

LOW ACTIVATION MATERIAL CANDIDATES FOR FUSION POWER PLANTS

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ABSTRACT

The neutron activation system EASY has been used to determine activation product inventories and response functions for three potential candidate materials proposed for future fusion power plants. The results obtained have been used to rank the materials for a number of key Safety and Environmental (S&E) issues. Materials exhibiting relatively superior S&E properties at short post irradiation times are shown to be relatively inferior at longer timescales and vice versa. It is concluded that the choice of structural material for fusion power stations should be viewed as a compromise between several S&E issues, and that the development of fusion structural materials should be pursued in a balanced way, without concentration on particular classes of materials.

1. INTRODUCTION

By analysing issues such as temperature rises following a severe loss of coolant accident (LOCA), mobilisation and transfer of activation products to the environment during accident and normal operation, occupational doses, waste management, and many others, the European Safety and Environmental Assessment of Fusion Power (SEAFP) study (1) was able to demonstrate the remarkably good safety and environmental (S&E) characteristics of electricity generation by fusion power. Two power station options were studied during the programme, namely the advanced Plant Model 1 (PM-1) employing a vanadium alloy, and the near-term PM-2, employing a martensitic steel structure.

In the successor to SEAFP - the Safety and Environmental Assessment of Fusion Power - Long Term (SEAL) Programme, additional S&E assessments have been performed of a number of variant structural materials, not previously covered in SEAFP. Calculations have been performed, using SEAFP methods, to determine several key S&E features and provide a relative ranking of these structural materials. The materials investigated were a new low-activation martensitic steel termed F-82H, an additional vanadium alloy, and silicon carbide composite (SiC).

2. CANDIDATE MATERIALS

2.1. Martensitic steel

Heat-resisting martensitic steels based on the Fe-Cr-Mo-Nb-V elements have, for many years, found application in conventional and nuclear steam generating plant (2).

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Creep and yield strengths are higher than those found in austenitic steels, and the capability of operating up to 550°C improves thermodynamic efficiency. An additional feature of martensitic steels useful in fusion applications lies in their low radiation swelling properties (3). The SEAFP PM-2 employed the low-activation martensitic steel, LA12TaLC (4) for all structural components of the first wall and blanket. Analysis elsewhere (5), has indicated that the fully martensitic steel, F-82H (nominal composition - Fe-0.1%C-8%Cr-2%W-0.04%Ta) has superior activation properties in the long term. This steel has therefore been proposed for the SEAL study. It is elementally tailored to improve activation properties, whilst retaining good metallurgical characteristics. Detailed compositional analysis is given by Dietz (6).

2.2. Vanadium alloy

A number of vanadium alloys have been suggested over the years, mainly containing additions of titanium, chromium, silicon and iron (7). Although much of the good activation properties of vanadium alloys derives from the base material, the alloying additions, with the exception of iron, also produce activation which rapidly decays to relatively low levels. Combinations of these additions thus yield alloys exhibiting extremely low-activating properties. The early developmental work performed at Argonne (8) favoured fairly high concentrations of alloying additions, e.g. the V-15%Cr-5%Ti and V-20%Ti alloys. The trends in recent years have been towards more dilute alloys, for example V-3%Ti-1%Si. The SEAFP PM-1 employed the V-5%Ti alloy, while the US vanadium alloy with nominal composition V-4.0%Ti-3.3%Cr specified by Dietz (6), has been adopted for this study.

2.3. Silicon carbide

Silicon carbide in ceramic, fibre and composite forms has also been studied for many years (9). Most of the emphasis in research has been on production techniques rather than detailed materials property characterisation. Even less data is available on behaviour in a hard neutron spectrum. Pure SiC possesses exceptional low activation properties with regard to short post irradiation times. At longer times the inevitable production of the ²⁶Al from the silicon results in a plateau in activation properties stretching to one million years. Dietz (6) has provided a detailed compositional breakdown for SiC, which is used in this study.

3. ACTIVATION CALCULATIONS

Taylor (10) has calculated the neutronics conditions pertinent to one of the four SEAL blanket option using the ANISN code. This blanket design option assumes water cooling, and non-flowing lithium-lead as the tritium generation material. The blanket structure is assumed to be made from one of the three material candidates described above. For activation purposes, a mid-blanket position is considered as most representative of the whole machine. The total neutron flux at this position is $2.25 \times 10^{18} \text{ n.m}^{-2}.\text{s}^{-1}$ which is partitioned into a 100 energy group spectrum.

The European Activation System (EASY) consists of the computer code FISPACT4.1 (11) linked with the EAF4-1 cross section, decay and other data libraries (12). FISPACT4.1 is primarily a neutron activation code, but also contains

routines for calculating fission yields and charged particle induced reactions. Using the appropriate material compositions, and neutron flux spectrum, activation product inventories were calculated for each candidate material after a 2.5 year irradiation and at selected post exposure times ranging between 10^{-4} to 10^5 years.

These activation product inventories were next used to calculate five important activation response functions, namely: specific activity, shown in Figure 1; contact γ dose rate, Figure 2; ingestion dose hazard, Figure 3; inhalation dose hazard, Figure 4; and decay power, Figure 5. The immediate point to note from Figures 1-5, is that in the time period 10^{-4} to about 100 years, the materials are invariably ranked in order of decreasing activation property as follows: steel \rightarrow V-alloy \rightarrow SiC. After about 100 years, however, this ordering is generally reversed, with SiC exhibiting the poorest activation response and F-82H the best. These relative activation property rankings can be further considered in detail, since each response function has some key S&E relevance which becomes important at different stages during the post shutdown time period. These are discussed in the following section.

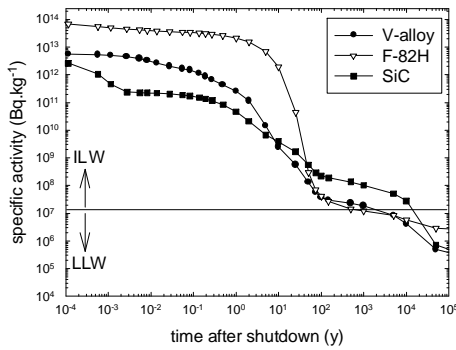


Figure 1. Specific activity response of the three material candidates.

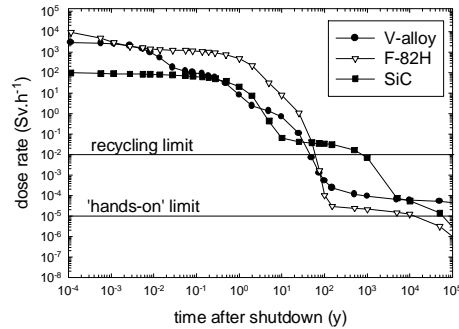


Figure 2. Contact γ dose rate response of the three material candidates.

4. KEY S&E ISSUES AND MATERIALS COMPARISON

Five key S&E areas of interest are: 1) temperature rises in the structure following a LOCA; 2) accidental release of radioactivity to the environment; 3) occupational radiation exposure to workers; 4) early handling and recycling of materials; and 5) waste management operations.

4.1. Temperature excursions following a hypothetical LOCA

Following a hypothetical loss of coolant accident in one or more blanket module, there is the potential for radioactive decay heat to cause a temperature rise within the structure of the machine. The total specific decay energy output, E , is used as a means of ranking the temperature rise within each material. This is calculated from the time integral of the decay power shown in Figure 5, H , thus:

$$E = \int_0^{\infty} H dt \quad (1)$$

where from past experience (13), the upper time limit of $t = 3$ months is found to typify the time constant for heat removal from the concrete cryostat. Evaluating the integral numerically yields the results and relative rankings shown in Table 1. For comparison, Table 1 also include calculations from the earlier SEAFP work, renormalised for consistency with the SEAL blanket conditions.

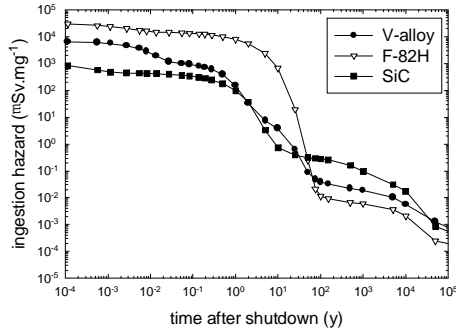


Figure 3. Ingestion dose hazard response of the three material candidates.

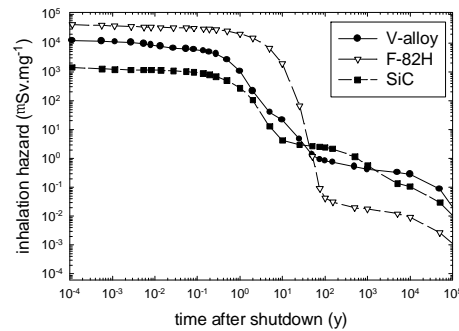


Figure 4. Inhalation dose hazard response of the three material candidates.

Table 1. Specific decay energy output ranking and comparison.

material	E (MJ.kg ⁻¹)	study	relative ranking
F-82H	6.81	SEAL	worse
V-alloy	0.78	SEAL	↓
SiC	0.38	SEAL	best
LA12TaLC	11.5	SEAFP (PM-2)	
V-5Ti	0.87	SEAFP (PM-1)	

With reference to the SEAFP study (1), it was previously found that the LA12TaLC steel employed in the PM-2 blanket, underwent a slow transient temperature rise to 1250K after LOCA assuming no active safety systems, while the V-5%Ti alloy used in the PM-1 blanket, showed no temperature excursion after the accident at all. Using the results presented in Table 1 coupled with the SEAFP experience, we are able to draw the following conclusions. It is likely that a blanket structure containing F-82H steel will show a similar temperature rise to that calculated for SEAFP PM-2, but may not reach the same peak temperature, since the specific decay energy output for F-82H is approximately 70% of that of the LA12TaLC steel. Similarities in the specific decay energy output between the V-4%Ti-3.3%Cr and V-5%Ti alloys, indicate that the SEAL V-alloy is unlikely to cause a temperature rise in the blanket after LOCA. The SiC blanket design, has a specific decay energy output half that of the V-alloy and would probably experience a temperature fall in a worst case accident.

4.2. Accidental release of radioactivity to the environment

With the temperature rises resulting from a LOCA described in the previous section, a potentially hazardous radio-inventory may become mobilised. As a general rule, the mobilisation increases exponentially with thermodynamic temperature (1). Full thermal hydraulic analysis is required (as in SEAFP) to determine the very small

fraction of mobilised material that eventually escapes from the fusion plant, but a relative measure of the biological hazard potential for each material can be found from Figures 3 and 4. The relevant time scale here is up to about one year.

In terms of potential ingestion hazard, i.e. the potential hazard associated with transfer of radionuclides from the lumen of the GI tract to various body organs via the blood, coupled with biological retention, there is clear ranking of the three materials shown in Table 2.

Table 2. Time-averaged biological hazard potentially associated with the candidate materials.

material	biological hazard (mSv.mg ⁻¹)		relative ranking
	ingestion dose	inhalation dose	
F-82H	25	40	worse
V-alloy	4	10	↓
SiC	0.8	1	best

Regarding inhalation, the potential hazard arises from transfer of radionuclides mainly contained in the pulmonary parenchyma (deep lung) to the blood followed by retention in various body organs. For some radionuclides, the lung-to-blood transfer coefficient is very low resulting in the lung receiving most of the exposure. The inhalation hazards potentially associated with the three candidate materials are broadly similar to those seen for ingestion as is shown in Table 2. It is further noted that the reduced relative hazard potentials from the advanced materials (V-alloy and SiC) are in addition to their reduced mobilisation potentials.

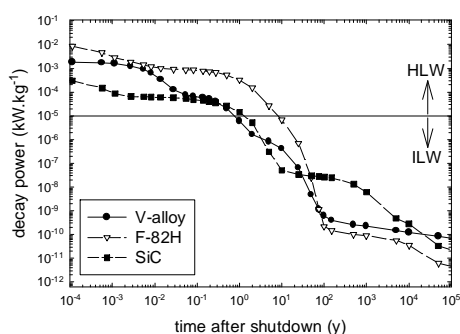


Figure 5. Decay power response for the three material candidates.

4.3. Occupational radiation exposure

As is the case with nuclear fission plant, most of the occupational exposure (ORE) is due to worker exposure from the primary circuit cooling loops (14). Radionuclides are transported in the flowing coolant to areas outside the biological shield and deposited on the insides of pipes and heat exchanger equipment. These plant areas are periodically inspected and maintained by plant workers who thus receive some γ -ray exposure from the decaying radionuclides. The relevant activation characteristic for

material comparison is therefore the γ dose rate shown in Figure 2. The important timescale is of the order of a few hours to about a month after shutdown.

Dose fields around cooling circuit plant are controlled partly by the decay physics of the active species, but mainly by factors involving mass transfer processes such as pipewall corrosion, dissolution and erosion, to name a few. These processes are critically material dependent and vary considerably depending on factors such as water chemistry, material preparation, operating temperature, etc. The γ dose rate curves alone, therefore offer only a basic relative index between materials that stop well short of indicating the likely magnitude of the γ dose fields surrounding cooling plant equipment. As such, they should be regarded as indicative only, and treated with caution. Nevertheless, the materials may be ranked as shown in Table 3.

Table 3. Time averaged occupational radiation exposure ranking.

material	contact g dose rates (kSv.h ⁻¹)	relative ranking
F-82H	4	worse
V-alloy	3	↓
SiC	0.1	best

4.4. Remote handling and recycling of material

A relative indication of the ease of remote handling and recycling of material is the contact γ dose rate received from exposure to an infinite slab of irradiated material. Figure 2 compares the three candidate materials and indicates the generally used ‘hands-on’ and recycling limits. The ‘hands-on’ limit of 10 μ Sv.h⁻¹ is equivalent to an annual exposure of 20mSv assuming a 2000 hour exposure time. The recycling limit is set at 1000 times the ‘hands-on’ limit, i.e. 10mSv.h⁻¹, and represents a somewhat arbitrary assessment of the level at which remote handling and recycling might be feasible. Times when candidate materials fall below these recycling limit are given in Table 4.

Table 4. Time required for remote handling and recycling operations to proceed.

material	time to cross ‘recycling’ limit (y)	relative ranking
V-alloy	50	best
F-82H	60	↓
SiC	700	worse

The reasonably short times for the V-alloy and F-82H to cross the limit indicate that recycling might be feasible for these two materials. The SiC γ dose rate, however, does not fall below 10mSv.h⁻¹ until about 700 years - far too long to be seriously considered as recyclable. None of the materials fall into the ‘hands-on’ category in any tolerably short timescale. Remote handling will therefore be essential in all decommissioning operations regardless of which material is employed.

4.5. Waste Management

Radioactive waste material is generally classified according to the necessity to perform active cooling, and its specific activity content. The ITER Joint Central Team favours definition of a heat generating limit at 50 W.m^{-3} as the dividing line between high level waste (HLW) and intermediate level waste (ILW) (15). A limit of 12MBq.kg^{-1} (for β/γ emitting nuclides) suitably marks the intermediate/low level waste boundary (16).

In the density range of $\rho = 3220 \text{ kg.m}^{-3}$ (SiC) to 8000 kg.m^{-3} (steel) this corresponds to the specific decay power limit $\approx 6.25 \times 10^{-6} - 1.55 \times 10^{-5} \text{ kW.kg}^{-1}$. A reasonable compromise is to set the HLW limit to $10^{-5} \text{ kW.kg}^{-1}$, which gives a good indication of the general behaviour. As may be seen from Figure 5, considerable variation in the criterion adopted would not alter the qualitative conclusions. The times required for each of the candidate materials to cross the two waste limits are given in Tables 5a and 5b.

Table 5a. Times required to achieve ILW category.

material	time to cross HLW→ILW limit (y)	relative ranking
V-alloy	0.7	best
SiC	1.3	↓
F-82H	8	worse

Table 5b. Times required to reach LLW category.

material	time to cross ILW→LLW limit (y)	relative ranking
F-82H	600	best
V-alloy	2000	↓
SiC	13000	worse

5. DISCUSSION AND CONCLUDING REMARKS

From the brief assessment of five key S&E issues, it is clear that the choice of structural material for a future power plant needs to be judged as a compromise between several competing factors. On issues important on the short timescale, such as plant integrity, public and personnel doses, SiC appears to be the most favourable choice, while F-82H steel would appear the least favourable (although it would still produce very good performance compared with fission plant) and the V-alloy somewhere in between. For medium-term issues, such as the time before remote handling and recycling could be envisaged, The V-alloy and steel are the best materials, while SiC would require unrealistically long times. For longer timescale issues, concerning mainly waste management, all three materials can be declassified as heat generating waste within a few years. For overall long-term activation characteristics, F-82H steel is consistently lower than the other two materials.

A general conclusion to be made from these results is that the development of structural materials for fusion power stations should be pursued in a balanced way, without concentration on particular classes of material.

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