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RADIOACTIVE WASTE PRODUCED BY DEMO AND COMMERCIAL FUSION REACTORS EXTRAPOLATED FROM ITER & ADVANCED DATA BASES

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ABSTRACT

The radioactive wastes that would be produced in demonstration (DEMO) and commercial (CFR) fusion reactors which could be extrapolated from the design data base that will be provided by ITER and its supporting R&D and from a design data base supplemented by advanced physics and advanced materials R&D programs are identified and characterized in terms of a number of possible criteria for near-surface burial. The results indicate that there is a possibility that all fusion wastes could satisfy a 'low level' waste criterion for 'near-surface' burial.

I. INTRODUCTION

The potential for providing energy with minimal environmental impact is a powerful motivation for the development of fusion. The environmental, safety and economic attributes of magnetic fusion in some ultimate manifestation, as represented by conceptual designs of reactors which might be built at some indefinite, but far-removed, time in the future have been the subject of a number of studies (e.g. [1-4]). However, the societal acceptability of magnetic fusion may well be decided 10-15 years from now, when decisions will be taken on the construction of fusion demonstration plants (DEMOs) to follow ITER [5] (if not much sooner when the construction decision is taken on ITER).

If past experience is any guide, the design features of these DEMOs will be based on relatively conservative extrapolations of the then existing physics and technology data base. Since ITER requirements can be expected to dominate the world fusion program over the intervening period, the major part of that data base will, perforce be the data base developed in support of ITER and by the operation of ITER--the "ITER data base". Other advanced physics and technology R&D programs operating in parallel with the ITER program will provide a small, but crucial, supplementary "advanced data base". Identification of the characteristics of a DEMO reactor (and of a subsequent commercial reactor) that would extrapolate from the anticipated "ITER data base" and from various possible

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supplemented "advanced data bases" can thus provide some insight into the characterization of the environmental, safety and economic attributes of magnetic fusion upon which decisions of societal acceptability may well be based. At this time, these attributes still can be affected by the directions taken by the ITER design and supporting R&D program and by the direction of advanced physics and technology R&D programs operating in parallel with the ITER R&D programs over the next 1-2 decades.

In this paper, we are interested in the radioactive waste management attributes of DEMOs (and follow-on commercial fusion reactors-CFRs). Previous workers (e.g. [1-2], [6]) have categorized the radioactivity of various neutron-induced radionuclides that could be produced in fusion reactors, have suggested [1] criteria for "low-activation" materials development based on minimization of specific activity, and have calculated [2] the activation of idealized representations of fusion reactor components made of various materials. We are specifically interested in this paper with the waste-management attributes of DEMOs which could be extrapolated from the "ITER" and "advanced data bases" defined below.

II. DEMO CHARACTERISTICS

For the purposes of this paper, we associate the "ITER data base" with the ITER design characteristics and objectives. In particular, we postulate 1) Nb₃Sn superconductor and 316LN stainless steel magnets that can produce about 13T at the conductor; 2) 316 stainless steel structural material cooled by H₂O; 3) dispersion-strengthened copper divertor structure cooled by H₂O and with a sacrificial coating; 4) energy confinement characterized by the ITER89-P scaling law with $H = 2$; and 5) plasma operating regimes characterized by ignition, $\beta_{Troyon} \leq 3.5$, $q_{95} \geq 2.8$, $\kappa = 1.5$, $\delta = .15$ and $\epsilon\beta_p \ll 1$. We postulate Li₂O as the breeding material in this data base, since it has been commonly used in previous ITER, INTOR and national designs of ITER-class tokamaks. Physics constraints and materials properties were taken from Refs. [7,8].

For the "advanced data base", we postulate: 1) the V-4Ti-4Cr/Li system [9] being developed as an advanced option in ITER for the structural/coolant-breeding system (including divertor); and 2) the advanced physics confinement ($H=4$) and operating regimes (steady-state, $\beta_{Troyon} = 4-5$, $\kappa = 2$, $\delta = .45$ and $\epsilon\beta_p \approx 1$) which will be explored by TPX.

The range of characteristics of minimum-size, ignited reactors which would extrapolate from the "ITER data base" and of minimum-size $Q=20$ steady-state reactors which would extrapolate from the supplemented "advanced data base" have been calculated [10]. The "ITER data base" extrapolates to rather large ($R \approx 8-10m$) pulsed-ignited tokamaks with rather large plasma currents ($\approx 20-30$ MA). The "advanced data base" extrapolates to smaller ($R \approx 5-7m$) reactors with smaller plasma currents ($\approx 10-20$ MA). The characteristics of DEMOs (and

follow-on CFRs) given in Table 1 were taken as representative for the waste-management study of this paper. The ITER-CDA blanket design was used with the "ITER data base", while a representative V/Li design was used with the "advanced data base. The same vacuum vessel and shield were used with both designs. The blanket thicknesses were set by the same tritium breeding and nuclear heat removal requirements, and the shield thicknesses were set by the same magnet nuclear heating and fluence limits, in both designs.

III. RADIOACTIVE WASTE PRODUCTION

A. Volume

The volume of radioactive waste was calculated for each component (first wall-FW; divertor channel wall-DW; divertor heat dump plate-DP; blanket-BLKT; vacuum vessel-VV; shield-SHLD) by calculating the volume of the component and the number of times it had to be replaced over the lifetime of the reactor. Component volumes were based on stress, heat flux, radiation attenuation, and physics limits [10]. The lifetime was characterized in terms of effective full power years (EFPY), calculated as the product of lifetime in years times plant factor. Radiation damage lifetimes of 200, 60 and 100 dpa were taken for V-4Ti-4Cr, 316SS and dispersion strengthened copper, respectively. Divertor lifetimes against the disruption erosion of a 5 mm Be coating were calculated [11] based on the greater disruption frequency of 10^{-2} per pulse or 10 per year. First-wall and divertor wall and plate thicknesses were chosen so that fatigue lifetimes were greater than radiation damage lifetimes. A component would not be replaced if > 90% of design EFPY could be achieved without doing so.

The total radioactive waste volume is shown in Fig. 1 for a range of DEMOs/CFRs extrapolated from the "ITER" and "advanced data bases", referred to hereafter as "ITER" and "ADV", respectively. Component volumes are shown in Figs. 2 and 3. The blanket and shield volumes are comparable for the two design types. The major differences in volumes arise from the lower radiation damage lifetime of 316SS than V-4Ti-4Cr first walls and divertor walls and the lower divertor erosion lifetime of pulsed ($\Delta t_{\text{burn}}=10^4\text{s}$) than steady-state reactors.

B. Radioactivity

Neutron fluxes in the various components were calculated with the multigroup transport code ONEDANT [12] and used in the radioactivity code REAC-2 [13] to calculate activation rates and dpa. The total activities for the two DEMO designs are shown at different times after shutdown in Fig. 4, and the component activities are shown in Figs. 5 and 6. The "ITER" DEMO design is an order of magnitude more radioactive than the "ADV" DEMO design, and the activity of the latter is dominated by the vacuum vessel and shield, which is about the same for both designs.

IV. WASTE MANAGEMENT CONSIDERATIONS

The environmental acceptability of magnetic fusion would be greatly enhanced if most, if not all, of the radioactive waste could be classified as 'low level' and disposed of in near-surface burial sites. 'Low level' burial criteria have yet to be developed for fusion wastes. The existing criteria for near-surface burial (based on fission and medical wastes) vary from country to country [14] and may not be applicable to fusion wastes [15]. However, they provide some guidance as to the likely acceptability of fusion wastes for near-surface burial.

The most straightforward criterion for near-surface burial is a maximum specific activity limit. Japan, for example, specifies a maximum of $1 \cdot 10^{-3}$ Ci/m³ in order for waste to qualify as low level [14]. Specific activities are shown, by component, in Figs. 7 and 8 for the "ITER" and "ADV" DEMO/CFR designs. None of the components in either type of design would meet this criterion within 10 years of shutdown, although the advanced (V/Li) blanket would do so soon afterwards.

Another relatively straightforward criterion is based on contact dose. The IAEA specifies < 2 mSv/hr (200 mRem/hr) in order for waste to qualify as low level [14]. Contact doses calculated on the basis of semi-infinite slab models of the activated waste produced by each component are shown in Figs. 9 and 10 for the "ITER" and "ADV" DEMO/CFR designs. The vanadium first wall, divertor and blanket would satisfy this criterion within about 10 years after shutdown, but none of the stainless steel or copper components would.

In the US, specific activity (Ci/m³) limits are prescribed by the Nuclear Regulatory Commission (NRC) for near-surface burial for several long-lived radionuclides [16], based on an inadvertent intruder (who may build a house and plant a garden) receiving a dose of no more than 500 mrem/yr (5 mSv/yr) at a time 500 years after burial. The radionuclides considered by the NRC are specific to fission, but the same methodology has been applied [17] to calculate specific activity limits of fusion-relevant radionuclides, from which maximum elemental concentration limits were back-calculated using a neutron spectrum typical of a first wall. These elemental concentration limits have been used to calculate 'component concentration factors' (CCF), defined as the sum over nuclides of the ratio of actual-to-limiting concentrations, which are shown in Fig. 11 for DEMO/CFRs extrapolated from the two data bases. All the components in the "ADV" designs except the stainless steel vacuum vessel and shield readily satisfy this criterion, but none of the components in the "ITER" designs do so. The concentration limits [17] for the blanket, vacuum vessel and shield are over-conservative because they are calculated with a much more energetic neutron distribution than would exist in these components, and the correct concentration

ratios for these components could be less than unity. However, it seems unlikely that the stainless steel first wall and divertor wall or the copper divertor plate could satisfy the NRC (class C) criterion for near surface burial. The "deep disposal index" corresponding to Fig. 11, which is the sum over those components for which $CCF > 1$ of the product of CCF and the corresponding component waste volume, is plotted in Fig. 12.

The US '10CFR61-type' criteria, which are based on analysis of the possible pathways by which a dose could be received, are less limiting than some other international criteria for 'low level' waste and 'near-surface' burial which are based on specific activity or potential dose levels alone. Any future dose criterion for fusion wastes is likely to be more conservative than the 500 mRem/yr 10CFR61 criterion. Figure 11 suggests that the first wall, divertor and blanket of the V/Li system would still satisfy the intruder dose concentration limits even if the dose criterion was reduced by two orders of magnitude.

V. CONCLUSION & FURTHER WORK

The above results indicate that there is a possibility that all fusion wastes could satisfy a 'low level' waste criterion for 'near-surface' burial. Further work that could contribute to the evaluation of this possibility falls into three categories: 1) improvement and generalization of the 'intruder dose' pathway analysis of radionuclide concentration limits; 2) comparison of DEMO/CFR design concepts that could meet a likely future 'low level' waste criterion for fusion with 'minimum-size' design concepts; and 3) identification of physics and technology developments that could contribute to satisfaction of a future 'low level' waste criterion for fusion.

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TABLE 1

DEMO & CFR CHARACTERISTICS

	DEMO		CFR	
	ITER Data Base	Advanced Data Base	ITER Data Base	Advanced Data Base
Fusion Power (MW)	2500	2500	2500	2500
Plasma Current (MA)	24.4	19.0	23.4	18.8
Toroidal Field (T)	13.2	13.2	13.2	13.2
Q _{plasma}	∞	20	∞	20
Burn Pulse (s)	10 ⁴	SS	10 ⁴	SS
Peak FW heat Flux (MW/m ²)	0.42	1.19	0.41	1.18
Av. Neut. Wall Load (MW/m ²)	1.48	2.35	1.45	2.34
Major Radius (m)	9.24	5.55	9.50	5.63
Plasma Minor Radius (m)	2.89	2.35	2.87	2.33
FW/DW Structure	316SS	V-4Ti-4Cr	316SS	V-4Ti-4Cr
FW/DW Coolant	H ₂ O	Li	H ₂ O	Li
Divertor Plate Structure	D.S.Cu	V-4Ti-4Cr	D.S.Cu	V-4Ti-4Cr
Divertor Plate Coolant	H ₂ O	Li	H ₂ O	Li
Blanket	$\left\{ \begin{array}{l} 316SS/7\% \\ H_2O/3\% \\ Li_2O/7\% \\ Be/83\% \end{array} \right.$	$\left\{ \begin{array}{l} V-4Ti-4Cr/17\% \\ Li/72\% \\ Be/11\% \end{array} \right.$	$\left\{ \begin{array}{l} 316SS/7\% \\ H_2O/3\% \\ Li_2O/7\% \\ Be/83\% \end{array} \right.$	$\left\{ \begin{array}{l} V-4Ti-4Cr/17\% \\ Li/72\% \\ Be/11\% \end{array} \right.$
Vacuum Vessel	316SS	316SS	316SS	316SS
Shield	$\left\{ \begin{array}{l} 316SS/56\% \\ H_2O/34\% \\ PbB_4C/10\% \end{array} \right.$	$\left\{ \begin{array}{l} 316SS/56\% \\ H_2O/34\% \\ PbB_4C/10\% \end{array} \right.$	$\left\{ \begin{array}{l} 316SS/56\% \\ H_2O/34\% \\ PbB_4C/10\% \end{array} \right.$	$\left\{ \begin{array}{l} 316SS/56\% \\ H_2O/34\% \\ PbB_4C/10\% \end{array} \right.$
Lifetime (yr)	20	20	40	40
Plant Factor	.25-.50	.25-.50	.50-.75	.50-.75

Fig. 1: TOTAL RADWASTE VOLUME

Fig. 2: COMPONENT WASTE VOLUME
(ITER DATA BASE)

Fig. 3: COMPONENT WASTE VOLUME
(ADVANCED DATA BASE)

Fig. 4: TOTAL RADIOACTIVITY
(DEMO-10EFPY)

Fig. 5: COMPONENT RADIOACTIVITY
DEMO(10 EFPY):ITER DATA BASE

Fig. 6: COMPONENT RADIOACTIVITY
DEMO(10EFPY):ADVANCED DATA BASE

Fig. 7: COMPONENT SPECIFIC ACTIVITY
ITER DATA BASE

Fig. 8: COMPONENT SPECIFIC ACTIVITY
ADVANCED DATA BASE

Fig. 9: COMPONENT CONTACT DOSE
ITER DATA BASE

Fig. 10: COMPONENT CONTACT DOSE
ADVANCED DATA BASE

Fig. 11: INTRUDER DOSE LIMITS
NUCLIDE CONCENTRATION RATIOS

Fig. 12: INTRUDER DOSE LIMITS
DEEP DISPOSAL INDEX

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