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THE INFLUENCE OF STEEL TYPE ON THE ACTIVATION AND DECAY
OF FUSION-REACTOR FIRST WALLS

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THE INFLUENCE OF STEEL TYPE ON THE
ACTIVATION AND DECAY OF FUSION-REACTOR FIRST WALLS*

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ABSTRACT

Five steels (PCA, HT-9, thermally stabilized 2.25 Cr-1 Mo, Nb stabilized 2.25 Cr-1 Mo, and 2.25 Cr-1 V) are compared as a function of time from the viewpoints of activation, afterheat, inhalation biological hazard potential (bhp), ingestion bhp, and feasibility of disposal by shallow land burial. An additional case uses the 2.25 Cr-1 V steel with a liquid metal wall (LMW) protective shield between the neutron source and the wall. (This geometry is feasible for inertial confinement fusion reactors.) The PCA steel is the worst choice and the LMW protected 2.25 Cr-1 V is the best choice by substantial margins from all five viewpoints. The HT-9 and two versions of 2.25 Cr-1 Mo are roughly the same at intermediate values. The 2.25 Cr-1 V has about the same afterheat as those three steels, but its waste disposal feasibility is considerably better. Under NRC's proposed low level waste disposal rule (10CFR61), only the 2.25 Cr-1 V could be considered low level waste suitable for shallow land burial.

INTRODUCTION

Fusion has long been touted as a radiologically clean alternative to fission power generation. Although fusion does not have the design problem of preventing afterheat from rearranging a large fuel supply into

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an uncontrolled energy producing mass, D-T fusion neutrons will be much more energetic than fission neutrons. Furthermore, in most fusion reactor designs, the fusion neutrons are unmoderated when they reach the reactor wall, and a host of high energy reactions becomes important. Consequently, fission activation codes and data libraries must be modified before being applied to fusion reactor geometries.

Fusion wall materials have traditionally been chosen from temperature, atomic number, strength, and corrosion viewpoints. In this paper, we compare five steels from the viewpoint of activation. Because the results vary considerably with steel type, we believe that earlier attention must be given to alloy selection; perhaps even to the point of isotopically tailoring some of the constituents.

METHODS OF CALCULATION

In a fusion reactor wall, there are a large number of nuclides, the activation and decay equations for many of the nuclides are coupled, both the neutron flux and cross sections vary with neutron energy, and the neutron flux varies with location. Hence, the problem is well suited for the use of computer codes which calculate the activity of each nuclide as a function of time.

The procedure for determining the radioactive build-up and decay in each fusion reactor configuration is to sequentially run three computer codes: a neutron transport code to produce energy and spatially resolved neutron fluxes, a cross section collapsing code to produce flux-weighted, energy-averaged activation cross sections, and an activation/decay code to solve the coupled rate equations as a function of time.

The neutron flux as a function of position and energy is calculated by the TART monte carlo neutron transport code.¹ The output is in a file that can be read directly by the cross section collapsing code, ORLIB.² ORLIB also requires the ACTL energy resolved cross section library,³ a brief instruction file specifying the location at which the flux is to be read, the neutron source strength, and the nuclides for which the cross sections are to be averaged. The output is a set of three cross section files; the first two files are read directly by the

FORIG activation/decay code⁴ and the third file is used as input to post-processing hand calculations that are sometimes useful in explaining the FORIG results.

The FORIG code is an adaptation for fusion reactor problems of the ORIGEN2 code.⁵ The basic changes are to read 11 rather than 6 standard reactions, and to allow up to 15 rather than 7 pathways for activation or decay of each nuclide. FORIG produces output in the same format as ORIGEN2; composition, activity, thermal power, inhalation biological hazard potential (bhp), ingestion bhp, chemical ingestion bhp, and gamma spectrum can be printed as a function of time for each nuclide or element. Also, both the total values or the fractional values of each quantity are available as a function of time.

The ACTL library and the TART, ORLIB, and FORIG codes are all available on the LLNL Octopus network and on the MMFECC network. In addition, ORLIB, FORIG, and ACTL are being sent to the Radiation Shielding Information Center (RSIC) at Oak Ridge National Laboratory. The ACTL library has been recently updated by Howerton for fusion reactor calculations.⁶ A list of the nuclides and reactions in the library is available from the authors. Additional nuclides and reactions will be added on request.

In analyzing the results of the computer codes, it is sometimes necessary to determine the principal sequences of reactions and decays responsible for the presence of important radionuclides. In addition, it is necessary to determine if the generation of nuclides not found in the computer decay library can be neglected. These and similar problems in analyzing computational results are addressed using analytical estimation techniques previously described by Lasche.⁷ Use of these hand calculations has also given us confidence in the FORIG calculations.

STEEL COMPOSITIONS INVESTIGATED

Several steels have been used in fusion reactor design studies (Table I). Primary Candidate Alloy, also called PCA (case N), is an advanced titanium modified type 316 stainless steel under consideration for first walls in magnetic fusion reactors. It was the material

Table 1. Materials Investigated. All compositions are in wt.%. 4

Element	Case				
	N PCA	O HT-9	P Nb stabilized 2.25 Cr	Q Thermally stabilized 2.25 Cr	R and S Case P with V replacing Mo
B	0.005	-	-	-	-
C	0.05	0.22	0.09	0.11	0.11
N	0.01	-	-	-	-
Al	0.03	-	-	-	-
Si	0.5	0.38	0.32	0.25	0.25
P	0.01	0.019	0.012	0.005	0.005
S	0.005	0.006	0.007	0.011	0.011
Ti	0.3	-	-	-	-
V	0.1	0.27	-	-	0.94
Cr	14	11.3	2.19	2.22	2.22
Mn	2	0.52	0.46	0.41	0.41
Fe	54.88	85.435	94.261	96.054	96.054
Co	0.03	-	0.0011	0.002	0.002
Ni	16	0.5	0.5489	0.0998	0.0998
Cu	0.02	-	-	-	-
As	0.02	-	-	-	-
Nb	0.03	-	1.13	-	-
Mo	2	0.85	0.98	0.94	-
Ta	0.01	-	-	-	-
W	-	0.5	-	-	-

selected for the STARFIRE commercial tokamak design study. HT-9 (case Q) is a ferritic steel containing 12% Cr; it has been used in the HIBALL heavy ion ICF design, the EAGLE light ion ICF design, and the WITAMIR tandem mirror design. The low chromium ferritic steel, 2.25 Cr-1 Mo, is extensively used in steam generators, and two variations have been investigated for use with liquid lithium. One version (case P) uses a small amount of Nb to stabilize the carbides against lithium corrosion. The other version, (case Q) which stabilizes the carbides with a heat treatment, is used in the HYLIFE laser or heavy ion ICF design. The 2.25 Cr-1 V steel (case R) is a modification to thermally stabilized 2.25 Cr-1 Mo in which the Mo is replaced by V to reduce the long term activity. Although this steel has not yet been evaluated from other viewpoints (e.g. weldability or corrosion resistance), we include it to quantify its benefits from the viewpoint of activation. The low activating alloy, 2.25 Cr-1 V, was also used with an ICF source and a 75-cm liquid lithium wall (LMW) protection (case S).

The calculations were done in one-dimensional geometry for all five materials. In each case, the neutron source was on for 30 years at a flux corresponding to 1 GWe chamber power and 70% capacity factor, and then the wall material was allowed to decay. The 14.1 MeV point source was enclosed by the 2-cm-thick spherical wall at 5-m radius. The neutron blanket/reflector consisted of 78 cm of lithium, 18 cm of graphite, 2 cm of boron carbide, and a 10-cm-thick outer wall. A companion paper,⁸ investigates the influence of geometry (wall radius, wall shape, distributed vs point source, etc.) on first wall activation.

NUMERICAL RESULTS

The activity is shown as a function of time in Fig. 1. The linear-linear form is used to present an undistorted visual comparison, because the apparent relative magnitudes in logarithmic form can be made large or small by the choice of the upper and lower cutoff decade. However, the linear scale has the disadvantage of not showing relative magnitudes at long decay times, and for this reason we have expanded that

Fig. 1 Activity as a function of time.

portion of the linear scale in the inset in Fig. 1. We have also generated a semilog plot to allow easy extraction of numerical values at all times of interest, and to allow estimation of the effective decay half life as a function of time from the slope of the decay curve, but space does not permit its use here.

At shutdown, all five unprotected walls have roughly equal activities ~ 1.6 GCi, and the LMW protected wall has a factor of 16 less activity. Ten years after shutdown, the activity of each wall has dropped by a factor of ~ 30 , and the five unprotected walls still have roughly equal activities.

Fifty years after shutdown (80 years after startup), a considerable spread has developed between the six cases as shown in Table 2. The PCA wall (case N) is by far the worst with an activity of 650 kCi, a factor of 2400 reduction from shutdown. The two versions of 2.25 Cr-1 Mo and the HT-9 (cases O, P, and Q) have activities of a few tens of kCi. The two 2.25 Cr-1 V walls (cases R and S) have activities of only a few kCi. Also, the LMW-protected 2.25 Cr-1 V wall (case S) activity is now over 400 times less than the PCA activity; it was only 16 times less at shutdown.

At 50 to 100 years after shutdown, all six cases have roughly equal effective decay rates. The slight difference for each material is because different nuclides are dominant. At 100 years after shutdown, ^{63}Ni is the shortest lived isotope still present in all six cases (92 year half life). As ^{63}Ni decays away, ^{93}Mo (2980 year half life) will dominate except for the two Mo-free walls (cases R and S). In these cases, ^{59}Ni (80,000 year half life) and ^{53}Mn (3,800,000 year half life) will dominate. However, all the steels have roughly equal amounts of ^{53}Mn since they all contain similar amounts of the parents, Fe and Mn. (The only exception is for the LMW-protected wall where the ^{53}Mn activity is ~ 40 times lower due to the softer flux.) Similarly, although ^{59}Ni does not show on fractional activity plots for the Mo-containing steels because it is swamped by the ^{63}Ni and ^{93}Mo activities, its actual activities are higher than in the Mo-free steel. For both ^{63}Ni and ^{59}Ni , the parents are Ni isotopes. The ratios of the activities of these isotopes to the initial nickel population are

Table 2. Activity 50 Years After Shutdown. The final two columns show the reduction of activity compared to shutdown and compared to PCA (50 yrs after shutdown).

<u>Case</u>	<u>Description</u>	<u>Activity 50 yrs after shutdown</u>	<u>Reduction since shutdown</u>	<u>Reduction from PCA</u>
N	PCA	650 kCi	2,400	1
O	HT-9	30 kCi	52,000	22
P	Nb stab. 2.25 Cr	44 kCi	36,000	15
Q	Thermally stab. 2.25 Cr	16 kCi	100,000	41
R	2.25 Cr-1 V	5.5 kCi	293,000	119
S	LMW protected 2.25 Cr-1 V	1.6 kCi	60,000	412

constant to within a few percent for all five unprotected steels. Similarly, the ratio of ^{93}Mo activity to initial Mo mass is constant to within 0.5% for all four Mo-containing walls. In the Nb stabilized 2.25 Cr-1 Mo steel, ^{94}Nb (20,300 year half life) will also be important at long times. In all six cases, tritium has been eliminated from consideration because the tritium that diffuses into the steel during operation is much more significant than the tritium produced in the steel by neutron reactions.⁹

Inspection of the FORIG output also revealed the importance of accounting for the activation of daughters and for changes in parent nuclide populations. In one example, the ^{55}Mn inventory tripled during 30 years of activation, and its activation daughters would be underestimated if the initial population was used in a hand calculation.

The afterheat in the six walls is shown as a function of time in Fig. 2. If a peak temperature of 1300 K is allowed, the spherical chamber can be buried in earth when its afterheat is ~ 14 kW if it is first crushed or ~ 61 kW if it is buried as a hollow sphere.¹⁰ Assuming hollow sphere burial, the PCA wall cannot be buried until 24 years after shutdown, the other four unprotected walls until 9 years after shutdown, and the LMW protected wall until 3 years after shutdown. For crushed sphere burial, the PCA wall must be held for 36 years after shutdown, the other four unprotected walls for ~ 14 years, and the LMW protected wall for 5 years.

The inhalation biological hazard potential (bhp) is shown for the six walls in Fig. 3. This index represents the amount of air required to dilute a fully vaporized wall such that the dose received by continuously breathing the mixture will not exceed 0.5 rem per year. The inhalation bhp is calculated for each nuclide by dividing the activity by the radioactivity concentration guide (RCG) taken from column 1 of Table II of 10CFR20 (Part 20, Title 10, Code of Federal Regulations). Since structure vaporization is only possible by applying large amounts of energy, inhalation bhp is only appropriate at shutdown or shortly thereafter. Three of the steels (HT-9, thermally stabilized 2.25 Cr, and 2.25 Cr-1 V) have roughly equal shutdown inhalation bhp's of $\sim 3 \times 10^8 \text{ km}^3$. The PCA and Nb stabilized 2.25 Cr walls are about

Fig. 2 Afterheat as a function of time. At 61 kW, the peak temperature of a buried hollow sphere wall would be 1300 K.

Fig. 3 Inhalation bhp as a function of time.

25% and 50% higher, respectively, while the LMW protected 2.25 Cr-1 V is a factor of 15 lower.

The ingestion bhp is the amount of water required to dilute a fully dissolved wall to the level that the dose received by drinking only this water will not exceed 0.5 rem per year. The ingestion bhp is calculated by using the RCG values taken from Column 2, Table II, 10CFR20. Dissolution of the wall into water is most likely after the material is buried (as waste). The ingestion bhp is shown for the six walls in Fig. 4. The data are normalized as a ratio of the radioactive ingestion bhp of the activated wall to the amount of water required to dilute an unactivated wall, from a chemical hazard viewpoint. Thus, when the normalized bhp falls to 1.0, dissolution of the activated wall is no worse than dissolving pure, clean steel. After only 15 and 28 years, the LMW protected and unprotected 2.25 Cr-1 V walls reach the level where the radioactive hazard of shallow land burial is identical to the routinely accepted chemical hazard of burying unirradiated steel. The other four walls reach roughly steady bhp values at ~ 35 years after shutdown. The HT-9 and thermally stabilized 2.25 Cr level is ~ 4, the Nb stabilized 2.25 Cr steady level is ~ 9, and the PCA wall reaches a level of ~ 20.

The ratios of radioactive to chemical ingestion bhp's at ~ 35 years after shutdown indicate that shallow burial might be feasible at that time. However, NRC has recently addressed the shallow burial issue in a new regulation, 10CFR61. This regulation lists the maximum allowable concentration of each nuclide in the solid waste (rather than in water or air). The actual concentrations are divided by the allowable concentrations, and the ratios are summed over all nuclides. The resulting sum (called the shallow burial index or SBI) must be less than 1.0 before burial is allowed. This technique has been applied to our six steels at a time of 50 years after shutdown. The values of PCA, HT-9, and both thermally and niobium stabilized 2.25 Cr steels are over 100 times above the proposed limits (due to the low allowable ⁹⁴Nb limit). The unprotected and LMW protected 2.25 Cr-1 V walls have indices of 0.14

Fig. 4 Ingestion bhp as a function of time. The ratio plotted compares the radiological ingestion bhp to the initial (unirradiated) chemical ingestion bhp.

and 0.6, respectively. Thus, only the 2.25 Cr-1 V walls could be buried fifty years after shutdown under the proposed rules. Since LMW protection would also reduce ^{94}Nb production in the other steels due to the softer and less intense neutron flux, LMW inertial fusion reactors will have a significant advantage over magnetic fusion reactors from the viewpoint of structural waste disposal.

The discrepancy between the ingestion bhp and the shallow burial index is disturbing. The contribution of ^{94}Nb to the SBI is about 2500 times its contribution to the normalized ingestion bhp. The proposed revision of 10CFR20 has an even higher ingestion RCG for ^{94}Nb , and the discrepancy will increase to a factor of 50,000. Conversely, the contribution of ^{93}Mo to the SBI is only about 10% of its contribution to the normalized bhp; this is because ^{137}Cs was used as a surrogate for ^{93}Mo as in the draft 10CFR61. We believe that 10CFR61 must be expanded to include more nuclides, and that the ^{94}Nb discrepancy between 10CFR61 and 10CFR20 must be resolved by the NRC.

COMPARISON OF THE SIX STEELS

The PCA steel appears to be a poor choice from both afterheat and disposal viewpoints. The HT-9 and both thermally and Nb stabilized 2.25 Cr steels are better from an afterheat viewpoint, but still unacceptable with respect to waste disposal. The unprotected 2.25 Cr-1 V has about the same time required to reduce the afterheat to an acceptable level, and it is acceptable for shallow burial. The liquid metal wall protected 2.25 Cr-1 V steel was by far the best of the six cases, with a short cooling time and legal disposal by shallow burial.

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