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NEUTRON ACTIVATION OF FOUR FERRITIC STEELS

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NEUTRON ACTIVATION OF FOUR FERRITIC STEELS*

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Activation Geometry

Four ferritic steels (Table 1) were compared using two simplified fusion reactor geometries. In the MFE geometry, a 14.1-MeV point source was centered inside a 5 m radius vessel. The 2 cm thick first wall was surrounded by a reflector consisting of 78 cm Li, 18 cm graphite, 2 cm B_4C , and a 10 cm thick outer wall. In the ICF geometry, the neutron source was in a compressed plasma ($\rho R = 3 \text{ g/cm}^2$), and the region between 0.5 and 2.0 m was filled with Li at 50% of the natural density.¹

Calculation Procedure

The TART neutronics code² was used to calculate the energy dependent neutron flux in the first wall. Then, the ORLIB code³ was used to collapse the energy-dependent ACTL cross section library,⁴ using the flux as a weighting function. The resulting energy-averaged cross sections for each geometry were used in a series of activation calculations using the FORIG code.^{5,6} A separate calculation was done for each of the 16 elements in the steels (Table 1), using both the MFE and the ICF fluxes. For the MFE calculations, the neutron flux was on at an average of 70% of 1 GW_e for five years; in the ICF calculations, 30 years of operation was assumed. Finally, the results were assembled for each of the 8 cases (4 steels, in both MFE And ICF geometries) by linearly combining the results of the elemental activation calculations, using the steel composition as the weighting function.

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24

Figures of Merit

Four figures of merit were used to compare the steels. The first two, afterheat and biological hazard potential, deal with safety. The third evaluates the feasibility for shallow land burial disposal of the activated wall. The final figure of merit, surface dose rate, impacts the hands-on-maintainability of the structure.

Afterheat is important because it can lead to structural melt or vaporization if the wall coolant is lost. If the decay heat is less than a few MW (in these geometries), radiation cooling alone could remove the afterheat;⁷ at higher afterheat levels, emergency wall cooling systems will be required. Because afterheat is most important shortly after shutdown, we present the results at times of 1 minute and 10 hours after shutdown.

The inhalation biological hazard potential (BHP) is the amount of air required to dilute the vaporized structure to breathing standards. Typical results are $\sim 10^{17} \text{ m}^3$ (10^8 km^3) which are extremely large numbers. However, it is unrealistic to expect the entire wall to be vaporized and released from the containment building; release fractions of order 10^{-6} have been used in some fusion accident analyses.⁸ Also, some accident analyses assume that, instead of wall vaporization, the wall is in contact with heated air, and that some alloying elements (e.g. Mo) are preferentially oxidized out of the structure. Our simple comparison assumes that the hazard is due to vaporization and release of 10^{-6} of the activated structure, and that there is no preferential release of oxidizable alloying elements. Since release of the wall is least improbable at times shortly after shutdown, we present the results at 1 and 10 hours after shutdown.

To evaluate the potential for disposal of the activated structure by shallow land burial (as low level waste), we should use the recently published NRC rule 10CFR61. However, this fission regulation ignores many of the nuclides produced in fusion walls, and it uses an inexplicably conservative limit for ^{94}Nb . Thus, we have used the procedure⁹ of calculating the amount of water required to dilute the activated (and dissolved) steel to drinking standards (ingestion BHP), and then comparing that dilution volume to the water volume required to dilute

clean unactivated steel to drinking standards (using EPA limits). When the ratio of the two dilution volumes falls to 1.0, burying the activated wall is similar to burying unirradiated steel, an accepted procedure. Since utilities could afford to hold decommissioned structures for decades, but not centuries, we present the waste disposal ratio at times of 50 and 100 years after plant shutdown. For the MFE geometry, the disposal ratios include the total ingestion BHPs for the six walls used in the plant life. However, the denominator of the ratio is the chemical BHP for only a single wall (to allow direct comparison of the ICF and MFE waste disposal ratios).

The final figure of merit is a very rough calculation of the dose rate to an unprotected person at the wall surface, using the procedure suggested by Dorn.¹⁰ The procedure assumes a slab wall of infinite extent laterally, but of the correct thickness. Photons are assumed to transport normal to the wall surface (hence underestimating the self shielding). Compton scattering is handled by using only one-half the cross section, rather than scattering the photon into a lower energy group. Because maintenance cannot be delayed indefinitely, we present the dose rates at times of 1 day and 1 month after shutdown. Values above 100 R/hr will probably preclude hands-on maintenance.

Results for the Four Steels

The four figures of merit are presented in Table 2 for the four steels in both MFE and ICF geometries. For afterheat, BHP, and dose rate, the differences between the steels are not significant, but the ICF geometry is 5-10 times better than the MFE geometry.

For waste disposal, the differences between geometries is much less significant, in fact, if only one of the six MFE walls was compared to the single ICF wall, the MFE wall would be slightly less dangerous. Also, for waste disposal, the results vary significantly among the four steels. The UCVS steel is acceptable in either geometry while the other three ferritic steels are within an order of magnitude of being acceptable. For comparison, the steel used in the STARFIRE tokamak design, PCA, would be another order of magnitude worse.⁸

For afterheat, the shutdown ICF levels ~ 1 MW are acceptable while the ~ 6 MW MFE levels are marginal. For BHP, the ICF levels of $\sim 20 \text{ km}^3$ are probably acceptable since evacuation to distances of a several km is feasible. Similarly, MFE levels of $\sim 200 \text{ km}^3$ are marginal since evacuation to several tens of km would be much more difficult. However, since we arbitrarily assumed a 10^{-6} release fraction, these numbers could shift to make both geometries either acceptable or not acceptable, depending on the release fraction. For dose rate values of $\sim 10^5$ to 10^6 R/hr will require remote maintenance in both geometries.

Improvements Possible by Using Isotopic Tailoring

The principal parent elements contributing to the figures of merit are shown in Table 3 which lists the top two contributors in each case. The top contributor elements are Fe, Mo, Cu, and Nb. Additional elements in the second rank are Cr, W, Ni, Mn, and V. Neither Mn nor Nb can be tailored since they consist of only one isotope each.

The dominance of Fe is discouraging since tailoring of $> 85\%$ of the steel is likely to be too expensive. Yet, if more than 10% effects are desired, Fe offers the only chance in 48 of the 64 cases presented (4 figures of merit at two times each, for two geometries and four steels). The 48 cases are the top contributors in afterheat, BHP, and dose rate for all steels and geometries. The next best element to consider tailoring is Mo, with 16 opportunities, all in the waste disposal category. Also in the waste disposal category, Cu offers four chances for improvement, and Ni offers two chances. In the afterheat and BHP areas, Cr offers three chances and W offers one.

The activation calculations were rerun for the isotopes of Fe and Mo; the best and worst isotopes are shown in Table 4. This information was used to evaluate various schemes of isotopic tailoring, as shown in Table 5. Combining Tables 2, 3, and 5 allows a specific comparison between the various steels. In most cases, a given scheme helps all the steels in both ICF and MFE geometries; however, removing ^{94}Mo alone will help only for MFE. Schemes that utilize a large fraction of the natural element will be less expensive; therefore, removing ^{54}Fe is

much more cost effective than concentrating ^{57}Fe , even though the result is not quite as dramatic. Similarly, it is better to remove ^{92}Mo and ^{94}Mo than to concentrate ^{97}Mo and ^{98}Mo . The schemes reduce the Fe and Mo contributions by 1-3 orders of magnitude; further reductions in these elements would be ineffective unless other alloying elements are also tailored. For afterheat, BHP, and waste disposal, the reductions would be enough to satisfy the suggested limits on the figures of merit. However, for surface dose rate, the reduction is still inadequate to allow contact maintenance of the wall.

Summary

Four ferritic steels were compared from an activation viewpoint for both ICF and MFE reactor applications. The comparison criteria were afterheat, inhalation BHP and surface dose rate at early times after shutdown, and waste disposal feasibility 50 to 100 years after shutdown. In general, the softer ICF flux leads to a significant advantage. The four steels are roughly equal, except that the UCVS-1 is superior from the waste disposal viewpoint. To improve the early performance (afterheat, BHP, and dose rate) by isotopic tailoring, Fe is the element that must be tailored, and that would be very expensive due to the large quantity of Fe in the steel. For waste disposal, Mo is the best element to tailor, and Mo tailoring would allow disposal of all four steels by shallow land burial within 50 years after shutdown.

Table 1. Compositions of the four steels (wt%).

Element	HT-9	Steel UCVS-1	2-1/4 Cr - 1 Mo	Nb stabilized 2-1/4 Cr
C	0.19	0.11	0.07	0.08
N	-	0.015	-	-
Al	-	0.043	0.01	-
Si	0.31	0.3	0.35	0.2
P	0.021	0.007	0.005	0.03
S	0.008	0.015	0.013	0.03
Ti	-	0.003	-	-
V	0.31	1.5	-	-
Cr	11.8	2.46	2.14	1.9
Mn	0.57	0.3	0.46	0.3
Fe	84.741	95.137	96.002	95.79
Ni	0.48	0.05	-	-
Cu	-	0.04	-	-
Nb	-	-	-	0.8
Mo	1.04	0.02	0.95	0.87
W	0.53	-	-	-

Table 2. Comparison of the four steels. A release fraction of 10^{-6} was used to calculate the BHP.

	Afterheat (MW)		BHP (km ³)		Waste disposal index		Dose rate, kR/hr	
	1 m	10 hr	1 hr	10 hr	50 yr	100 yr	1 day	1 month
<u>ICF Geometry</u>								
HT-9	1.07	0.149	19.7	18.2	2.04	1.95	110	68.3
UCVS-1	0.689	0.116	17.9	16.6	0.138	0.104	104	66.0
2-1/4 Cr - 1 Mo	0.687	0.127	18.9	17.5	1.65	1.63	107	67.0
Nb Stab 2-1/4 Cr	0.681	0.148	25.2	23.7	5.09	5.07	153	91.5
<u>MFE Geometry</u>								
HT-9	5.55	0.942	180	168	5.89	5.60	809	711
UCVS-1	5.72	0.945	157	145	0.798	0.592	799	704
2-1/4 Cr - 1 Mo	5.73	0.951	162	149	4.75	4.70	802	728
Nb Stab 2-1/4 Cr	5.64	0.942	226	211	8.52	8.42	826	715

Table 3. Top contributors to the figures of merit (in percent of the totals).

	Afterheat		BHP		Waste disposal		Dose rate	
	1 m	10 hr	1 hr	10 hr	50 yr	100 yr	1 day	1 month
<u>ICF Geometry</u>								
T-9	Fe 45.0	Fe 63.6	Fe 76.6	Fe 77.5	Mo 88.7	Mo 91.8	Fe 79.9	Fe 82.4
	Cr 36.0	W 15.9	W 6.8	W 6.6	Ni 11.2	Ni 8.0	Ni 7.7	Ni 9.8
UCVS-1	Fe 78.7	Fe 91.4	Fe 95.0	Fe 95.8	Cu 55.4	Cu 50.0	Fe 94.9	Fe 95.8
	Mn 9.3	Mn 4.9	Mn 2.6	Mn 2.6	Mo 25.2	Mo 33.1	Mn 2.1	Mn 2.9
2-1/4 Cr - 1 Mo	Fe 79.5	Fe 84.3	Fe 90.5	Fe 91.5	Mo 99.9	Mo 99.9	Fe 93.1	Fe 95.2
	Mn 14.3	Mo 8.1	Mo 5.1	Mo 4.9	Fe 0.1	Fe 0.1	Mo 3.7	Mn 4.4
Nb Stab 2-1/4 Cr	Fe 80.0	Fe 67.7	Fe 67.9	Fe 67.5	Nb 70.3	Nb 70.4	Fe 64.9	Fe 69.5
	Mn 9.4	Nb 22.0	Nb 25.9	Nb 27.0	Mo 30.0	Mo 29.6	Nb 31.2	Nb 28.2
<u>MFE Geometry</u>								
HT-9	Fe 85.6	Fe 81.6	Fe 68.9	Fe 67.9	Mo 87.3	Mo 90.7	Fe 78.5	Fe 82.4
	Cr 7.6	Mn 6.8	Cr 14.6	Cr 15.7	Ni 11.9	Ni 8.3	Mn 9.9	Mn 10.6
UCVS-1	Fe 93.4	Fe 91.4	Fe 88.5	Fe 87.6	Cu 70.7	Cu 65.2	Fe 89.2	Fe 93.5
	V 1.7	Mn 3.6	Mn 4.0	Mn 4.2	Mo 12.4	Mo 16.5	Mn 5.3	Mn 5.6
2-1/4 Cr - 1 Mo	Fe 94.1	Fe 91.7	Fe 79.6	Fe 86.6	Mo 98.7	Mo 98.7	Fe 89.7	Fe 91.2
	Mn 2.3	Mn 5.4	Mn 5.9	Mn 6.3	Fe 1.3	Fe 1.3	Mn 8.1	Mn 8.3
Nb Stab 2-1/4 Cr	Fe 95.2	Fe 92.4	Fe 56.6	Fe 60.7	Mo 50.5	Mo 50.5	Fe 86.8	Fe 92.7
	Mn 1.5	Mn 3.6	Nb 30.3	Nb 31.7	Nb 48.8	Nb 45.8	Nb 6.2	Mn 5.5

Table 4. Ratios of the values for pure isotopes compared to the natural elements. In each box, the ICF ratio is shown over the MFE ratio.

Isotope	Natural wt%	Afterheat		BHP		Waste disposal		Dose rate	
		1 m	10 hr	1 hr	10 hr	50 yr	100 yr	1 day	1 month
⁵⁴ Fe	5.60	2.69	11.7	14.9	15.8			17.3	17.4
		1.54	9.28	11.5	12.5			15.6	15.8
⁵⁷ Fe	2.14	0.193	0.181	0.0713	0.0743			0.014	0.015
		0.195	0.0242	0.0098	0.0060			0.0018	0.0013
⁹² Mo	14.2					6.44	6.40		
						2.54	2.54		
⁹⁴ Mo	9.10					0.95	0.95		
						6.79	6.80		
⁹⁷ Mo	9.70					0.00056	0.00052		
						0.0010	0.00034		
⁹⁸ Mo	24.6					0.0027	0.0028		
						0.00088	0.00088		

Table 5. Reduction of the Fe or Mo contributions due to various isotopic tailoring schemes. In each box, the percent reduction for ICF is shown above the MFE reduction.

Scheme	Wt% of element retained	Afterheat		BHP		Waste disposal		Dose rate	
		1 m	10 hr	1 hr	10 hr	50 yr	100 yr	1 day	1 month
Remove ⁵⁴ Fe	94.4	10.1 3.2	63.6 49.2	82.4 62.4	87.8 68.4			96.7 86.7	97.5 87.5
Retain ⁵⁷ Fe only	2.14	81.3 80.5	81.4 97.6	92.9 99.0	92.6 99.4			98.6 99.8	98.5 99.9
Remove ⁹² Mo	85.8					90.0 25.5	89.3 25.6		
Remove ⁹⁴ Mo	90.9					-0.5 58.0	-0.5 58.1		
Remove ⁹² Mo and ⁹⁴ Mo	76.7					99.6 97.2	99.3 97.4		
Keep ⁹⁷ Mo and ⁹⁵ Mo	34.3					99.8 99.9	99.8 99.9		

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