# Overview

Some of the most serious safety and environmental concerns for future fusion reactors involve induced radioactivity in the first wall and blanket structures. One problem caused by the induced radioactivity in a reactor constructed from the conventional austenitic and ferritic steels presently being considered as structural materials would be the disposal of the highly radioactive structures after their service lifetimes. To simplify the waste-disposal process, "low-activation" or "reduced-activation" alloys are being developed. The objective for such materials is that they qualify for shallow land burial, as opposed to the much more expensive deep geologic disposal, or alternatively, that they can be recycled after a suitable period of storage. To qualify for such handling, the induced radioactivity would have to decay to specified low levels in tens of years rather than the hundreds of years required by most conventional alloys.

Work to develop such materials originated in the early 1980s, following studies by investigators in England and the United States on the decay characteristics of the radioactive isotopes that would be produced in a fusion reactor from the various elements that make up typical structural materials. Today, work on reduced-activation materials is in progress in Europe, Japan, and the United States.

Before starting work on these materials, the possibility of developing structural materials that were truly "low activation" was explored. Such materials would either not become radioactive during service in a fusion reactor, or the induced radioactivity would decay to low levels in a matter of hours after shutdown. With such low-activation materials, both safety and waste-disposal would be greatly facilitated; in addition, hands-on maintenance of the reactor would be possible. In 1983, a U.S. Department of Energy panel set up to study the possibility of such low-activation materials concluded that the technology for commercially producing and fabricating material that would meet the low-activation criteria was not available and was unlikely to be available in the near future (high-purity silicon carbide was the only true low-activation material that could be suggested by the panel). The panel recommended that materials be developed to help avoid a nuclear waste-disposal problem that would occur when fusion reactor components had to be discarded.

As stated above, alloys with radioactive decay characteristics that would allow for simplified waste-disposal techniques are referred to as "low-activation" or "reduced-activation" alloys. Neither of these terms adequately describes the behavior of the alloys, for when irradiated in a fusion reactor, all of the alloys to be discussed will become highly radioactive. Nevertheless, both terms continue in common use and are used in papers throughout this publication to describe the materials. For the title of this volume and for this discussion, reduced activation was chosen to describe the materials, since the original conception of low-activation materials concerned different materials from those discussed here. As an alternative designation, the authors of one of the papers in this proceedings suggest calling them fast induced-radioactivity decay (FIRD) alloys.

Although progress on the development of reduced-activation alloys has been reported over the past several years, no publication dedicated to the subject has been issued. In order to bring research workers together to discuss the latest developments on these materials, the last day of the 14th International Symposium on the Effects of Radiation on Materials at Andover, MA, June 27–30, 1988, was devoted to presenting recent research activities on reduced-activation materials. Those sessions on reduced-activation materials fit into the symposium because many papers on the effect of irradiation on conventional structural materials for fusion reactor applications were delivered in the first three days of the symposium.

This Special Technical Publication (STP) is a result of the presentations on reduced-activation materials at the symposium. Unlike the papers appearing in the companion STP 1046 that covered the material presented on the first three days of the symposium, this volume includes papers on unirradiated materials. In the development of new materials, such as these, it is necessary to insure that the materials have satisfactory properties in the unirradiated condition. Once materials with satisfactory unirradiated properties are available, considerable testing of the materials after irradiation will be required before the materials can be used in a fusion reactor.

For materials to qualify for shallow land burial, certain elements must be minimized. These include molybdenum, niobium, nickel, copper, and nitrogen. Before the start of the development of reduced-activation materials, conventional nickel-stabilized austenitic stainless steels and Cr-Mo ferritic steels were considered prime candidates for structural materials. Most of the development activities for the reduced-activation alloys involve the modification of the conventional steels by replacing the elements that must be restricted.

In the austenitic steels, this means that a replacement must be sought for nickel. The possibility of developing manganese-stabilized austenitic stainless steels is being investigated. In the conventional Cr-Mo ferritic steels that are considered candidate alloys, the main elements to be replaced are molybdenum and niobium. Tungsten has been proposed as a replacement for molybdenum, although in some cases vanadium has been used. Niobium has generally been replaced by a greater use of vanadium, titanium, and especially by tantalum, because tantalum has chemical characteristics in common with niobium. The use of tantalum may cause problems, however, because its transmutation products produce high levels of radioactivity immediately after fission-reactor irradiation, which may make such irradiated steels difficult to study. (With no fusion test reactor presently available, fission reactor irradiation is the principal means of studying property changes caused by irradiation.)

Vanadium alloys make up the final class of reduced-activation materials being considered. From the reduced-activation viewpoint, vanadium alloys have the most promise, because of the rapid decay characteristics of the radioactive isotopes produced when vanadium is irradiated in a fusion neutron spectrum. These products decay much more rapidly than the isotopes produced from iron, which are generally limiting for a steel. Furthermore, the isotopes produced from chromium, titanium, and silicon, common alloying elements for vanadium alloys, also have decay characteristics that are superior to those of iron.

The papers in this volume are divided into three categories, to the alloy type: austenitic stainless steels, ferritic steels, and vanadium alloys.

## Austenitic Stainless Steels

Most of the papers on the austenitic stainless steels involved studies in the unirradiated condition. In all cases, the materials that were examined were high-manganese steels, where the manganese was used to replace the nickel in conventional stainless steels. The objective was an austenitic matrix for the steel, similar to the microstructure in a nickel-stabilized stainless steel, such as Type 316. If the composition is not properly adjusted, the matrix can contain delta-ferrite or martensite, or both. For nickel-stabilized steels, phase-composition relationships are given by the Schaeffler diagram.

Because manganese is not as strong an austenite stabilizer as nickel is for the conventional stainless steels, the authors of one of the papers used simple alloys for an experimental determination of the austenite-stabilizing characteristics of manganese. From this work it was concluded that it should be possible to establish an austenitic Fe-Mn-Cr-C base composition, which can then be alloyed for strength and irradiation resistance. A modified Schaeffler diagram was determined that was considerably different from the conventional diagram. A possible Fe-Mn-Cr-C base composition was determined, and the strength of this alloy was comparable to the strength of Type 316 stainless steel.

Another approach to the design of reduced-activation austenitic steels used a d-electron concept and molecular orbital calculations to determine appropriate stable compositions. By combining this theoretical technique with experimental studies, phase stability predictions were obtained that were superior to those arrived at from the Schaeffler diagram.

Precipitate behavior can have important effects on the mechanical properties in both the unirradiated and irradiated conditions. In particular, strength can be enhanced by fine MC-type precipitates, while precipitate phases such as sigma can have deleterious effects on mechanical properties. Four of the papers concerned investigations of precipitation that occurred for different alloy compositions and the effect of these compositions on phase stability.

Phase and precipitate stability can also be affected by irradiation. In one of the two papers that discusses the results of irradiation on the high-manganese steels, some of the instabilities that occur have been investigated. Just as is the case in the unirradiated condition, alloy composition plays an important role in the stability of alloys during irradiation. Likewise, composition can play a role on the strength of irradiated high-manganese steels, as shown in the paper that investigated the effect of irradiation on tensile and impact properties.

In a fusion reactor, large amounts of transmutation hydrogen will be generated within the first wall. The possible effect of hydrogen on the ductility of an Fe-Cr-Mn alloy was investigated. From the results presented in that paper, it was concluded that hydrogen would not significantly affect these steels below 400°C.

### Ferritic Steels

Of the three papers on reduced-activation ferritic steels, two of the papers concerned tensile and impact properties and transmission electron microscopy (TEM) studies on unirradiated specimens, while the third paper described such studies on both irradiated and unirradiated specimens. The authors of these papers investigated both Cr-W and Cr-V steels, where the tungsten concentration varied up to 4% and the vanadium up to 1%. Two of the papers concerned chromium compositions that varied from 2% to 12%. The third paper concentrated on steels with 2¼% chromium with varying concentrations of vanadium and tungsten. Attempts were made to correlate the mechanical property results with microstructures. All indications are that Cr-W type alloys can be developed that will have properties comparable to the Cr-Mo steels that they will replace.

### Vanadium Alloys

Four of the seven papers on vanadium alloys concerned the effect of irradiation. Since large amounts of transmutation helium will form in the structural materials of the first wall and blanket structure of a fusion reactor, two of the papers concerned the effect of helium on swelling and tensile properties. Two different techniques were used to generate the helium. For one investigation, the tritium trick was used to place the helium in a series of alloys before irradiation in a fission reactor. Tensile measurements after irradiation indicated that irradiation hardening, which led to reduced ductility, was the dominant effect. This hardening was not greatly influenced by the helium. In the second investigation, 1% $B^{10}$ was added to vanadium, and the helium was generated by an $(n,\alpha)$ reaction during irradiation in a fission reactor. A comparison of the B-doped vanadium with undoped vanadium by TEM indicated no large differences caused by helium.

Two papers concerned studies of the microstructures of irradiated vanadium alloys, where irradiation was carried out in the absence of helium. One group of investigators irradiated vanadium and a series of binary alloys in a fast reactor. Some interesting differences were obtained between the alloys containing molybdenum, titanium, carbon, and chromium. The other group used high-voltage electron microscopy (HVEM) to irradiate several vanadium alloys. These studies uncovered some difficulties with using HVEM for studying irradiation effects on vanadium alloys.

Because only limited experience is available for vanadium alloys, considerable development work on fabrication processes will be required if these alloys are to be used as structural materials for fusion reactors. Three of the papers on vanadium concern investigations of processes that might be used to fabricate components. Electron-beam welds made in several binary alloys indicated that these alloys were embrittled by the welding process. In the other two papers, the bonding of vanadium alloys to ceramics was investigated. The results provide the first information available on the possibility of bonding vanadium alloys with alumina and silicon carbide.

A broad range of work is presented in this publication, and it should help researchers in this field better assess the development of reduced-activation materials and the direction of future work.

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