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THE RESPONSE OF ISSEC PROTECTED FIRST WALLS TO DT AND DD PLASMA NEUTRONS

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ABSTRACT

It has been demonstrated that the displacement damage and gas production rates can be reduced in CTR first walls by employing passive carbon shields. Reductions in displacement damage range from 3 to 5 for 12.5 cm shield thickness and from 7 to 14 in gas production rates with the same carbon thickness. The factors of reduction are 8 to 20 for the displacements and 17 to 80 for the gas production if a 25 cm shield is used. Depending on whether the isotopes causing the radioactivity are produced as a result of fast or thermal neutron activation, the first wall radioactivity can either go up or down with the increasing carbon shield thickness. It has been found that at shutdown radioactivity in 316 SS, Al, and Nb first walls is reduced with increasing carbon thickness while the activities in V and Ta is increased. Long term radioactivity displays the same trends in Al, 316 SS and Ta as short term radioactivity. However, the long term activity in Nb increases and that in V decreases with increasing shield thickness.

It has also been found that systems operating on a D-D plasma cycle have higher displacement rates than respective D-T cycle systems. Gas production rates are slightly lower in D-D systems except for He production in 316 SS. This is due to the higher Ni^{59} (n,α) cross sections for thermal neutrons.

INTRODUCTION

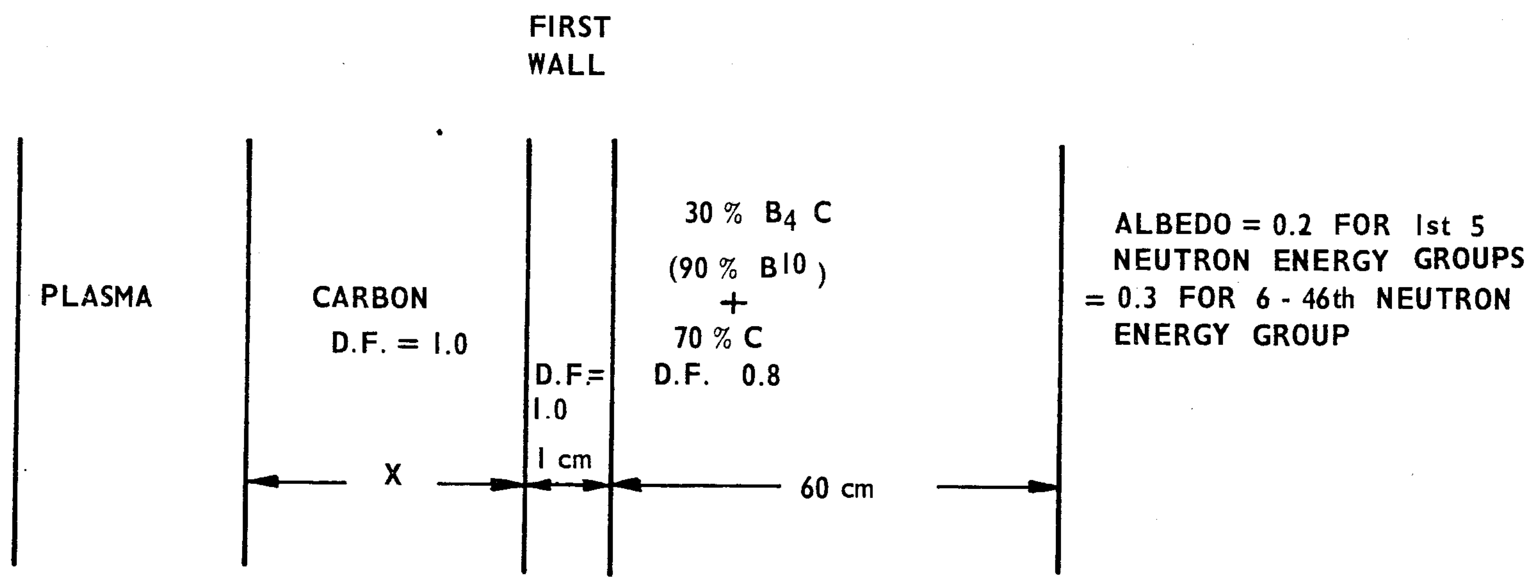
The use of passive carbon shields to protect the plasma and the metallic first walls of a fusion reactor has been recently proposed.[1,2] Carbon curtains were shown to reduce the plasma energy losses due to impurity atom buildup, while at the same time protecting the first wall from erosion due to plasma ion induced blistering and sputtering. It was also demonstrated that increasing the thickness of the curtain degrades the neutron spectrum sufficiently such that displacement damage and gas production rates are reduced in various CTR first wall materials.[3] The latter study revealed that short and long term radioactivities may either go up or down with increasing shield thickness depending on whether the activity is produced by thermal or high energy neutrons. The general concept was given the acronym ISSEC, for Internal Spectral Shifter and Energy Converter.[2]

Temperature and heat transfer characteristics of ISSECs have also been extensively analyzed in a previous paper.[4] It was shown that an upper temperature of about 2000°C would be imposed on the graphite ISSEC because the vapor pressure of graphite at this temperature becomes comparable to the pressure in the vacuum chamber, i.e. $\sim 10^{-5}$ torr. Two separate ideas have been developed as a result of these studies; the full ISSEC and the partial ISSEC. In the case of full ISSEC, the carbon extends all the way around the plasma and the plasma is never exposed directly to the first wall. In the partial ISSEC concept, carbon is used to protect only the inner blanket, nearest to the axis of a Tokamak where access and maintenance is most difficult. It was also shown that 2000°C maximum temperature would limit the full ISSEC thickness to ~6 cm and partial ISSEC thickness to ~30 cm at 1 MW/m^2 neutron wall loading and 10 $watts/cm^2$ surface heat load in a Tokamak reactor operating on a D-T plasma cycle.

The purpose of this paper is to expand the ISSEC concept to reactors operating with a D-D plasma and to compare the results with the D-T fuel cycle. We will not discuss this concept of internal tritium breeding as this is treated elsewhere.[2]

CALCULATIONAL PROCEDURES

The one dimensional-homogeneous blanket design used for this work is shown in Figure 1. A variable thickness carbon zone was placed between the plasma and the first wall. A density factor (D.F.) of 1.0 was used for the neutronic calculations although in practice a D.F. of ~0.7 would be more reasonable and would result in a thicker ISSEC region. However, the neutron "optical" thickness would be the same in both cases. The first wall thickness of 1 cm at a D.F. of 1.0 is intended to cover most reactor design cases. Again, lower D.F.'s and increased thickness would be used in practice to include coolant (which we assumed to be helium gas) and void spaces. The first wall is followed by a 60 cm thick reflector-



D.F. = DENSITY FACTOR.

FIG. 1 MODEL BLANKET DESIGN USED TO STUDY THE EFFECT OF GRAPHITE SPECTRAL SHIFTER ON THE RADIATION DAMAGE PARAMETERS IN THE FIRST WALL.

shield region composed of 30% B_4C (enriched to 90% B-10) and 70% carbon. An albedo of 0.2 was used to simulate the final shield for the first five neutron energy groups (9 to 14.9 MeV) and an albedo of 0.3 was used for neutrons of lower energy. Obviously, no attempt was made to breed tritium in this reactor design but only to highlight the anticipated structural materials responses to the degraded neutron spectra.

The nuclear performance of this type of reactor design was studied by solving the discrete ordinates form of the neutron transport equation for a slab using the ANISN[5] program with a S_4-P_3 approximation. It has been shown elsewhere[6] that this approximation is adequate to predict integral parameters such as tritium breeding and gas production rates to within approximately 2% of a higher order calculation like the S_{16}-P_5. The neutron multigroup cross sections (except for gas production in molybdenum) were processed using the program SUPERTOG[7] from nuclear data in ENDF/B3.[8] Gas production cross sections for Mo were calculated by Pearlstein.[9] The displacement cross sections were calculated from a computer code developed by Doran[10,11] and the values used in these calculations are given in Appendix A. All calculations were performed using 46 energy groups.

The reactions considered for the radioactivity calculations, along with appropriate branching ratios and half lifes are given in reference 3, The radioactivity and appropriate decay factors for 316 SS were calculated using a special computer program developed at the University of Wisconsin.[12] The composition of 316 SS was assumed to be 70% Fe, 18% Cr and 12% Ni for all calculations except radioactivities.

All the calculations are done for two different reactors operating with deuterium-tritium (D-T) and deuterium-deuterium (D-D) plasma cycles. The blanket structure shown on Figure 1 was used for both calculations. All the results are normalized to 1 MW/m^2 of neutrons passing through the first wall (or inner ISSEC surface). In D-D case, it is assumed that all the tritium that is produced through one branch of the D-D fusion reaction is consumed in the reactor, As a result, the energy of 50% of the neutrons generated in D-D plasma is 14.1 MeV and the energy of the outer half is 2.45 MeV. In the D-T case, all neutrons are of 14.1 MeV energy. With this assumption in mind, we can calculate the incident neutron fluxes corresponding to the 1 MW/m^2 neutronic wall loading in the two cases. In the D-T case,

$$(14.1\ \frac{\text{MeV}}{\text{n}})(1.602\text{x}10^{-19}\ \frac{\text{MW-sec}}{\text{MeV}})(4.43\text{x}10^{13}\ \frac{\text{n}}{\text{cm}^2\text{-sec}})(10^4\ \frac{\text{cm}^2}{\text{m}^2})=1\ \frac{\text{MW}}{\text{m}^2}(\text{neutronic})$$

In the D-D case,

$$(\frac{14.1+2.45}{2}\ \frac{\text{MeV}}{\text{n}})(1.602\text{x}10^{-19}\ \frac{\text{MW-sec}}{\text{MeV}})(7.56\text{x}10^{13}\ \frac{\text{n}}{\text{cm}^2\text{-sec}})(10^4\frac{\text{cm}^2}{\text{m}^2})=1\ \frac{\text{MW}}{\text{m}^2}(\text{neutronic})$$

The incident flux required to give a 1 MW/m^2 neutronic wall loading is 4.43×10^{13} n/cm^2-sec for the D-T reaction and in the D-D case, it is 7.56×10^{13} n/cm^2-sec, (3.78×10^{13} n/cm^2-sec of 14.1 MeV and 3.78×10^{13} n/cm^2-sec of 2.45 MeV neutrons).

RESULTS AND ANALYSIS

Reduction of Displacement Damage

Typical 316 SS first wall neutron spectra for D-T and D-D plasma cases with 0, 12.5 cm and 25 cm ISSEC thicknesses are tabulated and plotted in Appendix B. The combination of such neutron spectra with displacement cross sections in Appendix A yield the displacement rates listed in Table 1 and displayed in Figures 2 to 4.

The reader should be cautioned that it is the relative and not absolute rates of damage which are important. This is because one can not accurately compare one element with another on dpa values alone; the homologous temperature of irradiation has as much or more influence on the final damage state as does the total damage level.

A few interesting observations can be made from Table 1. For the same neuron wall loading, even though the number of 14.1 MeV neutrons incident on the first wall from the D-D plasma is approximately 85% as much as from a D-T plasma, the displacement rates are higher in D-D systems by 20-35%. The reason for this is that (1) the 2.45 MeV neutrons will cause considerable displacement damage compared to 14.1 MeV neutrons (~80% as much despite the factor of 6 difference in energy) and (2) more total neutrons (~70%) are requred to achieve a neutronic wall laoding of 1 MW/m^2. However, the <u>relative</u> effect of the ISSEC in reducing displacement damage is about the same.

It is also observed that the ISSEC has a greater effect in reducing the displacement damage in high Z elements as compared to low Z elements.

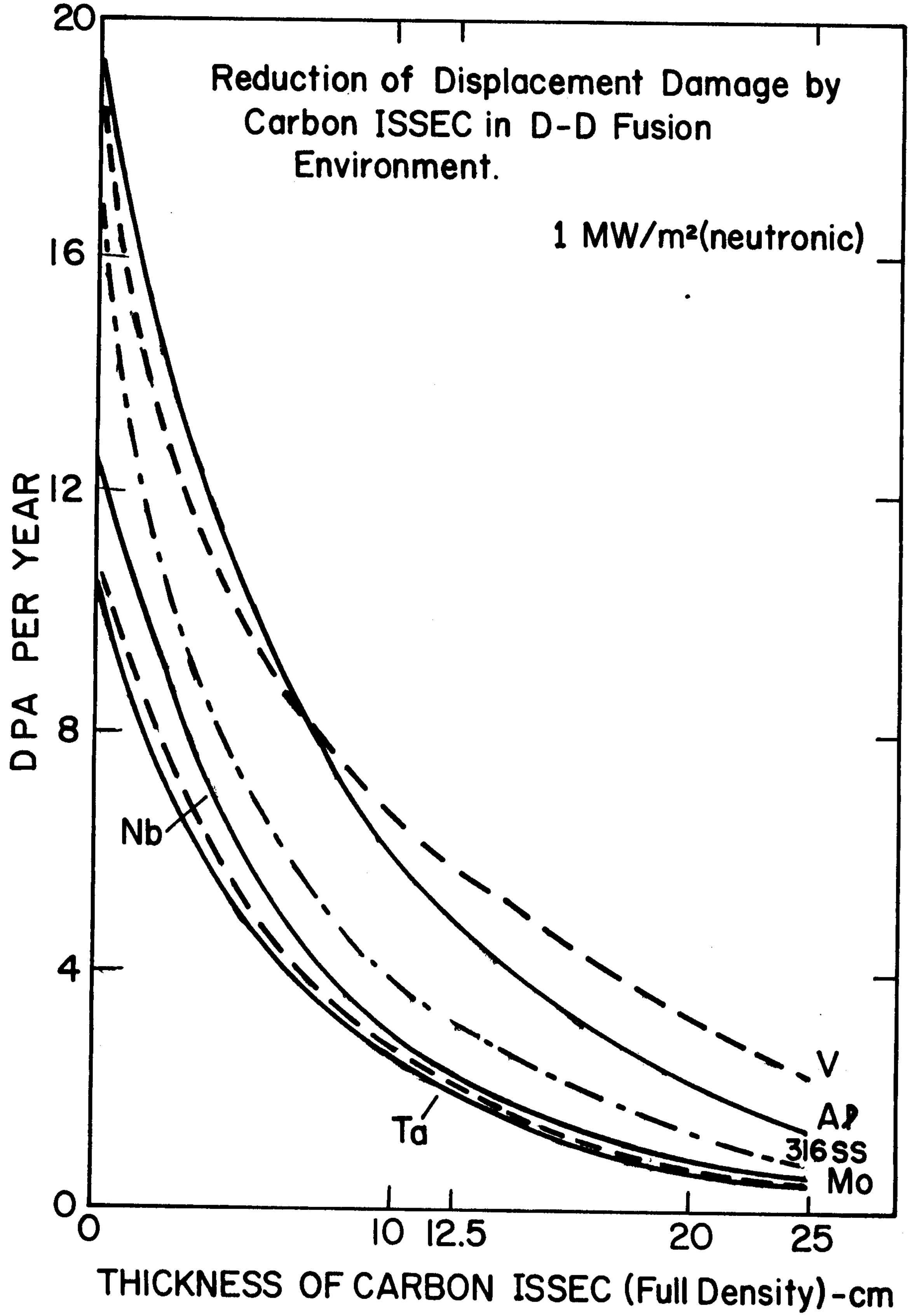
Table 1

Factors of ISSEC Produced Reduction in Displacement Damage in Various CTR First Wall Materials in D-T and D-D Fusion Environments

dpa/year[a]

Material	No ISSEC	12.5 cm C	12.5 cm C Damage Ratio	25 cm C
		D-D Fusion		
Al	19.8	4.8	0.24	1.32
V	18.4	5.8	0.32	2.22
316 SS	16.8	3.2	0.19	0.86
Nb	10.8	2.14	0.20	0.54
Mo	12.2	2.34	0.19	0.6
Ta	10.5	2.08	0.20	0.52
		D-T Fusion		
Al	12.7	3.4	0.27	
V	12.9	3.8	0.29	
316 SS	11.3	2.50	0.22	
Nb	8.48	1.64	0.19	
Mo	9.47	1.77	0.19	
Ta	8.42	1.60	0.19	

(a) 1 MW/m^2 neutron wall loading and 100% Duty Factor



Reduction of Displacement Damage by Carbon ISSEC in D-D Fusion Environment.
1 MW/m²(neutronic)
DPA PER YEAR
THICKNESS OF CARBON ISSEC (Full Density)-cm
0
4
8
12
16
20
0
10
12.5
20
25
V
Al
316 SS
Mo
Nb
Ta

Figure 2

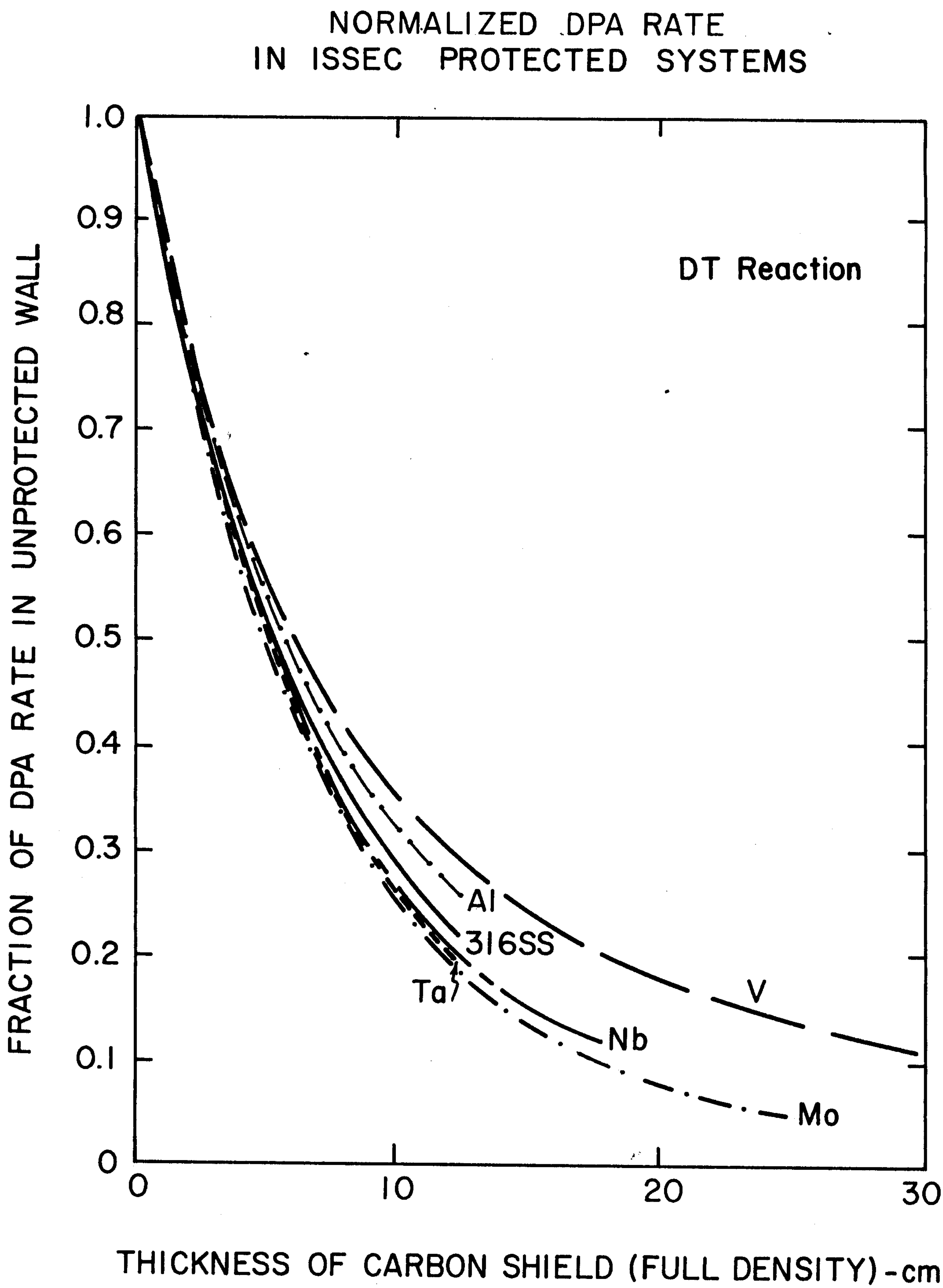
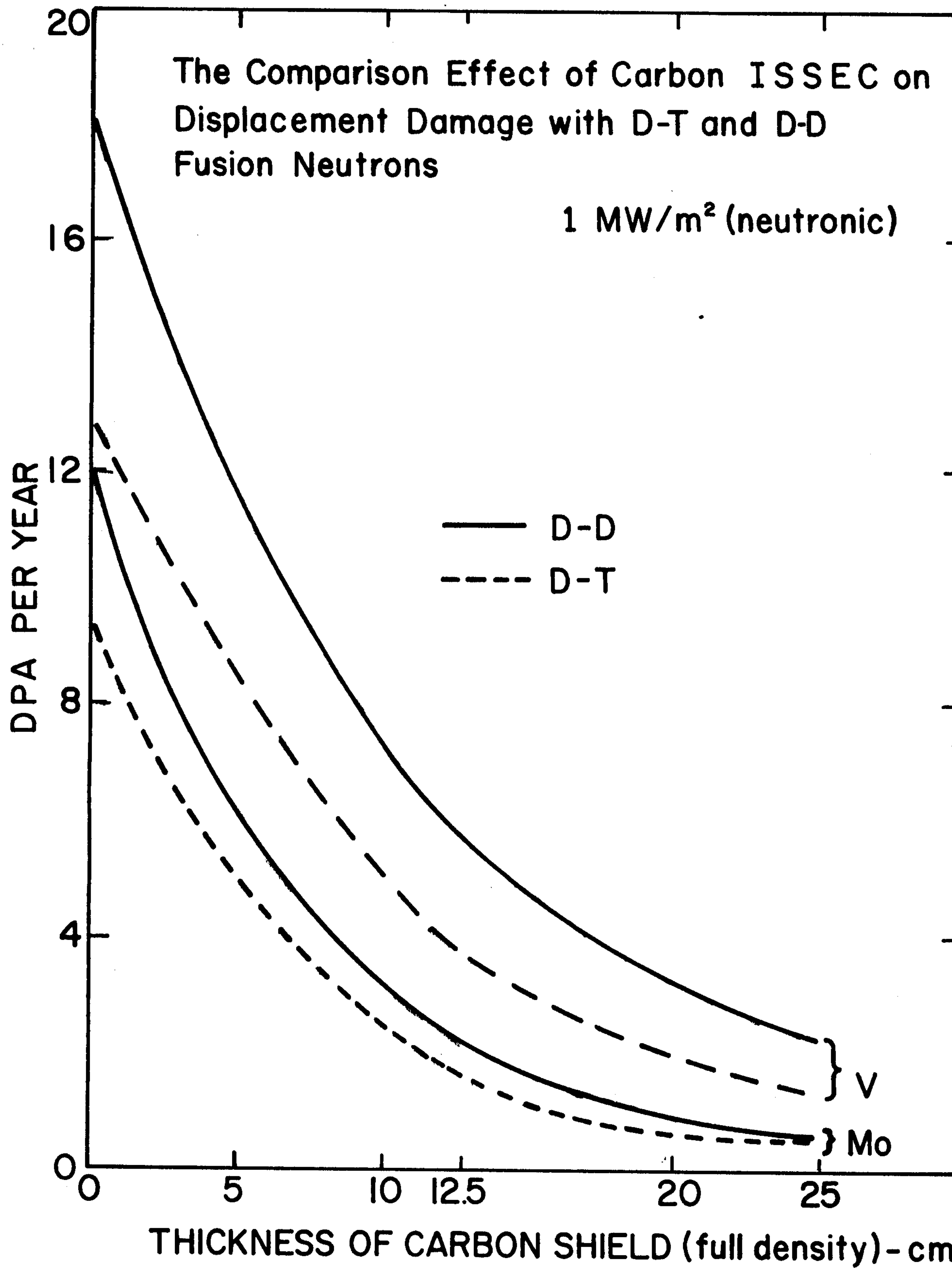

NORMALIZED DPA RATE
IN ISSEC PROTECTED SYSTEMS
FRACTION OF DPA RATE IN UNPROTECTED WALL
THICKNESS OF CARBON SHIELD (FULL DENSITY) - cm
DT Reaction
Al
316SS
Ta
V
Nb
Mo
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30

Figure 3



The Comparison Effect of Carbon ISSEC on Displacement Damage with D-T and D-D Fusion Neutrons
1 MW/m² (neutronic)
D-D
D-T
V
Mo
DPA PER YEAR
THICKNESS OF CARBON SHIELD (full density) - cm
0
4
8
12
16
20
0
5
10
12.5
20
25

Figure 4

The reason is complex but can be roughly explained by the low ionization threshold in low Z elements.[13] This means that the primary knock on atoms in Al lose much less energy in elastic (displacement) collisions than do the PKAs in Nb. For example, in Al 107 keV is lost to displaced atoms per PKA produced by 14 MeV neutrons and 51 keV from 1 MeV neutrons (a ratio of 2.1). The elastic energy lost by an average PKA in Nb is 213 keV from 14 MeV neutrons and 56 keV from 1 MeV neutrons (a ratio of 3.8). Hence, the reduction in neutron energy by the ISSEC is more effective in Nb than in Al.

It should be noted here that the displacement cross sections treat charged particle-out reactions [(n,p), (n,α), etc] as (n,n') reactions. Recent analysis shows that this underestimates damage done by higher energy neutrons by the following factors[14]

	% Underestimate of Damage at 14 MeV
Al	16
V	5
316 SS	17
Nb	3
Mo	No data
Ta	0.06

The inclusion of these contributions would increase the dpa level in the low Z elements for the case of no ISSEC, but would have little effect on the dpa values in ISSEC protected systems. This would tend to make the ISSEC somewhat more effective for low Z elements than stated here. However, even including these correction factors, there still would be a slight advantage to using ISSECs with high Z as compared to low Z elements.

Turning to relative reduction in displacement damage as a function of carbon thickness, we see in Figure 3 that a reduction of 3-5 can be achieved using 12.5 cm of carbon while reductions by a factor of 20 can be accomplished by using 25 cm of carbon ISSEC in front of Mo. The significance of this observation is that if the wall life is predominantly determined by the level of the total displacement damage (without regard to the spatial configuration of defects) then one might extend the wall life due to radiation damage alone by factors of 5-20 in Mo and similar values in other systems. The relative reduction in dpa rate achieved with the D-D system are within 10-30% of the D-T case and are not presented graphically here.

Reduction of He and H Production Rates

Table 2 lists the effect of carbon ISSEC on He gas generation rates in potential CTR first wall materials subjected to neutrons from D-D plasma and Table 3 gives the results for hydrogen production. The same results for the D-T plasma are shown in Table 4. Analysis of the cross section data reveals that almost all the helium and hydrogen production reactions in the materials considered for this study have thresholds over 2.5 MeV. This means that the helium and hydrogen production rates in the D-D plasma case are lower than in the D-T case by a factor almost identical to the reduction in the 14.1 MeV component of the incident flux per 1 MW/m^2 neutronic wall loading; namely by the factor of 4.43/3.78 (1.17).

The absolute effect of carbon ISSEC on helium generation in metals for the D-T case is shown on Figure 5. The same general behavior holds true for the D-D neutrons. The absolute effect here is much more pronounced than in the case of displacement damage. Reductions in helium gas productions range from 7 to 14 for 12.5 cm carbon and from 7 to 11 for hydrogen production with the same carbon thickness. The factors of reduction are 27-80 and 17-55, respectively for a 25 cm carbon ISSEC. Except for V and Al, the reduction in He production is always greater than that for the reduction in hydrogen production. The reduction in helium gas production in Ta is a factor of 2 more than the redcution in V. This is due to the lower threshold for (n,α) reactions in V (~7 MeV) than for Ta (11 MeV).

The relative reduction values are plotted in Figure 6 and it is to be noted that on a linear scale, there is little difference between the elements. If there is a discernable trend, it is that the relative reduction is greater for high Z elements than for low Z elements. This is undoubtedly due to the high coulomb barrier (and therefore higher threshold energies) for (n,α) reactions in the high Z elements.

There is one major thing missing in the data we have presented so far as the helium generation in 316 SS is concerned. As we increase the

Table 2

Effect of Carbon ISSEC on the Helium Gas Production Rate in Potential CTR Materials in D-D Fusion Environment

	Appm He/Year[a]		
Material	No ISSEC	12.5 cm C	25 cm C
Al	405	42.8	8.90
V	67.0	9.72	2.46
316 SS[b]	239	22.8	4.6
Nb	27.8	2.82	0.58
Mo	62.0	5.94	1.2
Ta	6.42	0.46	0.08

(a) 1 MW/m^2 neutron wall loading, 100% Duty Factor.

(b) Neglecting helium from Ni^{59}.

Table 3

Effect of Carbon ISSEC on the Hydrogen Gas Production Rate in Potential CTR First Wall Materials in D-D Fusion Environment

Appm H/Year[(a)]

Material	No ISSEC	12.5 cm C	25 cm C
Al	944	95.2	20.0
V	122	24.4	7.32
316 SS	675	88.4	20.6
Nb	93.6	10.7	2.32
Mo	127	11.7	2.32
Ta	0	0	0

(a) 1 MW/m^2 neutron wall loading, 100% Duty Factor.

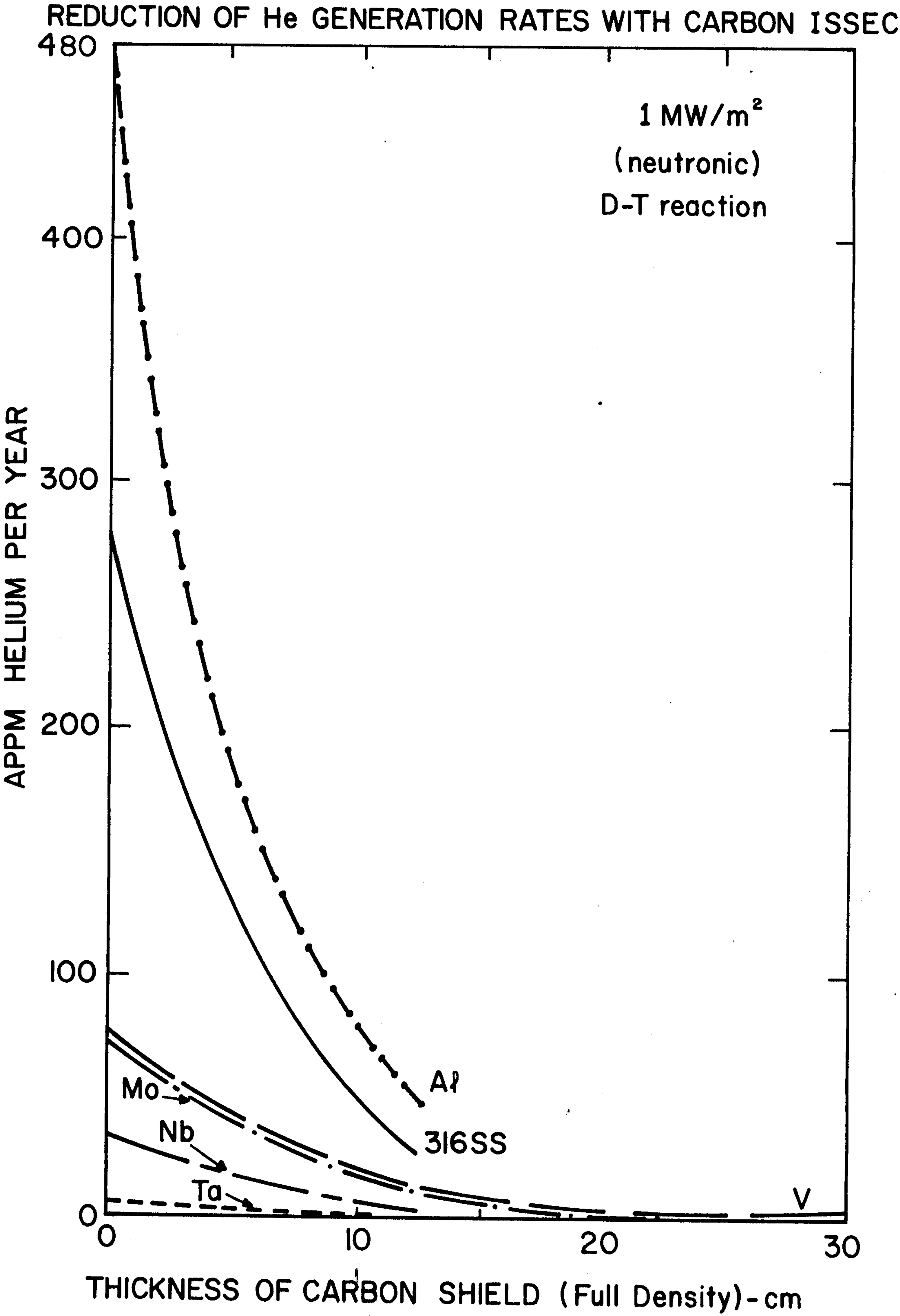
Table 4

Effect of Carbon ISSEC Thickness on the Gas Production Rates in Potential CTR Materials(a)

D-T Plasma

Material	appm He/yr No ISSEC	appm He/yr 12.5 cm ISSEC	Damage Ratio	appm H/year No ISSEC	appm H/year 12.5 cm ISSEC	Damage Ratio
Al	476	50.1	0.11	1110	111	0.10
V	78.6	11.4	0.15	143	28.6	0.20
316 SS	280	26.8	0.10	736	100	0.14
Nb	32.7	3.32	0.10	110	12.6	0.11
Mo	72.6	6.95	0.10	149	13.7	0.09
Ta	7.52	0.55	0.07	0	0	-

(a) 1 MW/m^2 neutronic wall loading, 100% Duty Factor


REDUCTION OF He GENERATION RATES WITH CARBON ISSEC
1 MW/m²
(neutronic)
D-T reaction
APPM HELIUM PER YEAR
480
400
300
200
100
0
Al
316SS
Mo
Nb
Ta
V
0
10
20
30
THICKNESS OF CARBON SHIELD (Full Density)-cm

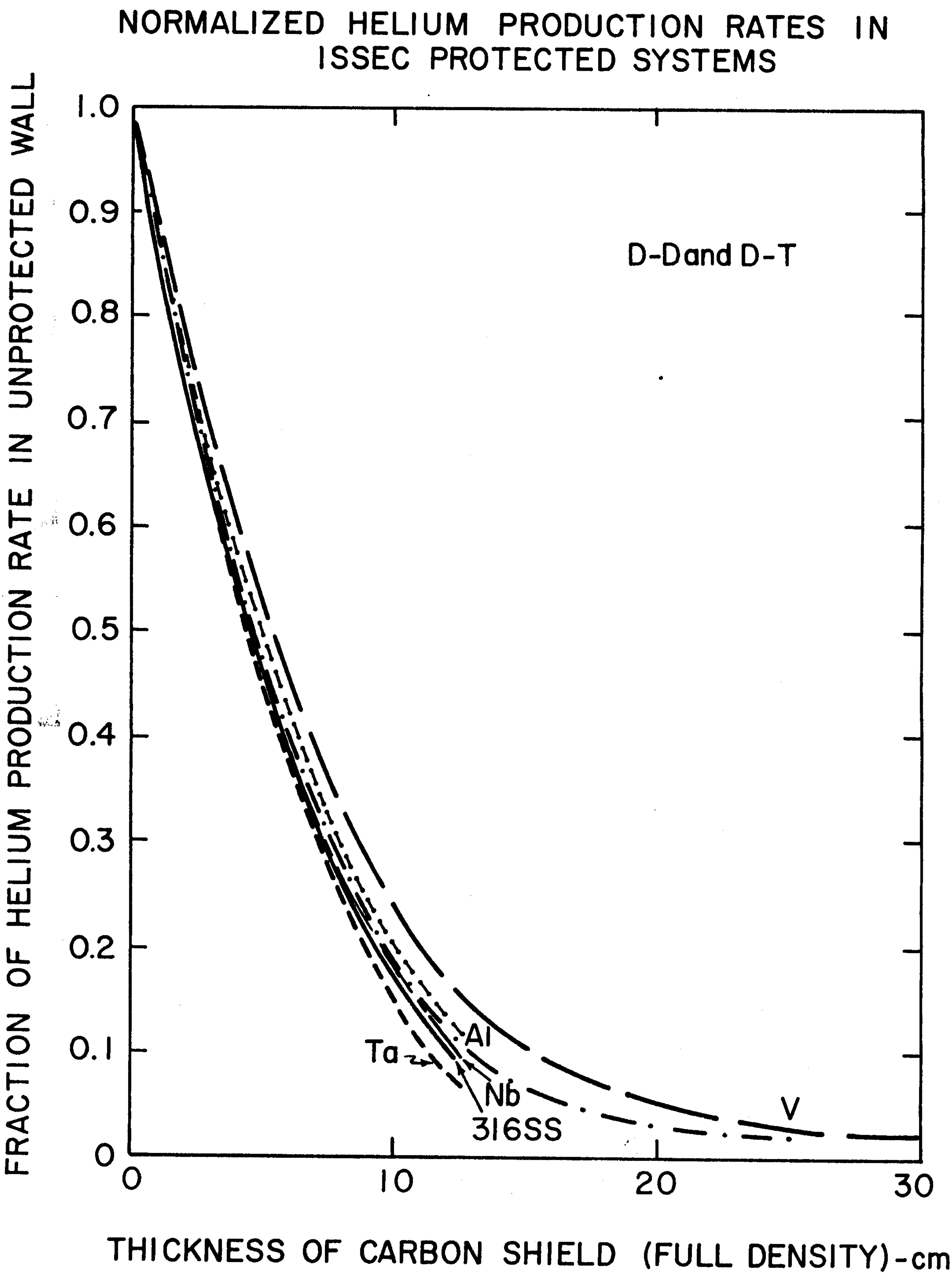

NORMALIZED HELIUM PRODUCTION RATES IN
ISSEC PROTECTED SYSTEMS
FRACTION OF HELIUM PRODUCTION RATE IN UNPROTECTED WALL
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
D-Dand D-T
Al
Ta
Nb
316SS
V
0
10
20
30
THICKNESS OF CARBON SHIELD (FULL DENSITY)-cm

Figure 6

thermal components of the flux in the first wall by putting carbon in front of it, the $Ni^{58}(n,\gamma)$ $Ni^{59}(n,\alpha)$ reaction sequence plays an important role and the helium generation in 316 SS increases dramatically. We have calculated this effect and the results are given in Table 5 for various plant operating times, with 100% duty factor, and for different ISSEC thicknesses. The calculational procedure for this is given in Appendix C. Table 6 lists the total amount (due to thermal and high energy neutron reactions) of He generated in 316 SS first wall. The results are also plotted in Figure 7. It is apparent that while this thermal neutron induced helium generation is negligible when we have no ISSEC in both D-D and D-T cases, it becomes increasingly important as the carbon thickness and the first wall lifetime increases. This is especially true in D-D because of the larger number of neutrons and the softer spectrum.

For the D-T case with 12.5 cm of ISSEC, the amount of helium generated from $Ni^{58}(n,\gamma)$, $Ni^{59}(n,\alpha)$ reactions never quite catches up with the amount of helium generated from (n,α) reaction with fast neutrons even after 20 years of operation. But in the D-D case, the thermally produced α's over-ride the fast neutron produced α's after about 4 years with 12.5 cm ISSEC, and after about 6 months with 25 cm of ISSEC.

Effect of ISSECs on the Neutron Induced Radioactivity

The effect of ISSECs on the neutron induced radioactivity depends on whether the isotopes causing the most radioactivity are produced as a result of fast neutron or thermal neutron activation. One may even get reversal of the trends depending on the half lives of the isotopes.

Table 7 lists the levels of neutron induced radioactivity in potential CTR first wall materials at various times after shutdown for a two year operating time in a D-D system. The results are tabulated for bare wall and two different ISSEC thicknesses. Table 8 lists the radioactivity after 20 years of irradiation time. Two year irradiation results are plotted in Figures 8, 9 and 10 at shutdown, 1 year after shutdown and 100 years after shutdown, respectively. At shutdown and 100 years after shutdown, results for D-T plasma case are given in Tables 9 and 10 along with the D-D results for comparison, The D-T neutronic calculations were done for only 0 and 12.5 cm ISSEC thicknesses. For

Table 5

Appm He* Generated in 316 SS from $Ni^{58}(n,\gamma)$, $Ni^{59}(n,\alpha)$ Reaction Sequence Only

D-D

Operation Time (years)	No ISSEC	12.5 cm C	25 cm C
1	0.0052	5.65	28.2
2	0.0212	22.6	113
5	0.133	141	704
10	0.531	565	2820
20	2.12	2260	11260

D-T

	No ISSEC	12.5 cm ISSEC
1	0.0023	1.14
2	0.0093	4.55
5	0.059	28.5
10	0.23	114
20	0.94	455

* Per 1 MW/m^2 neutron wall loading, 100% Duty Factor

Table 6

Total Appm He Generated in 316 SS*

D-D

Operation Time (Year)	No ISSEC	12.5 cm ISSEC	25 cm ISSEC
1	239	28.5	32.8
2	477	68.2	122
5	1190	255	727
10	2390	793	2861
20	4770	2720	11400

D-T

	No ISSEC	12.5 cm ISSEC
1	280	27.9
2	560	58.2
5	1400	163
10	2800	382
20	5600	991

* Per 1 MW/m^2 neutron wall loading, 100% Duty Factor and includes threshold and thermally produced gas.

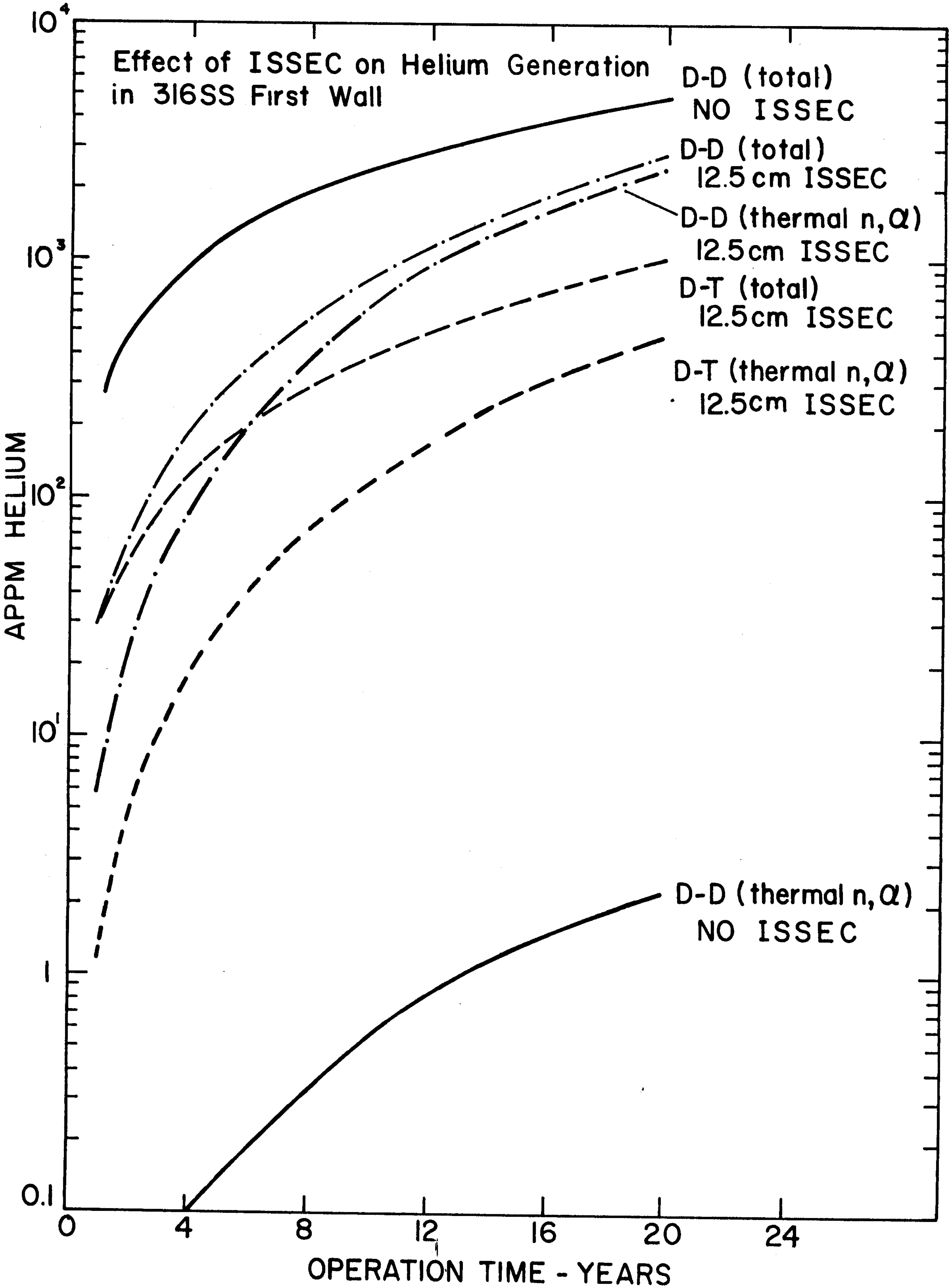

Effect of ISSEC on Helium Generation in 316SS First Wall
D-D (total) NO ISSEC
D-D (total) 12.5 cm ISSEC
D-D (thermal n,α) 12.5cm ISSEC
D-T (total) 12.5cm ISSEC
D-T (thermal n,α) 12.5cm ISSEC
D-D (thermal n,α) NO ISSEC
APPM HELIUM
OPERATION TIME - YEARS
0
4
8
12
16
20
24
0.1
1
10¹
10²
10³
10⁴

Table 7

Level of Neutron Induced Radioactivity at Various Times After Shutdown in the First Wall of a Carbon ISSEC Protected System After 2 Years of Operation/DD Plasma

Curies/cm^3 (a)

		Shutdown	1 day	1 week	1 year	20 years	100 years
	No ISSEC	39.8	6.84	8.8×10^{-3}	1.3×10^{-5}	1.3×10^{-5}	1.3×10^{-5}
Al	12.5 cm ISSEC	11.2	0.72	9.4×10^{-4}	7.7×10^{-7}	7.7×10^{-7}	7.7×10^{-7}
	25 cm ISSEC	17.9	0.15	1.9×10^{-4}	1.3×10^{-7}	1.3×10^{-7}	1.3×10^{-7}
	No ISSEC	27.2	5.52	.56	~0	~0	~0
V	12.5 cm ISSEC	95.4	.4	.04	~0	~0	~0
	25 cm ISSEC	345.4	.1	1.3×10^{-2}	~0	~0	~0
	No ISSEC	183.4	146.4	96.6	1.9×10^{-3}	1.9×10^{-3}	1.9×10^{-3}
Nb	12.5 cm ISSEC	122.2	12.9	8.5	8.4×10^{-3}	8.4×10^{-3}	8.4×10^{-3}
	25 cm ISSEC	126.2	2.5	1.64	9.6×10^{-3}	9.6×10^{-3}	9.6×10^{-3}
	No ISSEC	497	164.8	120.8	13.9	9.0×10^{-18}	~0
Ta	12.5 cm ISSEC	1951.	1270.	1221.	140.6	9.2×10^{-17}	~0
	25 cm ISSEC	2478	1632	1573	181	1.2×10^{-16}	~0
	No ISSEC	83.5	58.1	--	25.5	2.1[(b)]	2.1×10^{-3}
316 SS	12.5 cm ISSEC	26.3	23.0	--	4.9	0.42[(b)]	1.81×10^{-4}
	25 cm ISSEC	47.0	45.2	--	7.9	0.71[(b)]	3.45×10^{-5}

(a) Per 1 MW/m^2 neutronic wall loading, 100% Duty Factor.

(b) Values at 10 years after shutdown

Table 8

Level[a] of Neutron Induced Radioactivity at Various After Shutdown Times in the First Wall of an ISSEC Protected System After 20 Years of Operation DD Plasma

Curies/cm³ (a)

		Shutdown	1 Day	1 Week	1 Year	20 Years	100 Years
	No ISSEC	39.8	6.84	9.0×10^{-3}	1.3×10^{-4}	1.3×10^{-4}	1.3×10^{-4}
Al	12.5 ISSEC	11.8	0.72	9.4×10^{-4}	7.8×10^{-6}	7.8×10^{-6}	7.8×10^{-6}
	25 cm ISSEC	17.9	0.15	2.0×10^{-4}	1.3×10^{-6}	1.3×10^{-6}	1.3×10^{-6}
	No ISSEC	27.2	5.52	.56	~0	~0	~0
V	12.5 cm ISSEC	95.4	.4	.04	~0	~0	~0
	25 cm ISSEC	345.4	.1	1.3×10^{-2}	~0	~0	~0
	No ISSEC	183.4	146.4	96.6	.019	.019	.019
Nb	12.5 cm ISSEC	122.2	12.9	8.58	.084	.084	.084
	25 cm ISSEC	126.4	2.58	1.74	.096	.096	.096
	No ISSEC	498.4	166.4	122.2	14.1	9.2×10^{-18}	~0
Ta	12.5 cm ISSEC	1966	1286	1236	142.4	9.2×10^{-17}	~0
	25 cm ISSEC	2498	1651	1592	183.2	1.2×10^{-16}	~0
	No ISSEC	125.5	99.6	--	57.2	5.2[b]	0.019
316 SS	12.5 cm ISSEC	32.1	28.8	--	11.3	1.02[b]	1.67×10^{-3}
	25 cm ISSEC	46.6	45.1	--	17.8	1.6[b]	3.14×10^{-4}

(a) units are curies/cm³ per 1 Mw/m² neutron wall loading at 100% duty factor.

(b) values at 10 years after shutdown

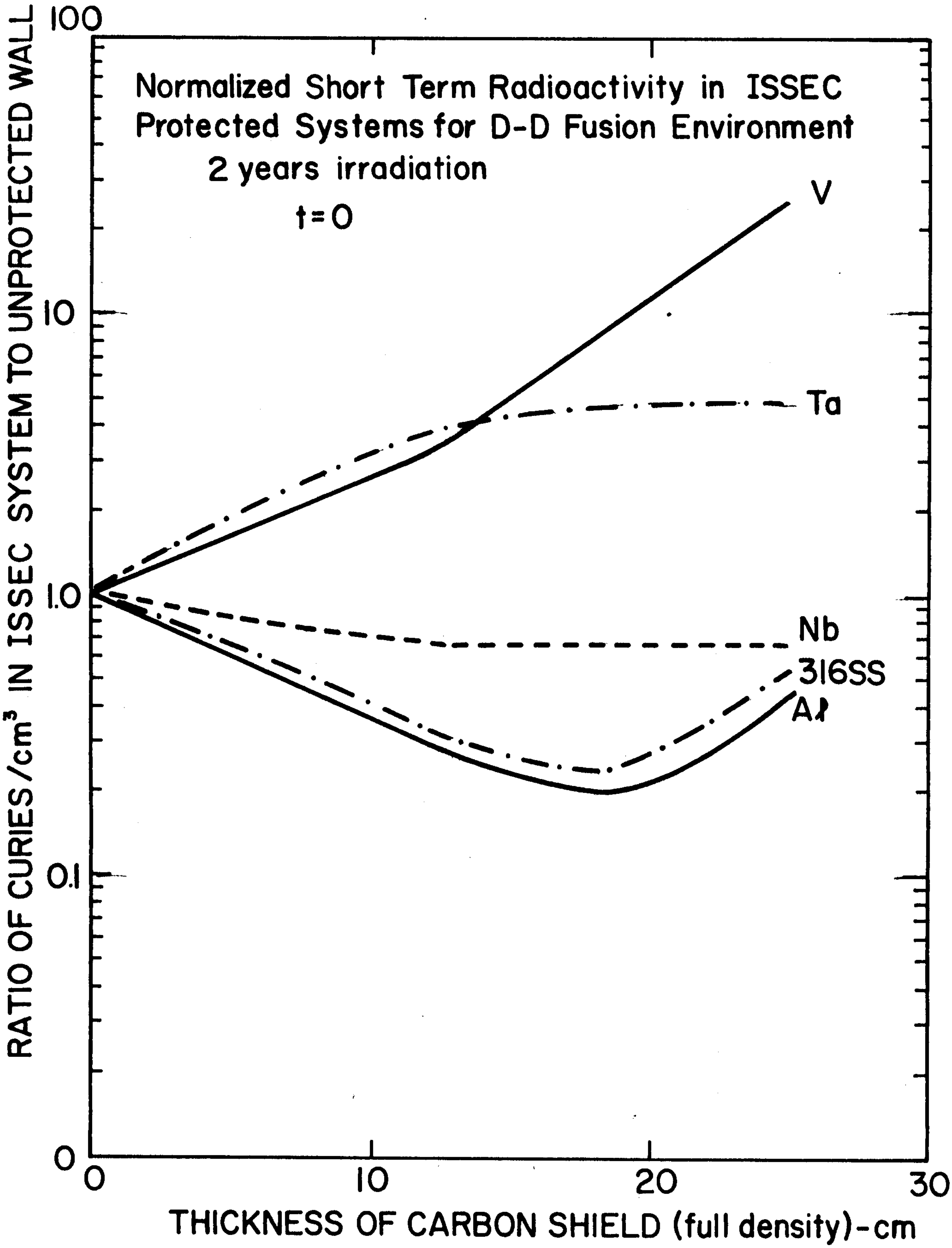
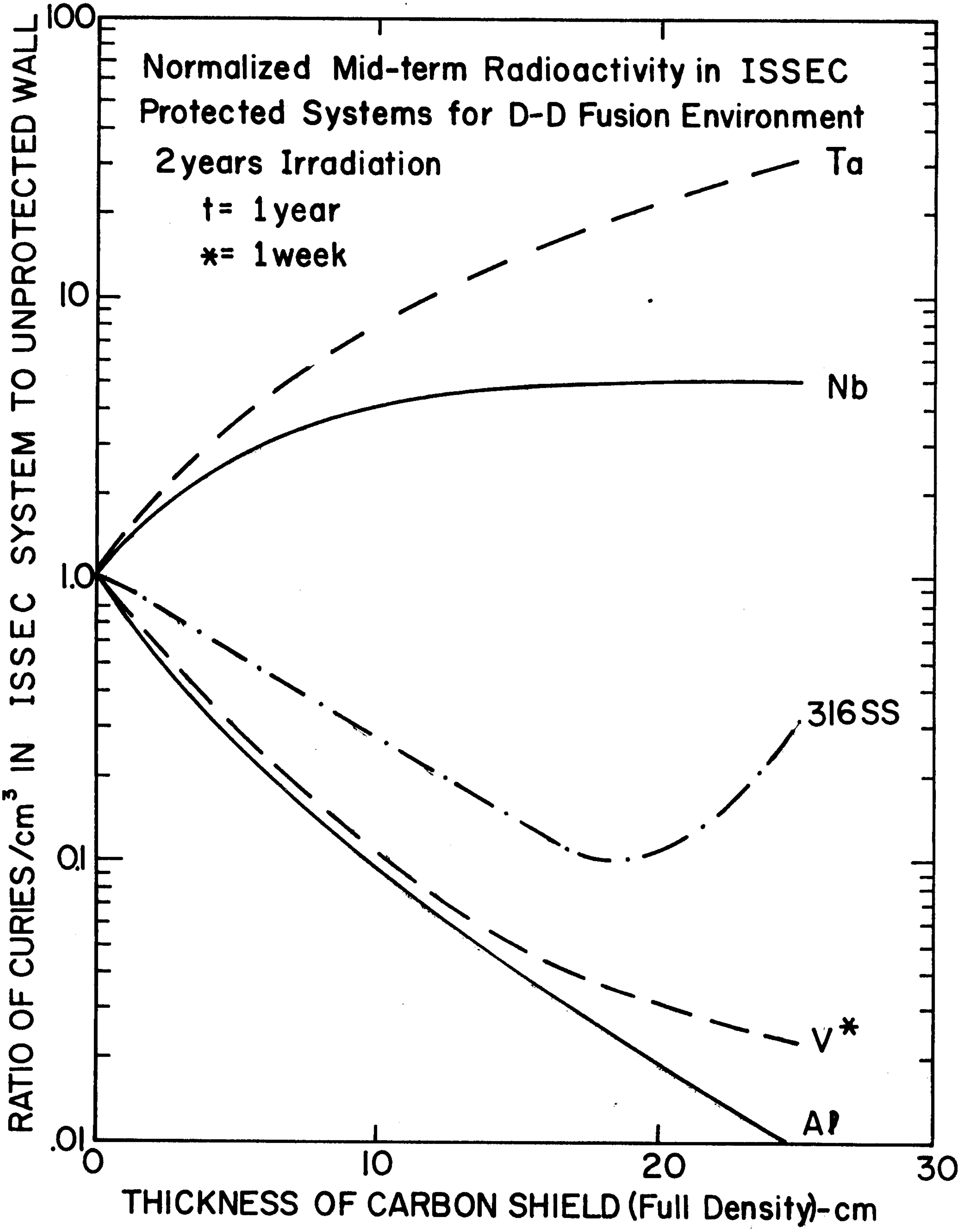

Normalized Short Term Radioactivity in ISSEC
Protected Systems for D-D Fusion Environment
2 years irradiation
t=0
V
Ta
Nb
316SS
Al
100
10
1.0
0.1
0
0
10
20
30
RATIO OF CURIES/cm³ IN ISSEC SYSTEM TO UNPROTECTED WALL
THICKNESS OF CARBON SHIELD (full density)-cm

Figure 8



Normalized Mid-term Radioactivity in ISSEC
Protected Systems for D-D Fusion Environment
2 years Irradiation
t= 1 year
*= 1 week
Ta
Nb
316SS
V*
Al
100
10
1.0
0.1
.01
0
10
20
30
RATIO OF CURIES/cm³ IN ISSEC SYSTEM TO UNPROTECTED WALL
THICKNESS OF CARBON SHIELD (Full Density)-cm

Figure 9

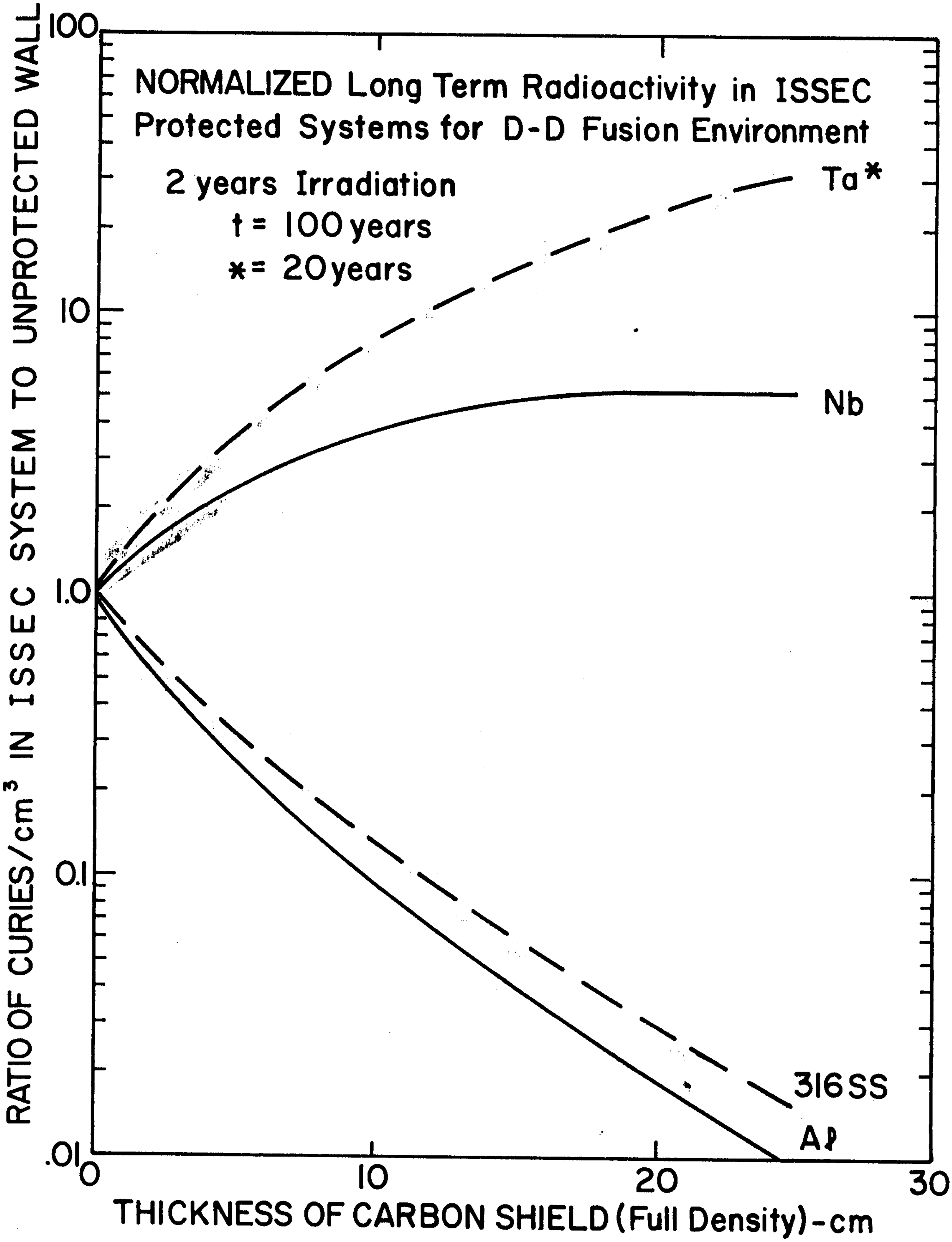

NORMALIZED Long Term Radioactivity in ISSEC
Protected Systems for D-D Fusion Environment
2 years Irradiation
t = 100 years
* = 20 years
Ta*
Nb
316SS
Al
RATIO OF CURIES/cm³ IN ISSEC SYSTEM TO UNPROTECTED WALL
100
10
1.0
0.1
.01
0
10
20
30
THICKNESS OF CARBON SHIELD (Full Density) - cm

Figure 10

Table 9

Level of Neutron Induced Radioactivity at Shutdown in First Wall in an ISSEC Protected System After 2 Years of Irradiation

D-T Plasma[a]

Material	No ISSEC	12.5 cm ISSEC	Fraction of Unprotected First Wall Values
Al	47.4	20.4	0.43 (decrease)
V	13.3	32.8	2.44 (increase)
316 SS	91.2	15.3	0.17 (decrease)
Nb	138	60.4	0.43 (decrease)
Mo	NA	NA	---
Ta	471	925	1.96 (increase)

D-D Plasma[a]

Material	No ISSEC	12.5 cm ISSEC	Fraction of Unprotected First Wall Values
Al	39.8	11.2	.28 (decrease)
V	27.2	95.4	3.51 (increase)
316 SS	83.5	26.3	.32 (decrease)
Nb	183	122	.67 (decrease)
Mo	NA	NA	---
Ta	497	1950	3.93 (increase)

(a) curies/cm^3 per 1 MW/m^2 neutron wall loading at 100% duty factor

NA - Not Available

Table 10

Level of Neutron Induced Radioactivity 100 Years After Shutdown in the First Wall of ISSEC Protected System After 2 Years of Irradiation

Material	No ISSEC	D-T Plasma[a] 12.5 cm of ISSEC	Fraction of Unprotected First Wall Values
Al	1.49×10^{-5}	9.14×10^{-7}	0.06 (decrease)
V	$<10^{-15}$	$<10^{-15}$	0.15[b] (decrease)
316 SS	3.42×10^{-3}	2.05×10^{-4}	0.06 (decrease)
Nb	0.001	0.0038	3.85 (increase)
Mo	NA	NA	----
Ta	$<10^{-15}$	$<10^{-15}$	8[c] (increase)

Material	No ISSEC	D-D Plasma[a] 12.5 cm of ISSEC	Fraction of Unprotected First Wall Values
Al	1.3×10^{-5}	7.7×10^{-7}	0.06 (decrease)
V	$<10^{-15}$	$<10^{-15}$	0.07[b] (decrease)
316 SS	2.1×10^{-3}	1.81×10^{-4}	0.09 (decrease)
Nb	1.9×10^{-3}	8.4×10^{-3}	4.42 (increase)
Mo	NA	NA	----
Ta	$<10^{-15}$	$<10^{-15}$	10.2[c] (increase)

(a) curies/cm^3 per 1 MW/m^2 neutronic wall loading, 100% duty factor
(b) value 1 week after shutdown
NA - Not Available
(c) values 20 years after shutdown

both D-D and D-T cases the trends are the same. The short term radioactivity decreases for Nb, 316 SS and Al, but it increases for V and Ta as the thickness of the carbon shield is increased to 12.5 cm. When one considers the long term radioactivity, V and Nb switch places and Ta and Nb have higher radioactivities while 316 SS, V and Al have lower radioactivities with 12.5 cm of ISSEC than they do with no ISSEC.

As the thickness of the ISSEC is increased over 12.5 cm, some interesting things start to happen. In Al and 316 SS those isotopes produced as a result of thermal neutron activation gain importance and the radioactivity curves start to rise. Nb and Ta total activities saturate but V keeps increasing. At 1 year after shutdown, 316 SS curve still has the same shape but Al radioactivity keeps decreasing because of the short half lives of those isotopes thermally produced. The Nb and Ta activities again tend to saturate. At 100 years after shutdown in 316 SS, the thermally activated radioisotopes have decayed away and the total radioactivity continues to decrease with increasing carbon thickness.

It should also be noted in Tables 9 and 10 that the ISSEC is more effective in reducing neutron induced radioactivity at shutdown in 316 SS and Nb for D-T than for D-D. It is also apparent that the ISSEC is more effective for Al in the D-D case than for the D-T case. At 100 years after shutdown, the reduction in radioactivity in 316 SS is less in the D-D system. The reduction factor is about the same in Al for both cases. At long times after shutdown radioactivity in V decays to insignificant levels. However, at 1 week after shutdown, it is reduced more in D-D system than in D-T. Long term radioactivities in Nb and Ta increase more for the D-D than the D-T case because long lived radioisotopes in Nb and Ta are produced as a result of thermal (n,γ) reactions.

Radiation Damage in the ISSEC

The reduction in metallic damage properties is partially taken up by the increased radiation damage in the carbon. The most serious questions have been assessed elsewhere[2] and they are:

1. Will any displacement damage survive at irradiation temperatures of 1500-200°C (0.5-0.66 T/Tm)?

2. What will the generation of large amounts of He (several thousand

appm) do to the carbon at high temperatures?
Unfortunately, there is no experimental evidence to answer these questions now, but the authors tend to think that the displacement damage will anneal at these high temperatures, but the helium may collect into bubbles causing dimensional instabilities. Some recent work done by Bauer et al.[15] give some reason to hope that little permanent damage will be done due to this high helium generation. It was found that the remission rate of helium bombarded carbon was very high (essentially 100%) at temperatures of 1200°C. If this holds true for the carbon in an ISSEC, then perhaps there is little cause for concern about the several thousand appm of helium generated per year of operation at 1 MW/m^2 neutron wall loading. Obviously, more work is needed in this area.

DISCUSSION

All the results presented so far in this paper and elsewhere[2,3] have been normalized to 1 MW/m^2 neutronic wall loading. When one considers only one type of reactor with a certain plasma cycle, this way of normalizing the radiation damage results is quite convenient. The response of different materials to neutron spectral shifting, provided the same blanket structure is used in all cases, is also straightforward. However, when one considers two different plasma reactions as we have, another way of comparing the radiation damage results might be to normalize on the basis of MW of power. In the real case, the difficulty is that one needs to breed tritium for the DT cycle whereas in the D-D cycle, this is not required. Therefore, it is quite probable that two completely different blanket structures would be used and the neutron energy multiplication, as well as γ heating, can be much different for the two cases. All the present calculations were done with the same non-breeding blanket scheme shown in Figure 1, so any comparison made on the basis of total power generation would not be meaningful.

Another way of quoting the damage would be to normalize it on the basis of a megawatt of power generated in the plasma. Such a comparison requires a knowledge of the burnup of tritium and He-3 atoms produced by the D-D reactions. Miley[16] has shown that at 30 keV, essentially all the tritium produced is consumed and approximately 20% of the He-3 is "burned".

The reactions taking place and the energies of various products (MeV) in a D-D plasma are given below.

$$D + D \rightarrow T(1.01) + p(3.03)$$
$$D + D \rightarrow He^3(0.82) + n(2.45)$$
$$D + T \rightarrow He^4(3.52) + n(14.06)$$
$$D + He^3 \rightarrow He^4(3.67) + p(14.67)$$

If we use the results of Miley, we can calculate the neutron flux associated with a 1 MW/m^2 wall loading based on the thermal power produced in the DD plasma.

$$1\ MW/m^2 \text{(plasma thermal)} = \text{(const.)} \times \left(\frac{4.04+3.27+17.60+0.2x18.3}{2}\right) \frac{MeV}{n} \times$$
$$(4.34 \times 10^{13}\ n/(cm^2\text{-sec})$$

In the D-T case,

$$1 \frac{MW}{m^2} \text{(plasma thermal)} = \text{(const.)} \times 17.6 \frac{MeV}{n} \times 3.55 \times 10^{13} \frac{n}{cm^2\text{-sec}}$$

where the conversion factor (const.) has a value of 1.602×10^{-15}. It appears that if we wanted to normalize our results to 1 MW/m^2 (plasma thermal), the D-T results (dpa, gas production, activation, etc.) would be approximately 20% less than presented here and the D-D results would be 43% less. These reductions tend to make the displacement rate equal in both systems and increase the advantage of the DD spectrum with respect to helium and hydrogen production.

For illustration, results for 316 SS are reproduced in Table 11 for the two normalizations. In this table, dpa and hydrogen production results are lower when they are normalized on the basis of plasma thermal by the factors given above; namely 20% in D-T and 43% in D-D cases. The same conclusions can be drawn about the other materials considered here.

Analysis of this work leads us to the observation that the radiation damage incurred in protected or unprotected D-D systems is almost the same as for the D-T systems. For example, as we see in Table 11 the displacement damage is higher in D-D systems when neutronic wall loading normalization is used, but this becomes about the same in the two systems when plasma thermal normalization is used. Gas production results are 10

Table 11

A Comparison of Possible Normalization Procedures for DD&DT Fusion Systems - 316 SS First Wall

		1MW/m2 Neutronic			1MW/m2 Plasma Thermal		
		D-D	DT	DD/DT	DD	DT	DD/DT
dpa/yr	No C	16.8	11.3	1.49	9.64	9.06	1.06
	12.5 cm C	3.2	2.5	1.28	1.97	2.0	0.99
	25 cm C	0.86		--	0.49		
Appm He 10 yrs.	No C	2387	2800	0.85	1370	2240	.61
	12.5 cm C	793	381	2.08	317	305	1.04
	25 cm C	2861			956		
Appm H/yr	No C	675	736	0.92	388	590	.66
	12.5 cm C	88.4	100	0.88	50.8	80.1	.63
	25 cm C	20.6	--	--	11.8	--	--

to 15% lower in D-D with 1 MW/m^2 (neutronic)normalization. This difference in gas production rates goes to 30-40% for the second normalization but it still is not much of an improvement over the D-T system.

CONCLUSIONS

A few general conclusions can be gathered from these studies about both DT and DD carbon ISSEC systems.

- Reduction in displacement rates of 3-5 can be obtained with 12.5 cm of carbon and 25 cm can reduce displacement damage by a factor of 8 to 20.
- With the exception of 316 SS, helium production can be reduced by factors of 7 to 14 with 12.5 cm of carbon and by factor of 27 to 80 with 25 cm of carbon.
- The use of carbon ISSEC to soften the neutron spectrum to 316 SS initially decreases the helium production rates by a factor of 8-10 for 12.5 cm (1 year). However, due to build-up of Ni-59 which has a high thermal (n,α) cross section, the total amount of helium generated after 10 years of operation is actually greater in D-D ISSEC system than that in an unprotected first wall.
- Depending on the mode of activation and time after shutdown the ISSEC systems can increase or decrease the induced radioactivity. In general, it decreases the short term radioactivity of Al, 316 SS, and Nb. It actually increases the activity in V and Ta. The behavior is somewhat different for long term activities in that the activity of V is decreased and that of Nb is increased over the unprotected case. (The rest of the values stay the same).

There are also several conclusions we can state for DD versus DT ISSEC protected systems that produce the same neutron power and have it passing through the same wall area.

Advantages of D-D ISSEC

- The helium production rates are approximately 15% lower for all elements except those containing Ni regardless of the ISSEC thickness.
- The short lived radioactivities is reduced without an ISSEC in Al (16%) and 316 SS (9%). Behind a 12.5 cm ISSEC this reduction is 45% for Al.

. The long lived radioactivity is reduced without an ISSEC in Al (13%) and 316 SS (39%). Behind a 12.5 cm ISSEC, it is reduced by 16% in Al and 12% in 316 SS.

Disadvantages of a D-D ISSEC

. The displacement damage is increased, without an ISSEC, in Al (56%), V (43%), 316 SS (49%), Nb (27%), Mo (29%), and Ta (25%). Behind 12.5 cm ISSEC the rates are still higher than in a DT system for Al (41%), V (53%), 316 SS (28%), Nb (30%), Mo (32%), and Ta (30%).

. The helium production from Ni^{59} is increased by a factor of 5 behind a carbon ISSEC.

. The total helium production is 2% greater after one year of DD neutrons and 270% greater after 20 years of irradiation for 12.5 cm ISSEC.

. The short lived radioactivity without an ISSEC is increased in V (105%), Nb (33%), and Ta (1%). Behind a 12.5 cm ISSEC, the same radioactivity is increased in V (188%), Nb (103%), Ta (111%) and 316 SS (72%) over the similar DT case.

. The long lived radioactivity is increased in the unprotected wall for Nb (90%) and Ta (61%). Behind a 12.5 cm ISSEC it is also increased for Nb (121%) and Ta (115%).

The above conclusions for the displacement rates will be altered by ~29% if the results are calculated on the basis of total power generated in the plasma. In general, this will tend to make the displacement rates about the same for both DT and DD systems and make the DD system more advantageous from the standpoint of helium and hydrogen production by high energy reactions. The exception is that the total amount of helium produced in Ni containing alloys will still be greater in DD as compared to DT systems.

The conclusions about the short and long lived activity will be the same except for one exception, the short lived activity of Ta without an ISSEC will be decreased, not increased.

An overall conclusion is that a DD system does <u>not</u> represent a significant advantage over a DT system unless relative difference of 20% in the amount of He produced in non-Ni containing alloys is a critical feature. Certainly a DD system represents no significant advantage over the DT case with respect to dpa, He and induced radioactivities in 316 SS.

ACKNOWLEDGEMENT

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Appendix A

Displacement Cross Sections - Used in this Work

Group	316 SS	Mo	Nb	V	Al	C
				Barns		
1	2225	1751	1717	2279	1924	1254
2	2078	1670	1613	2169	1909	1378
3	1993	1557	1518	2097	1883	1364
4	1955	1461	1435	2056	1823	1015
5	1913	1362	1372	2009	1733	1107
6	1903	1281	1305	1973	1710	1038
7	1898	1254	1238	1938	1710	1704
8	1848	1156	1165	1899	1695	789
9	1763	1108	1088	1861	1568	966.5
10	1703	1048	1010	1816	1703	829.7
11	1660	965	935	1752	1658	914.7
12	1623	916.2	863	1690	1620	1047
13	1560	887	797	1626	1549	1512
14	1493	843.2	737	1566	1568	1519
15	1410	780	683	1502	1538	1855
16	1375	759	637	1457	1500	1101
17	1295	741.1	610	1379	1474	1428
18	1275	711.9	610	1346	1556	844.6
19	1070	639.2	569	1073	1379	867.8
20	788	534.6	500	967.1	1211	915.5
21	634.4	442.1	461.6	849.8	1068	985.4
22	462.8	378.4	425.8	581.6	1023	1013
23	398.3	342.6	373.5	463.2	860.8	997.1
24	373	287.3	256	387.9	831.4	941.9
25	301.4	247.6	173.7	382.2	601.5	863
26	195.6	201.2	138.5	309.4	511.8	763
27	196.8	164.8	109.6	285.8	545.6	647
28	180.3	128.9	87.3	285.8	597.4	560
29	120.8	93.5	68.1	190.6	330.7	547
30	68.6	44.5	34.3	109	136.9	358

Appendix A

Displacement Cross Sections - Used in this Work

Group	316 SS	Mo	Nb	V	Al	C
31	93.1	20.1	17.6	212.6	231.5	193.5
32	26.3	13.8	9.3	106.3	132.1	99.4
33	15.8	6.7	5.2	146.5	97.4	49.5
34	5.2	3.6	1.9	8.44	32.5	24.6
35	3.56	2.2	1.5	.51	14.7	12.0
36	1.04	1.9	1.3	.26	6.3	5.8
37	.13	1.1	1.3	.36	2.3	2.8
38	.19	2.0	1.3	.36	.64	1.4
39	.27	8.0	1.3	.37	.88	0
40	.4	1.4	1.1	.54	1.11	0
41	.58	.41	.045	.78	1.41	0
42	.84	.19	.065	1.1	2.7	0
43	1.2	.23	.095	1.65	3.8	0
44	1.79	.33	.14	2.4	4.5	0
45	2.6	.48	0.2	3.5	8.3	0
46	5.3	1.0	0.4	6.83	14.6	0

The above 46 group displacement cross sections for 316 SS, Mo, Nb, V and Al are condensed from the 100 group cross sections given in references 8 and 9. The displacement threshold energies used are 24, 37, 36, 24 and 16 eV for 316 SS, Mo, Nb, V, and Al, respectively.[11] The secondary displacement function used is:

$$\nu(T) = \beta \frac{L(\varepsilon)}{\varepsilon} \frac{T}{2E_d}$$

where E_d is the effective displacement energy, taken to be 5/3 times displacement threshold energy,

$\varepsilon = A_L T$ and for pure materials of atomic number A and atomic weight A,

$$A_L = \frac{0.01151}{(Z)^{7/3}} \; eV^{-1}$$

$$L(\varepsilon) = \frac{\varepsilon}{[1 + K_L g(\varepsilon)]}$$

where $g(\varepsilon) = \varepsilon + 0.40244\ \varepsilon^{3/4} + 3.4008\ \varepsilon^{1/6}$

and $K_L = \frac{0.1334\ (Z)^{2/3}}{A^{1/2}}$

$\beta \simeq 0.8$

The carbon displacement cross sections are from W. C. Morgan, ref. 17.

APPENDIX B

46 Group Neutron Fluxes at the First Mesh Point in the 316 SS First Wall Normalized to 10^{15} n's/cm^2-sec Incident

Group #	D-T Reaction No ISSEC	D-T Reaction 12.5 cm ISSEC	D-D Reaction No ISSEC	D-D Reaction 12.5 cm ISSEC	D-D Reaction 25 cm ISSEC
1	2.3259 + 15*	1.4262 + 14	1.1630 + 15	7.1309 + 13	1.1786 + 13
2	1.1157 + 14	5.3754 + 13	5.5786 + 13	2.6877 + 13	6.4653 + 12
3	7.1843 + 13	3.2674 + 13	3.5922 + 13	1.6337 + 13	4.0183 + 12
4	7.1850 + 13	2.6311 + 13	3.5925 + 13	1.3156 + 13	3.4260 + 12
5	4.5608 + 13	1.4463 + 13	2.2804 + 13	7.2314 + 12	2.0268 + 12
6	6.2184 + 13	3.63 + 13	3.1092 + 13	1.8146 + 13	4.7694 + 12
7	6.5990 + 13	2.8585 + 13	3.2995 + 13	1.4292 + 13	3.0461 + 12
8	4.1854 + 13	3.708 + 13	2.0927 + 13	1.8540 + 13	6.4088 + 12
9	3.2631 + 13	2.202 + 13	1.6316 + 13	1.1010 + 13	3.4242 + 12
10	3.9763 + 13	3.0527 + 13	1.9882 + 13	1.5263 + 13	5.1483 + 12
11	3.4660 + 13	2.4321 + 13	1.7330 + 13	1.2161 + 13	4.3510 + 12
12	3.7632 + 13	2.619 + 13	1.8816 + 13	1.3095 + 13	4.6437 + 12
13	3.7388 + 13	2.373 + 13	1.8694 + 13	1.1865 + 13	4.2978 + 12
14	3.8695 + 13	2.0927 + 13	1.9348 + 13	1.0464 + 13	3.7237 + 12
15	3.8637 + 13	1.7992 + 13	1.9319 + 13	8.9960 + 12	2.9962 + 12
16	4.6361 + 13	2.5186 + 13	2.3181 + 13	1.2593 + 13	4.2887 + 12
17	5.3827 + 13	2.5719 + 13	2.6914 + 13	1.2860 + 13	4.1963 + 12
18	7.3905 + 13	3.7625 + 13	1.3012 + 15	5.2485 + 13	9.7131 + 12
19	2.6462 + 14	1.2979 + 14	6.1531 + 14	1.5594 + 14	3.4937 + 13
20	3.1852 + 14	1.4280 + 14	5.7805 + 14	1.7685 + 14	4.1899 + 13
21	3.3476 + 14	1.4062 + 14	4.7819 + 14	1.7416 + 14	4.3548 + 13
22	3.2385 + 14	1.3157 + 14	3.8235 + 14	1.6134 + 14	4.2282 + 13
23	3.1759 + 14	1.2470 + 14	3.4328 + 14	1.5177 + 14	4.1311 + 13
24	2.6452 + 14	1.1129 + 14	2.7949 + 14	1.3558 + 14	3.8236 + 13
25	2.5470 + 14	1.0689 + 14	2.6271 + 14	1.3043 + 14	3.7916 + 13
26	1.9964 + 14	9.5222 + 13	2.0284 + 14	1.1671 + 14	3.4966 + 13
27	1.5899 + 14	8.6641 + 13	1.6136 + 14	1.0685 + 14	3.3019 + 13
28	1.3552 + 14	8.2045 + 13	1.3766 + 14	1.0181 + 14	3.2428 + 13
29	1.6988 + 14	1.4102 + 14	1.7222 + 14	1.7686 + 14	5.9809 + 13
30	9.8588 + 13	1.4172 + 14	1.0110 + 14	1.7994 + 14	6.5620 + 13
31	5.0216 + 13	1.3015 + 14	5.5265 + 13	1.6697 + 14	6.5834 + 13
32	2.3768 + 13	1.1606 + 14	2.7266 + 13	1.4983 + 14	6.3376 + 13
33	1.0200 + 13	1.0957 + 14	1.1779 + 13	1.4212 + 14	6.4468 + 13
34	2.8255 + 12	9.2084 + 13	3.2466 + 12	1.9780 + 14	5.8018 + 13
35	6.4045 + 11	7.9846 + 13	7.2662 + 11	1.0409 + 14	5.3751 + 13
36	1.5887 + 11	7.4086 + 13	1.7246 + 11	9.6718 + 13	5.3051 + 13
37	3.8813 + 10	6.9059 + 13	3.8855 + 10	9.0236 + 13	5.2371 + 13
38	9.1479 + 09	6.4237 + 13	7.6487 + 09	8.3988 + 13	5.1422 + 13
39	2.4159 + 09	5.9756 + 13	1.6621 + 09	7.8163 + 13	5.0374 + 13
40	3.4589 + 08	5.5683 + 13	2.3594 + 08	7.2856 + 13	4.9335 + 13
41	5.1950 + 07	5.1885 + 13	3.4355 + 07	6.7901 + 13	4.8236 + 13
42	9.4679 + 06	4.8350 + 13	5.8077 + 06	6.3283 + 13	4.7106 + 13
43	1.7284 + 06	4.5004 + 13	9.9778 + 05	5.8909 + 13	4.5900 + 13
44	2.0956 + 05	4.1743 + 13	1.2089 + 05	5.4644 + 13	4.4526 + 13
45	2.4277 + 04	3.8506 + 13	1.4075 + 04	5.0410 + 13	4.2932 + 13
46	2.2899 + 03	4.6434 + 14	1.3989 + 03	6.0794 + 14	1.5575 + 15

* Numbers in this table should be read as $a \pm n = a \times 10^{\pm n}$

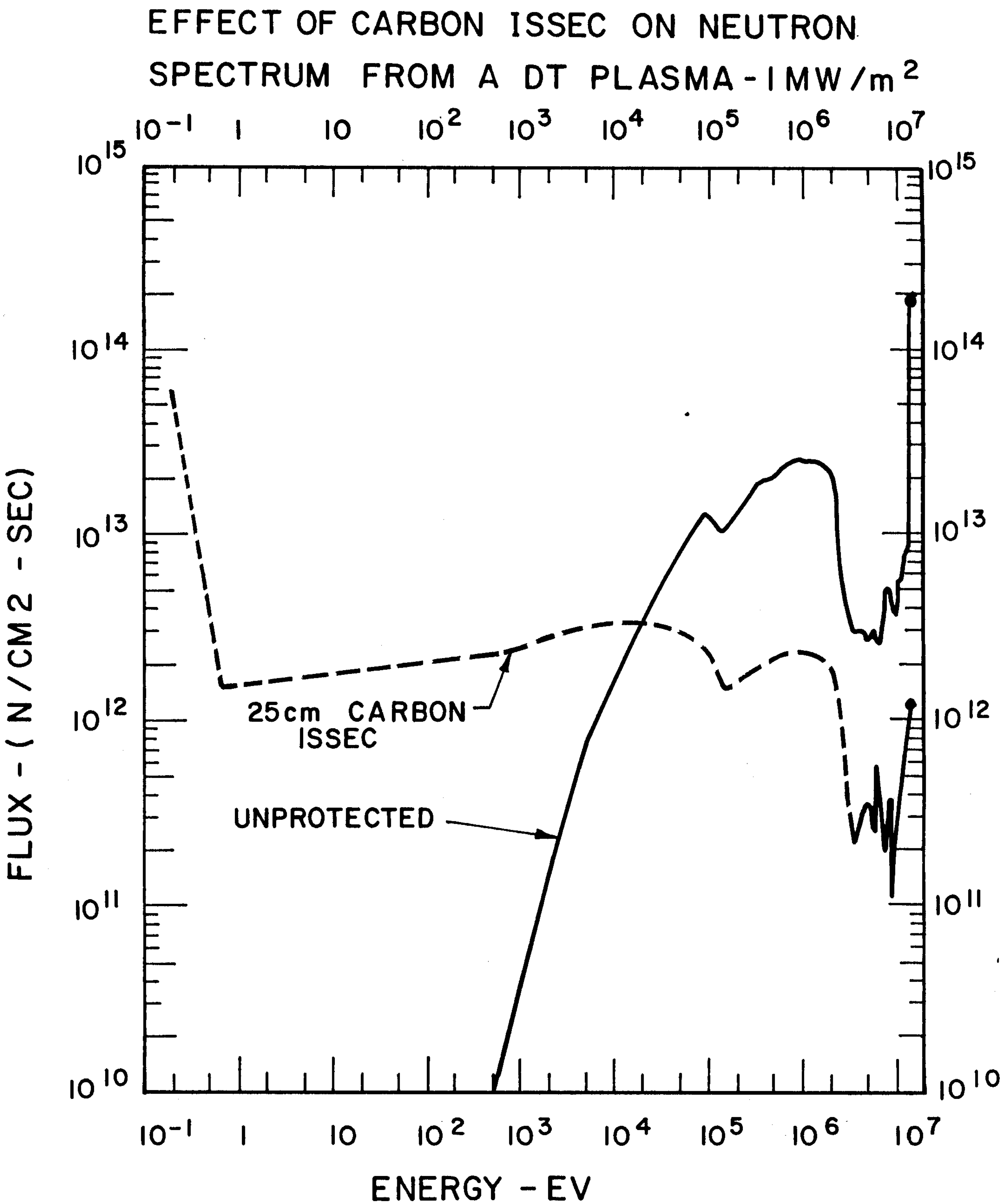
EFFECT OF CARBON ISSEC ON NEUTRON SPECTRUM FROM A DT PLASMA - 1 MW/m²
FLUX - (N/CM2 - SEC)
ENERGY - EV
25cm CARBON ISSEC
UNPROTECTED
10^-1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^15
10^14
10^13
10^12
10^11
10^10

Figure B-1

APPENDIX C

It has been known for some time that anomalous helium production occurs in Ni because of $^{58}Ni(n,\gamma)$ $^{59}Ni(n,\alpha)$ reaction sequence. Therefore, calculations were performed to test how important the ^{59}Ni reaction is to helium production in 316 SS first wall with the comparatively softer spectrum characteristic of 12.5 and 25 cm of ISSEC. Ignoring the burnout of ^{58}Ni atoms, the number of ^{59}Ni atoms as a function of time, N^{59}, due to a concentration of N^{58} of ^{58}Ni atoms undergoing (n,γ) reaction with a cross section σ^{γ}, is

$$N^{59}(t) = \sum_i N^{58}\sigma_i^{\gamma}\phi_i t,$$

where ϕ_i is the neutron flux in the i^{th} energy group. The number of helium atoms, N^{He}, produced in time, T, is then

$$N^{He} = \int_o^T \sum_j N^{59}(t)\sigma_j^{\alpha}\phi_j \, dt$$

$$= \frac{N^{58}T^2}{2} \sum_j \sum_i \sigma_i^{\gamma}\sigma_j^{\alpha}\phi_i\phi_j$$

where σ^{α} is the (n,α) cross section for ^{59}Ni. A more precise treatment would show that as the ^{59}Ni concentration reached steady state, N^{He} would be proportional to T, rather than T^2, which means the results presented here will give a pessimistic estimate of helium production. The (n,α) cross section of Kirouac (Nucl. Sci. Eng., 46, 427, 1971) was used.

FIGURE LIST