Transmutation Effects in CTR Materials

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UWFDM-42

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FDM 42

I. Introduction

One of the largest differences between fission and fusion reactors is the energy spectrum of neutrons which bombard the reactor structural members. (See Figure 1). The higher energy neutrons of a fusion reactor have a much greater probability for producing both metallic and gaseous transmutation products than do the neutrons in a typical fission plant.

Metallic transmutation products can have a significant effect on the mechanical properties of most pure metals, especially if the new elements exceed the solubility limit in the host material. The precipitation of second phase particles along with solid solution hardening in general will increase the yield strength and decrease the ductility of most pure metals.

Gaseous products, namely hydrogen and helium have been known for a long time to adversely affect the ductility of metals. Helium tends to precipitate into bubbles which collect at dislocations or grain boundaries and thus promote premature fracture. This topic has been the subject of many reports and discussions of this data and will not be repeated here.

The object of this report is to calculate the transmutation rates for three potential CTR structural materials, 316 stainless steel, V-20Ti, and Nb-1Zr. The neutron spectra and structural design is that described at the Austin Meeting by the Wisconsin Design Group.

Calculational Procedure

The neutron spectra at various points throughout the UWCTR have been calculated using the ANISN computer code as reported at the Austin Meeting.[1] These spectra are for a stainless steel structural material. The reaction cross sections were taken from ENDF/B-III as processed by MACK[2]. When cross section information was not available in ENDF, BNL-325 was used. Titanium cross sections were obtained from ANL-7387. Equal amounts of the structural materials Nb-1Zr and V-20Ti were substituted for 316 SS to calculate the transmutation rates. The neutron spectra was not re-calculated with the new materials in place of 316 SS but it is felt that this will not affect the final numbers by more than 10%. Certainly the accuracy of our cross section values and calculation computer codes is much cruder than 10%.

Table I

Typical Chemical Analyses of Commercial Grade Materials
Parts Per Million by Weight

Element	316 Stainless Steel	Nb-1Zr	V-20Ti
Al	500	<20*	220
As	300*		
B	10	<1	<1
Co	500*	<10*	<10*
Cr	18%	<20*	<20*
Cu	1,000	<40*	<40*
Fe	Bal	<50*	100
Mn	2%	<20*	<20*
Mo	2%	<20*	<20*
Nb	500*	~987,000	<50*
Ni	14%	<10*	50*
P	200		
S	100*		
Si	.7%	<50	350
Ta	200*	<500	40*
Ti	100	40	~200,000
V	2,000	<20*	~795,000
Zr		~10,000	
C	600	40	150
H		6*	4*
N	100	35	150
O	<200	100	800

*Not Considered for this Work

It was decided to investigate the effect of typical impurities on the results of such calculations and Table I represents what are felt to be commercial purities of the three materials. The interstitial impurities (O, N, C, Si) vary from company to company, but the numbers in Table I are felt to be fairly representative. Those elements noted with an asterisk were not used for the calculations for various reasons ranging from low concentrations to lack of valid cross sections. Maximum values were used when limits are indicated.

The reactions considered for the three materials are listed in Table II and those not considered (which may be examined later) are listed in Table III. The isotopes of Mo, As, Co and S were left out because of the lack of cross sections. A large number of (n,γ) reactions were also ignored if the impurity concentration was small or the parent isotope has a low abundance. Finally, a large number of low abundance isotopes were neglected for (n,p) and (n,α) reactions.

The only calculations quoted here will be for the first wall which should be the limiting case in all the alloys considered. The transmutation rates are given in atomic parts per million/MW/m^2/year. We will refer to these production units as "amys." One can convert amy units to appm by multiplying by the wall loading and the time of irradiation in years. Results will be quoted throughout the paper in terms of what we consider the most severe conditions, 10 MW/m^2, and for more conservative wall loadings, 0.5 MW/m^2. The maximum irradiation time is considered to be 20 years.

Results

The complete listing of the transmutation rates for each alloy is given in Appendix A. A summary of the important metallic transmutation products is given in Table IV and Tables V and VI summarizes the gaseous production rates

Discussion of Specific Results

V-20Ti

The major metallic impurity change in V-20Ti is the amount of Cr produced from the $V^{51}(n,\gamma)$ reactions. The production rate of Cr is ~100 amys which means that operation at 10 MW/m^2 for 20 years will produce 1000 times the Cr originally present in the alloy as an impurity. Such a high wall loading could result in a 2% Cr concentration after 20 years of operation. The addition of Cr to V-Ti alloys

Table II

Transmutation Reactions Considered for These Calculations

Isotopic Abundance-%	Reaction	Important Isotope for 20 Year Plant
100	$Al^{27}(n,2n)$	Mg^{26}
"	$Al^{27}(n,p)$	Al^{27}
"	$Al^{27}(n,\alpha)$	Na^{24}
18.7	$B^{10}(n,\alpha)$	Li^{7}
Total	Cr(n,p)	15% V, 85% Cr
"	Cr(n,2n)	0.2% Ti, 99.8% V
"	$Cr(n,\alpha)$	98% Ti, 2% V
Total	Cu(n,2n)	Ni
"	Cu(n,p)	90% Ni, 10% Cu
"	$Cu(n,\alpha)$	Ni
Total	Fe(n,p)	25% Mn, 75% Fe
"	Fe(n,2n)	98% Mn, 2% Fe
"	$Fe(n,\alpha)$	90% Cr, 10% V
100	$Mn^{55}(n,p)$	Mn
"	$Mn^{55}(n,2n)$	Cr
"	$Mn^{55}(n,\alpha)$	Cr
100	$Nb^{93}(n,2n)$	33% Zr, 67% Nb
"	$Nb^{93}(n,p)$	Zr^{93}
"	$Nb(n,\alpha)$	Zr^{90}
Total	Ni(n,p)	82% Fe, 18% Ni
"	$Ni(n,\alpha)$	68% Mn, 28% Fe, 4% Co
100	$P^{31}(n,p)$	P
"	$P^{31}(n,\alpha)$	Si
Total	Si(n,p)	Si
"	$Si(n,\alpha)$	97% Mg, 3% Si
99.987	$Ta^{181}(n,p)$	Ta^{181}
"	$Ta^{181}(n,a)$	Hf^{178}
99.76	$V^{51}(n,\alpha)$	Cr^{52}
"	$V^{51}(n,p)$	V^{51}
"	$V^{51}(n,\alpha)$	Ti^{48}

Table II (cont.)

Isotopic Abundance-%	Reaction	Important Isotope for 20 Year Plant
51.46	$Zr^{90}(n,p)$	Zr^{90}
"	$Zr^{90}(n,2n)$	Y^{89}
"	$Zr^{90}(n,\alpha)$	Sr^{87}
11.23	$Zr^{91}(n,p)$	Zr^{91}
17.11	$Zr^{92}(n,p)$	Zr^{92}
"	$Zr^{92}(n,\alpha)$	Y^{89} (Sr^{89})
17.4	$Zr^{94}(n,p)$	Zr^{94}
"	$Zr^{94}(n,\alpha)$	Zr^{91}
98.892	$C^{12}(n,\alpha)$	Be^{9}
"	$C^{12}(n,n')$	$3\ He^{4}$
99.635	$N^{14}(n,p)$	C^{13}
"	$N^{14}(n,p)$	C^{14}
"	$N^{14}(n,\alpha)$	B^{11}
99.759	$O^{16}(n,p)$	O^{16}
"	$O^{16}(n,\alpha)$	C^{13}
Total	Ti(n,2n)	8% Sc, 92% Ti
"	Ti(n,p)	Ti
"	Ti(n,α)	21% Ca, 74% Sc, 5% Ti

Table III

Transmutations Reactions Not Considered for These Calculations

Isotopic Abundance-%	Reaction	Important Isotope for 20 Year Plant
100	$Al^{27}(n,\gamma)$	Si
100	$As^{75}[(n,\gamma),(n,p),(n,\alpha)]$	Se, Ge, As
18.7	$B^{10}[(n,p),(n,T)]$	Be, He
81.3	$B^{11}[(n,p),(n,\alpha),(n,\gamma)]$	B, He, C
100	$Co^{59}[(n,\gamma),(n,p),(n,\alpha)]$	Ni, Fe
4.31	$Cr^{50}(n,\gamma)$	V^{51}
2.38	$Cr^{54}(n,\gamma)$	Mn^{55}
Total	$Cu(n,\gamma)$	Zn
5.84	$Fe^{54}(n,\gamma)$	Mn^{50}
100	$Mn^{55}(n,\gamma)$	Fe^{56}
Total	$Mo[(n,\gamma),(n,p),(n,\alpha),(n,2n)]$	Tc, Ru, Zr, Y
100	$Nb^{93}[(n,np),(n,T)]$	Zr
1.16	$Ni^{64}(n,\gamma)$	Cu^{65}
100	$P^{31}(n,\gamma)$	S
Total	$Si(n,2n)$	Al, Si
Total	$S[(n,\gamma),(n,p)(n,\alpha)]$	Si, Cl
99.987	$Ta^{181}(n,\gamma)$	W^{182}
0.013	$Ta^{180}[(n,p),(n,2n),(n,\alpha)]$	Hf
0.24	$V^{50}[(n,p),(n,2n),(n,\alpha)]$	Ti
11.23	$Zr^{91}(n,\gamma)$	Sr^{88}
17.4	$Zr^{94}(n,\gamma)$	Mo^{95}
98.892	$C^{12}(n,p)$	C^{12}
	$C^{12}(n,2n)$	B^{11}
0.108	$C^{13}[(n,p),(n,\alpha)]$	C. Be
0.365	$N^{15}[(n,\ ),(n,p),(n,\alpha)]$	O, N, C
99.759	$O^{16}(n,2n)$	N^{15}
0.037	$O^{17}[(n,p),(n,\gamma)]$	O, C
0.204	$O^{18}[(n,\gamma),(n,p),(n,\alpha)]$	F, O, N

Table IV

Major Metallic Transmutation Reactions in

in Potential CTR Materials

	Element	Production Rate appm/MW/m^2/yr.	after 20 yrs. UWCTR Atomic %	% Change[a]	20 years at 10 MW/m^2 At. % of Alloy	% Change[a]
V-20Ti	V	- 162	-0.162	- 0.2	- 3.24	-5.18
	Cr	+ 99	+0.099	+260	+ 1.98	+5200
	Ti	+ 53	+0.053	+ 0.27	+ 1.06	+5.3
	Sc	+ 9.1	+0.0091	NA	+ 0.18	NA
Nb-1Zr	Nb	-1485	-1.485	- 1.48	-29.6	-29.5
	Zr	+1473[b]	+1.473	+147	+29.4	+2940
	Y	+ 11.7	+0.0117	NA	+ 0.234	NA
316 SS	Fe	-1224	-1.224	- 1.96	-24.5	-39.1
	Cr	+ 24	+0.024	+ 0.13	+ 0.48	+ 2.7
	Ni	- 177	-0.177	- 1.26	- 3.54	-25.3
	Mn	+1160	+1.160	+ 58.0	+23.20	+1150
	V	+ 177	+0.177	+ 80.0	+ 3.54	+1600
	Ti	+ 45	+0.045	+390	+ 0.9	+7800

(a)based on original composition

(b)no burn out included

NA-Not Applicable

Table V

Gas Production Rates in Potential CTR Materials

	appm/MW/m^2/year		appm in 20 Years 0.5 MW/m^2 UWCTR		10 MW/m^2	
Alloy	He	H	He	H	He	H
V-20Ti	71.8	219.3	718	2193	14,360	43,860
Nb-1Zr	36.2	113.8	362	1138	7,240	22,760
316 SS	278.7	636.5	2787	6365	55,740	127,300

Table VI

Major Contributors to Gas Production in Potential CTR Materials

Alloy	Host Metal	% Contribution: Major Alloying Agent	% Contribution: All Impurities
		HELIUM	
V-20Ti	88	6 (Ti)	6 (C-2.9%)
Nb-1Zr	96	0.3 (Zr)	3.7 (C-2.8%)
316 SS	72	16 (Cr) 2.3 (Ni)	9.7 (Si-4.5%) (C-3.3%)
		HYDROGEN	
V-20Ti	52	47 (Ti)	<1 (Si-0.3%)
Nb-1Zr	98	1 (Zr)	<1 (Si,N-0.2%)
316 SS	49	13(Cr) 34(Ni)	4 (Si-2.8%)

seems to have no adverse effects, in fact, it may even improve the tensile properties. Hence no particular problem is anticipated from the transmutations at wall loadings of 10 MW/m^2. The only other significant reaction is the production of Ti at the rate of 53 amys. However, since the alloy we considered is originally 20% Ti, such a production rate should have little significance. This would not be the case in pure vanadium where as much as 1% Ti could be produced in 20 years at 10 MW/m^2. The effect of titanium on mechanical properties of V is shown in Figure 2.[3]

A small amount of Sc is also produced at a rate of 9.1 amys, but even after 20 years at 10 MW/m^2 this could amount to no more than 0.2% Sc. No particularly adverse effects of this impurity are expected.

Table VI shows that the helium production rate in V-20Ti of 71.8 amys is predominantly due to V (87.6%). Titanium is an "underproducer" in the sense that 20% Ti only produces 6% of the helium. Another 6% or so comes from normal impurities in V-20Ti with carbon (2.1%) and oxygen (1.3%) the most notable.

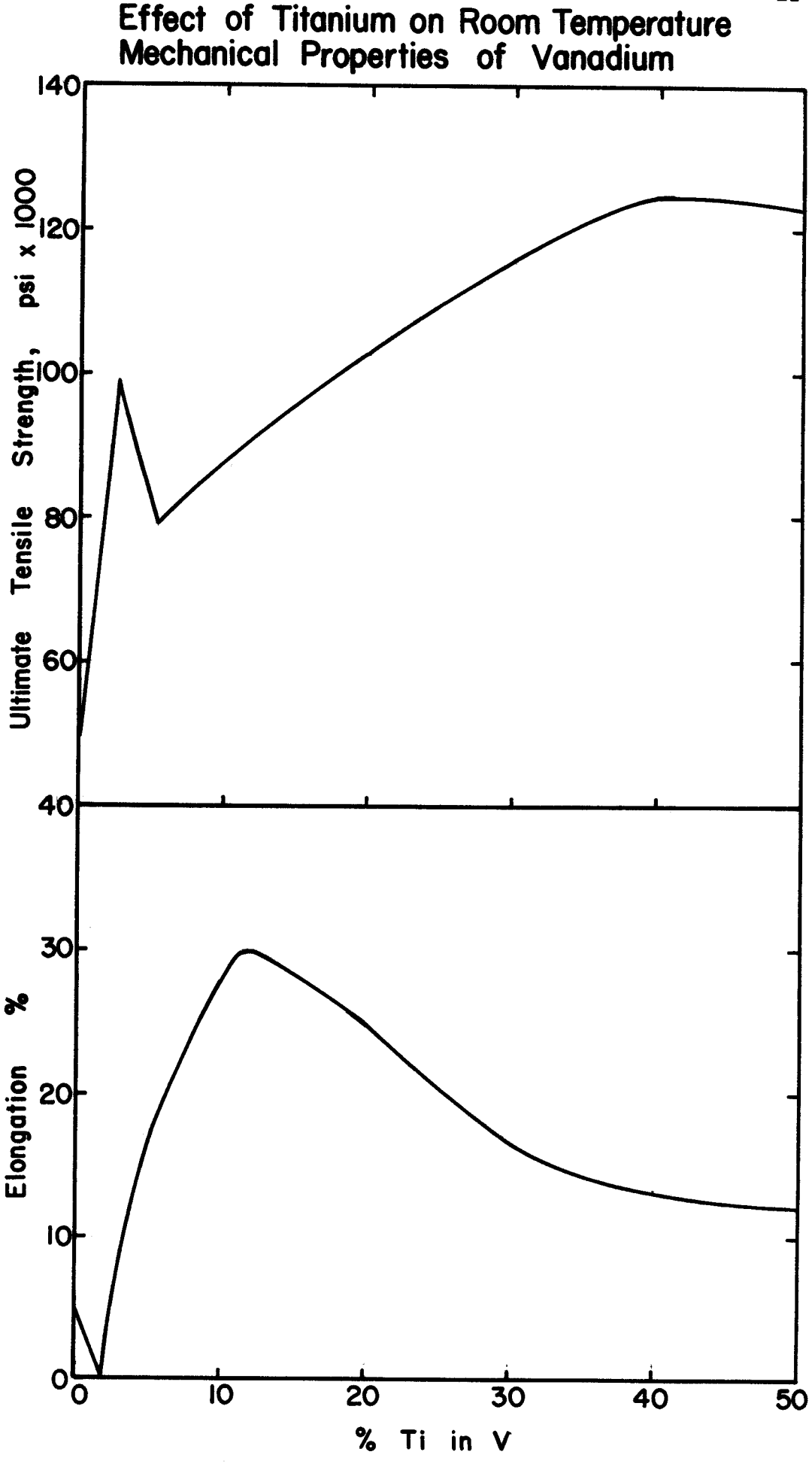
In contrast to its low importance as a helium producer, titanium is a major contributor to the hydrogen generation rate in this alloy. Approximately 47% of the total hydrogen production rate (219.3 amys) comes from the Ti atoms. Vanadium produces 52% of the hydrogen and less than 1% comes from the nominal impurities.

Nb-1Zr

The major feature of Nb-1Zr systems is the high production rate of Zr from Nb. The Zr comes from the ^{93}Nb(n,2n)^{92}Nb reaction when 1/3 of the ^{92}Nb atoms decay to ^{92}Zr by orbital electron capture with a half life of ~10 days. The production rate of ~ 1.5%/year at 10 MW/m^2 can have some serious consequences from a phase stability standpoint[4] as can be seen from Figure 3. The solubility of Zr in Nb is ~15% but recent conversations with metallurgists at Wah Chang indicate that second phase particles begin to form at 10% Zr. Therefore a Nb-1Zr wall could stand no more than a 3 MW/m^2 neutron wall loading for 20 years. (Assuming that the first wall is not changed in that time period.)

The mechanical properties of Nb-Zr alloys[5] are a function of Zr content as shown in Figure 4. The minimum ductility at 5% Zr is of concern, but the embrittlement due to helium atom generation (see below) is expected to over-shadow this effect. Finally, it should be noted that operation at 0.5 MW/m^2 for 20 years will only increase the Zr content by ~ 70% to Nb-1.7Zr. The mechanical properties of this alloy are

FIGURE 2


Effect of Titanium on Room Temperature Mechanical Properties of Vanadium
Ultimate Tensile Strength, psi x 1000
140
120
100
80
60
40
Elongation %
30
20
10
0
0
10
20
30
40
50
% Ti in V

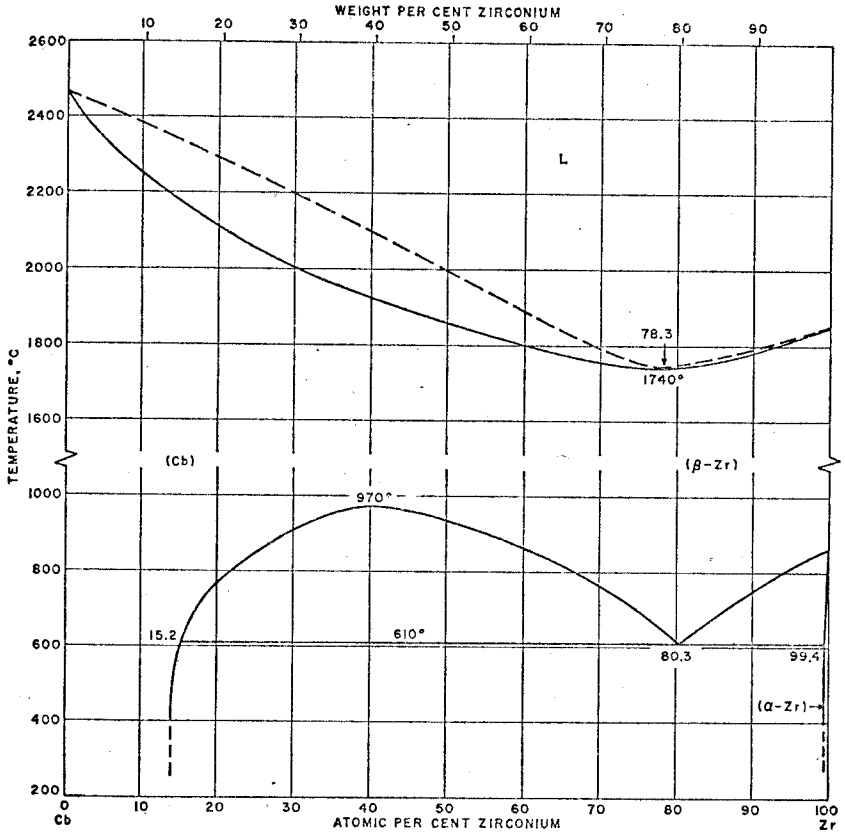
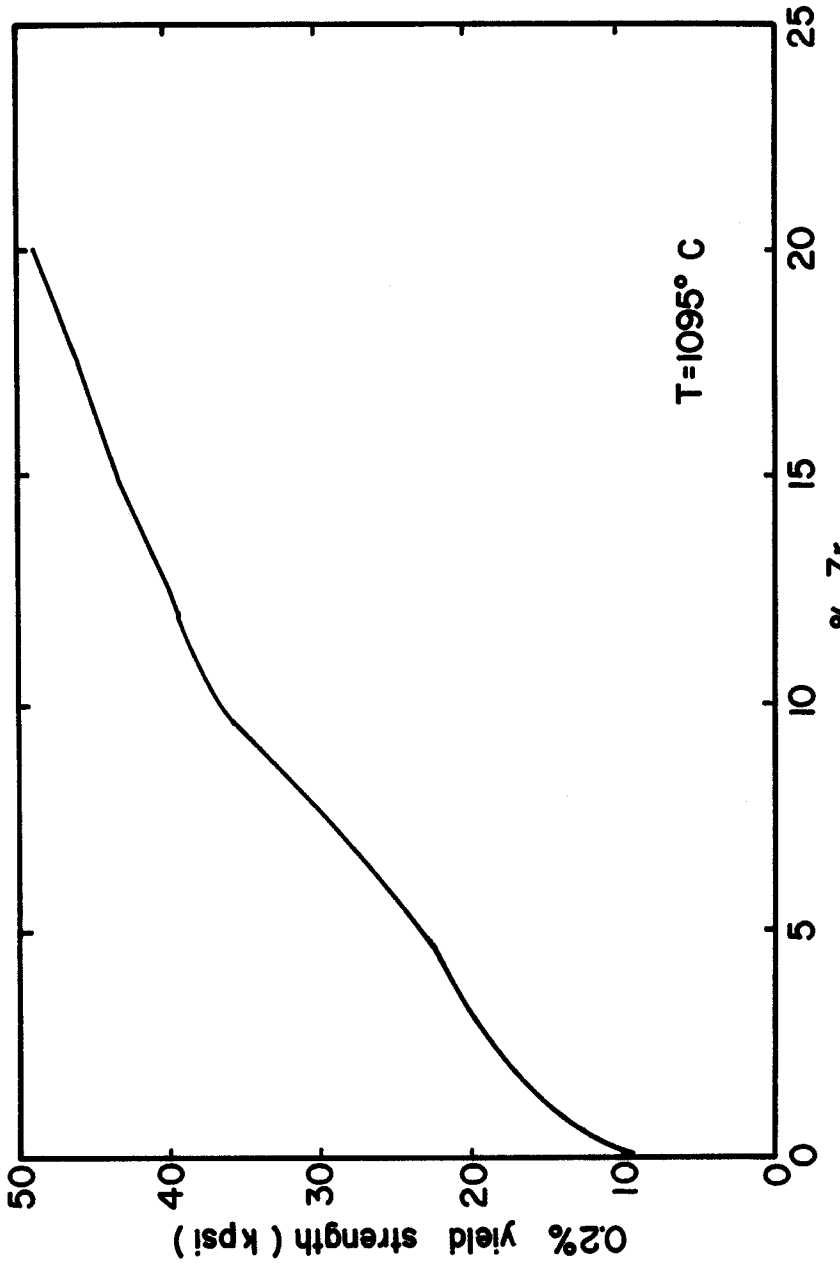
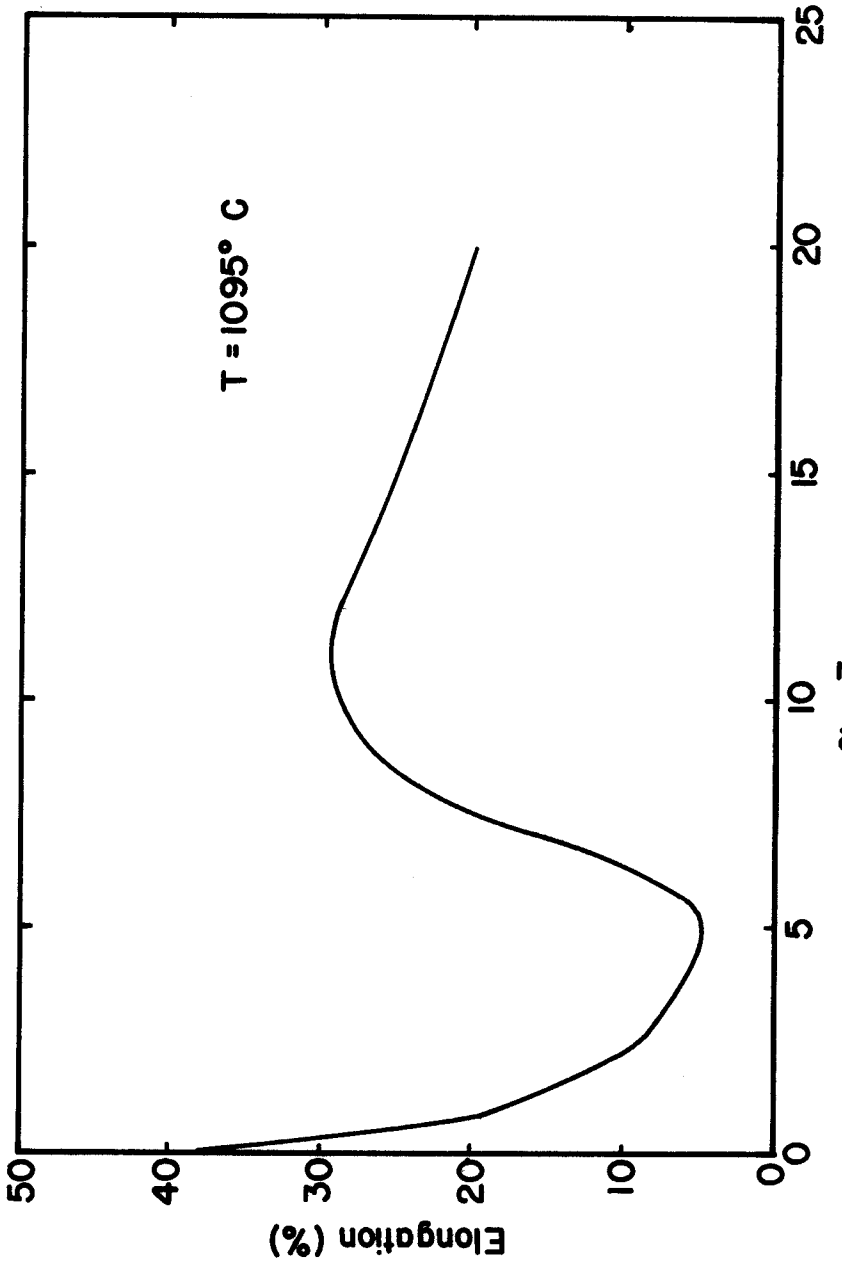


FIGURE 3 - Niobium-Zirconium Phase Diagram[4]



Effect of Zirconium on the Yield Strength of Niobium

FIGURE 4a



Effect of Zirconium on Ductility of Niobium

FIGURE 4b

similar to Nb-1Zr so that no particular problem would be envisioned.

The other important transmutation product in Nb-1Zr is Y which comes from (n,α) reactions with Zr. The production of Y at the rate of 12 amys should not present any problems even at 10 MW/m^2 for 20 years. This most severe case would only result in 0.3% Y in the alloy and it is expected that this amount would be completely soluble in Nb.

There is an interesting sidelight to the production of Y from Zr which we would like to call to the readers attention. Zirconium-92 can be converted to ^{89}Sr ($t_{1/2}$ = 51 days) by a (n,α) reaction. Because Sr isotopes have such a low MPC (maximum permissible concentration) in the environment, we decided to investigate the total number of curies of ^{89}Sr in the first wall.

The total activity from the original zirconium should saturate after a few hundred days to an amount predicted by the equation 1 below:

$$Ci(Sr^{89}) = A\, f_{Zr} f^{i}_{Zr}92 M \int_{E_{th}}^{14\ MeV} \sigma_{\alpha}(E)\phi(E)dE \qquad (1)$$

where A = constant to convert dps to curies and to take into account volume of first wall

f_{Zr} = fraction of Zr in original Nb alloy

$f_{Zr}92$ = isotope abundance of Zr^{92} (17.11%)

M = wall loading in MW/m^2

$\sigma_{\alpha}(E)$ = energy dependent (n,α) cross section for Zr^{92}

$\phi(E)$ = neutron energy spectra per MW/m^2

E_{th} = threshold for $Zr^{92}(n,\alpha)\ Sr^{89}$ reaction

Equation 1 does <u>not</u> take into account the ^{89}Sr which comes from the ^{92}Zr produced by the (n,2n) reaction with ^{93}Nb. When this source is included and the neutron energy spectra, various cross sections and total wall volume ($9.6 \times 10^6 cm^3$) is inserted in equation 1, the total number of curies of ^{89}Sr in the Nb-1Zr first wall is,

$$Ci(^{89}Sr) = 1.51 \times 10^4\ M[1.71 + 1.24\ tM] \qquad (2)$$

where t is the irradiation time in years

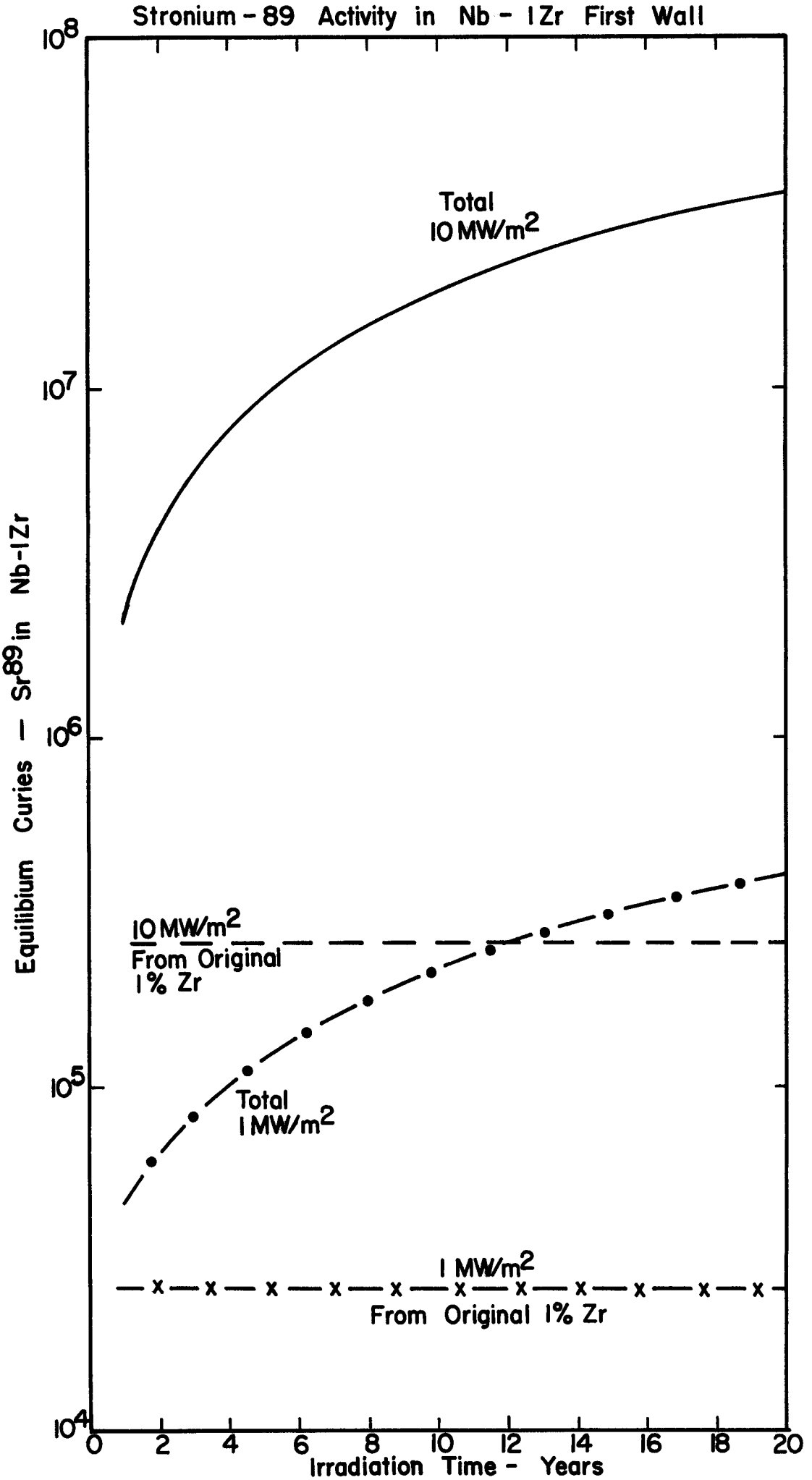

Stronium - 89 Activity in Nb - 1Zr First Wall
Equilibium Curies - Sr^{89} in Nb-1Zr
10^8
10^7
10^6
10^5
10^4
Total
10 MW/m2
10 MW/m2
From Original
1% Zr
Total
1 MW/m2
1 MW/m2
From Original 1% Zr
0
2
4
6
8
10
12
14
16
18
20
Irradiation Time - Years

FIGURE 5

It should be noted from equation 2 that at high wall loadings and long irradiation times, the activity of ^{89}Sr goes as M^2. This is because ^{92}Zr is being produced at such a high rate that it quickly exceeds the original amount of ^{92}Zr (0.171%) in the Nb-1Zr.

The total activity of ^{89}Sr in the Nb-1Zr first wall is plotted in Figure 5 where the case for M=1 and 10 MW/m^2 is shown. In both cases, it is noted that most of the ^{89}Sr activity does not come from the original Zr in the alloy but rather from that Zr produced by the Nb(n,2n) reactions. Hence the results quoted here are characteristics of all Nb alloys.

The surprising feature of this exercise is that at 10 MW/m^2, the activity of ^{89}Sr in the first wall is 4×10^7 curies, comparable to that of the tritium in the system. Furthermore, the MPC of ^{89}Sr is almost 1000 times smaller than that for tritium.

The comparison in Table VII may help the reader assess the importance of the reaction. We have used the same format as Steiner (Nuclear Safety,13,353,1972) in quoting the Biological Hazard Potential as the activity - MPC for airborn activity. We have also included ^{95}Nb to show that ^{89}Sr is not the only isotope to consider from a hazards standpoint. The fusion reactor numbers correspond to the Wisconsin system and the fission numbers come from Steiner. There are three major points to note in Table VII. First, the total BHP (Biological Hazard Potential) for the UWCTR operated at 0.5 MW/m^2 wall loading for 10 years is only 1% of that for a fission reactor. Secondly, the BHP of the ^{95}Nb and ^{89}Sr is many times greater than that for the tritium in the same system. Third, since both ^{95}Nb and ^{89}Sr are formed by successive capture reactions, the level after a few years is proportioned to M^2. The values for a 10 MW/m^2 and 5000 MW (th) plant are also shown in Table VII. In this extreme case it can be seen that the total BHP is comparable to a fission system.

We think that the M^2 dependence of potentially dangerous isotopes should be emphasized. We have not examined every potential CTR material for this effect but certainly in a Nb system, the M^2 dependence is a good reason for operating at lower wall loading for given power levels.

There is one obvious response to the observations we have just made; and that is; "the ^{89}Sr and ^{95}Nb is tied up in the solid structural material and therefore could not be released to the environment in the event of an accident." If we dismissed, for the time being, the possibility of a lithium fire in which Nb oxide would be formed and carried away, we still must face the amount of activity in the Li due to corrosion of the first wall. Calculations reveal that the activity in th the Li is 10^{-3} of that in Table VII. Such numbers assume a 0.0025 cm/year corrosion rate and that isotopes such as ^{95}Nb and ^{89}Sr would be present in such small amounts (·10 appm) in the Li that effective removal could not take place. A complete burn of the Li in a CTR under the most severe conditions (10MW/m^2) would then

Table VII

Radioactive Inventories in UWCTR Nb-1Zr
First Wall after 20 Years

Isotope	Activity Ci/kW_t	MPC[a] $\mu Ci/cm^3$	Biological Potential Hazard = Activity ÷ MPC, $(km^3$ of air$)/kW_t$
		UWCTR	
^{3}H	60	2×10^{-7}	0.3
^{95}Nb	30[b]	3×10^{-9}	10
	2020[c]	3×10^{-9}	670
^{89}Sr	0.11[b]	3×10^{-10}	0.37
	7.4[c]	3×10^{-10}	25
		Fission Reactor	
^{131}I	31.6	1×10^{-10}	330
^{239}Pu	0.06	6×10^{-14}	1,000

a. AEC-Part 20, December 1968
b. 0.5 MW/m^2, 1140 MWt
c. 10 MW/m^2, 5000 MWt

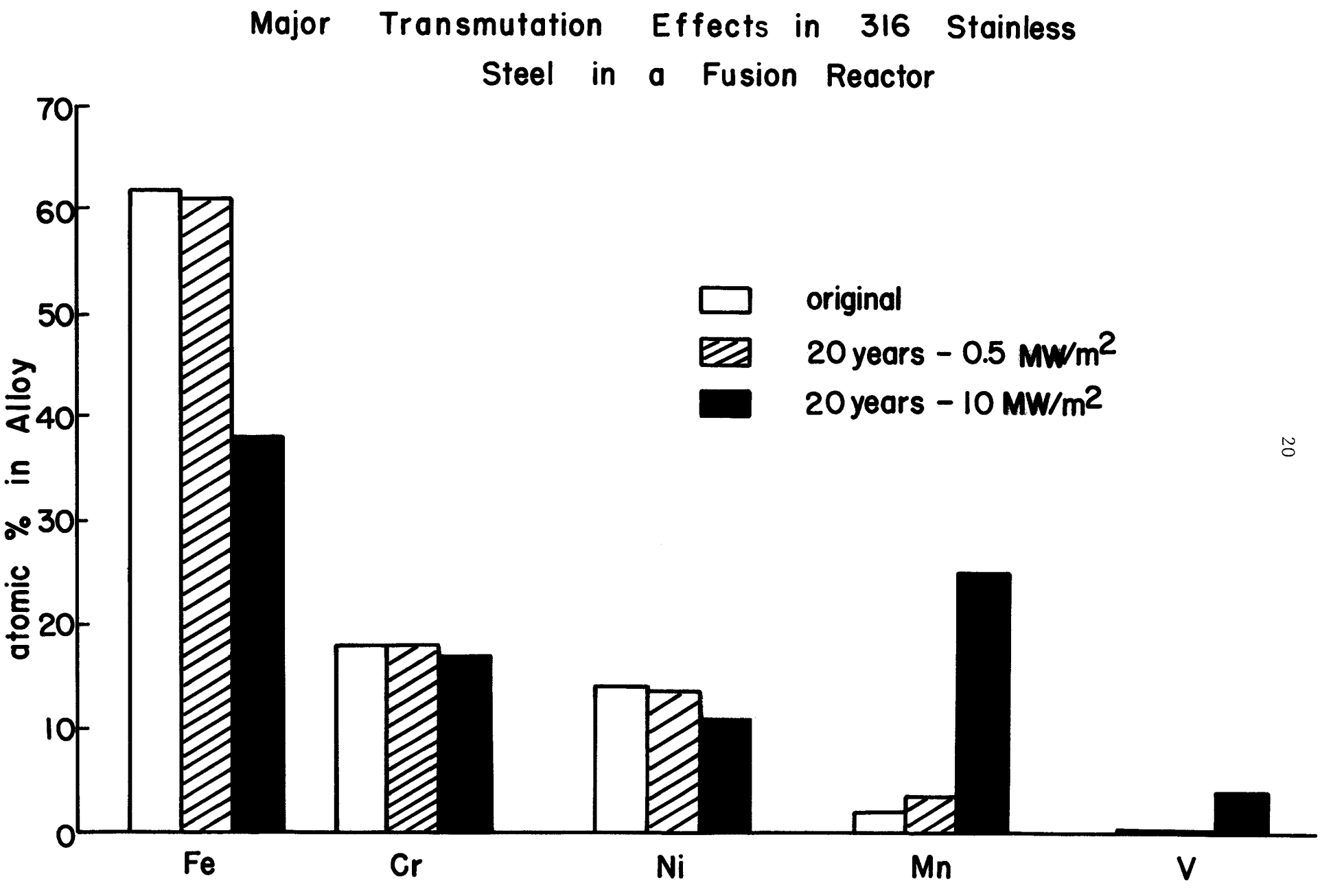

Major Transmutation Effects in 316 Stainless Steel in a Fusion Reactor
atomic % in Alloy
70
60
50
40
30
20
10
0
original
20 years - 0.5 MW/m2
20 years - 10 MW/m2
Fe
Cr
Ni
Mn
V

FIGURE 6

release 10^7 curies of ^{95}Nb and 4 x 10^4 curies of ^{89}Sr. Under th3se circumstances and taking into account the differences in MPC, the hazard with ^{89}Sr and ^{95}Nb would be twice that of releasing of the tritium. This hazard would remain for only the first month or two, but it is serious enough to warrant further investigation. The point which we wish to make here is that we have just considered a few isotopes and on the basis of a few simplifying assumptions, have been able to show cause for concern. How many other isotopes are there that we haven't considered? We hope to spend some time on this subject in the future.

The helium production rate in Nb-1Zr of 36 amys is the lowest of the three alloys considered here. Most of the helium comes from the Nb (96%) but again, a disproportional amount comes from the carbon in the alloy. Table V shows that even though the helium production rate is low, there could be 362 appm in the alloy after 20 years at 0.5 MW/m^2. This number would grow to ~7000appm for 20 years at 10 MW/m^2. Such levels of helium would be quite detrimental to the ductility of the alloy.

The hydrogen production rate is also the lowest in Nb-1Zr. The production rate of ~114 amys would produce ~1100 appm H at 0.5 MW/m^2 for 20 years, most of which will probably diffuse out of the alloy. The effect of Zr on the hold up of hydrogen, as well as the effect of hydrogen on the room temperature ductility of the first wall during shut down, must be assessed before we can dismiss hydrogen embrittlement.

316 Stainless Steel

The interesting feature of the complex alloy 316 SS is that its major constitutents (Fe, Cr, Ni, and Mn) tend to transmute to each other. Table IV shows that iron is "burned up" at the rate of 1224 amys and Ni is lost at the rate of 177 amys. Operation for 20 years is the UWCTR produces a total loss of ~1.2% of the iron and ~0.2% of the nickel. The reaction products are Cr(+0.02%), Mn(+1.6%), V(+0.177%) and Ti(+ 0.45%). The changes in Fe, Ni and Cr are minimal in the 0.5 MW/m^2 system and will present no problem from a metallic transmutation standpoint.

The situation is considerable different for a 10 MW/m^2 wall loading as shown in Table IV and illustrated in Figure 6. The total iron composition drops from 62.6% to ~38% after 20 years while the manganese content raises from 2% to ~25%. (No burn up of the transmutation products is included in this calculation). The chromium content is almost unaffected, even at this high wall loading, while the Ni content drops from 14% to ~10.5%. The amount of V is increased by ~1600% over its original concentration to 3.5% and the Ti concentration is increased by 7800% to 0.9%.

The effect of such wide composition changes is difficult to assess at this time because of the high Mn content. In all other respects, the composition of 316 SS after 20 years at 10 MW/m^2 is similar to a 200 series stainless steel with high amounts of Ti and V to control the carbon in the alloy. There may be some concern over the loss of the austenizing agent Ni but the high Mn content more than offsets this effect. It is expected that an alloy of the composition indicated in Figure 6 would be even a more stable form of austenitic (non-magnetic) than the original 316 SS. The only concern here is the very high Mn content and we have not been able to locate such an alloy in the literature to see if it has any adverse properties. Therefore, even though there are large changes in metallic composition, there is no apparent limit (<10 MW/m^2) on the wall loading for a 20 year stainless steel fusion plant.*

The situation with respect to gaseous transmutation products is not so optimistic. Table V shows that 316 SS has the highest helium and hydrogen production rates in a CTR spectrum of any of the three alloys considered. The high helium production comes from Fe(72%), Cr(16%), Si(45%), C(3.3%), Ni(2.3%) and ~2% from other impurities (Table VI). The major isotopic contributor is ^{56}Fe for which we have only calculated (n,α) cross sections available in the ENDF files. It is also interesting to note that almost 10% of the helium in 316 SS comes from the "impurities" in the alloy. The Si and C content are especially critical and should be closely watched in the future. It must also be pointed out that no $(n,n\alpha)$, (n,np), etc. reactions were considered nor was the $^{58}Ni(n,\gamma)^{59}Ni(n,\alpha)^{56}Fe$ reaction. This latter reaction is noted for its helium production in thermal and fast fission reactors and could take on added importance farther back in the blanket. Investigation of this effect is underway.

The severity of the situation can be seen by noting that even at the 0.5 MW/m^2 wall loading, the helium is being produced at ~140 appm/year. Ductility values of <1% have been observed at helium concentrations (associated with displacement damage) of 3-30 appm. If a 1% uniform elongation limit is placed on the first wall, then we might say that the ductility limit would be reached in a few months of operation at 0.5 MW/m^2. (We won't even consider the 10 MW/m^2 case). More information on the effect of helium on the ductility of steel is obviously required but the situation does not appear to be favorable even if we are off by a factor of 10 and can stand 300 appm helium in the metal. The time limitation in this very optimistic case is ~2 years for a 0.5 MW/m^2 loading. The solution may be to change the wall at that time or lower the wall loading to 0.05 MW/m^2 for 20 year operation (a wholly unsatisfactory solution from an economic standpoint).

*It should be noted that if we had included neutron reactions with Mn, the major transmutation product would be Cr from the high (n,2n) cross section.

Conclusions

The following conclusions can be drawn from the standpoint of only metallic transmutations in the three alloys considered.

1. Vanadium-20Ti seems to present no problems <10 MW/m^2.

2. Type 316 SS undergoes no significant change at 0.5 MW/m^2 but is considerably altered at 10 MW/m^2. The production of ~25% Mn may even enhance the stability of the austenite phase, but it is not recommended that a wall loading of 10 MW/m^2 be exceeded because of uncertainties in the Mn solubility.

3. Nb-1Zr is definitely limited to <3 MW/m^2 by the generation of Zr which would exceed the 10-15% solubility limit in Nb. A potential problem with ^{89}Sr as a transmutation product should be investigated more closely and the total Biological Hazard Potential of Nb alloys is of some concern.

The situation with respect to gaseous transmutation products can be summarized as follows.

1. Nb-1Zr has the lowest helium and hydrogen generation rates with V-20Ti higher by a factor of 2 and 316 SS by a factor of 6-8.

2. On the basis of available data for 316 SS, wall loading should not exceed ~0.05 MW/m^2 and may even have to be a factor of 10 lower if ~1% ductility is to be retained.

3. Interstitial impurities such as O, N, C, and Si can contribute up to 10% of the He in 316 SS.

4. No wall loading limit on V or Nb alloys can be made because of a lack of data, but is not expected that they would be higher than 0.2 MW/m^2 for V-20Ti and 0.4 MW/m^2 for Nb-1Zr.

Recommendations for Future Work

1. A more detailed consideration of the reactions in Table III to see if they significantly change any of the conclusions of this work.

2. There is a need for more cross section data on those isotopes that could not be treated here, and experimental checks on the calculated gas production cross section in ENDF should be made.

3. A consideration of the thermal (n,α) cross section for ^{59}Ni and its effects in a CTR is required.

4. The inclusion of (n,n'p),(n,αn'),etc. reactions in these reactions and estimates of what they might contribute to the overall gas production rates should be made.

5. A more detailed consideration is required of the radioisotopes with low MPC and the ways in which they could reach the environment around a CTR.

6. More data on what effect helium and hydrogen have on the ductility and void swelling characteristics of potential CTR materials is desperately needed.

Acknowledgements

The authors would like to thank Dr. D. Klein and Professor R. W. Conn for their helpful comments and criticisms.

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APPENDIX A

Summary of the Transmutation Reactions

in

V-20Ti, Nb-1Zr and 316 Stainless Steel

Table A-1

Summary of Transmutations in V-20Ti

Element	Original Concentration-appm	appm/Mw/m^2/yr New	Burned Up	Net Change
V	~795,000	114.9	276.9	-162
Ti	~200,000	233	180	+ 53
Al	415	0.1	0.4	-0.3
B	5	0.3	0.1	+0.2
Cr	20	99.1	N	+99.1
Fe	100	N	0.2	-0.2
Mn	20	0.2	N	+0.2
Si	640	0.8	1.3	-0.5
C	640	1.8	1	+0.8
N	550	N	0.7	-0.7
O	2550	0.4	1.7	-1.3
Be	N	0.4	N	+0.4
Ca	N	0.9	N	+0.9
Mg	N	0.6	N	+0.6
Na	N	0.2	N	+0.2
Sc	N	9.1	N	+9.1

N = Not reported or negligible

Table A-2

Summary of Gas Production Rates in V-20Ti (First Wall)

From	Original Concentration Of Parent Alloy-appm	appm/MW/m^2/yr He	appm/MW/m^2/yr H	Atomic % He	Atomic % H
V	795,000	62.9	114.9	87.6	52.4
Ti	200,000	4.4	102.8	6.1	46.9
O	2,550	1.3	0.4	1.8	0.2
C	640	2.1	N	2.9	N
N	550	0.3	0.4	0.4	0.2
Si	640	0.5	0.7	0.7	0.3
Al	415	0.3	0.1	0.4	N
	Total	71.8	219.3		

N = negligible, <0.1 amy.

Table A-3

Summary of Transmutations in Nb-1Zr

Element	Original Concentration appm	appm/MW/m^2/year New	Burned Up	Net Change	
Nb	987,000	2706	4191	-1485	
Zr	10,000	1486	13.1	+1473	(a)
B	9	0.1	N	+0.1	
Si	165	0.2	0.3	-0.1	
Ti	200	0.2	0.2	---	
C	310	0.4	0.5	-0.1	
N	230	N	0.3	-0.3	
O	580	0.1	0.4	-0.3	
Mg	N	0.1	----	+0.1	
Y	N	11.7	----	+11.7	

N = Negligible

a) Zr^{92}, no burn out included

Table A-4

Summary of Gas Production in

Nb-1Zr First Wall Material

From	Original Concentration appm	appm/MW/m^2/year		Atomic Percent	
		He	H	He	H
Nb	987,000	34.6	112	95.9	98.4
Zr	10,000	0.1	1.3	0.3	1.1
N	230	0.1	0.2	0.3	0.2
O	580	0.3	0.1	0.8	0.1
C	310	1.0	N	2.8	N
Si	165	0.1	0.2	0.3	0.2
		36.2	113.8		

N = Negligible

Table A-5

Summary of Major Metallic Transmutation Rates in 316 Stainless Steel

Element	Original Concentration appm	appm/MW/m^2/year New	Burned Up	Net Change
Fe	626,000	253	1,477	-1,224
Cr	180,000	296	272	+ 24
Ni	140,000	44	221	- 177
Mn	20,000	1,213	53	+1,160
Si	14,950	18	30	- 12
Cu	1,000	0.4	6	- 5.6
Al	1,030	0.3	0.9	- 0.6
B	52	0.2	0.3	- 0.1
Co	500	0.3	N	+ 0.3
Nb	300	0.8	1.3	- 0.5
P	360	0.2	0.3	- 0.1
Ti	115	45.1	N	+ 45.1
V	2,200	177.5	0.8	+ 176.7
C	2,800	0.7	4.1	- 3.4
O	400	0.1	0.5	- 0.4
N	400	-	0.5	- 0.5
Be	N	1.6	N	+ 1.6
Mg	N	12.3	N	+ 12.3
Na	N	0.5	N	+ 0.5
Zr	N	0.5	N	+ 0.5

N = Negligible

Table A-6

Summary of Gas Production in 316 Stainless Steel

From	Original Concentration appm	appm/MW/m^2/year He	appm/MW/m^2/year H	Atomic % He	Atomic % H
Fe	626,000	201	310	72.1	48.7
Cr	180,000	44.8	81.9	16.1	12.9
Ni	140,000	6.5	214	2.3	33.6
Mn	20,000	2.6	8	0.9	1.3
Si	14,950	12.6	17.6	4.5	2.8
N	400	0.2	0.3	0.1	N
O	400	0.4	0.1	0.1	N
C	2,800	9.3	N	3.3	N
B	52	0.3	N	0.1	N
Al	1,030	0.5	0.3	0.2	N
V	2,200	0.2	0.3	0.1	N
Cu	1,000	0.1	3.8	N	0.6
P	360	0.2	0.2	0.1	N
		278.7	636.5		

N = Negligible