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R. HANCOX
B. MITCHELL
G. J. BUTTERWORTH

CULHAM LABORATORY
Abingdon, Oxfordshire
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RADIOLOGICAL IMPLICATIONS OF LOW ACTIVATION STEELS AS STRUCTURAL MATERIALS IN FUSION REACTORS

R Hancox, B Mitchell* and G J Butterworth

Culham Laboratory, Abingdon, Oxon. OX14 3DB, U.K.
(Euratom/UKAEA Fusion Association)

*Associated Nuclear Services, Epsom, KT17 1HB, England

Abstract

New austenitic and martensitic steels are being developed as possible alternative structural materials in a fusion reactor, with elemental modifications designed to reduce their levels of activity after exposure to high-energy neutrons. The radiological advantages of using such materials are discussed. No advantage is found for severe accident situations, there may be some benefit in reducing occupational exposures and the main advantages appear in long-term waste disposal and the possibility of recycling structural materials.

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1. Introduction

Nuclear fusion research is undertaken because it offers the prospect of a new energy source based on abundant fuel resources and with safety and environmental advantages. The ideal nuclear reaction would be one in which all reaction products are charged and remain in the plasma, minimizing radiation hazards and allowing a wide choice of constructional materials for the reactor. The first generation of fusion reactors will, however, almost certainly operate with deuterium-tritium fuel to reduce plasma confinement requirements and capital costs, with the result that 14 MeV neutrons will activate the structural materials. It is therefore of interest to consider alternative structural materials that minimize the hazards associated with this induced radioactivity, and to assess the radiological implications of possible 'low-activation' materials. In this context 'low-activation' is used to denote any material having a residual radioactivity below that of conventional stainless steels.

The development of low activation materials for fusion reactors has followed three routes - elemental substitution in existing and well-tested materials such as steels, the development of new or unproven alloys, and the use of isotopically tailored elements. Only the first of these offers the possibility of the large scale, economic, production of material in time for a demonstration fusion reactor, although the other routes may eventually offer materials with greater advantages. Development effort has therefore concentrated on alternative austenitic and martensitic steels with modifications designed to eliminate elements that give rise to significant long-lived activity after irradiation with 14 MeV neutrons [1].

2. Materials and assessment indices

Four steels were considered in the assessment which represent a range of activation behaviour and all of which possess potentially suitable engineering characteristics. These were:-

1. AISI type 316 austenitic stainless steel (0.03%C, 17%Cr, 12%Ni, 2.5%Mo). This material has been chosen for several reactor designs, including INTOR and NET, on the basis of the broad data base obtained from its use in fission reactors.

2. The martensitic steel FV448 (0.15%C, 11%Cr, 0.25%V, 0.3%Nb, 0.6%Mo, 0.75%Ni). This alloy is similar to the DIN 1.4914 steel which is considered as an alternative for NET and has been proposed on the basis of reduced swelling under irradiation and reduced thermal fatigue.

3. A low-activation austenitic composition OPTSTAB, in which the usual nickel component is replaced by manganese (12%) and nitrogen (0.3%), and molybdenum is replaced by tungsten (2%) [2].

4. A low-activation martensitic steel LA7, based on FV448 steel with molybdenum replaced by tungsten (3%) [3].

For comparison, calculations were also made for the vanadium alloy V-15%Cr-5%Ti and silicon carbide. There is, however, less information on possible impurities in these materials and a greater uncertainty as to their mechanical and corrosion properties in the

fusion reactor environment. The specific activities of these materials as a function of time were calculated and the effect of impurities assessed as far as is possible on current information. From the calculated specific activities, several hazard indices were derived as a basis for assessment of the radiological implications of the selected materials. These indices were:

1. Specific radioactivity. This parameter is the primary means of expressing the activation of materials, though it takes no account of the widely varying nuclear, chemical or biological properties of the different radionuclides.

2. Contact γ dose-rate. For convenience, the contact dose-rate at the surface of an infinite half-space of uniformly contaminated material was calculated.

3. Biological hazard index for ingestion. This was expressed as a multiple of the ICRP annual limit of intake for radiation workers relative to one kilogram of the activated material.

4. Biological hazard index for inhalation. This was calculated in a similar way to the index for ingestion.

Although the last two indices provide a simple way of comparing the potential hazards of different mixtures of nuclides, they fail to take account of mechanisms for the release and transport of radionuclides to the point where they are ingested or inhaled or of differences in material properties that affect the probability of their release during accidents.

Examples of the variation of two of these indices with time after shutdown of the reactor are illustrated in figure 1. The values correspond to the relatively hard neutron spectrum at the first wall position in a reactor with liquid lithium breeder, following 2.5y irradiation at $5 MWm^{-2}$ neutron power flux. On the basis of these indices the radiological implications of alternative materials have been assessed in several situations.

3. Maintenance of the coolant system

Contact γ dose rates around the coolant circuit of a water-cooled fusion reactor may be comparable with those found in pressurized water fission reactors, where they are a major contributor to occupational radiation doses. The main contributions in the PWR arise from deposition of ^{58}Co, ^{54}Mn and ^{60}Co, with ^{58}Co arising mainly from nickel released by corrosion from the Inconel steam generator tubes and then irradiated during its passage through the high neutron flux region.

The above considerations indicate that it will be necessary to avoid the use of high activation materials throughout the circuit in order to reduce γ dose rates around the coolant circuit in water-cooled fusion systems. The use of the low-activation martensitic steel would only lead to a limited improvement since it would provide similar sources of ^{54}Mn, while the low-activation austenitic steel could give higher doses on account of its higher manganese content. The effect of using low-activation materials is difficult to estimate, however, since corrosion and transport properties will be at least as important as the nuclear properties. Nevertheless, relative to fission reactors, fusion

systems have the advantage that the use of corrosion inhibitors is not limited by their nuclear properties.

In helium-cooled systems, corrosion by impurities and erosion by particulates provide mechanisms for the transport of materials into the high flux regions. However, neutron sputtering is believed to be the most important means of introducing wall materials into the coolant and, therefore, coolant contamination should be characteristic of first wall/blanket piping materials. Calculations for conventional steel walls [4] indicated that the nuclides ^{54}Mn and ^{56}Mn would give rise to about 60% of total contact γ dose rates. Hence the use of low-activation steels only offers the prospect of slightly reduced γ dose rates from coolant system components. The use of vanadium alloys might offer substantial reductions in γ dose rates during maintenance of the cooling circuits.

4. Reactor maintenance and component repair

To minimize reactor down-time, the maintenance strategy will probably involve the replacement of components or modules, followed by their repair in workshops after an appropriate cooling time. Only remote maintenance will be used within the shielding and it is highly probable that similar techniques will be used throughout the reactor hall, though the option of limited human access to regions outside the shielding may remain as a possibility.

Low-activation steels show no significant advantage for short times after shutdown, when dose rates are dominated by ^{54}Mn. The dose rate for the vanadium alloy falls quite rapidly over the first week or so, associated with the decay of ^{48}Sc, but this fall is not maintained as ^{46}Sc and ^{51}Cr dominate for longer times and a factor of 10 to 100 below the steels appears to be the best that can be achieved with this particular alloy. Dose rates for silicon carbide fall very rapidly and are likely to be dominated by impurities after a few days.

For workshop repairs to be performed routinely by manual operations, it is necessary for γ dose rates to fall to values typically below $25\mu Sv h^{-1}$. Pure low-activation steels would have to be stored for about 100y before dose rates diminished to this value. In addition, part per million concentrations of impurities such as niobium, silver, europium, terbium, holmium, iridium and bismuth give rise to dose rates comparable with or greater than this value [5]. Hence it is likely that, although radiation shielding requirements may be somewhat reduced, low-activation steels will not offer an alternative maintenance strategy.

5. Release of activation products in severe accidents

The nature of mechanisms that could cause significant releases of activation products is a subject of current debate, with lithium fires and radioactive decay heating as the most likely causes of extensive mobilization of radionuclides. On the assumption that exposure will largely be caused by drinking contaminated water and by eating contaminated crops and animals, rather than by direct inhalation of radionuclides, the relative merits of the materials may most easily be compared using the ingestion hazard index. Those radionuclides that are active for times up to a few years may be expected to be significant. Low- activation steels exhibit no significant advantage during this period because the nuclides ^{54}Mn and ^{55}Fe which contribute

most to the ingestion hazard index arise from the activation of iron. The alloy V-15%Cr-5%Ti has a hazard index that is at least a factor 10 lower than those of the steels and the hazard index of pure silicon carbide is about six orders of magnitude lower.

6. Radioactive waste disposal

The ingestion hazard index is considered to be the most appropriate quantity for the comparison of different materials for the purposes of radioactive waste disposal, since it is assumed that transport in contaminated groundwater, followed by ingestion in plants or animals represents the most likely route for human exposure. For waste disposal it is appropriate to compare the materials for times greater than 100 years after removal from the reactor. After this time all ^{60}Co will have decayed. The low-activation materials nevertheless demonstrate a substantial advantage over the conventional steels because of the much lower levels of the very long-lived activation products arising from irradiation of nickel (^{63}Ni and ^{59}Ni), molybdenum (^{93}Mo and ^{99}Tc) and niobium (^{93m}Nb and ^{94}Nb). The most persistent radionuclide resulting from irradiation of the low-activation steels is ^{14}C, arising from the nitrogen content. Although the long-term ingestion hazard index from this ^{14}C is smaller, by a factor 100, than the indices of the conventional steels, it may be noted that the specific activity of ^{14}C is some 10 to 100 times greater than that permitted in 'low-level' waste under current UK regulations.

7. Recycling of structural materials

Resource limitations or restrictions on disposal may necessitate the recycling of structural materials. Recent studies indicate that the operations involved in the recycling of steel scrap are feasible at surface γ dose rates up to about $10mSvh^{-1}$ [6], compared with the current notional 'hands-on' dose rate of $25\mu Svh^{-1}$. Dose rates of conventional steels, however, do not fall below $10mSvh^{-1}$ for at least several hundred years and therefore recycling is not a reasonable possibility with these materials.

Surface dose rates of pure low-activation steels decline to less than $10mSvh^{-1}$ after a few decades, ^{54}Mn and ^{60}Co being the dominant radionuclides during this period. Thus recycling should be possible with low-activation steels. It should be noted, however, that dose rates during this period are dependent on the neutron spectrum in the blanket and calculations for different blanket designs have given variations by a factor 2 in the delay required. The existence of nickel and cobalt impurities causes increased dose rates but it is the presence of impurities such as silver, terbium and niobium at the part per million level that gives rise to long-lived γ emitters and causes the most marked departures from the characteristics of the pure material. For a mixture of impurities based on current estimates, surface dose rates for low-activation steels fall to $10mSvh^{-1}$ at times only slightly greater than those corresponding to the pure material but they decline very slowly thereafter.

The continued recycling of materials through the reactor will lead to some differences in these contributions compared with those from the first irradiation. The nuclide ^{94}Nb may be expected to build up linearly with the number of irradiation cycles and ^{60}Co, although decaying almost completely between irradiations, will undergo

accelerated build-up during irradiation as its precursor, stable ^{59}Co, is produced from ^{58}Fe. Since ^{60}Co is produced via two successive (n,γ) reactions its rate of production is sensitive to the neutron spectrum.

8. Conclusions

The use of low-activation steels in a fusion reactor is expected to offer radiological advantages mainly in relation to recycling and long-term waste disposal of structural materials rather than to short-term maintenance or repair.

Whereas the post-service dose rates of conventional steels remain for indefinite periods above the level at which recycling is considered feasible, the low-activation compositions would allow reclamation after storage for about 70y. The storage time required, as well as the dose rate level reached, is controlled by certain trace elements and it is important to achieve the lowest feasible concentrations of these impurities in order to gain full benefit from the use of the low-activation materials.

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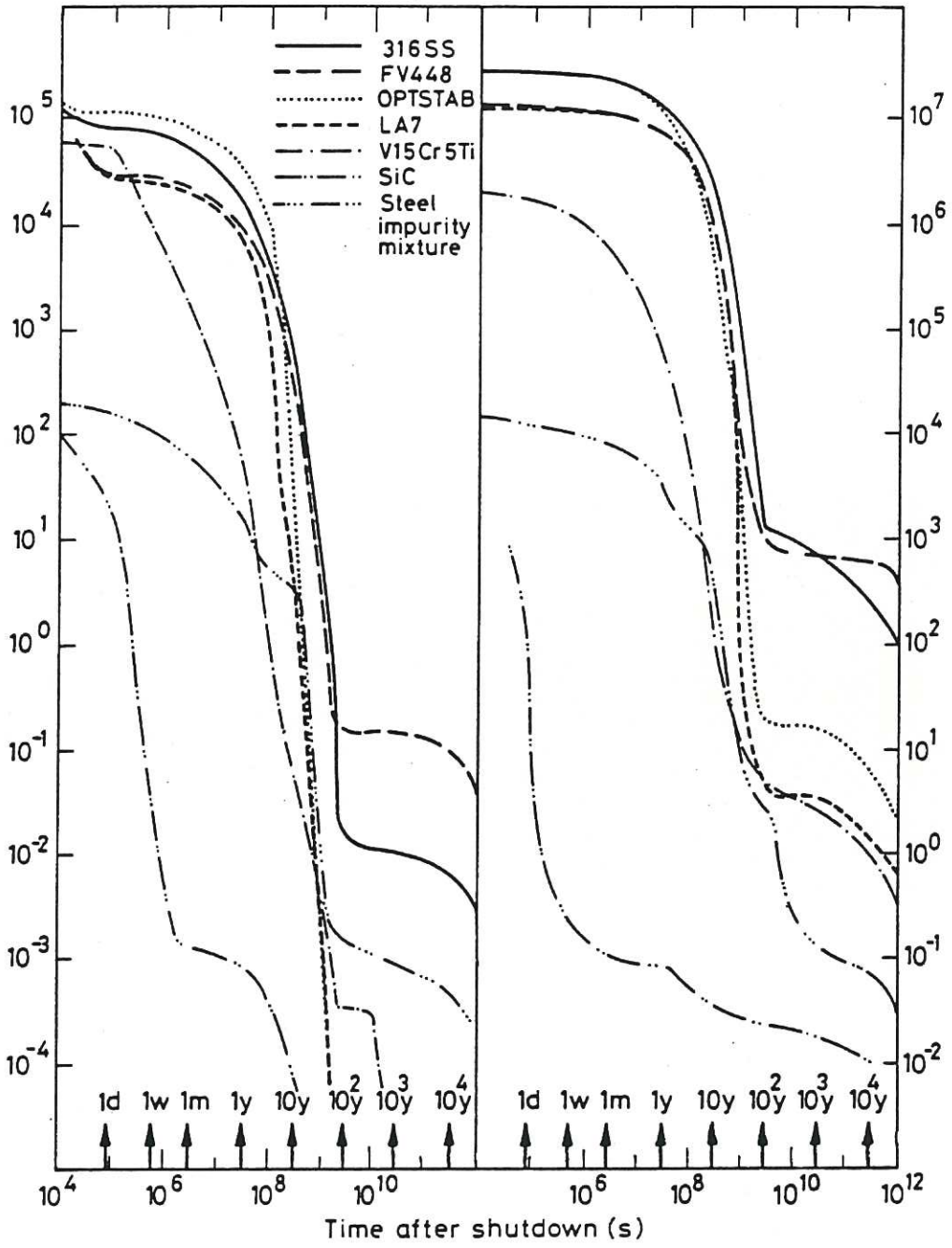

Fig. 1 Contact γ ray dose rate (Svh^{-1}) and specific ingestion hazard index (ICRP AL1 kg^{-1}) for representative materials following irradiation for 2.5y at $5MWm^{-2}$.

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