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LONG-TERM RADIOACTIVITY IN FUSION REACTORS *

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The specific activity limits for shallow land ("Class C") waste disposal of all long-lived radionuclides with atomic number less than 88 have been calculated using the 10 CFR 61 methodology. These specific activity limits were used to determine the concentration limits of nearly all naturally-occurring elements in fusion reactor blanket materials. Of the elements that could be constituents of or impurities in blanket materials, aluminum, silicon, nickel, zirconium, tantalum, and tungsten were found to be limited to concentrations of 0.1 to 10%, and niobium, molybdenum, silver, gadolinium, terbium, and holmium were found to be restricted to 0.1 to 10 parts per million.

1. Introduction

A major goal of fusion energy research should be to greatly reduce the radiological hazards of energy production compared with fission in order to gain safety-related public acceptance advantages or cost reductions that could be crucial to fusion's ultimate success. Fusion fuel cycles do not produce radioactive products directly, but the neutrons produced in fusion reactions do produce radioactivity in the surrounding reactor structure. The hazard posed by neutron activation depends on the composition of reactor materials, neutron flux, and length of exposure.

With regard to radioactive wastes, a qualitative improvement over fission might be achieved if fusion reactors did not produce any high-level radioactive waste. A consensus of recent investigations in this area was that materials could be developed for fusion structural and tritium-breeding materials that would yield only low-level waste [1]. These materials could be developed by carefully selected the alloying and compounding elements in existing materials and by limiting the concentration of certain impurity elements.

The purpose of this paper is to determine the concentration of elements that can be allowed in fusion reactor blanket material if they are to be acceptable as low-level waste. Section 2 discusses current regulations for low-level waste disposal in the U.S. and, based on these regulations, presents estimates for the specific activity limits of all long-lived radionuclides with atomic number less than 88. Section 3 gives the results of activation calculations for 81 naturally-occurring elements exposed in the first-wall of a typical lithium-cooled fusion reactor. The elemental concentration limits for low-level waste disposal are then presented and discussed.

2. Waste disposal issues

The Nuclear Regulatory Commission (NRC) has introduced regulations for the shallow burial of low-level fission wastes; these regulations are referred to as "10 CFR 61" [2]. It is assume here that a regulation similar to 10 CFR 61 will apply to radioactive fusion wastes. Table 1 gives the 10 CFR 61 classification rules for radioactive waste. For a given class of waste, 10 CFR 61

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Table 1
Nuclear waste classification under 10 CFR 61 rules

Waste class	Definition	Disposal
Class A Segregated waste	Decays to acceptable levels during side occupancy	Segregated, minimum requirements
Class B Stable waste	Stabilized and decays to levels that do not pose a danger to public health and safety in 100 years	Covered to reduce surface radiation to a few percent of natural background
Class C Intruder waste	Does not decay to safe levels in 100 y. Decays to acceptable safe levels in 500 y [a]	Five meters below surface with natural or engineered barrier
Waste that does not meet Class C definition	Does not qualify for near-surface disposal. Proposed disposal methods are considered on a case-by-case basis	Geologic

[a] 10 CFR 61 defines "acceptably safe levels" to mean that the inadvertent entry into the waste would result in a whole-body dose of less than 0.5 rem/y. Natural background radiation gives an average yearly dose of about 0.1 rem/y.

limits the specific activity of long-lived radionuclides. The disposal class that permits shallow burial of material with the highest specific activities is called "Class C" or "layered waste". Class C wastes are buried at least five meters below the surface.

2.1. 10 CFR 61 regulations

The guiding philosophy behind 10 CFR 61 is that no member of the public, at any time in the future, should be exposed to an unacceptable risk from accidental exposure to radioactive waste. Of the various exposure scenarios that were considered in the Environmental Impact Statement for 10 CFR 61 [3,4], the so-called "intruder" scenario produced the highest dose to individuals. The intruder scenario begins with the construction of a house on the waste-disposal site after the period of institutional control ends. The period of institutional control, which corresponds to the time period that governments can be expected to prevent access to the site, is assumed to be 100 years. Construction workers are exposed to direct gamma radiation from the waste and inhale waste particles while digging the foundation. If the waste is still stable – that is, recognizable to the workers as radioactive waste – then construction is assumed to stop after six hours. Class C waste is assumed to be stable for 500 years.

If the waste is not stable, the workers do not realize that they are in a waste-disposal site and construction continues for 500 hours. The completed house is occupied, and the inhabitants inhale suspended waste particles and are exposed to direct gamma radiation from the waste. In addition, they are assumed to grow half of all their food – vegetables, meat, and milk – on the waste site. The inhabitants therefore ingest radionuclides deposited on the leaves of plants and absorbed through their roots, either directly in the case of vegetables, or indirectly through the meat and milk of cows in the case of grass. 10 CFR 61 limits the specific activity of radionuclides so that the 50-year whole-body dose commitment ("intruder dose") to workers from construction activity or the 50-year dose commitment to inhabitants from exposure during the first year does not exceed 0.5 rem (5 mSv), which is currently the maximum permissible dose per year for members of the public.

10 CFR 61 gives specific activity limits for only a dozen radionuclides, and many of these are fission products or transuranics that are of little interest to fusion. We have developed a modified version of the NRC's intruder model to calculate limits for other long-lived radionuclides. This was an attempt to complement 10 CFR 61, not to replicate it, and there are several differences between the NRC model and the model used here. First, several errors in the original NRC calculations were corrected. For example, the NRC's computer program divides instead of multiplies by the number of days in a year at one point, the uptake of technetium is underestimated by an order of magnitude, etc.; these corrections, which in most cases do not affect the results, are described in ref. [5]. Second, the calculations done here are somewhat more detailed. For example, plants were divided into two categories (produce and forage), more accurate transfer coefficients and dose conversion factors were used, and the shielding provided by soil was calculated for each radionuclide. Although our calculations are more precise, we do not necessarily believe that they are more accurate

considering the huge uncertainties in many variables of the model. We do, however, think that *relative* hazard of different radionuclides is better represented by our model. Finally, the NRC model limits the whole-body dose to 0.5 rem *or* the dose to any single organ to 1.5 rem, while our model considers only the whole-body dose. This difference is only important for radionuclides whose decay energy is accounted for almost entirely by particles that have short ranges in tissue (i.e., alpha and beta particles and low-energy X-rays), and which concentrate heavily in one organ of the body. This is not an important consideration for most fusion-reactor materials, as will be shown below. (We are currently in the process of removing this limitation from our model.) The model and data used are described in detail in refs. [5] and [6], and ref. [7] demonstrates the value of the model in evaluating the waste-disposal hazard of several fusion reactor materials.

2.2. Concentration limits for long-lived radionuclides

Table 2 lists all known radionuclides with atomic number less than 88 that have half-lives greater than five years and less than 10^{12} years [8], and the corresponding specific activity limits for Class C disposal calculated here. Radionuclides with half-lives less than five years are not limited by 10 CFR 61 since it is assumed that wastes can be isolated from the public for at least 100 years. Those with half-lives greater than 10^{12} years pose little hazard because their rate of decay is so slow. Indeed, the results given below indicate that only those radionuclides with half-lives less than 10^9 years are potential waste-disposal hazards. Radionuclides with atomic numbers greater than radium will be considered in a future article in order to set an upper limit on thorium and uranium impurities in fusion reactor materials.

Table 2 also lists estimates of the specific activity limits by others [9,10,11] and the values given in 10 CFR 61 [1]. Except for radionuclides that emit a large fraction of their decay energy as high-energy photons (Nb-94 and Cs-137), the correspondence between our calculations and the 10 CFR 61 values is poor. This is due mostly to differences in the assumptions made about the nature of the waste. The 10 CFR 61 limits are based on calculations for a worst-case waste form, while ours assume activated metal. Although the NRC model is capable of calculating doses for different waste forms, the NRC preferred to set generic limits that were independent of waste form. 10 CFR 61 allows the specific activity limits for radionuclides in activated metal to be a factor of ten greater than the generic limits, but this

Table 2
Specific activity limits for all radionuclides with $Z < 88$ and halflives greater than 5 y and less than 10^{12} y

Radionuclide	Halflife	Specific activity limit (Ci/m^3) [a]	Other values [b]
H-3	12.3 y	TMSA [c]	TMSA (10 CFR 61)
Be-10	1.6 My	3,000	7,000 [10]; 3 [11]
C-14	5.7 ky	700–7,000	80 (10 CFR 61)
Al-26	720. ky	0.09	0.1 [9]
Si-32	104. y	900–4,000	600 [10]; 30 [11]
Cl-36	301. ky	10–100	3 [11]
Ar-39	269. y	10,000	2,000 [11]
Ar-42	33. y	20,000	0.8 [9] 7,000 [11]
K-40	1.3 Gy	1.5	
Ca-41	103. ky	8,000–20,000	3 [11]
Ti-44	47. y	200	0.06 [9]; 300 [11]
Mn-53	3.7 My	TMSA	600 [10]; 30 [11]
Fe-60	100. ky	0.1	0.01 [9]; 0.1 [11]
Co-60	5.3 y	3.E+08	TMSA (10 CFR 61)
Ni-59	75. ky	900	220 (10 CFR 61)
Ni-63	100. y	1.E+6–1.E+7	7.00 (10 CFR 61)
Se-79	65. ky	100–1,000	3 [11]
Kr-81	210. ky	30	300 [11]
Kr-85	10.7 y	TMSA	
Rb-87	48. Gy	TMSA	
Sr-90	28.5 y	1.E+6–9.E+6	70,000 (10 CFR 61) [d]
Zr-93	1.5 My	2,000	200 [10]; 10 [11]
Nb-91	680. y	200	
Nb-92	36. My	0.2	0.3 [9]
Nb-93m	13.6 y	TMSA	
Nb-94	20. ky	0.2	0.2 (10 CFR 61)
Mo-93	3.5 ky	300	30 [10,11]
Tc-97	2.6 My	1–10	
Tc-98	4.2 My	0.03–0.1	0.02 [9]
Tc-99	213. ky	0.2–2	30 (10 CFR 61) [d]
Pd-107	6.5 My	TMSA	
Ag-108m	127.	3	3 [9,11]
Cd-113m	13.7 y	TMSA	
Sn-121m	55. y	100,00	3,000 [11]
Sn-126	100. ky	0.1	0.01 [9]
I-129	15.7 My	30	0.8 (10 CFR 61) [d]
Cs-135	3.0 My	TMSA	8,400 (10 CFR 61) [d]; 3 [11]
Cs-137	30.0 y	50,000	46,000 (10 CFR 61) [d]
Ba-133	10.5 y	2.E+8	55 [9]
La-137	60. ky	30	
La-138	106. Gy	TMSA	
Pm-145	17.7 y	TMSA	
Pm-146	5.5 y	TMSA	
Sm-146	103. My	TMSA	
Sm-147	106. Gy	TMSA	
Sm-151	90. y	TMSA	3,000 [11]
Eu-150m	36. y	3,000	3,000 [11]

Table 2 (continued)

Radionuclide	Halflife	Specific activity limit (Ci/m^3) [a]	Other values [b]
Eu-152	13.3 y	300,000	
Eu-154	8.8 y	5.E+6	
Gd-148	98. y	7.E+5–7.E+6	
Gd-150	1.8 My	TMSA	
Tb-157	150. y	1,000	
Tb-158	150. y	4	5 [11]
Dy-154	2.9 My	TMSA	
Ho-166m	1.2 ky	0.2	0.2 [11]
Lu-176	35.9 Gy	TMSA	
Hf-178m$_2$	31. y	9,000	0.25 [9]; 3,000 [11]
Hf-182	9.0 My	0.2	0.02 [9]
Re-186m	200. ky	9.0	10 [11]
Re-187	40. Gy	TMSA	
Os-194	6.0 y	TMSA	
Ir-192m$_2$	241. y	2	1 [11]
Pt-190	600. Gy	TMSA	
Pt-193	50. y	9.E+6	
Hg-194	520. y	0.5	
Pb-202	53. ky	0.6	0.07 [9]
Pb-205	19. My	TMSA	5 [10]; 3 [11]
Pb-210	22.3 y	9.E+6–8.E+7	
Bi-207	32.2 y	8,000	17,000 [9]
Bi-208	368. ky	0.09	0.1 [9,11]
Bi-210m	3.0 My	1	2 [9], 0.5 [11]
Po-209	102. y	3,000	

[a] Specific activity limit depends on waste form indices; for those familiar with 10 CFR 61, the indices used are: IE = 2, IS = 1, IL = 1, IG = 0, IH = 0, IPO = 2, IIC = 110, I5 = 0, I6 = 1, I7 = 0, and I9 varies from 2 to 3, which are the same as those used in ref. [4] for non-fuel reactor components and high-activity industrial waste.

[b] Values are for radionuclides contained in or permanently fixed to metal.

[c] Theoretical Maximum Specific Activity (i.e., the activity of 1 m^3 of the pure radionuclide at normal density).

[d] The 10 CFR 61 specific activity limits for Sr-90, Tc-99, I-129, and Cs-137 are multiplied by a factor of ten because they are assumed to be contained in activated metal. See ref. [4] value for Cs-155 from ref. [4].

factor of ten has basis in the model only for those radionuclides that emit high-energy photons. The calculations presented here, on the other hand, explicitly consider the waste form. The waste form indices used are the same as those used by the NRC for activated fission-reactor components such as fuel cladding and pressure vessels. The degree of corrosion is varied, which gives rise to the range of values for the specific activity limit for some radionuclides in table 2. Note that, except for Tc-99, the limits calculated here are greater than those given by 10 CFR 61 (the limit for Co-60 appears lower, but this is only because the NRC considered such high specific activities to be unrealistic). Notice also that the values given by Maninger [9], Kennedy [10], and Ponti [11] often vary considerably from those given here. In general, this is because they based their estimates on extrapolations of 10 CFR 61 values. Although this works well for radionuclides with strong gamma emissions (e.g., Al-26, Nb-92, Ag-108m, etc.), it is much less accurate for other radionuclides where the dose depends sensitively on the properties of a particular element and the nature of the waste.

Table 3 classifies the radionuclides according to the fraction of their theoretical maximum specific activity (TMSA) that would be permitted in Class C waste. This table gives a good idea of the relative potency of the radionuclides. For example, during the operation of a fusion reactor only about ten out of every billion atoms need be transmuted into Ag-108m for that material to be unacceptable as Class C waste, although a solid block of Re-187 would be acceptable.

Table 3
Fraction of the theoretical maximum specific activity (TMSA) necessary to exceed limits in table 2

C/TMSA [a]	Radionuclides
>1	H-3, Mn-53, Kr-85, Rb-87, Nb-93m, Pd-107, Cd-113m, Cs-135, La-138, Pm-145, Pm-146, Sm-146, Sm-147, Dy-154, Lu-176, Re-187, Os-194, Pt-190, Pb-205
$1–10^{-1}$	K-40, Zr-93, Ba-133, Sm-151, Gd-150
$10^{-1}–10^{-2}$	Be-10, Ca-41, Co-60, I-129, Pt-193, Pb-210
$10^{-2}–10^{-3}$	Ni-59, Ni-63, Sr-90, Eu-154, Gd-148
$10^{-3}–10^{-4}$	Cl-36, Ar-39, Se-79, Kr-81, Nb-92, Sn-121m, Cs-137, La-137, Eu-152, Bi-210m
$10^{-4}–10^{-5}$	C-14, Ar-42, Mo-93, Tc-97, Hf-178m$_2$, Hf-182, Re-186m, Bi-207, Po-209
$10^{-5}–10^{-6}$	Al-26, Si-32, Nb-91, Tc-98, Tc-99, Eu-150, Tb-157, Pb-202, Bi-208
$10^{-6}–10^{-7}$	Ti-44, Fe-60, Nb-94, Sn-126
$10^{-7}–10^{-8}$	Ag-108m, Tb-158, Ho-166m
$10^{-8}–10^{-9}$	Ir-192m$_2$, Hg-194

[a] C is the lowest specific activity limit given in table 2; TMSA is the Theoretical Maximum Specific Activity (see table 2, footnote c).

3. Long-term radioactivity in fusion materials

A study was performed of long-lived radionuclides induced in D–T fusion reactors. The neutron fluxes used were those typical in the first wall of a lithium-cooled blanket with vanadium-alloy structure. The first wall is 1 cm thick and is composed of 40% vanadium alloy, 37.5% lithium, and 22.5% void by volume. Behind the first wall is a 1 cm gap, a 30 cm thick blanket, a 25 cm reflector, and a 20 cm shield. The blanket and reflector are composed of 20% vanadium alloy and 80% lithium by volume. The shield is made of 90% vanadium alloy and 10% lithium. The Li-6 content in the lithium coolant was varied from 2% to 75% to explore the effect of changing the neutron spectrum, particularly the low-energy neutrons. It is interesting to note that the difference in the spectrum occurs mainly at energies below 1 MeV between these two designs. The neutron fluxes were calculated using the one-dimensional discrete ordinates transport code ANISN [12], and the ENDF/B-V-based nuclear data library MATSX5 [13]. The radioactivity calculations were performed with the code REAC and its successor, REAC*2 [14]. The activation cross section and decay data libraries used are quite comprehensive, containing about 6000 reactions covering 340 nuclides, many of which are radionuclides [15]. There are uncertainties in many of the calculated cross sections that may affects the specific activity limits, however, so the results presented here should be considered preliminary. The total neutron exposure was 20 MW-y/m^2 at 5 MW/m^2 neutron wall loading. The time step was 0.2 year over a total operating time of four years.

Several radionuclides listed in table 2 were not produced by REAC: K-40, Ti-44, Sn-126, Gd-148, Dy-154, Pt-190, Hg-194, Pb-202, Pb-210, and Po-209. The fact that these radionuclides did not appear in the REAC output is due either to a lack of cross-section data or the fact that REAC fails to consider nuclides that do not reach a certain minimum concentration in each time step. Two or more consecutive reactions are generally required to produce these radionuclides from stable nuclides. Computer memory and time limitations restrict the number of nuclides that can be followed by the code, and those produced in very small concentrations (less than 10^{-14} Ci/m^3) are dropped. Of the radionuclides listed above, K-40, Dy-154, and Pt-190 have specific activity limits so high that they need not be considered further. Because of its potential importance for vanadium alloys, the production of Ti-44 was estimated by hand. Because of its very low specific activity limit, Hg-194 production should receive special consideration for materials containing an appreciable amount of mercury. This radionuclide is produced mainly by the reactions Hg-196(n, 2n)Hg-195(n, 2n); cross-sections for the latter reaction were not available in the REAC library.

The concentration limits for each naturally-occurring element were then calculated for the first wall of the fusion reactor blanket described above with 2% and 75% Li-6, assuming that the elements are contained in metal. The results appear in tables 4 through 7. In most cases, the design with 2% Li-6 gives the highest activities because of higher activation levels resulting from a higher neutron flux at low energies. The concentration limit varies with the degree of corrosion only for those radionuclides that emit very little of their decay energy as high-energy photons, because the dose is then dominated by biologically-controlled processes such as ingestion and inhalation rather than direct exposure, as mentioned previously.

Table 4 shows the limits on elements that have been or might be considered as intentional constituents of first-wall structural materials. Note that the use of molybdenum is prohibited, and that the use of aluminum and tungsten is restricted severely. The limits of zirconium, tin, and tantalum should pose no practical problem for ordinary first-wall materials, although the use of silicon, nickel, copper, and lead may be restricted. The limit for silicon is especially surprising, since silicon is usually described as a very-low-activation material. Because the main silicon-based material under consideration, silicon-carbide, is not a metal, the concentration limit has been reduced by an additional

Table 4
Concentration limits for potential first-wall materials

Z	Element	Concentration limit (%)	Major contributors
13	Al	0.09	Al-26
14	Si	2.5 [a]	Al-26
28	Ni	10	Fe-60, Ni-59
29	Cu	40–100 [b]	Ni-63, Fe-60
40	Zr	4	Nb-94
42	Mo	0.7–6 ppm [b]	Tc-99, Tc-98, Nb-94
50	Sn	2–8 [c]	Sn-121m, Ag-108m
73	Ta	6	Hf-178m
74	W	0.1–7 [c]	Re-186m, Hf-178m
82	Pb	10–25 [c]	Bi-208

[a] Concentration limit reduced by a factor of ten because SiC is not metal.
[b] Concentration limit varies with metal corrosion.
[c] Concentration limit varies with Li-6 enrichment.

Table 5
Concentration limits for elements that may be impurities in first-wall materials

Z	Element	Crustal abundance (ppm)	Concentration limit (ppm)	Major contributors
41	Nb	20	0.4–9 [b]	Nb-94
42	Mo	1.5	0.7–6 [a]	Tc-99, Tc-98, Nb-94
46	Pc	0.01	30	Ag-108m
47	Ag	0.07	0.5–1 [b]	Ag-108m
48	Cd	0.2	30	Ag-108m
63	Eu	1.2	200	Eu-150m, Eu-152
64	Gd	5.4	4–20 [b]	Tb-158
65	Tb	0.9	0.2	Tb-158
66	Dy	3.0	200	Tb-158
67	Ho	1.2	0.4–10 [b]	Ho-166m
68	Er	2.8	20–70 [b]	Ho-166m
69	Tm	0.47	200	Ho-166m
72	Hf	2	90–300 [b]	Hf-178m
76	Os	0.0015	0.1–10 [b]	Ir-192m
77	Ir	0.001	0.05–0.1 [b]	Ir-192m
83	Bi	0.17	20–40 [b]	Bi-208

[a] Concentration limit varies with waste form indices.
[b] Concentration limit varies with Li-6 enrichment.

factor of ten to account for decreased self-shielding of photon emissions. The hazard from silicon is due to Al-26, which is produced mainly by the reactions Si-28(n, n′p)Al-27(n, 2n). Since the cross-sections of these reactions are well-known, it may be that other computer codes have underestimated Al-26 production because they do not allow the stable isotope Al-27 to be activated. This matter is under investigation.

Table 5 shows the limits for elements that may appear as impurities in first-wall materials. Of special importance are niobium, molybdenum, gadolinium, terbium, and holmium, whose limiting concentrations can be less than the average concentration of these elements in the earth's crust [16]. Also important are silver and erbium, whose concentration limits are within an order of magnitude of their crustal abundance. In cases where one of these impurity elements is naturally associated with a reactor material, it may be difficult to achieve the required impurity levels at acceptable cost. Silver is an impurity in lead, for example, and even electrolytically-refined lead has been found to contain 7 ppm silver [17].

Note that the variation of specific activity limits with waste form and the use of whole-body rather than organ-specific doses rarely makes a difference in setting concentration limits. Only two of the elements in tables 4 and 5 – copper and molybdenum – are influenced by these considerations. The major long-lived radionuclides produced in these materials, Ni-63 in copper and Tc-99 in molybdenum, have no high-energy photon emissions, so the concentration limits vary with the nature of the waste. The case of Tc-99 is especially complicated, because although technetium concentrates in the thyroid by over a factor of 100, the thyroid dose is not considered separately. Moreover, estimates of the rate at which technetium is adsorbed through the roots of plants vary by a large factor. In the absence of better data, the concentration limit for molybdenum given here should be considered an upper limit.

Table 6 shows those elements which could produce an intruder dose greater than 0.5 rem, but which are unlikely to pose any practical problems due to the scarcity of the element and/or its undesirability as a reactor material. Table 7 lists the elements whose use is not restricted at all. This includes many elements that have been considered for use in blanket materials, such as lithium, beryllium, boron, carbon, fluorine, titanium, vanadium, chromium, manganese, and iron.

Table 6
Concentration limits having little practical significance for first-wall materials

Z	Element	Crustal abundance (ppm)	Concentration limit
7	N	20.	4–50% [a]
17	Cl	130.	3–100% [a]
18	Ar	3.5	1%
19	K	2.09%	2%
20	Ca	4.15%	15%
27	Co	25.	8–100% [b]
34	Se	0.05	0.6–6% [a]
35	Br	2.5	2–70% [a]
36	Kr	0.0001	8%
44	Ru	0.001	0.04–0.3% [a]
45	Rh	0.001	0.06–0.7% [a]
49	In	0.1	2%
51	Sb	0.2	15–40% [b]
57	La	30.	4%
58	Ce	60.	20%
59	Pr	8.2	40%
62	Sm	6.0	7–15% [b]
71	Lu	0.5	0.03–100% [b]
75	Re	0.005	6–700 ppm [b]
78	Pt	0.005	30–100 ppm [b]
79	Au	0.004	0.5–1% [b]

[a] Concentration limit varies with waste form indices.
[b] Concentration limit varies with Li-6 enrichment.

Table 7
Elements having no concentration limit in first-wall materials

As, B, Ba, Be, C, Cr, Cs, F, Fe, Ga, Ge, H, He, Hg, I, Li, Mg, Mn, Na, Nd, Ne, O, P, Rb, S, Sc, Sr, Te, Ti, Tl, V, Xe, Y, Yb, Zn

The concentration limits given here are for first-wall materials. One might assume that if the first-wall does not meet Class C standards, this relatively small volume of material could simply be diluted with less radioactive material. The NRC, however, does not generally approve of dilution. Analogous to fission-reactor decommissioning, blanket structures might be cut into small pieces and packed into barrels, and the void spaces filled with grout. If the first-wall and blanket structures are disposed of together, the waste would be acceptable for shallow burial if the waste package with the highest average specific activity met the Class C standards. Assuming that the first-wall and blanket use the same structural materials, this procedure might in some cases result in waste with a specific activity about an order of magnitude less than that of the first wall structure. There is no indication, however, that the NRC will allow highly-radioactive first-wall materials to be diluted with large volumes of concrete or shield materials in order to meet Class C standards.

4. Conclusions

We have evaluated, using 10 CFR 61, the specific activity limits for shallow land burial of long-lived radionuclides that could be induced in fusion reactor materials. These specific activity limits were used to determine the concentration limits, for materials located in the first-wall region, of nearly all naturally-occurring elements that could be intentional constituents or impurities in reactor materials.

Aluminum, silicon, nickel, zirconium, tantalum, and tungsten were found to be important alloying and compounding elements whose concentrations in reactor materials should be limited to 0.1 to 10%. Niobium, molybdenum, silver, gadolinium, terbium, and holmium were identified as elements whose concentration must be limited to 0.1 to 10 parts per million. The concentration limits for other elements generally do not present practical problems, but each case should be considered individually.

A major revision of the present federal regulations on low-level radioactive waste disposal will be required to properly and fairly regulate fusion wastes. 10 CFR 61 does not contain many important long-lived radionuclides that could be present in activated fusion structures, and the current specific activity limits, which are based on worst-case waste forms, differ considerably from our evaluations for non-gamma-emitting radionuclides contained in metal.

References

[1] R.W. Conn et al., Low activation materials and magnetic fusion reactors, Nucl. Technol./Fusion 5 (1984) 291.
[2] Code of Federal Regulations, Licensing Requirements for Land Disposal of Radioactive Waste, Title 10, Part 61, Washington, DC: Nuclear Regulatory Commission (December 30, 1982).
[3] U.S. Nuclear Regulatory Commission, Final Environmental Impact Statement on 10 CFR Part 61 'Licensing Requirements for Land Disposal of Radioactive Waste', NUREG-0945, Washington, DC: Nuclear Regulatory Commission (November 1982).
[4] U.S Nuclear Regulatory Commission, Draft Environmental Impact Statement on 10 CFR Part 61 'Licensing Requirements for Land Disposal of Radioactive Waste', NUREG-0782, Washington, DC: Nuclear Regulatory Commission (September 1981).
[5] Steve Fetter, Radiological hazards of fusion reactors: Models and comparisons, Ph.D. dissertation, University of California, Berkeley, Energy and Resources Group (1985).
[6] Steve Fetter, A calculational methodology for comparing the accident, occupational, and waste-disposal hazards of fusion reactor designs, Fusion Technol. 8 (July 1985) 359.
[7] Steve Fetter, Radiological hazards of magnetic fusion reactors, Fusion Techol. 11 (March 1987) 400.
[8] Edgardo Browne and Richard B. Firestone, Table of Radioactive Isotopes (John Wiley & Sons, New York, 1986).
[9] R. Carroll Maninger, Impact of long-lived radionuclides on waste classification for fusion, Transactions of the American Nuclear Society 49 (1985) 65; R. Carroll Maninger, Qualitative comparison of fusion reactor materials for waste handling and disposal, Fusion Technol. 8 (July 1985) 1367; R. Carroll Maninger and David W. Dorn, Radiation safety criteria for maintenance and waste management in the mirror Advanced Reactor Study, Fusion Technol. 6 (November 1984) 616.
[10] W.E. Kennedy, Jr. and P.A. Peloquin, Potential low-level Waste Disposal Limits for Activation Products from Fusion, PNL-4844, Richland, WA: Pacific Northwest Laboratory (September 1983); W.E. Kennedy, Jr. and F.M. Mann, Potential low-level disposal limits for fusion radionuclides, transactions of the American Nuclear Society 45 (1983) 51.

[11] C. Ponti, Low activation elements for fusion reactor materials, IAEA Technical Committee on Fusion Reactor Safety, Culham, UK (3–7 November 1986).
[12] W.W. Engle, Jr., A User's Manual for ANISN, a One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering, K-1693, Oak Ridge, TN: Oak Ridge Gaseous Diffusion Plant (March 1967).
[13] R. MacFarlane, Los Alamos National Laboratory, private communication.
[14] F.M. Mann, Transmutation of Alloys in MFE Facilities as Calculated by REAC (A Computer Code for Activation and Transmutation), HEDL-TME 81-37, Hanford, WA: Hanford Engineering Development Laboratory (1982).
[15] F.M. Mann et al., REAC nuclear data libraries, Proceedings of the International Conference on Nuclear Data for Basic and Applied Science, Santa Fe, New Mexico, May 1985.
[16] Robert C. Weast, ed., CRC Handbook of Chemistry and Physics, 65th edition (Boca Raton, FL: CRC Press, 1984).
[17] Andrew White, University of Wisconsin, personal communication.