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LOW ACTIVATION MATERIALS FOR FUSION\*

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ABSTRACT

The viability of fusion as a future energy source may eventually be determined by safety and environmental factors. Control of the induced radioactivity characteristics of the materials used in the first wall and blanket could have a major favorable impact on these issues. In the United States, materials program efforts are focused on developing new structural alloys with radioactive decay characteristics which would greatly simplify long-term waste disposal of reactor components. A range of alloy systems is being explored in order to maintain the maximum number of design options. Significant progress has been made, and it now appears probable that reduced-activation engineering alloys with properties at least equivalent to conventional alloys can be successfully developed and commercialized.

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## 1.0 INTRODUCTION

With the approach of a demonstration of scientific breakeven, increasing attention is being focused on the challenge of proving the engineering feasibility and the licensability of magnetic fusion energy (MFE) systems. Central to this challenge are the questions of safety and environmental impact. Indeed, it is possible that these issues could become the overriding factors that determine the viability of fusion as a major energy source. Both fossil and fission technologies, having advanced to a mature stage of development, are now having to address serious environmental concerns. Fusion, however, is in the relatively advantageous position of being able to address safety and environmental issues, particularly those arising from induced radioactivity, at a very early stage of technological development.

Four major issues have been identified which arise from the induced radioactivity of the vacuum vessel, blanket structure, and in-vessel components:

1. The environmental impact (and cost) of disposing of radioactive components.
2. Radioactivity release to the environment during accident conditions.
3. Occupational exposure related to maintenance.
4. Recycling of critical or expensive materials.

To some extent the scale of these problems can be influenced by system design, reactor power, frequency of component replacement, etc. However, by far the most powerful means of controlling the radioactivity inventory is through the selection of structural materials and other materials that comprise the blanket volume. For a given neutron flux and spectrum, the radioactive inventory will depend upon the chemical and isotopic composition of the materials used to build the structure.

## 2.0 THE U.S. PROGRAM ON REDUCED ACTIVATION MATERIALS

The prime importance of tackling the radioactivity issue was recognized within the U.S. Department of Energy (USDOE) in 1982. Definitions of the problem and recommended approaches were embodied in the Conn Panel Report on Low Activation Materials [1]. The current U.S. program on reduced-activation materials was initiated in response to the panel findings, with primary emphasis on simplifying waste disposal.

The development of new engineering materials is a long-range activity which evolves through feasibility and developmental stages before entering a final commercialization stage. The feasibility stage involves a large number of small (~1 kg) heats of material covering a broad matrix of compositions. Regions of promising composition space are determined on the basis of microstructural stability and short-term mechanical testing. Exploratory corrosion, welding, and radiation testing are then carried out on promising alloys. Further compositional adjustments are made and the cycle of testing repeated until the feasibility of developing an engineering alloy with the desired properties has been established. The developmental stage involves a much smaller number of promising compositions

fabricated by a commercial vendor on a larger scale ( $\sim 10^2$  kg quantities). This stage involves mechanical and corrosion testing over a broad range of testing conditions. Using fission reactor irradiation facilities, dimensional stability and mechanical behavior are determined under the conditions of temperature, fluence, damage rate, and helium generation rate appropriate to the fusion system.

The commercialization stage involves demonstrating that industrial vendors can meet the required specifications in large quantities ( $\sim 10^3$  kg) and produce the required product form. It also involves stimulating commercial interest, as well as meeting various national and international standards and Code Case qualifications. The timescale for each of these overlapping stages typically ranges from 5 to 10 years, depending upon funding.

The major difficulty in defining a practical approach to alloy development is the lack of any widely accepted guidelines dealing with any of the four major radioactivity issues confronting fusion (waste disposal, accidental release, maintenance, and recycling). In fact, these issues may have conflicting requirements (e.g., a reduced activation material which simplifies waste disposal may aggravate problems associated with short-term radioactivity release during accident conditions). Therefore, as a starting point, it was decided to adopt the U.S. 10CFR61 regulations which establish isotopic concentration limits for near-surface burial of medical and fission waste streams. The 10CFR61 calculations were extended to include other radionuclides relevant to fusion [2]. Five elements were identified as having a major impact on waste disposal — N, Ni, Mo, Cu, and Nb. The allowable concentration limits were calculated which would qualify a material for Class C waste disposal following exposure to several conceptual reactor first-wall spectra. The concentration limits depend on neutron fluence and spectrum and on the amount of dilution allowed following decommissioning. Furthermore, it is possible that near-surface burial will be replaced by engineered structures, thus giving rise to major changes in acceptable concentrations in the future. Given the large uncertainties in what constitutes acceptable concentration limits, the U.S. program has adopted the pragmatic approach of setting the concentration limits for N, Ni, Mo, Cu, and Nb at the levels of impurity attainable by current melting and fabrication technology, and of using these concentration limits as a set of guidelines for alloy development. Accordingly, the guideline concentrations for these elements are 50, 100, 10, 10, and 1.0 wt ppm, respectively. Efforts are continuing to establish internationally acceptable guidelines specific to fusion.

### 3.0 STATUS OF ALLOY DEVELOPMENT

To allow designers to consider the widest possible range of fusion concepts, a broad range of materials options is being pursued. Three alloy classes were chosen for development — namely, ferritic/martensitic and bainitic stainless steels, austenitic stainless steels, and vanadium alloys. For the stainless steels, a good properties data base exists for

fully commercialized alloys, such as AISI 316, and the ferritic steels HT-9, Mod. 9Cr-1Mo, and 2¼Cr-1Mo. The intent is to develop new reduced-activation stainless steels with properties at least equivalent to those of the conventional commercial alloys.

### 3.1 Ferritic Stainless Steels

These alloys are based upon the Fe-Cr-C alloy system with chromium contents ranging from 2 to 12 wt %. Of the restricted elements, neither Cu, Ni, nor N are essential alloying constituents of the bainitic and martensitic stainless steels. Small amounts of nickel are sometimes used to control  $\delta$ -ferrite formation in the 12 Cr steels, but this can also be accomplished by adjusting the carbon and manganese concentration. The elements V, Ti, and Ta present alternatives to the use of niobium for strengthening purposes. Molybdenum plays a crucial role in the metallurgy of these steels; the only viable alternative replacement elements having similar metallurgical characteristics are tungsten and vanadium.

Some 30 different compositions have been evaluated in terms of microstructure, tensile properties, and Charpy impact properties [3]. Preliminary liquid metal corrosion studies [4] and welding tests [5] have been carried out on selected alloys. An initial survey of radiation response has been carried out following fission reactor irradiation to a dose of ~40 displacements per atom (dpa) [6]. These studies clearly demonstrate the feasibility of developing reduced-activation ferritic steels having mechanical properties similar to those of conventional steels. Martensitic steels with chromium contents in the range 7 to 9 wt % have been developed with microstructural characteristics, tensile, and Charpy impact properties that are similar to conventional steels. Initial welding and liquid metal corrosion studies also suggest performance equivalent to conventional steels; irradiation behavior over the range 420 to 590°C is also very promising. In the bainitic steel class, 2¼ Cr steels strengthened with 2% W and 0.25% V have been developed with tensile properties that are superior to those of the conventional 2¼Cr-1Mo steels [7]. A major concern for both the bainitic and martensitic steels is the potential for radiation-induced brittle cleavage failure at low temperatures (<200°C). Figure 1 shows the

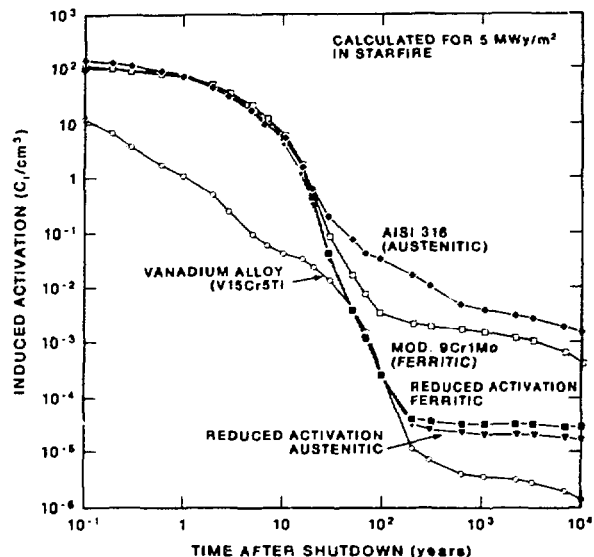


FIG. 1. Decay of induced radioactivity for conventional stainless steels compared with new reduced-activation alloys.

induced radioactivity as a function of time after reactor shutdown for one of the 9Cr-2WV steels having the allowable concentrations of N, Ni, Mo, Cu, and Nb. Compared to a conventional Mod. 9Cr-1Mo steels, the radioactivity of the new alloy is lower by nearly three orders of magnitude following a 100-year cooldown period. This material could qualify as Class C waste under the U.S. 10CFR61 regulations. Future work will focus on a smaller number of promising alloys in both the bainitic and martensitic alloy classes.

### 3.2 Austenitic Stainless Steels

For this alloy class, adoption of the elemental restrictions described above implies a radical metallurgical change, since nickel is a major alloying element (~15 wt %). Manganese is used for austenite stability in many commercial alloys as a means of reducing cost and conserving nickel. However, most of the commercial manganese steels contain some nickel and nitrogen and do not meet the guideline concentration limits adopted in the U.S. program. Consequently, the program is attempting to develop a new manganese-stabilized alloy with the reduced-activation properties, mechanical and corrosion behavior, and radiation resistance appropriate for fusion applications. Such a material could be a candidate for current International Thermonuclear Experimental Reactor (ITER) concepts which are based on austenitic stainless steel/water-cooled systems operating at <400°C. Significant progress has been made in this direction. The Fe-Cr-Mn-C system has been re-examined to define the regions of composition space having maximum austenite stability [8]. Information gained from studying the radiation response of conventional austenitic steels is being applied in alloying with P, B, Ti, V, and W to confer strength, swelling resistance, and resistance to stress corrosion cracking.

Initial results are promising, and several alloys have been developed which have tensile properties superior to those of AISI 316 over the temperature range 50 to 650°C. Future work on these new materials will include weldability studies, irradiation testing, and corrosion behavior in aqueous environments. It has been established that these alloys are inferior to the conventional austenitic steels in terms of liquid metal corrosion properties [4]. The radioactive decay characteristics of a new Fe-12Cr-10Mn austenitic stainless steel is shown in Fig. 1. This material exhibits a three orders of magnitude reduction in radioactivity following a 100-year cooldown compared to a conventional austenitic.

### 3.3 Vanadium Alloys

Vanadium alloys offer some attractive advantages over the ferritic and austenitic stainless steels. A wide range of alloying options are available which would meet 10CFR61 guidelines for class C waste. Nuclear heating, hydrogen, and helium generation rates are lower than in the steels; creep rupture and thermal stress properties are also superior. Limited data sug-

gest that welding, corrosion, and radiation-induced swelling behavior are quite promising for reduced-activation alloys such as V-3Ti-1Ti and V-15Cr-5Ti. The radioactive decay characteristics of the latter alloy are shown in Fig. 1. A major concern is the potential for impurities such as C, O, N, and H to embrittle vanadium alloys under certain circumstances. Strict environmental control is required during fabrication and welding and concentrations of carbon and nitrogen in liquid metal coolants will have to be maintained at <10 wt ppm. Vanadium alloy systems have not yet been extensively explored, and experience on a commercial scale is rather limited. A much greater effort is required in the areas of fabrication, welding, mechanical behavior, corrosion and radiation effects if the full potential of these materials is to be realized.

## REFERENCES

- [1] R. W. Conn et al., *Report of the DOE Panel on Low Activation Materials for Fusion Applications*, UCLA School of Engineering and Applied Sciences, UCLA/PPG-728 (June 1983).
- [2] F. M. Mann, *Fusion Technol.* 6 (1984) 273.
- [3] R. L. Klueh, D. S. Gelles, and T. A. Lechtenberg, "Development of Ferritic Steels for Reduced Activation: The U.S. Program," *J. Nucl. Mat.* 141-143 (1986) 1081-1087.
- [4] P. F. Tortorelli, "Corrosion Studies in Thermally Convective Lithium; Low Activation Austenitic and Ferritic Alloys," *Fusion Reactor Materials Semiann. Prog. Rep.*, USDOE/ER-0313/1, pp. 316-321.
- [5] H. T. Lin and B. A. Chin, "Properties of Welded Low-Activation Alloys," *Fusion Reactor Materials Semiann. Prog. Rep.*, USDOE/ER-0313/2, pp. 135-150.
- [6] D. S. Gelles, "Effects of Irradiation on Low Activation Ferritic Alloys; A Review," Paper presented at Proc. Int. Symp. on Reduced Activation Alloys for Fusion Service, June 29-30, 1988, Andover, Mass. (in press).
- [7] R. L. Klueh and P. J. Maziasz, "Low Chromium Reduced Activation Ferritic Steels," Paper presented at Proc. Int. Symp. on Reduced Activation Alloys for Fusion Service, June 29-30, 1988, Andover, Mass. (in press).
- [8] R. L. Klueh and P. J. Maziasz, "Reduced Activation Austenitic Stainless Steels: The Fe-Cr-Mn-C System," Paper presented at Proc. Int. Symp. on Reduced Activation Alloys for Fusion Service, June 29-30, 1988, Andover, Mass. (in press).
- [9] D. R. Diercks and B. A. Loomis, "Alloying and Impurity Effects in Vanadium-Base Alloys," *J. Nucl. Mater.* 141-143 (1986) 1117-1124.
- [10] D. N. Braski, "The Postirradiation Tensile Properties and Microstructure of Several Vanadium Alloys," Paper presented at Proc. Int. Symp. on Reduced Activation Alloys for Fusion Service, June 29-30, 1988, Andover, Mass. (in press).