-centered and body-centered cubic alloy systems with well characterized specimens from both a chemical and a microstructural point of view.

Theory of damage production
Develop the theory of heavy-ion simulation of neutron damage.
Improve the theory of the effects of defects on mechanical properties.

Simulation of reactor neutron damage
Establish the range of validity (that is, energy, displacement level, displacement rate and temperature) of ion and electron simulation techniques in providing an accurate means for anticipating fission and fusion neutron-damage effects.
Devise techniques for simulation studies of changes in the mechanical properties such as creep and embrittlement with and without externally applied stress.

Hydrogen and helium in metals
Develop an understanding of the effects of hydrogen and helium on the mechanical properties of alloy systems by both theoretical and experimental methods.

Interaction of surfaces with radiation
Investigate charge exchange and the energy and particle reflection coefficients for hydrogen and helium atoms and ions in the energy range from 100 eV to 20 keV for ultrahigh-vacuum surfaces and for surfaces covered with adsorbed hydrogen.

Insulators
Extend to high temperature, high doses and high fluxes studies of the electrical, mechanical and optical properties as well as the effects of radiation on processes such as diffusion and creep.

Superconductivity
Measure the superconductor parameters critical current, critical field and critical temperature as a function of neutron fluence, particularly at 4 K.

Table 1. Economic impacts[a] of deficiency in understanding of radiation effects on materials

	1974	1982
	(Millions per year)	
Light-water reactors		
Pressure-vessel steel, rise in nil-ductility temperature	$20–30	$100–300
Zirconium fuel cladding, loss of ductility under irradiation	>$100	>$500
Reactor-core internals—stainless-steel core supports, control rods and guides, flow shrouds, loss of ductility, distortion	$50	Potentially >$200
Breeder reactors		
Stainless-steel cladding and structures, swelling (void formation) and loss of ductility	$200 (R&D)	<$100, if solved[b]; >$3000 (after 1985) if not solved[b] and alternative energy used
Graphite and fuel carbides; Shrinkage, swelling, distortion	<$50 (R&D)	$100–500
Fusion reactors		
Structural materials (stainless steel, vanadium, niobium), sputtering, swelling, loss of ductility	<$50 (R&D)	<$50 or >$3000 (after 2000) if not solved[b] and alternative energy used

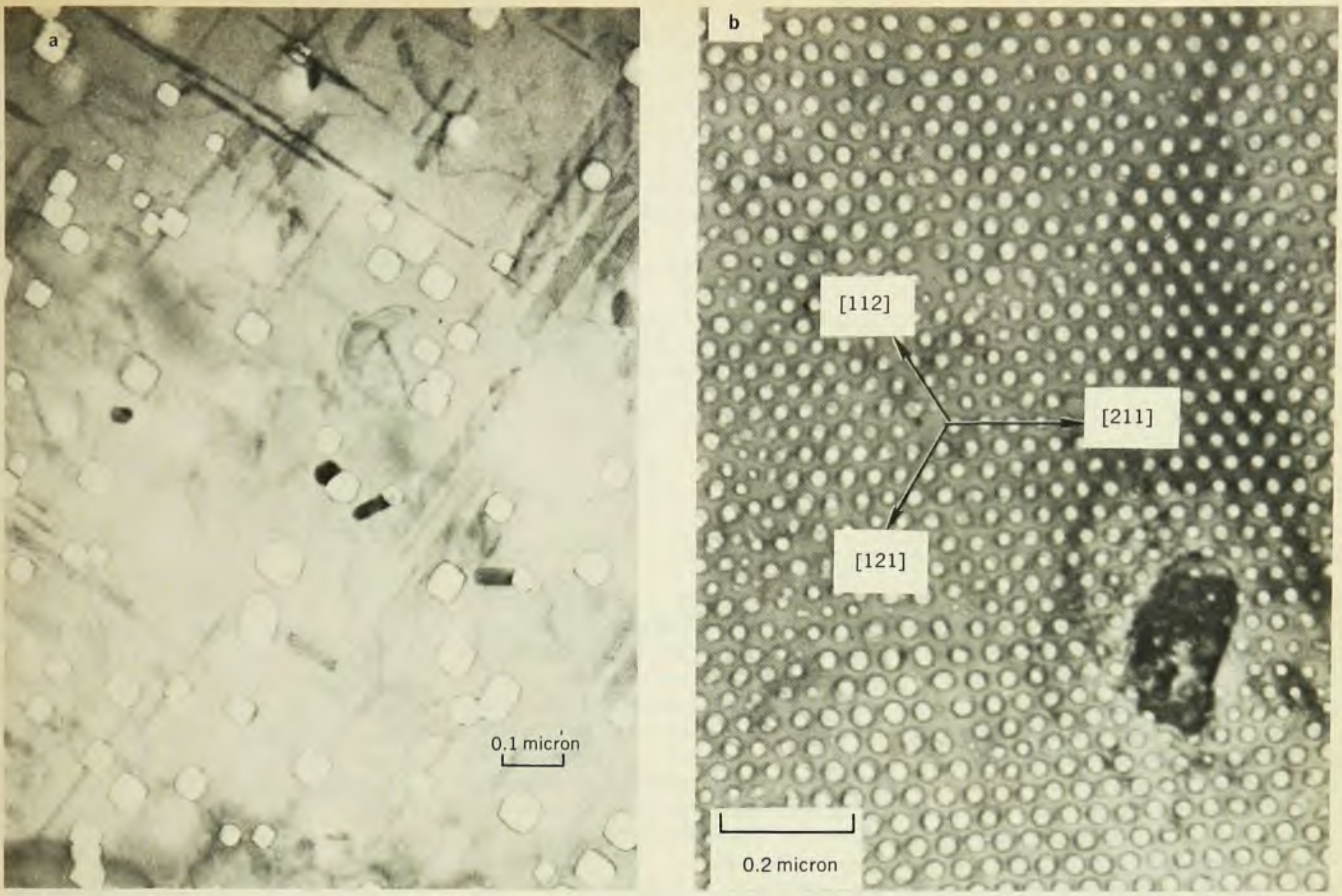
[a] The economic impacts listed are the costs due to the following factors, allocated to consequences of radiation effects: added inspection, maintenance and replacement; added design margins (use of lower performance level to cover uncertainties in data); large-scale specific R&D and testing imposed by limitations of basic knowledge, and delay in the feasibility or availability of a renewable energy source (fission breeder, fusion or hybrid), forcing the use of higher-cost energy sources.
[b] "Solved" implies a significant advance in the state of the art, which facilitates practical application.

increase the parameter known as the "nil-ductility temperature." This is the temperature below which failure would be by brittle cleavage. Above the nil-ductility temperature failure is by ductile tearing. At a temperature typically about 100 Fahrenheit degrees above the nil-ductility temperature, the energy required to cause a crack to grow in a failure mode achieves a high and relatively stable value called the "upper shelf value." Above this temperature there is a large temperature range in which the steel maintains its strength and is in optimum condition for use in a pressure vessel. The toughness (the energy required to expose an additional unit area of surface through crack growth) and the fracture toughness (a parameter proportional to the geometric mean of the toughness and the theoretical ultimate strength) are very high there. In this region any fracture—or any growth of cracks on the way to fracture—would be accompanied by considerable work expended in ductile deformation. The stress concentration that normally occurs at the tips of cracks would be substantially reduced because of local plastic strain.

As the reactor is operated, neutrons irradiating the pressure vessel cause an increase in the nil-ductility temperature. The irradiated steels thus become brittle at temperatures higher than before the radiation exposure. The irradiated steel, although stronger in that its tensile strength is higher, has a reduced temperature region within which it is ductile. The obvious danger lies in the fact that pressure vessels can become brittle at room temperature or even at the operating temperature of the reactor, leading to the possibility of failure of the vessel.

Because of our lack of understanding, both of the phenomena of this embrittlement and of the changes caused by radiation damage, a monitoring program has been set up. This involves periodic physical inspections of the vessel together with the testing for embrittlement of small steel samples located on the vessel walls. The expenses caused by both this surveillance program and the fact that these reactors must operate under less than optimal conditions because of this hazard are indicated in Table 1. Thus, research into radiation embrittlement of steels can have important consequences for the safe operation of reactors under more efficient conditions.

Consider now the embrittlement and loss of ductility of the zirconium alloy used as fuel cladding, which is subjected to a neutron flux of approximately 10^{13} neutrons/cm^2-sec. This embrittlement increases the frequency of cladding rupture, which may lead to the release of radioactivity to the primary cooling circuit. The necessity for frequent re-



Voids produced by bombardment with 7.5-MeV tantalum ions. In vanadium **(a)**, bombardment at 700 deg C has caused about 30 displacements per atom, while the niobium in **b** was bombarded to 300 displacements per atom at 800 deg C. Here the vacancies have precipitated into a three-dimensional superlattice of voids. The swelling causes problems in reactors. (Photos: G.L. Kulcinski.) Figure 2

placement of ruptured fuel elements prior to optimum burn-up results in inefficient operating conditions. If improved understanding of the radiation embrittlement of the fuel-cladding material led to an embrittlement-resistant material, it would bring about important economics in reactor operations.

Problems of breeder reactors

As the number of thermal light-water reactors increases to an estimated 100 by 1980, the consumption and cost of fissionable U^{235} will increase greatly. In order that fission remain a major source of energy, it is proposed that light-water reactors be supplemented by breeder reactors, which consume and theoretically can utilize 50–80% of the uranium and thorium resources.[3] The fuel rods of a breeder reactor contain initially about 20% plutonium dioxide and 80% uranium dioxide. The latter portion consists of the relatively plentiful natural U^{238}. In the breeder, the fuel elements in the core are surrounded by a blanket of "fertile material" consisting of U^{238}, which is bombarded by the excess neutrons emitted in fission in the reactor core. Gradually these excess neutrons convert the U^{238} into plutonium. The number of excess neutrons that perform this conversion is not large, so that a reactor that can double its plutonium in a decade is considered to be breeding satisfactorily.

The late 1980's is the time projected for the completion of the first US demonstration breeder reactor, to be located at Oak Ridge, Tennessee. This reactor is of the type known as the "liquid-metal-cooled fast breeder reactor." Experimental power breeder reactors have been operating in the US since 1951; they are also in operation in the United Kingdom, France and the USSR.

The fast-neutron fluxes to be expected in a typical fast breeder reactor are about 10^{16} neutrons/cm^2-sec, compared to fluxes of a few times 10^{13} in thermal reactors. The high fluxes and fluences (in neutrons/cm^2) for fast breeder fuel assemblies will lead to materials problems not previously experienced or anticipated. In addition, the problems encountered in thermal reactors, such as loss in ductility, now become much more serious. They will have a more pronounced effect on the economic viability of breeder reactors.

The most crucial materials problem in fast breeder reactors at the present time is swelling associated with void formation.[4] At the high fluxes in these reactors there is a rapid generation of vacant lattice sites (vacancies) and interstitial atoms (self interstitials). At reactor temperatures these point defects are mobile and the great majority recombine, but the annihilation is not complete and a steady-state supersaturation of vacancies and interstitials occurs.

The excess interstitials cluster into platelets, which collapse to form dislocation loops. An appreciable number of the vacancies nucleate (probably on impurity gas atoms) three-dimensional precipitates, about 100 Å in diameter, called "voids;" these are easily observable with transmission-electron microscopy, as shown in figure 2. As part b of that figure shows, the voids sometimes form a superlattice. The total irradiation of the niobium sample shown has caused each atom to be displaced an average of 300 times.

As a result of void formation, the metal swells—volume increases of approximately 20% have been observed in reactor components irradiated to neutron doses that would be accumulated during their expected lifetime in the reactor. This swelling has particularly serious effects on the breeding process. The fuel pins have to be more widely spaced to provide sufficient cooling as they swell. Furthermore, the nonuni-

Table 2. Simulation of neutron damage with charged particles

Advantages	Disadvantages
Damage rates are accelerated by 10^5–10^6	Short particle ranges produce damage not well suited to the study of mechanical properties
Simulation allows selective impurity doping	Nonuniform damage
Allows separation of atomic displacement	Temperature shift required to scale diffusion rates
Nonradioactive samples	Different energy distributions of primary knock-on atoms, particularly for high-voltage electron microscopy
Defect structures can be examined by electron microscopy as they develop	Precipitation not necessarily simulated
Low cost	
Rapid screening tool for new alloy development	

formity of the neutron flux results in nonuniform swelling, causing the fuel pins to bow, so that the density of fuel in the reactor core must be reduced even further. This decrease in core density reduces the average energy of the neutron spectrum, substantially decreasing the breeding ratio.

The development of materials that resist swelling will play an important role in the development of breeder reactors. Several possibilities to control the void swelling exist. For example, the annihilation process can be more highly favored through the retention of interstitial atoms by trapping them with precipitates or impurity atoms. Alternately, it may be possible to force the vacancy clusters to form dislocation loops instead of voids. Alloys low in swelling have been developed recently by the systematic addition of trace impurities such as silicon and titanium. The fundamental reasons for this reduction in swelling, however, are unknown.

The examples above illustrate the importance of fundamental point-defect research.[5] Particularly required are studies of the interaction of point defects with each other, with impurities and with strain fields and other mechanical properties. New and promising experimental techniques to study point defects include positron annihilation,[6] x-ray diffuse scattering,[7] field-ion microscopy,[8] field-desorption microscopy,[9] ion implantation, channelling, backscattering and ion-induced nuclear reactions.[10]

Another area where fundamental information is needed is in the development of experimental techniques and models of radiation damage that will permit the simulation of the large neutron fluxes and fluences encountered in fast breeder reactors. Some of the materials problems can be investigated and eventually solved on the basis of experience with reactors but the accumulation of radiation damage in reactors is slow. The use of heavy-ion or electron bombardment as an experimental simulation technique has great utility.[11] An amount of void swelling that takes years to develop in existing steady-state reactors can in principle be produced in hours by charged-particle bombardment. Figure 3 shows that bombardment by ions is several orders of magnitude more damaging to nickel than that by neutrons.

The difficulty in properly assessing the results of ion experiments in terms of correlation with neutron bombardment lies in accounting for the differences in displacement-cascade effects, in the kinetic effects due to the much higher defect-production rates and in the effects of (n,p) and (n,α) reactions. These are obvious areas where fundamental radiation-damage concepts play an important role. Table 2 compares the advantages and disadvantages of simulating neutron damage by bombardment with charged particles.

Alteration of mechanical properties as a result of irradiation ranks with void swelling as a major concern. Irradiation creep, stress effects on swelling and thermal creep are deformation mechanisms that control the behavior of the reactor core. It is essential that these deformation mechanisms be understood in terms of their dependence on temperature, flux, fluence, stress and other parameters. Reduction of ductility due to reduced uniform strain at temperatures below 500°C in steels and due to enhanced intergranular fracture above 500°C may become a limiting factor. Extremely low fracture strains are observed after radiation fluences of 10^{23} neutrons/cm^2. Of particular concern is the behavior under short temperature transients. Progress in this area is hindered by a lack of understanding of the controlling deformation and fracture mechanisms in the absence of radiation—and even less understanding of the effect of irradiation-produced defects on the mechanisms or in changing the mechanisms.

Table 3. Materials that will be damaged during operation in thermonuclear reactors

Material function	Typical examples
Structural components of first wall and blanket	Austenitic stainless steels Nickel-based alloys (PE16, Inconel, Incoloy) Refractory metals (V, Nb, Mo or alloys of those metals with Ti, Zr, or Cr) Sintered aluminum product, silicon carbide, graphite
Reflection, moderation	Graphite
Neutron multiplication	Be, BeO
Breeding	Li, Li_2O, $Li_2Al_2O_4$, Li–Al,
Radiation shielding	B, B_4C, Pb, austenitic steel
Electric insulation (especially for pulsed reactors)	Al_2O_3, MgO, Y_2O_3
Optics for laser systems	Windows: Ge, alkali halides, chalcogenides (GaAs, CdSe) Mirrors: Al, Al-7178, Al–Ni, Be–Ni, Be–Cu
Thermal insulation (for superconducting magnets)	Mylar or other hydrocarbons
Superconduction magnet filaments	NbTi, Nb_3Sn, V_3Ga
Superconduction stabilizing materials	Cu, Al
Magnet-support structure (below 10 K)	Austenitic steel

Fusion reactors

The proposed successor to the breeder reactor is the controlled thermonuclear fusion reactor. At the heart of such a reactor lies a plasma, probably of deuterium and tritium, which is heated to temperatures of 100 to 500 million kelvins. In the deuterium–tritium fusion reaction,

$$D + T \rightarrow He^4 + n + 17.6\ \text{MeV}$$

80% of the energy released is carried off by the approximately 14-MeV neutrons. Encouraging experiments in the last four years have suggested that controlled fusion is probably attainable with magnetic confinement systems. Other approaches use laser[12] or electron beams to heat the fuel.[13]

Nuclear fusion has the great advantage of virtually unlimited fuel resources. Of the two heavy isotopes of hydrogen that are commonly considered the likely fuels for fusion, one, deuterium, is extremely plentiful in sea water and would be a cheap fuel, but the other, tritium, would have to be bred in a fusion reactor. This would probably be done by the interaction of the neutrons with lithium, which is proposed both as a heat-transfer medium and a tritium breeder.

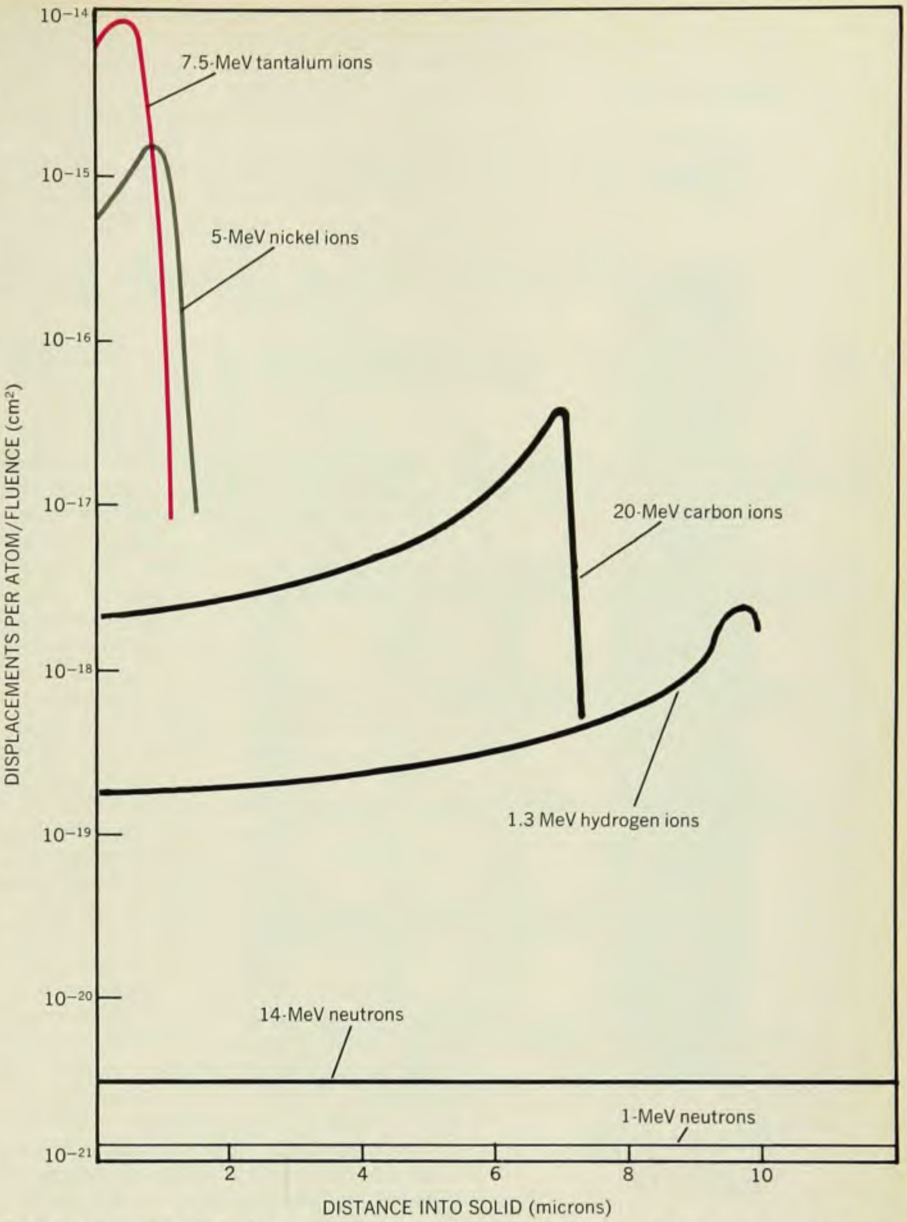
The temperatures for fusing deuterium and tritium are so high that no material can contain the fuel without melting. Therefore, magnetic fields are proposed to keep the hot plasma from touching any wall. The neutrons released in the deuterium–tritium reaction are, however, not affected by the magnetic field. The energy of the neutrons is converted into heat when they are slowed down by collisions in a solid or liquid material. This is one function of the materials surrounding the first wall, called the "blanket." Its other function is to use the neutrons to breed the fuel tritium from lithium. Because the fusion of a deuteron with a triton produces only one neutron and yet consumes one triton, the problems of neutron economy and multiplication require careful design of the blanket.

Second only to the basic problem of plasma confinement and heating is plasma contamination. Intense gamma rays and energetic particles from the plasma cause the release of atoms from the wall into the plasma, contaminating the plasma as well as seriously damaging and eroding the wall. The interactions of radiation with surfaces and near surfaces of materials are therefore particularly important.[14]

As figure 1 shows schematically, surface processes important to the plasma include:

- the reflection of particles (and energy) back into the plasma,
- charge exchange of plasma particles at the wall,
- secondary-electron and photon production, as well as contamination of the plasma by
- desorption of adsorbed species,
- sputtering of wall materials, and
- blister formation and exfoliation of the wall.

In time, as these critical surface and near-surface problems are solved and successful heating of magnetically confined plasmas is achieved, the problems of wall degradation will become critical.



Calculated number of displacements that each atom of a nickel sample has undergone relative to the number of incident particles per cm^2 of irradiation exposure, as a function of the distance from the surface. The curves show that the simulation of neutron irradiation with ions can accelerate the damage processes by as many as six orders of magnitude; also see Table 2. (From reference 11.) Figure 3

One of these problems is sputtering, which occurs when the bombardment of the wall with ions causes wall atoms to be knocked out of the metal. Erosion rates may reach a level approaching 0.1 mm per year. In addition, the wall is sensitive to mechanical creep and ductility changes due to defects and foreign atoms introduced into the wall.

The neutron flux through the first wall will be as intense as any anticipated in a fission reactor and will be of a harder spectrum because of the higher energy of the neutrons. Because 14-MeV neutron sources for engineering testing are not expected to be readily available in the near future, greater reliance and importance must be placed on a fundamental understanding of radiation damage to the materials of interest, such as those listed, along with their functions, in Table 3.

Materials-compatibility problems of various types are also important. Void production and swelling occur but may not, however, be as important as metal embrittlement produced by (n,α) reactions. The helium produced is not soluble in the metal and accumulates in grain boundaries, which leads to intergranular fracture.

The general problems of hydrogen in metals are of importance as well as those of helium. The technological problems related to hydrogen are:

- embrittlement of refractory metal alloy systems (such as those of niobium, vanadium and zirconium), of stainless steels, nickel-base alloys and low-alloy steels;

- accelerated high-temperature creep and fatigue failure;
- stress corrosion of the iron–chromium–nickel alloys;
- containment of the tritium generated and used as fuel;
- fusion-plasma contamination by hydrogen leakage from the first wall;
- gas-bubble formation (H_2, CH_4, H_2O);
- helium production by tritium decay;
- internal hydriding of substitutional solutes, and
- void nucleation.

Many of the concepts of thermonuclear reactors involve plasma containment by very strong magnetic fields (approximately 50–150 kilogauss), to be produced by superconducting magnets. The power required to create the magnetic fields by normal magnets would be far too large for economic operations. The power output of a given machine can vary as the fourth power of the magnetic field, so that high fields are desirable. The temperature gradients in fusion reactors are truly remarkable—from hundreds of millions of degrees at the plasma to near absolute zero within a few meters.

Although the neutrons emitted by the fusion reactor are partially absorbed by the blanket and shield surrounding the fusion chamber, some will bombard the superconducting materials of the magnet. The magnitude of this neutron flux will be determined by the best compromise for liquid-helium loss due to absorption of all forms of radiant energy, magnet size and the effect of irradiation on the properties of superconductors. Because it is estimated that two thirds of the capital cost will be in the magnets, it is essential that the effects of neutron irradiation on the properties of superconductors be understood. The basic unknowns of radiation damage to superconductors are changes in the superconducting parameters for critical current, critical field and critical temperatures as functions of neutron fluence, particularly at 4 K.

Recommendations

The more detailed specific recommendations of the summer workshop are contained in the study report. The most urgent of these are summarized in the box on page 36.

To attack the most important problems that limit progress in energy applications, the study group recommended increased efforts in the following general areas:

- A much firmer experimental and theoretical base should be established for simulation of neutron damage by ions and electrons for both fission and fusion.
- Increased emphasis should be placed on understanding the effects of impurities on the production, migration and agglomeration of radiation-produced defects, particularly the nucleation and growth of voids and dislocation loops.
- The experimental and theoretical understanding of mechanical properties as they are affected by point defects and their agglomerates, impurities and defect–impurity combinations should be significantly improved.
- Experimental and theoretical understanding should be established for the dynamic effects of high-flux radiations such as enhanced diffusion, creep, precipitation and re-solution.

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