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IN A FUSION POWER REACTOR

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ACTIVATION AND AFTERHEAT IN A FUSION POWER REACTOR

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ABSTRACT

A series of calculations has been performed to analyze the activation of the structure of the Princeton Reference Design D-T Fusion Power Reactor. The relevant isotope transmutation chains have been solved numerically for 30 years' operation (3/4 load factor) at 5310 MW (t).

Decay heat and activity curves versus time after shutdown have been obtained for the reference stainless steel structure and for a vanadium alloy as an alternate. After-heat appears not to pose a safety hazard because of the large blanket heat capacity; however, the large amount of cobalt-60 produced in the steel (2.82×10^7 curies) may make the ultimate disposal of that material difficult. Although the activation in the vanadium is comparable to that in the steel, the short half-lives of the radio-isotopes (less than a year) greatly reduce the disposal problems.

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1. INTRODUCTION

One of the principal advantages of fusion power over fission power is the freedom from the hazards of radioactive fission products. A fusion reactor will not be devoid of radioactive materials, however, because of the activation of its structure by fusion-generated neutrons. (Very high neutron fluxes are an essential feature of reactors based on D-T fusion and an unavoidable adjunct of D-D fusion.) Studies have been made by Steiner [1] of the degree of activation that might be expected in a D-T "Tokamak" with a niobium structure, and similar studies have been reported by Blow [2] for reactors built with niobium, with molybdenum, and with the nickel alloy, PE-16. These suggest that the afterheat from decay of short-lived radioisotopes cannot be ignored in emergency analyses, that production of long-lived radioisotopes will make plant maintenance difficult and may complicate the decommissioning of old plants, and that in niobium, at least, gross transmutations to other elements will occur.

This paper is a preliminary report of some transmutation and activation analyses performed in support of the design of a "Reference Fusion Power Plant" at the Princeton Plasma Physics Laboratory. This 2000 MWe (5310 MW_t) plant is designed around a large D-T fueled "Tokamak"-type reactor. The reactor is cooled by high-pressure helium (coupled to a steam turbine); tritium fuel is bred in a blanket containing the molten salt flibe (LiF-BeF_2); and the structural material is type 304 stainless steel. (The design principles dictate that the structural material be a conventional alloy; 304 stainless is representative of these and

has been chosen somewhat arbitrarily as the basis of this preliminary activation analysis.)

2. THEORY

Using standard notation, the equations describing the transmutation process can be written

$$\frac{dN_i}{dt} = + \sum_{\text{all } j} \phi \sigma_{j \rightarrow i} N_j - \phi \sigma_i N_i - \lambda_i N_i \quad (1)$$

for each isotope i .

The whole set of linear differential equations can be represented by a single matrix equation,

$$\frac{d}{dt} \underline{N} = \underline{M} \underline{N}, \quad (2)$$

where the vector $\underline{N}$ is composed of the isotope densities, and $\underline{M}$ is a transfer matrix. The solution to this simple matrix differential equation is, formally [3],

$$\underline{N}(t) = \exp(\underline{M} t) \underline{N}(0), \quad (3)$$

using the matrix exponential

$$\exp(\underline{M} t) = \underline{I} + \underline{M} \frac{t}{1!} + \underline{M}^2 \frac{t^2}{2!} + \dots \quad (4)$$

and taking $\underline{N}(0)$ as the vector of initial densities.

An approximate solution for $\underline{N}(t)$ can be obtained by

actually forming the series expansion of $\exp(\underline{M}t)$ and truncating it when the latest term becomes suitably small. Furthermore, once this is done then

$$\underline{N}(2t) = \exp(\underline{M}t) \underline{N}(t),$$

etc. can all be found quite easily. The problem with this procedure is that any large element in $\underline{M}$, for example the decay constant ($\lambda = \ln 2/t_{1/2}$) for a short half-life, will cause the convergence of the matrix exponential series to be very slow. The only practical way to avoid this is to pick out such large λ_k , remove the k^{th} equation from the system, and eliminate N_k from all the other equations.

A transmutation Chain Analysis Program (TCAP) [4] has been written to study the fusion reactor transmutation problem. TCAP reads the initial densities, the half-lives, the cross sections, and the flux, and forms a trial transfer matrix $\underline{M}$. It then looks for short-lived isotopes. An isotope with a short half-life is assumed to come into quick equilibrium with its sources, and consequently the N_k equation and N_k contributions to other N_i are eliminated by approximating $dN_k/dt = 0$. Since TCAP uses this automatic equilibration procedure, it is possible to feed it all potential transmutation and decay schemes without any premanipulation to eliminate troublesome isotopes. TCAP finally calculates $\underline{N}(t)$, $\underline{N}(2t)$, etc., and also the radioisotope decay rates and powers.

3. DATA

The data for the reference design calculation allow analysis of the transmutation and decay scheme shown in Fig. 1. The initial isotope densities are derived from the reactor blanket model shown in Fig. 2; Table 1 gives the volume fractions of the constituents in each region. (The stainless steel is nominally 70% Fe, 19% Cr, 9.5% Ni, 1.5% Mn.)

The flux which will cause the transmutations has been calculated with the S_8 discrete ordinates option of the transport code ANISN. [5] Since this code will treat only one spatial dimension, the reactor was modeled as an infinite cylinder with concentric layers as described in Fig. 2 (i.e. it was assumed that the "toroidal" curvature could be neglected). The cross sections used for the neutron transport were taken from a 52-group P_3 library made available by D. Steiner [6] of the Oak Ridge National Library.

Spectra at the first wall and in the middle of the blanket are shown in Fig. 3. Obviously, the flux is both space and energy dependent. Since the transmutation cross sections are energy dependent and the isotope densities space dependent, the following scheme was adopted to calculate the reaction rates " $\phi \sigma N$ " required for the transmutation code. The distribution of all the isotopes is assumed to be the same as the initial distribution of the structural isotopes, i.e. $N(r) = N * F(r)$. Then the total reaction rate $\phi \sigma N$ can be evaluated as

$$N * \sum_{\text{all groups}} \sigma^g \int \phi^g(r) F(r) dr = N \overline{\sigma \phi}. \quad (5)$$

This approximation is probably not very accurate for "second-generation" reactions, but these tend to have unimportant products ("third-generation" isotopes with low densities).

The energy-dependent transmutation cross sections $\sigma_{i \rightarrow j}^g$ have been taken from a preliminary version of the CASDAR library, made available by D. Jenkins [7] of ORNL. This library contains cross section information obtained principally from ENDF/B-III, UCRL - 50484 [8], and the ORNL GAM-THERMOS library, all converted to a standard 123 group structure. A deficiency of this library is that it has almost no cross sections for radioactive isotopes or for reactions whose products are stable. The most important cross sections in the latter category have been estimated by assigning cross sections for the elements to their principal isotopes, but the evaluation of gross elemental transmutation is rather less accurate than the evaluation of activation, which CASDAR covers quite thoroughly.

The decay schemes and half-lives of the radioactive isotopes have been taken from the "Table of the Isotopes." [9] Average energies of most emitted beta particles, needed to calculate decay energies, were found in the Radiological Health Handbook [10], although a few were estimated directly from the decay schemes. All gamma energies were taken directly from the decay charts in the "Table of the Isotopes."

TCAP has been used to solve the transmutation equations for the reference design blanket through 30 years of plant operation. The average flux was taken to be $3/4$ of nominal to simulate a reasonable plant load factor. (The decay rates of short-lived isotopes have been adjusted, however, to reflect sustained operation at full power just before shutdown.)

4. DECAY HEAT

The decay heat in the blanket structure is quite substantial, 50.5 MW at shutdown. To this must be added the decay heat from the flibe, 195.6 MW, giving a total initial afterheat of 246.1 MW. The afterheat is plotted against time in Figs. 4 and 5 (for short times in the former, and for long times in the latter).

The short term afterheat is dominated by 158.7 MW from 7 N^{16} , quickly decaying with a half-life of 7.2 seconds, and 39.1 MW from 25 Mn^{56} , decaying with a half-life of 2.58 hours. In the long run the afterheat is principally due to 25 Mn^{54} (303 days half-life), 26 Fe^{55} (2.6 years), and finally 27 Co^{60} (5.26 years). A small amount of 28 Ni^{63} (with a half-life of 92 years) will be produced. ENDF cross sections for the element nickel had to be used to estimate the burnout of this isotope (which proceeds much faster than the decay) so the calculated initial activity of 6 megacuries is quite uncertain.

These estimates of afterheat for the PPL blanket of flibe and stainless steel can be compared to those of Steiner for the ORNL lithium and niobium blanket. He reports [1], for 20 years'

full power operation at 5000 MW (t), an initial afterheat of 52 MW. Of this, 4 MW is from the lithium and decays away in seconds, while the long term component is due to 41 Nb^{95} , with an initial power of 25 MW and a half-life of 35 days.

Because of the enormous mass of a fusion reactor blanket, a large afterheat power may not actually pose a safety problem. In the first hour after shutdown the PPL blanket would produce 1.82×10^{11} joules of decay heat, but this could be absorbed by the steel and flibe with a temperature rise of only 30°C . (Distributed gamma heating and circulation of the flibe should prevent local temperature changes from greatly exceeding this bulk average.)

5. ACTIVITY

Since the activated material in the blanket is effectively nondispersable (being an integral part of the structure) it poses a radioactive hazard only in terms of plant maintenance and ultimate disposal. Ignoring radioisotopes with half-lives shorter than a week, the initial total activity is 3.83×10^9 curies (compared to Steiner's value of about 2×10^{10} curies). Making allowance for the fall-off through the blanket of both the flux and the volume fraction of structure, this corresponds to about 10 curies/cm^3 of structure near the vacuum wall, or a dose rate on the order of $3 \times 10^5 \text{ Rad/hr}$.

The long term activity is plotted in Fig. 6. It is dominated first by Co^{57} (half-life of 270 days) and Mn^{54} (303 days), and then Co^{60} , with an initial 2.82×10^7 curies decaying with a 5.26 year half-life. (The Fe^{55} is discounted because it decays by electron capture without emitting gammas.) In the very long term the 6×10^6 curies of Ni^{63} with a half-life of 92 years will be the largest activity, but since it decays by β^- emission without gammas (and $E_\beta < 67$ KeV) it should not be difficult to handle.

The transmutation of elements does not appear to be an important consideration for the stainless steel wall, probably because of the large number of stable isotopes in the vicinity of iron and also perhaps a balance between β^- and β^+ decay. The compositions of the steel before and after the nominal 30 years of operation are shown in Table 2. Radiation damage will certainly cause much more trouble than these changes in alloy composition.

6. VANADIUM

Because of growing concern for the problems of long-term storage of radioactive waste, it has been suggested (e.g. by Steiner and Fraas [11]) that vanadium be used as the structural material in a fusion reactor blanket. Vanadium appears to be reasonably easy to fabricate, is worse than niobium but better than steel for high temperature strength, and has very small activation cross sections. (It is, however, not at all a

conventional structural material.)

To estimate the reduced levels of activation that might be achieved in a blanket structure of vanadium, the transmutation chain analyses described above were repeated substituting an alloy of 85% vanadium, 10% titanium, and 5% chromium (by weight, at 5.90 g/cm³) for the type 304 stainless steel. Note that the material volume fractions were not altered, nor was the flux distribution revised; the object was to obtain realistic estimates of activation rather than real values for a proper vanadium reactor design. The transmutation and decay scheme studied is shown in Fig. 7.

The immediate afterheat problem appears to be more severe for vanadium than for either steel or niobium because of the large $V^{51} (n, \gamma) V^{52}$ reaction rate. The initial afterheat is calculated to be 149MW in the structure (compared to 50 MW for the steel), of which 142 MW is due to the beta decay of V^{52} , with a half-life of 3.75 minutes. Of course this quickly disappears, and if the heating transient can be accommodated, the total decay energy release is less than in the steel (causing a blanket temperature rise of only 14°C).

On a longer time scale, the Sc^{46} is dominant for about a year (initially at 0.31 MW, with a half-life of 84 days) and then V^{49} (initially only about 13 KW, with a half-life of 331 days). Thus, the ultimate waste disposal problem should be relatively easy to solve, unless the vanadium should be contaminated with some easily activated material. The short-term and long-term decay powers are plotted in Figs. 8 and 9 respectively.

The specific activity in the structural material near the vacuum wall is only about 1 curie/cm³, corresponding to a dose rate of 2.5×10^4 Rad/hour. This is mostly due to the Sc⁴⁶, however, and so decays with an 84 day half-life. The V⁴⁹, which lasts longest, decays by electron capture without gammas, so that it is relatively harmless.

Finally, Table 3 gives the element weight fractions of the structural material before and after the 30 years' operation at 3/4 power. It can be seen that there is relatively more transmutation in this vanadium alloy than in the steel; there is a shift of about 2.5% from vanadium to chromium. (Incidentally, this might provide a justification for choosing an alloy which is formulated to include some small fraction of chromium.)

7. CONCLUSIONS

In summary, it appears that the activation of a stainless steel structure would be comparable to that of a niobium structure, and that a vanadium structure would be preferable to either. Steel perhaps has an edge over niobium because of its low rate of alloy composition change and the lack of very long-lived activation products (Cf. the 2×10^4 year half-life for Nb⁹⁴). The use of vanadium would accentuate the emergency afterheat cooling problem somewhat, but could practically eliminate the long-term waste disposal problem. This observation must be qualified, however, by noting that minor alloy components or even trace contamination in the 100 to 1000 ppm range might provide

a dominant long-term activity.

In any case, the choice of the structural material for a fusion reactor blanket will probably be determined by considerations of fabricability and resistance to radiation damage, with little freedom to avoid substantial structural activation.

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TABLE 1. Volume fractions of the material regions in the reference design blanket.

Region	Inner Radius	Outer Radius	Helium vol. frac.	Flibe vol. frac.	Steel vol. frac.	Region
1	360.cm	362.86	.404	.169	.427	1
2	362.86	375.	.255	.610	.135	2
3	375.	390.	.200	.695	.105	3
4	390.	405.	.145	.777	.078	4
5	405.	420.	.095	.853	.052	5
6	420.	440.	.050	.925	.025	6

TABLE 2. Weight fractions of stainless steel components before and after plant operation for 30 years at 3/4 load factor.

Element	Before	After
Vanadium	0.	.0014
Chromium	.190	.1887
Manganese	.015	.0215
Iron	.700	.6957
Nickel	.095	.0927

TABLE 3. Weight fractions of vanadium alloy components before and after plant operation for 30 years at 3/4 load factor.

Element	Before	After
Titanium	.100	.0969
Vanadium	.850	.8249
Chromium	.050	.0782

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Fig. 1. Chart of the transmutation and decay scheme studied for the stainless steel structure.

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Fig. 2. Toroidal model of the blanket of the reference design reactor.

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Fig. 3. Neutron spectra at the vacuum wall and in the blanket of the reference design reactor cylindricized model.

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Fig. 4. Decay heat in the steel structure for short times after shutdown.

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Fig. 5. Decay heat in the steel structure for long times after shutdown.

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Fig. 6. Activity in the steel structure for long times after shutdown.

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Fig. 7. Chart of the transmutation and decay scheme studied for the vanadium alloy structure.

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Fig. 8. Decay heat in the vanadium structure for short times after shutdown.

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Fig. 9. Decay heat in the vanadium structure for long times after shutdown.

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