WASTE MANAGEMENT OF FIRST WALL AND BLANKET STRUCTURAL MATERIALS FOR TOKAMAK FUSION REACTORS[a]

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ABSTRACT

A comparison has been made of the induced radioactivities in the first wall and structural materials of the breeder blanket in the high-flux region for two different fusion-reactor types. One system is the STARFIRE, a tokamak reactor with PCA, a modified stainless steel, as a first wall and a $LiAlO_2$ breeder blanket; the other is a reactor based on the STARFIRE design with a vanadium alloy as the first wall and structural material, and circulating molten lithium as the breeder/coolant. The recycling or disposal of these structural materials is evaluated.

INTRODUCTION

Among the goals of the fusion power program are the minimization of radioactive waste requiring disposal and the minimization of the impact of a fusion reactor economy upon the available natural resources. Both of these goals can be achieved by selecting structural materials that yield low amounts of radioactivity and hence can more easily be recycled. This reduces the strain on resources and reduces the impact of waste disposal.

A comparison was made between the structural material specified for the STARFIRE reactor and a vanadium alloy, a representative of a class of materials termed "low activation materials". In order to optimize the properties of the vanadium alloy, a design was chosen using molten lithium as the breeder material and coolant.

The STARFIRE[1] fusion reactor design is a 1200 MWe central station fusion power plant that utilizes a deuterium-tritium fueled tokamak reactor as the heat source, water as the heat transfer medium and a conventional steam cycle for producing electricity. The fusion plasma is contained within the first wall; beyond the first wall is the blanket containing the breeder material. The design is such that the first wall, breeder, neutron multiplier, and neutron reflector are included in an integral sector unit, with 24 sectors completing the torus. Based on the current design and the proposed operational procedure four of the 24 first wall/blanket sectors are removed annually and are replaced. The four removed sectors contain 7.5×10^7 g (75 Mg) of PCA[b] plus the $LiAlO_2$ breeder, the Zr_5Pb_3 neutron multiplier, and the graphite neutron reflector.

The vanadium-containing reactor of the same electrical output as STARFIRE, also contains 24 sectors.[2] The use of vanadium alloys results in a relatively long lifetime, approximately twice that for stainless steel structures.[3] Only two sectors have to be processed annually, containing 4.7×10^7 g (47 Mg) of vanadium. The breeder/coolant is removed before sector removal and only the vanadium alloy and graphite have to be processed.

REQUIREMENTS FOR DISPOSAL OF RADIOACTIVE MATERIALS

The disposal of radioactive materials in shallow land burial is controlled by the proposed Nuclear Regulatory Commission (NRC) rule 10 CFR 61,[4] based upon the radioactivity content of the waste. The wastes are classified first by the long-lived isotopes, ^{14}C, ^{59}Ni, and ^{94}Nb and the allowable limits are indicated in Table 1.

If the waste contains less than 0.1% of the indicated concentration, the material is a Class A waste. If the concentration exceeds 0.1 and is not greater than the value shown, the material is Class C. Material with a radioactive content that exceeds

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[b]Prime candidate alloy, a titanium-modified austenitic stainless steel.

Table 1. Concentration Limits for Long-Lived Radionuclides for Shallow Land Burial

Radionuclide	Concentration Curies/cm3
^{14}C in activated metal	8.0(-5)[a]
^{59}Ni in activated metal	2.2(-4)
^{94}Nb in activated metal	2. (-7)

[a]Read as 8.0×10^{-5}.

these limits is not generally acceptable for near-surface disposal. After the preliminary classification based upon the long-lived isotopes, the short-lived isotopes in Table 2 are next considered.

If the material has not been classified Class C by any long-lived radionuclides then the class is determined by whether the limit in that class is exceeded. If the waste contains a mixture of radionuclides, then the sum of the fractions obtained by dividing each nuclide's concentration by the appropriate limit should be less than one.

RADIOACTIVITY IN STRUCTURAL MATERIALS

The radioactivities expected in the structural materials have been derived from calculations based on a Radioactivity Calculation Code RACC,[5] along with the associated activation data libraries. The radioactivities were calculated as a function of time after removal from the fusion reactor. A comparison of the radioactivities of the two structural materials is shown in Table 3. At one year decay, the radioactivity in the vanadium is three percent of that in the PCA, decreasing to 0.05 percent at ten years with the same ratio persisting through 100 years decay.

The radionuclides from fusion reactors that limit shallow land burial for disposal of materials are ^{14}C, ^{59}Ni, ^{94}Nb, ^{3}H, ^{60}Co, and ^{63}Ni; the limit for ^{94}Nb is particularly low at 0.2 $\mu Ci/cm^3$ (0.2 Ci/m^3). The radioactivity content of PCA (Table 3) exceeds the limits for ^{94}Nb and ^{63}Ni at all reasonable decay

Table 2. Concentrations of Short-Lived Radionuclides for Establishing Waste Classification

Radionuclide	Concentration, Curies/cm^3 of Waste		
	Class A[a]	Class B	Class C
Total of all nuclides with less than 5 year half-life	7.0(-4)[b]	c	c
^{3}H	4.0(-5)	c	c
^{60}Co	7.0(-4)	c	c
^{63}Ni	3.5(-6)	7.0(-5)	7.0(-4)
^{63}Ni in activated metal	3.5(-5)	7.0(-4)	7.0(-3)
^{90}Sr	4.0(-8)	1.5(-4)	7.0(-3)

[a]Class A, has no stability requirements, but it should be segregated from other wastes. Limits are established by dose limits of 500 mrem/y to an intruder after 100 years of institutional control.

Class B, is buried in a stable form, with the upper limit determined by a dose of 500 mrem/y to a potential intruder after 100 years of institutional control.

Class C, is buried in a stable form. A barrier is provided against potential, inadvertent intrusion for up to 500 years from the start of institutional control.

[b]Read as 7.0×10^{-4}.

[c]There are no limits for these nuclides in Class B or C wastes.

times because of the long half-lives. Thus, PCA is not acceptable for near-surface disposal. Some more restrictive isolation technique (e.g., deep geologic disposal) would be required. For the vanadium alloy all the radionuclides are below the specified limits except for ^{94}Nb which exceeds the limit by a factor of three. Dilution can reduce this value. It is assumed that the vanadium alloy will be placed in a 55 gallon drum (0.21 m^3) with a packing fraction of 25%, thus bringing the ^{94}Nb content per emplaced volume below the allowable limit for shallow land burial. It should be noted that the values given in Table 3 are for the first wall material with the greatest neutron flux. The rest of the vanadium contains less ^{94}Nb.

BURIAL OF STRUCTURAL MATERIALS

A. Vanadium Alloy

Before disposal of the vanadium alloy a decay period is necessary to permit reduction of the shorter lived isotopes because disposal costs in a near-surface burial site are based on volume and an excess activity surcharge. A standard 55 gallon drum used as the package contains 0.05 m^3 of the vanadium alloy assuming a 25% packing fraction. The amount of vanadium

Table 3. Radioactivity of the First Wall from a Fusion Reactor First-Wall Blanket System with PCA[a] or V15Cr5Ti[b]

	Activity Ci/cm^3							
Material	PCA				V15Cr5Ti			
Time (Y)	1	10	50	100	1	10	50	100
Total Activity	1.4(2)[c]	1.2(1)	2.0(-1)	1.4(-1)	4.3(0)	5.6(-3)	9.3(-5)	8.2(-5)
^{14}C	7.5(-5)	7.5(-5)	7.4(-5)	7.4(-5)	6.7(-5)	6.7(-5)	6.7(-5)	6.7(-5)
^{26}Al	4.4(-8)	4.4(-8)	4.4(-8)	4.4(-8)	4.6(-9)	4.5(-9)	4.5(-9)	4.5(-9)
^{45}Ca	1.0(-2)	1.1(-8)	d	d	1.1(-1)	1.2(-7)	d	d
^{49}V	3.0(-1)	2.6(-4)	d	d	4.1(0)	4.1(-3)	d	d
^{54}Mn	9.8(0)	4.0(-3)	d	d	e	e	e	e
^{55}Fe	1.2(2)	1.1(1)	2.5(-4)	4.1(-10)	1.4(-2)	1.2(-3)	2.9(-8)	4.6(-14)
^{60}Co	4.6(0)	1.4(0)	7.0(-3)	9.4(-5)	2.3(-4)	7.0(-5)	3.5(-7)	4.8(-10)
^{63}Ni	2.6(-1)	2.4(-1)	1.7(-1)	1.2(-1)	1.8(-6)	1.7(-6)	1.3(-6)	8.7(-7)
^{94}Nb	1.3(-5)	1.3(-5)	1.3(-5)	1.3(-5)	6.8(-7)	6.8(-7)	6.8(-7)	6.8(-7)
^{93m}Nb	2.1(-3)	3.9(-3)	6.5(-3)	6.7(-3)	1.4(-4)	8.6(-5)	1.7(-5)	6.7(-6)
^{93}Mo	8.3(-3)	8.2(-3)	8.0(-3)	7.8(-3)	7.3(-6)	7.3(-6)	7.1(-6)	6.8(-6)

[a] Calculations based on a Zr_5Pb_3 neutron multiplier, graphite reflector, and $LiAlO_2$ breeder.
[b] Calculations based on a graphite reflector and liquid lithium breeder.
[c] Read as 1.4×10^2.
[d] Activity content $<<10^{-10}$ Ci/cm^3.
[e] Not present.

requiring disposal annually is 4.7×10^7 g ($7.82\ m^3$) yielding approximately 160 drums annually. At one year after removal from the reactor, each drum would contain 2.2×10^4 Ci/drum. The disposal cost for each drum is estimated at $90 plus an activity surcharge of ~$5700/drum,[6] yielding a total annual cost of over $900,000 per year. By permitting the vanadium to decay for an additional nine years, the average radioactivity content of each drum would drop to approximately 35 Ci and the activity surcharge would disappear based on current practice. At this point the total disposal cost would be about $14,000. For shipment of such wastes a shielded container would probably be necessary, i.e., CNS-195H[7] which can contain 14-55 gallon drums. Approximately 12 shipments per year would be necessary to handle the 160 drums. Assuming a 1600 km (1000 mi) trip from reactor to disposal site, and an oversized load with two drivers, the cost per shipment would be $3900 or $47,000 for the 12 shipments.[8]

B. PCA

The ^{94}Nb and ^{63}Ni contents for PCA (Table 3) exceed the limits permitted in shallow land burial (Tables 1 and 2) and thus it is assumed that the PCA will be emplaced in a geologic repository. The waste canisters are 0.61 m x 3.05 m (2 ft x 10 ft) and 44 canisters are required to accommodate the $9.6\ m^3$ of PCA per year at a 25% packing fraction. This size has been selected for the waste containers because such containers have been chosen for the solidified waste from the Savannah River Plant (SRP). These canisters are of a relatively simple design and should be fabricable for approximately $7500. Transportation of the canisters to the storage site is assumed to be by rail and to provide adequate radiation protection a shielded cask containing three canisters is required.[9] The cost for a round trip for a total distance of 4800 km (3000 miles) is about $37,500.[8]

Estimates for the costs for deep geologic storage have been obtained from a recent (1982) study of mined geologic repositories for the disposal of nuclear waste.[10] The geologic repository was designed to accommodate approximately 300,000 spent fuel assemblies. Several techniques for storing the wastes were considered and evaluated including the simplest, namely a single PWR element in its own canister. The emplacement cost for each such element was calculated to be $43,000 using the average of the calculated costs for each of the media studied, i.e., salt, granite, basalt, and tuff. The canisters containing fusion wastes are approximately twice the volume of the fuel element canisters and assuming that the unit costs are directly related to volume occupied[a] yields a cost of approximately $90,000 corrected for current dollars. The total annual cost for the disposal of the PCA, including canisters, shipment and emplacement is $4.9 million per year.

RECYCLE OF VANADIUM ALLOY

For the vanadium alloy, the radiosctivity is low enough that recycle can be considered. The benefit of recycle is the reuse of material in the refabrication of fresh blanket sectors. The techniques employed will depend upon the residual radioactivity. If the radioactivity of the piece being fabricated yields a contact dose rate of less than 2.5 mrem/h, unrestricted manipulation will be possible. With higher dose rates more limited close contact would be permitted. Finally at even higher levels, the periods for direct manipulation would be so short as to be unproductive and remote operations would be necessary. These handling limitations would extend beyond recovery to the refabrication steps, unless radionuclides were removed during processing. Dose rate calculations indicate that the contact dose rate for a one-meter sphere of vanadium alloy is 600 mrem/h after 30 years decay, too high for effective hands-on operation. After 30 years decay, the long-lived ^{94}Nb content determines the dose rate which remains constant as a function of time. If the ^{94}Nb content can be reduced by removal of the ^{94}Nb or by initially reducing the impurity primarily responsible for the formation of ^{94}Nb, the dose rate of the residual material decreases with time. It reaches a value of about 10 mrem/h at 70 years which makes consideration of hands-on operation feasible. It should be noted that with continued improvement in remote manipulation and with progress in robotics, safe manipulation and operation with highly radioactive materials may be achieved and recycle of materials soon after removal from the reactor could be effected.

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[a]The cost estimates for emplacement in a geologic medium are intricate with interactions between many of the variables. The assumption is overly simplified but adequate for the current comparison.

C. Conclusions

Disposal costs for vanadium in shallow land burial are approximately 1% the cost of disposing of PCA in a geologic medium. Estimates of the costs of shallow land burial are rather firm, based on current practice. The estimates for disposal in a geologic medium are a bit more tenuous as they are based on engineering estimates for a facility that has never been built. Among some of the uncertainties are the state of materials after long periods of standing before reprocessing commences, the advances to be expected in robotics that may permit the use of sophisticated refabrication techniques to be performed remotely. These results indicate the advantage of directing wastes (wherever possible) to shallow land burial.

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