ISSUES IN RADIOACTIVE-WASTE MANAGEMENT FOR FUSION POWER

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Abstract

Analysis of recent conceptual designs reveals that commercial fusion power systems will raise issues of occupational and public health and safety. This paper focuses on radioactive wastes from fusion reactor materials activated by neutrons. The analysis shows that different selections of materials and neutronic designs can make differences in orders-of-magnitude of the kinds and amounts of radioactivity to be expected. By careful and early evaluation of the impacts of the selections on waste management, designers can produce fusion power systems with radiation from waste well below today's limits for occupational and public health and safety.

Introduction

As fusion research moves closer to engineering development and as conceptual designs for commercial fusion power reactors emerge, it becomes increasingly clear that fusion power systems could generate large quantities of radioactive materials.[1-6] This radioactivity is the normal result of the absorption of the neutrons given off in the D-D and D-T fusion reactions and the consequent transmutation (activation) of the elements in the structural materials of the reactor. The design and the selection of materials for a fusion reactor will strongly affect the radioactivity produced. This, in turn, will impact public and occupational health and safety for reactor operation *and maintenance, for accidents, for waste disposal*, and for the decommissioning of reactors. The consequences of design and materials selections on potential radioactive waste problems should, therefore, be carefully considered from the beginning.

A number of authors have proposed ways to mitigate the activation, both for safe reactor operation and for minimizing the potential impact of fusion radioactivity on the health and safety of the public and the environment.[7-16,31] These studies treat the relative hazards of different radioactive materials in terms of their maximum permissible concentrations (MPC) from the NRC regulations 10CFR20. However, the regulations are concerned only with maximum permissible exposures of workers and the general public to radioactivity and they do not give reactor *designers any quantitative criteria or guidelines* that can be directly and simply related to specific choices of design and materials. The development by the NRC of the proposed rule 10CFR61 for land disposal of radioactive wastes[24,25] provides a new basis for a methodology to assign quantitative ratings with respect to wastes for the designs and the materials in fusion reactors. This paper illustrates the use of such a methodology for two specific conceptual designs of a commercial fusion power reactor, the Mirror Advanced Reactor Study (MARS). This study is being conducted by the Lawrence Livermore National Laboratory, the University of Wisconsin, and TRW, Inc. for the national Fusion Energy Program of the U. S. Department of Energy.

Waste Rating Methodology

We assume that fusion wastes will be disposed of under institutional conditions much the same as fission wastes. That is, the disposal will be regulated through a public participation process in which nontechnical occupational and public health and safety issues (such as "how safe is safe?) can be coupled to the technical aspects of waste problems. We also assume that radioactivity will be treated the same regardless of its origin. Currently, there are no regulations written specifically for the handling of fusion waste. However, there are a number of similarities between fission and fusion wastes. The activation of steel and other structural materials used in fuel assemblies and containment vessels for fission reactors produces radioactive wastes very similar to those anticipated from fusion reactors. These similarities have been used to form analogies between fission and fusion wastes. These analogies enable one to use the large amount of available information *on fission wastes to estimate* the requirements expected to be encountered with fusion wastes. Specifically, the NRC regulation, 10CFR60, "Disposal of High Level Radioactive Wastes in Geologic Repositories," and the proposed regulation 10CFR61, "Licensing Requirements for Land Disposal of Radioactive Waste," along with background information on them,[22-28] provide the basis for inferring acceptable practices for *fusion waste disposal*.

A key concept in 10CFR61 that furnishes the connection between waste disposal requirements and fusion reactor design is that of setting concentration limits on radioactive isotopes for various classes of waste. This concept provides quantitative criteria for disposal based upon isotopic composition *and isotopic activities of materials*. *These criteria* can be translated into design guides for selection of compositions of structural materials and for neutronic configurations. Even though 10CFR61 is specific to fission wastes and explicitly covers only a few of the long-lived isotopes of interest to fusion, these few are the important ones. Limiting concentrations for the elements not listed in 10CFR61 were estimated for this report by semiquantitative analogies based on similarities to listed isotopes with respect to half-lives, radiation types and biological hazards. Table 1 shows the list of concentration limits for Class-C waste from the proposed 10CFR61 and the limits suggested here for fusion wastes.

As stipulated in 10CFR61, the concentration limit of an isotope in Table 1 applies when that isotope is the only radioactive one occurring in the waste. When the waste contains a mixture of radioactive isotopes, the sum of the ratios of isotope concentrations in the waste to the concentrations given in Table 1 shall not exceed 1. This condition on isotope concentrations is used here to define a quantity called the Waste Disposal Rating (WDR) for a waste containing one or more radioactive isotopes:

$$\mathrm{WDR} = \sum_i \mathrm{A}(i)/\mathrm{L}(i) \quad ,$$

where A(i) is the specific activity of isotope i and L(i) is the limit from Table 1 for isotope i (units are Ci/m^3). For an alloy or mixture to be eligible for near-surface disposal, the condition WDR $\leq$ 1 is required. Thus, WDR can be used as a "figure-of-merit" for wastes with respect to near-surface disposal. A waste material with WDR > 1 cannot be disposed of by near-surface burial. However, it may be possible to dilute the waste to reduce the specific

Table 1. Concentrations of class-C wastes for near-surface disposal.

Isotope	Maximum concentrations (Ci/m^3) Fission* (10CFR61)	Fusion (this paper)
Any with half life <5 yr	TMSA**	TMSA
H-3	TMSA	TMSA
C-14	0.8	8
Mn-53***	--	22
Ni-59	2.2	22
Co-60	TMSA	TMSA
Ni-63	70	700
Zr-93***	--	0.02
Mo-93***	--	22
Nb-94	0.002	0.02
Sr-90	700	7000
Tc-99	0.3	3
I-129	0.008	0.08
Cs-135	84	840
Cs-137	4600	46,000

*Based on Table 1, Federal Register, Vol. 46, No. 142, p. 38097. For isotopes contained in metals, metal alloys, or permanently fixed on metals as contamination, the values given in this column may be increased by a factor of ten.

**Theoretical Maximum Specific Activity (TMSA) - The activity that would result if all the element were converted to this radioactive daughter.

***Not explicitly covered in the proposed 10CFR61. The limit given is an estimate based on the closest analogy in terms of isotope half life, type of radiation and decay energy to an isotope explicitly covered in 10CFR61.

activity to an effective WDR to ≤ 1. The magnitude of WDR is numerically equal to the volume to which a unit volume of material could be diluted with inert material to meet 10CFR61 criteria on concentrations for near-surface burial. Caution should be exercised though; dilution may lead to total quantities of material that exceed the allowed capacity of a burial site, even though the concentration criteria are satisfied. Thus, processing methods other than dilution may be required to treat fusion structural materials as low level waste. These methods may include elemental and isotopic tailoring as discussed in Ref. 12. As discussed below, the application of the waste disposal rating concept to specific reactor designs furnishes a guide for decisions upon materials selections and processing.

Application of Waste Disposal Rating to a Conceptual Design

This paper gives examples of the application of the waste disposal rating to two preliminary conceptual designs of the first-wall and first-shield regions of the central power-generating cell sections from the Mirror Advanced Reactor Study.[4,18] These designs are the WITAMIR (U. WISC.) and MARS (TRW) central cells described in Refs. 4,18. The relatively more compact structure of the MARS (TRW) central cell uses a thicker breeder section with less reflector and shield. Designs for WITAMIR (U. WISC.) and MARS (TRW) also differ in the postulated fast neutron loading on the first wall. WITAMIR (U. WISC.) is designed to have a neutron loading of 2.4 MW/m^2 with a planned first wall/blanket replacement time of 5 years.[17] The comparable numbers for MARS (TRW) are 4.8 MW/m^2 and 3 years.[18] For this study, we assumed that, in both cases, the shield will last for thirty years. Based on neutronic calculations done at the University of Wisconsin[17] and at TRW[18], these wall loadings correspond to the neutron fluxes presented in Table 2.

Table 2. Neutron flux assumptions.

Design	Neutron flux* (10^{18} neutrons/m^2-s) First wall	Shield
WITAMIR (U.WISC.)		
(0-1 MeV)	26.6	1.9
(1-15 MeV)	3.6	5E-3
MARS (TRW)		
(0-1 MeV)	30.9	2E-1
(1-15 MeV)	9.9	2.3E-3

*Neutron fluxes are taken in the first calculational zone of the first wall and in the first calculational zone of the shield. These zones are on the plasma side of the particular component as shown in Fig. 1.

The neutron fluxes listed in Table 2 represent the fluxes expected to be seen in a small test volume at a radial point in the component. As such, they can be used to calculate specific activities in the test volume at that point.

The calculations of activities for different structural steels were done using neutron cross sections averaged over energy for the neutron fluxes supplied by U. Wisconsin and TRW. It is assumed that the neutron fluxes are not appreciably changed by substituting different steels. For convenience and for accommodating the relative hardness of the neutron spectra, a two-group energy structure was assumed with the energy group boundary put at one MeV.

Neutron induced reactions considered in this report are shown in Table 3. In fusion reactors, multiple activation/decay reaction chains will be significant. For instance, there can be an n,p reaction followed by an n,gamma. At the same time, the radioactive products will decay to their daughters which in turn will undergo subsequent neutron induced reactions. Calculations of product radioactivities from these and other kinds of chains were done using MFE/ACT[19] and the neutron cross sections from the ACTL Library maintained by Howerton, LLNL.[20] For those cases where little or no neutron cross section data were in the library, patterns of cross section variations from similar isotopes were used to estimate the missing data. Radioactive half lives were taken from the "Table of Isotopes".[21] For the purposes of permanent radioactive waste disposal considerations, only daughters with half lives greater than five years are considered here in accord with the proposed 10CFR61. With these data, the natural elements commonly contained in steels and which generate long lived radioactive daughters are shown in Table 4. While all of these radioactive daughters have been examined, only a few of them appear to occur at levels which impact significantly on long-term waste disposal. These are Ni^{59}, Ni^{63}, Nb^{94}, Mo^{93}, Tc^{99}, and Mn^{53}.

The five critical natural elements of some steels considered to be possible candidates for structural materials in fusion reactors are shown in Table 5.

These few alloying elements for steels give rise to radioactive daughters which cause problems in meeting the limits proposed in 10CFR61 for Class C near-surface disposal. The other elements in the alloys give daughters that contribute to high radioactivity immediately after shut-down of a fusion

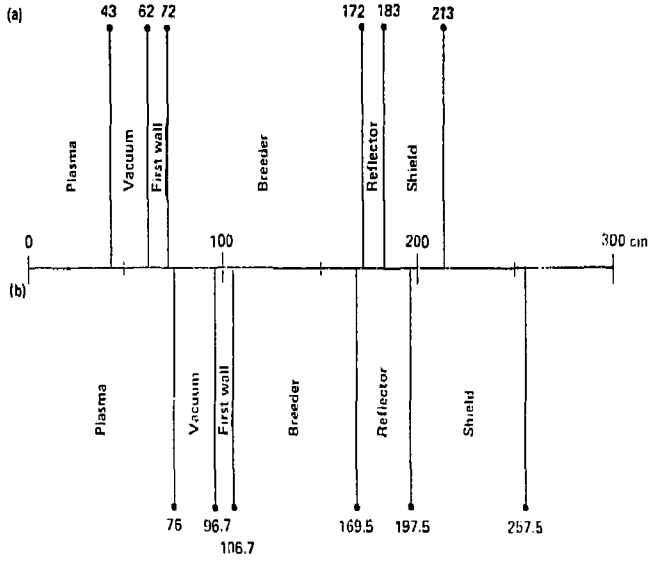

Fig. 1. (a) MARS, (b) WITAMIR.

Table 3. Major neutron induced reactions.

n,gamma	n,alpha
n,2n	n,n'alpha
n,3n	n,d
n,p	n,n'd
n,n'p	n,t

Table 4. Long lived radioactive daughters from natural elements in steel alloys.

Parent element	Daughter isotope	Daughter half-life (yrs)
C	C-14	5.7E3
N	C-14	5.7E3
Al	Al-26	7.4E5
Cr	Mn-53	1.9E6
Mn	Mn-53	1.9E6
Fe	Mn-53	1.9E6
Co	Ni-59	8.0E4
Ni	Ni-59	8.0E4
	Ni-63	9.2E1
Cu	Ni-63	9.2E1
Zr	Sr-90	2.8E1
	Zr-93	1.5E6
Nb	Zr-93	1.5E6
	Nb-94	2.0E4
Mo	Nb-94	2.0E4
	Mo-93	3.6E3
	Tc-99	2.1E5

Table 5. Critical natural elements in various steel alloys.

Alloy*	Weight percent					
	Fe	Mn	Ni	Nb	Mo	Other**
SS316	64.44	1.43	14	--	2.8	17.33
PCA	64.68	1.8	16	0.03	2.0	15.49
HT-9	85.1	0.55	0.5	--	1.0	12.85
2.25-1	94.58	0.45	--	--	1.0	3.97
TENELON	68.0	14.5	--	--	--	17.5
NOMAGNE	79.35	15.0	2.2	--	--	3.45
NM-1	76.92	20.0	--	--	--	3.08
25-5-1	66.22	26.0	1.2	0.07	--	6.51
32-7	60.24	31.6	0.23	--	--	7.93
JUS289-N	72.45	20.0	--	--	--	7.55
JUS289-V	72.15	20.0	--	--	--	7.85

*NOMAGNE is made by Kobe Steel, NM-1 by Nippon Korean, 25-5-1 by Nippon Steel Ltd., and 32-7, JUS289-N and JUS289-V by Japan Steel Works. Tenelon is a steel developed by the U.S. Steel Corp. We have no information on these steels regarding radiation damage in high flux neutron fields. The other steels are discussed in Ref. 30.

**Not critical for long term waste disposal.

reactor; however, the half lives are short enough for the radioactivity to decay after 20 to 30 years to levels not significant to long-term disposal of waste. Tables 6 through 9 show the calculated specific waste disposal ratings for the steels in Table 5.

Of the steels examined, only Tenelon, NM-1, JUS289-N, and JUS289-V, can be used in the first walls and shields of WITAMIR (U. WISC.) or MARS (TRW) and have the resultant induced radioactivity low enough that the waste stream can be disposed of directly by near-surface burial. The 2.25 chrome/1 moly steel can be disposed of directly when used in the shields but not in the first walls. The major alloying elements causing difficulty in the various steels are nickel, molybdenum, and niobium.

If one decides that it is desirable to dispose of the radioactive waste products from a fusion reactor by burial in a near-surface radioactive waste disposal facility, then assuming *little or no dilution*, it may be necessary to make modifications to the composition of the steels to meet the requirements for a Class-C waste. There are at least two approaches to this.[12,29] In the first, one can eliminate the particular element causing the problem in disposal by substitution of another non-problem element that will not change the properties of the steel significantly. For example, it may be possible to substitute vanadium for molybdenum in some steels. In the second approach, one can attempt to eliminate only the particular isotopes giving rise to daughters causing the waste to exceed the guidelines; presumably, this method will have no effect on the properties of the steel since the elemental composition is not changed.

If the isotopic modification route is taken,[29] only the specific isotopes which give rise to problem daughters must be reduced to levels which will allow treatment of the alloy as Class-C waste after irradiation. For example, when using HT-9 in the MARS first wall, depleting the Ni-62 and Ni-64 by 60%, reduces the Ni-63 to an acceptable level. In the same way, 90% depletion of Mo-92 and Mo-94 and 25% depletion of Mo-98 and Mo-100 drop the Mo daughters to acceptable levels.

Conclusions

Fusion reactors have no radioactive waste products inherent in the fusion reactions. However, the fusion D-D and D-T reactions do produce both high energy and low energy neutrons. These neutrons in turn then produce transmutations in structural and other components of the fusion reactor causing induced radioactivity. With proper design and suitable selection of structural materials,[30] one could build a fusion power reactor that produces wastes suitable for near-surface burial. While the costs of processing these wastes would be low, perhaps more importantly, it may be possible for one to co-locate the fusion reactor and the low-level waste disposal site. This

Table 6. Waste disposal ratings (WDR).
First Wall: WITAMIR at 2.4 MW/m^2 and 5 years
(parent elements in parentheses)

Alloy	WDR						Alloy total
	Ni-59	Ni-63	Nb-94	Mo-93	Tc-99	MN-53	
SS316	26(Ni)	69(Ni)	0.5(Mo)	16(Mo)	2.7(Mo)	0.21(Fe)	114
PCA	29(Ni)	77(Ni)	1800(Nb)	12(Mo)	2.0(Mo)	0.21(Fe)	1920
HT-9	0.91(Ni)	2.4(Ni)	0.15(Mo)	5.9(Mo)	1.0(Mo)	0.27(Fe)	11
2.25-1	--	--	0.15(Mo)	5.9(Mo)	1.0(Mo)	0.31(Fe)	7.4
TENELON	--	--	--	--	--	0.23(Fe/Mn)	0.23
NOMAGNE	3.6(Ni)	11(Ni)	--	--	--	0.26(Fe/Mn)	15
NM-1	--	--	--	--	--	0.26(Fe/Mn)	0.26
25-5-1	2(Ni)	5.7(Ni)	4200(Nb)	--	--	0.23(Fe/Mn)	4210
32-7	0.39(Ni)	1.1(Ni)	--	--	--	0.21(Fe/Mn)	1.7
JUS289-N	--	--	--	--	--	0.24(Fe/Mn)	0.24
JUS289-V	--	--	--	--	--	0.24(Fe/Mn)	0.24

Table 7. Waste disposal ratings (WDR).
First Wall: MARS (TRW) at 4.8 MW/m^2 and 3 years
(parent elements in parentheses)

Alloy	WDR						Alloy total
	Ni-59	Ni-63	Nb-94	Mo-93	Tc-99	MN-53	
SS316	23.0(Ni)	71.0(Ni)	1.5(Mo)	26.0(Mo)	3.7(Mo)	0.33(Fe)	130
PCA	26.0(Ni)	83.0(Ni)	1400(Nb)	18.0(Mo)	2.7(Mo)	0.33(Fe)	1500
HT-9	0.82(Ni)	2.6(Ni)	0.5(Mo)	9.1(Mo)	1.3(Mo)	0.42(Fe)	15
2.25-1	--	--	0.5(Mo)	9.1(Mo)	1.3(Mo)	0.45(Fe)	11
TENELON	--	--	--	--	--	0.37(Fe/Mn)	0.37
NOMAGNE	3.6(Ni)	11.0(Ni)	--	--	--	0.42(Fe/Mn)	15
NM-1	--	--	--	--	--	0.42(Fe/Mn)	0.42
25-5-1	2.0(Ni)	6.1(Ni)	3200(Nb)	9.1E-5	--	0.37(Fe/Mn)	3200
32-7	0.36(Ni)	1.2(Ni)	--	--	--	0.35(Fe/Mn)	1.9
JUS289-N	--	--	--	--	--	0.43(Fe/Mn)	0.43
JUS289-V	--	--	--	--	--	0.43(Fe/Mn)	0.43

Table 8. Waste disposal ratings (WDR).
Shield: WITAMIR (U. WISC.) at 2.4 MW/m^2 (First Wall) and 30 Years Life
(parent elements in parentheses)

Alloy	WDR						Alloy total
	Ni-59	Ni-63	Nb-94	Mo-93	Tc-99	MN-53	
SS316	18.0(Ni)	100.0(Ni)	5E-5(Mo)	4.6E-2(Mo)	1E-2(Mo)	2E-3(Fe)	1.8
PCA	21.0(Ni)	114.0(Ni)	1200(Nb)	3.2E-2(Mo)	6.7E-3(Mo)	2E-3(Fe)	1300
HT-9	0.64(Ni)	3.6(Ni)	2E-5(Mo)	1.8E-2(Mo)	3.3E-3(Mo)	3E-3(Fe)	4.7
2.25-1	--	--	2E-5(Mo)	1.8E-2(Mo)	3.3E-3(Mo)	3E-3(Fe)	~0
TENELON	--	--	--	--	--	2E-3(Fe)	~0
NOMAGNE	2.7(Ni)	14.0(Ni)	--	--	--	3E-3(Fe)	17
NM-1	--	--	--	--	--	2E-3(Fe)	~0
25-5-1	1.5(Ni)	8.6(Ni)	2800(Nb)	--	--	2E-3(Fe)	2800
32-7	0.27(Ni)	1.7(Ni)	--	--	--	2E-3(Fe)	2
JUS289-N	--	--	--	--	--	2E-3(Fe)	~0
JUS289-V	--	--	--	--	--	2E-3(Fe)	~0

Table 9. Waste disposal ratings (WDR).
Shield: MARS (TRW) at 4.8 MW/m^2 (First Wall) and 30 Years Life
(parent elements in parentheses)

Alloy	WDR						Alloy total
	Ni-59	Ni-63	Nb-94	Mo-93	Tc-99	MN-53	
SS316	6.36(Ni)	26.0(Ni)	1E-4(Mo)	1.4E-2(Mo)	2E-3(Mo)	7.3E-5(Fe)	32
PCA	7.3(Ni)	29.0(Ni)	300(Nb)	9.1E-3(Mo)	1.3E-3(Mo)	7.3E-5(Fe)	340
HT-9	0.23(Ni)	0.91(Ni)	3E-5(Mo)	4.6E-3(Mo)	6.7E-4(Mo)	9.6E-5(Fe)	1.1
2.25-1	--	--	3E-5(Mo)	4.6E-3(Mo)	6.7E-4(Mo)	7.3E-5(Fe)	~0
TENELON	--	--	--	--	--	8.6E-5(Fe)	~0
NOMAGNE	0.91(Ni)	4.0(Ni)	--	--	--	8.6E-5(Fe)	5
NM-1	--	--	--	--	--	7.3E-5(Fe)	~0
25-5-1	0.46(Ni)	2.1(Ni)	650(Nb)	--	--	7.3E-5(Fe)	652
32-7	9.1E-2(Ni)	0.43(Ni)	--	--	--	6.8E-5(Fe)	0.5
JUS289-N	--	--	--	--	--	8.2E-5(Fe)	~0
JUS289-V	--	--	--	--	--	8.2E-5(Fe)	~0

would eliminate the costs of packaging wastes for transport and the costs and societal problems of long distance transport and disposal of radioactive materials.

This study has shown that there are only two major natural elements in the steels considered that prevent near-surface disposal of the activated steels according to the proposed 10CFR61. These are nickel and molybdenum. Cobalt, copper, niobium, and zirconium could also prevent near-surface disposal but they generally can be avoided completely in the structural alloys. The natural isotopes of nickel and molybdenum that are particularly troublesome are Ni-58, Ni-60, Ni-62, Ni-64, Mo-92, Mo-94, Mo-95, Mo-98 and Mo-100.

There are three alternatives for selecting structural materials for fusion reactors that produce radioactive wastes that can be disposed of solely by near-surface burial. Two of these alternatives are elemental tailoring (eliminating offending elements in the steels) and isotopic tailoring (reducing the relative amounts of specific natural isotopes causing unacceptable activities for near-surface burial). The third alternative would be the use of nonferrous alloys with short-lived activation products which are acceptable for near-surface burial.[5,6,14] This last alternative has not been considered here; however, the methods of analysis could be extended to nonferrous materials without modification to determine their waste disposal ratings.

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