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Isotopically enriched structural materials in nuclear devices

L.W.G. Morgan[a,*], J. Shimwell[a,b], M.R. Gilbert[a]

[a] CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK
[b] Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK

HIGHLIGHTS

- C-B analysis of isotopic enrichment of structural materials is presented.
- Some, previously, prohibited elements could be used as alloying elements in LAM's.
- Adding enriched molybdenum and nickel, to EUROFER, could increase availability.
- Isotope enrichment for EUROFER could be cost-effective.
- Isotopically enriching copper, in CuCrZr, can reduce helium production by 50%.

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ABSTRACT

A large number of materials exist which have been labeled as low activation structural materials (LAM). Most often, these materials have been designed in order to substitute-out or completely remove elements that become activated and contribute significantly to shut-down activity after being irradiated by neutrons in a reactor environment. To date, one of the fundamental principles from which LAMs have been developed is that natural elemental compositions are the building blocks of LAMs. Thus, elements such as Co, Al, Ni, Mo, Nb, N and Cu that produce long-lived decay products are significantly reduced or removed from the LAM composition. These elements have an important part to play in the composition of steels and the removal/substitution can have a negative impact on materials properties such as yield stress and fracture toughness. This paper looks in more detail at whether using isotopic selection of the more mechanically desirable, but prohibited due to activation, elements can improve matters. In particular, this paper focuses on the activation of Eurofer.

Carefully chosen isotopically enriched elements, which are normally considered to be on the prohibited element list, are added to EUROFER steel as potential alloying elements. The EUROFER activation results show that some prohibited elements can be used as alloying elements in LAM steels, providing the selected isotopes do not have a significant impact on waste disposal rating or shut-down dose. The economic implications of isotopically enriching elements and the potential implications for decommissioning are considered. It is shown that the addition of molybdenum and nickel in small concentrations (<2% mass) could have the potential to increase availability to such an extent that the capital investment associated with isotope enrichment is negated and profits from electricity sale increased.

Another important issue for materials exposed to neutron irradiation is the production of gases, in particular helium, as a result of nuclear interactions. Helium accumulation in materials can cause embrittlement and so mitigating the rate of production is an important consideration when selecting materials. The second part of this paper considers whether helium production can be reduced in CuCrZr by isotopic tailoring. CuCrZr is a candidate bonding material for tungsten at first wall locations, however it suffers from degradation due to helium production. Inventory calculations show that isotopically enriching the copper, in CuCrZr, can reduce helium production by approximately 50%. However, cost–benefit analysis suggests that the cost of enriching copper is not cost-effective due to the high price of electromagnetic enrichment that is required for copper.

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* Corresponding author. Tel.: +44 01235 466656.
E-mail address: Lee.Morgan@ccfe.ac.uk (L.W.G. Morgan).

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1. Introduction

The structural materials within the ITER experimental fusion reactor vessel will be exposed to unprecedented neutron irradiation. As a result, the incident neutrons will cause macroscopic defects and nuclear transmutations within the structural materials. One of the problems that is encountered when transmutations occur is the production of activated nuclides that decay with long half-lives, which have radiological and waste disposal implications. Next-step fusion devices, such as DEMO, will be subject to significantly higher neutron fluences than will be experienced by ITER, resulting in higher activation. Hence, the need to reduce the amount of activated nuclides produced in these fusion devices will become increasingly important. One principle, which has been adopted in order to reduce the amount of activated products is the substitution of elements, that are particularly susceptible to activation, with chemically similar elements with a lower susceptibility to activation. F82H and EUROFER steels are low activation structural materials (LAM), where niobium has been replaced by tantalum [1,2], molybdenum has been replaced by tungsten [3], titanium has been replaced by vanadium [4] and manganese has been replaced by chromium [5].

The subject of LAMs is most often focused on the reduction of radioactive waste. This is, of course, very important. However, reducing the amount of long-lived nuclides produced is only one of the advantages of adopting the LAMs. Reducing the amount of short-lived nuclides that affect the shut-down dose during periods of maintenance is also important, as it can increase plant availability due to reduction of the cool-off period before maintenance. Very short-lived activation products could be problematic during an accident. Thus, a truly low activation material will have a low activation profile for short, medium and long-lived nuclides. Unfortunately, achieving this goal in entirety is likely to be impossible. However, a principle that has yet to be fully investigated, which could help move towards this goal, is the use of isotopically enriched elements within LAMs [6] in order to complement particular elemental reductions and substitutions. A commonly used method to produce LAMs is to eliminate the parent nuclides of alloying elements, such as Co, Al, Ni, Mo, Nb, N, B and Cu, which produce long-lived decay products [5,7,8]. In some cases, the replacement only works to a limited degree, for instance the replacement of manganese with chromium and the replacement of molybdenum with tungsten [4].

This method of producing LAMs assumes that the alloying elements have a natural isotopic composition. However, removing particular isotopes of the alloying elements may enable some elements to be used in LAMs, which had previously been eliminated from the composition. Isotopes of the same element have almost identical chemical properties but differ significantly in their nuclear properties. This method of careful isotope selection allows the bulk material to benefit from the elements chemical properties without suffering decremental effects due to an individual isotopes nuclear properties.

Other important issues for materials exposed to neutron irradiation are atomic displacements, resulting in lattice defects, and the production of gases, in particular helium, as a result of nuclear interactions. Helium accumulation in materials can cause swelling and embrittlement thus mitigating the rate of production is an important consideration when selecting materials. Gas production is especially problematic in the fusion environment due to the 14 MeV fusion neutrons being above many of the gas producing, energy threshold reactions which are not of concern in the fission environment, where neutron energies generally less than 2 MeV.

Isotopically enriching elements is likely to significantly increase the cost of the raw materials required for LAMs. Thus, isotopically enrichment is more likely to be adopted if there is a financial incentive for doing so. Financial incentives which may be able to offset the initial capital investment are:

- reducing cool-down period required for maintenance, thus increasing plant availability.
- reducing shielding required within the fusion vessel and within waste processing plants.
- reducing the amount of and classification of radioactive waste that would need to be sent for land burial.
- increased availability gained by adopting materials with increased longevity.
- reducing the cost of replacing components.
- increased thermodynamic efficiency.

Safety-based incentives include [9]:

- reduced radioactive impact to the environment during normal and accident scenarios.
- reduction of decay heat during loss of coolant accident.
- reduced gamma-ray dose during maintenance.

Other incentives such as legacy, responsibility and public perception should also be considered when deciding the extent of isotopic enrichment in LAMs. Only the benefit of increased availability has been included in the cost–benefit analysis in this paper.

Isotopic tailoring is quite prevalent in the literature and has a variety of applications that include ^{6}Li enrichment in tritium breeding blankets [10–12], minimizing activation [13,6,14,15] and simulating increased gas production for damage studies [16–19]. However, cost–benefit analysis of isotope enrichment has not been fully addressed in the literature.

This paper focuses on EUROFER and CuCrZr in order to ascertain if their performance can be improved and if any improvement is cost-effective:

1. The examination of the post-irradiation activity of EUROFER steel that has been modified to include isotopically enriched prohibited alloying elements molybdenum and nickel. cost–benefit analysis is performed, considering cost of enrichment, cost of waste disposal, possible increased availability and possible increased thermodynamic efficiency.
2. The study of gas production in CuCrZr. cost–benefit analysis is performed considering increased availability against cost of enrichment.

2. EUROFER

This section focuses on the selection of isotopes to be used in isotopically enriched low action materials (IELAM), the reduction of activity achieved by IELAMS and the economic case for IELAMS in relation to nuclear fusion devices.

The first step in ascertaining the financial viability of isotopic enrichment involves defining the susceptibility of constituent steel isotopes to activation. Figs. 1 and 2 show nuclide maps [20] illustrate the magnitude of the dose (after 12 days shutdown) and activity (after 100 years shutdown) for nuclides produced as a result of 5 full power years (FPY), 1.25 GW DT fusion power. The dose, at 12 days, is dominated by ^{54}Mn ($\sim$92% from ^{54}Fe(n, p)) and ^{182}Ta ($\sim$100% from ^{181}Ta(n, γ)). After 100 years shut-down, the activity is dominated by ^{63}Ni ($\sim$100% from ^{64}Ni(n, 2n)), closely followed by ^{53}Mn ($\sim$92% from ^{54}Fe(n, p)), ^{3}H ($\sim$99% from ^{10}B(n, t)) and ^{14}C ($\sim$100% from ^{13}C(n, γ)). These EUROFER results will help steer the isotopic design of an IELAM.