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(HFIR, ORR, and EBR-II) Neutron Spectra**

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Fission Reactor (HFIR, ORR, and EBR-II) Neutron Spectra

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ABSTRACT

In order to plan radiation damage experiments in fission reactors keyed toward fusion reactor applications, it is necessary to have available for these facilities displacement per atom (dpa) and gas production rates for many potential materials. This report supplies such data for the elemental constituents of alloys of interest to the United States fusion reactor alloy development program. The calculations are presented for positions of interest in the HFIR, ORR, and EBR-II reactors. DPA and gas production rates in alloys of interest can be synthesized from these results.

I. INTRODUCTION

In a previous paper¹, the calculated irradiation response (damage) in displacements per atom (dpa) and gas production rates in the elemental constituents of many alloys of interest was obtained for a fusion reactor first-wall neutron spectrum. These sets of data allowed a self-consistent evaluation of the effect of alloy modification on dpa and gas production, and defined the levels of anticipated damage for the first wall of a fusion device. In this work similar calculated data are presented for various locations within the HFIR, ORR, and EBR-II fission reactors. The purpose of these data is to provide information to experimentalists for planning and evaluating fission reactor experiments in the light of fusion reactor needs.

II. METHOD OF CALCULATION

The methods used to calculate the irradiation response of elements of interest have been described in detail in Refs. 1, 2, and 3. All elastic, inelastic, charged particle, (n,2n), capture reactions, etc., which are considered in ENDFB/IV, have been included in this analysis. Nuclear data are taken from the ENDFB/IV file, and displacement damage calculations follow the recommendations of the IAEA working group.⁴ Since the particular dpa cross sections used in this work represent a revised set from those used in Ref. 1, the data reported in Ref. 1 dealing with dpa's have been recalculated with the revised set to maintain consistency. The revisions include better integration techniques, (n,p) and (n, α) cross sections for Mo which are not included in ENDFB/IV, and the corrections of small errors noted in the original data set. These corrections reduce

the MFE dpa data reported in Ref. 1 by $\sim 7\%$ and less than 4% for fission type spectra.

The neutron fluxes for the three reactors were taken from 2- and 3-D transport calculations.^{5,6,7} Shown in Fig. 1 are the total fluxes for the HFIR (100 MWt) and ORR (30 MWt) reactors at various locations. Also shown are the fraction of the flux above 0.111 MeV and the fraction that constitutes the thermal flux. Given in Fig. 2 is a typical core loading for the ORR reactor. The location treated in this paper is the C-3 position. The EBR-II fluxes used are for row 2 positions $z = 0$ cm, $r = 5.2$ cm and $z = 60$ cm, $r = 5.2$ cm for run 50H.⁷ The total fluxes at these locations for a reactor power of 62.5 MWt are 2.69×10^{15} and 3.54×10^{14} n/cm² sec, respectively.⁷ The fraction of the flux ≥ 0.111 MeV in the EBR-II positions are 0.882, and 0.425, respectively. It must be remembered that the neutron fluxes presented are for one particular core loading. Variation in core loading of ORR or EBR-II will produce different fluxes and thereby different material responses. The cycle averaged HFIR flux varies very little from cycle to cycle.

Due to the large thermal fluxes in HFIR and ORR, helium production will be dominated in Ni and Ni-bearing alloys by the following reaction

[⁵⁸Ni constitutes 68% of nickel.]

Previous analytic fits to experimental data have yielded an expression proportional to the thermal fluence to the 1.68 power which approximately fitted the currently available experimental data. Since then new data have become available and a better expression for the gas produced has been deduced.⁸ The results are as follows:

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Fig. 1. Variation of cycle averaged total flux as a function of position within the HFIR PTP position and within the ORR C3 position. Also given are the fraction of the thermal flux and fraction of the total flux with energy ≥ 0.111 MeV.

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POOL
W

A-1 Be	A-2 Be	A-3 210	A-4 195	A-5 135	A-6 195	A-7 180	A-8 Be	A-9 Be
B-1 Be	B-2 Be	B-3 225	B-4 SR 110	B-5 135	B-6 SR 110	B-7 165	B-8 150	B-9 Be
C-1 Be	C-2 240	C-3 E	C-4 120	C-5 120	C-6 120	C-7 E	C-8 240	C-9 Be
D-1 Be	D-2 150	D-3 135	D-4 SR 140	D-5 150	D-6 SR 140	D-7 195	D-8 H.T.	D-9 Be
E-1 Be	E-2 210	E-3 E	E-4 180	E-5 E	E-6 180	E-7 E	E-8 210	E-9 Be
F-1 Be	F-2 225	F-3 165	F-4 SR 80	F-5 240	F-6 SR 80	F-7 165	F-8 225	F-9 Be
G-1 Be	G-2 Be	G-3 Be	G-4 Be	G-5 Be	G-6 Be	G-7 Be	G-8 Be	G-9 Be

E

NUMBERS REPRESENT FUEL LOADINGS IN g OF ^{235}U

Be – BERYLLIUM ELEMENT

H.T. – HYDRAULIC TUBE

SR – SHIM ROD

E – EXPERIMENT

Fig. 2. Typical ORR core loading.

$$\frac{N_{\text{He}}}{N_{58\text{Ni}}} = 0.12608 + 0.00664 e^{-92.0\Phi} - 0.13272 e^{-4.6\Phi}$$

where Φ is the 2200 m/s fluence in neutrons/barn units. The relationship

between the 2000 m/s fluence and the thermal fluence

$\left(\int_0^{0.414\text{eV}} \int_0^t \phi(E,t) dE dt \right)$ averages to $\phi_{\text{thermal}} = (1.28 \pm 0.07) \phi_{2200 \text{ m/s}}$ for the reactor positions used in the experiment.⁸ It is recommended that this expression be used in calculating helium production in Ni and Ni-bearing alloys.

The thermal fluences for HFIR and ORR can be obtained from Fig. 1.

III. RESULTS

The effective displacement energies (e.d.e.) used in the calculations are given in Table 1. Presented in Tables 2-16 are the dpa and gas production rates per unit fluence in fission reactors for many elements commonly found in many of the alloys under consideration for application in fusion reactors. To a good approximation, the dpa data given in these tables can be converted to other e.d.e. by multiplying the data given in the tables by the e.d.e. given in Table 1 and by dividing by the new e.d.e. Only the direct contribution to the helium produced in Ni has been included in the tables. Tables 2-7 are for various axial positions within the PTP for the HFIR reactor. Tables 8-13 are for different positions within C3 for the ORR reactor. Tables 14 and 15 are for the two row-2 EBR-II positions. Given in Table 16 for comparative purposes are the data for the first wall fusion device described in Ref. 1. The data given in parentheses in several of the tables are the dpa rates calculated by Doran and Graves.⁷ The only differences noted between the data presented here and that in Ref. 7 are for W and Ta (see Table 2). This disagreement is due to the omission of the (n, γ) displacement cross section in Ref. 7. In nonthermal neutron environments such as the EBR-II

reactor, similar results are obtained for W and Ta (see Table 14).

To illustrate the use of the raw data presented in Tables 2-16, Fig. 1, and in the text, the dpa and He production levels obtained for several alloys and elements after one year of irradiation are given in Table 17. The positions considered for the fission reactors are those with the maximum flux. The e.d.e. used for the alloys is 40 e.v. For Ni and for the Ni-bearing alloys irradiated in thermal environments such as ORR and HFIR, the He production was calculated using Eq. (1) given in the text.

The axial variations of the dpa and He production rates for Fe irradiated in ORR-C3 and HFIR-PTP are given in Fig. 3. Only half of the HFIR data are presented due to the symmetry of the core flux.

IV. CONCLUSIONS

Data have been presented which will aid experimentalists in planning fission reactor experiments and analyzing experimental data in the light of fusion reactor needs. The elemental constituents of most alloys of interest have been included for frequently used positions in HFIR, ORR and EBR-II.

V. AVAILABLE ADDITIONAL CALCULATIONS

Results similar to those presented here are also available for other HFIR, ORR and EBR-II positions. Additional calculations can be performed as required by experimentors. Please contact one of the authors if you need calculations not given in this report. For reactors or reactor positions not covered by ORNL data on file, 100 energy group (GAM-II)^{2,3} neutron energy spectra are required as input to the calculations.

Fig. 3. Spatial variation of the dpa and He production rates for the HFIR (PTP) and ORR (C3) reactors.

Table 1
EFFECTIVE DISPLACEMENT THRESHOLD ENERGIES

Element	Effective Displacement Threshold Energy (eV)
Iron	40
Nickel	40
Chromium	40
Manganese	40
Vanadium	40
Niobium	60
Molybdenum	60
Titanium	30
Zirconium	40
Aluminum	25
Magnesium	25
Copper	30
Cobalt	40
Tungsten	90
Tantalum-181	90
Beryllium	25
Silicon	25

Notes on the Use of Tables 2-16

Defect production rates and gas production rates are given per unit total fluence for fluences in units of neutrons/cm². The dpa rates may be modified for other effective displacement energies by multiplying by the e.d.e. given in Table 1 and by dividing by the new e.d.e. The data may be renormalized to per unit damage flux by dividing by the fraction of flux ≥ 0.111 MeV.

Table 2

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 0.00 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.185E-21(193) ^a	0.517E-22	0.952E-21
NI	0.198E-21(200)	0.773E-21	0.122E-19
CR	0.211E-21(219)	0.180E-22	0.271E-21
MN	0.237E-21	0.195E-22	0.211E-21
V	0.229E-21(235)	0.330E-23	0.165E-21
NB	0.121E-21(125)	0.130E-22	0.935E-22
MO	0.130E-21(126)	0.123E-22	0.248E-22
TI	0.295E-21	0.249E-22	0.402E-22
ZR	0.171E-21(179)	0.255E-24	0.531E-22
AL	0.367E-21(386)	0.112E-21	0.640E-21
MG	0.371E-21	0.461E-21	0.192E-21
CU	0.249E-21(255)	0.498E-22	0.291E-20
CD	0.242E-21	0.259E-22	0.466E-21
W	0.639E-22(510)	0.0	0.624E-25
TA	0.741E-22(520)	0.0	0.959E-23
BE	0.182E-21	0.459E-19	0.205E-24
SI	0.356E-21	0.517E-21	0.120E-20
C		0.281E-21	0.0
N		0.148E-19	0.722E-18
O		0.119E-20	0.353E-23
B10		0.151E-14	0.183E-21
B11		0.609E-23	0.347E-24
LI6		0.369E-15	0.369E-15
LI7		0.414E-20	0.414E-20

^aCoran and Graves, Ref. 7, to be read as 0.193×10^{-21} .

Table 3

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 12.70 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.188E-21	0.526E-22	0.967E-21
NI	0.201E-21	0.785E-21	0.124E-19
CR	0.214E-21	0.183E-22	0.275E-21
MN	0.240E-21	0.198E-22	0.214E-21
V	0.232E-21	0.336E-23	0.167E-21
NB	0.123E-21	0.132E-22	0.950E-22
MO	0.132E-21	0.125E-22	0.252E-22
TI	0.299E-21	0.253E-22	0.408E-22
ZR	0.174E-21	0.259E-24	0.540E-22
AL	0.373E-21	0.114E-21	0.651E-21
MG	0.377E-21	0.468E-21	0.195E-21
CU	0.253E-21	0.506E-22	0.296E-20
CO	0.245E-21	0.264E-22	0.474E-21
W	0.646E-22	0.0	0.634E-25
TA	0.749E-22	0.0	0.974E-23
BE	0.185E-21	0.466E-19	0.208E-24
SI	0.362E-21	0.526E-21	0.122E-20
C		0.285E-21	0.0
N		0.151E-19	0.713E-18
O		0.121E-20	0.359E-23
B10		0.149E-14	0.186E-21
B11		0.619E-23	0.353E-24
LI6		0.364E-15	0.364E-15
LI7		0.420E-20	0.420E-20

Table 4

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 19.05 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.188E-21	0.527E-22	0.969E-21
NI	0.201E-21	0.787E-21	0.124E-19
CR	0.214E-21	0.183E-22	0.276E-21
MN	0.240E-21	0.199E-22	0.215E-21
V	0.232E-21	0.336E-23	0.168E-21
NB	0.123E-21	0.133E-22	0.952E-22
MO	0.132E-21	0.126E-22	0.253E-22
TI	0.299E-21	0.253E-22	0.409E-22
ZR	0.174E-21	0.259E-24	0.541E-22
AL	0.373E-21	0.114E-21	0.652E-21
MG	0.377E-21	0.469E-21	0.196E-21
CU	0.253E-21	0.507E-22	0.296E-20
CO	0.245E-21	0.264E-22	0.475E-21
W	0.646E-22	0.0	0.635E-25
TA	0.748E-22	0.0	0.976E-23
BE	0.185E-21	0.467E-19	0.209E-24
SI	0.362E-21	0.527E-21	0.122E-20
C		0.286E-21	0.0
N		0.151E-19	0.716E-18
O		0.121E-20	0.359E-23
B10		0.149E-14	0.186E-21
B11		0.620E-23	0.353E-24
LI6		0.366E-15	0.366E-15
LI7		0.421E-20	0.421E-20

Table 5

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 25.40 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.152E-21	0.419E-22	0.771E-21
NI	0.165E-21	0.626E-21	0.987E-20
CR	0.173E-21	0.146E-22	0.220E-21
MN	0.200E-21	0.158E-22	0.171E-21
V	0.189E-21	0.268E-23	0.133E-21
NB	0.986E-22	0.105E-22	0.757E-22
MO	0.107E-21	0.100E-22	0.201E-22
TI	0.244E-21	0.201E-22	0.326E-22
ZR	0.140E-21	0.206E-24	0.431E-22
AL	0.300E-21	0.908E-22	0.519E-21
MG	0.303E-21	0.373E-21	0.156E-21
CU	0.205E-21	0.404E-22	0.236E-20
CO	0.215E-21	0.210E-22	0.378E-21
W	0.550E-22	0.0	0.505E-25
TA	0.642E-22	0.0	0.777E-23
BE	0.149E-21	0.372E-19	0.166E-24
SI	0.290E-21	0.419E-21	0.971E-21
C		0.228E-21	0.0
N		0.120E-19	0.842E-18
O		0.962E-21	0.286E-23
B10		0.176E-14	0.148E-21
B11		0.494E-23	0.281E-24
LI6		0.432E-15	0.432E-15
LI7		0.335E-20	0.335E-20

Table 6

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 27.94 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.122E-21	0.330E-22	0.607E-21
NI	0.134E-21	0.493E-21	0.778E-20
CP	0.139E-21	0.115E-22	0.173E-21
MN	0.167E-21	0.124E-22	0.135E-21
V	0.153E-21	0.211E-23	0.105E-21
NE	0.787E-22	0.831E-23	0.597E-22
MO	0.863E-22	0.788E-23	0.158E-22
TI	0.198E-21	0.159E-22	0.256E-22
ZR	0.111E-21	0.162E-24	0.339E-22
AL	0.239E-21	0.715E-22	0.409E-21
MG	0.242E-21	0.294E-21	0.123E-21
CU	0.166E-21	0.318E-22	0.186E-20
CO	0.190E-21	0.166E-22	0.298E-21
W	0.470E-22	0.0	0.398E-25
TA	0.554E-22	0.0	0.612E-23
BE	0.120E-21	0.293E-19	0.131E-24
SI	0.231E-21	0.330E-21	0.765E-21
C		0.179E-21	0.0
N		0.947E-20	0.945E-18
O		0.758E-21	0.225E-23
B10		0.198E-14	0.117E-21
B11		0.389E-23	0.221E-24
Li6		0.486E-15	0.486E-15
Li7		0.264E-20	0.264E-20

Table 7

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE NEUTRON SPECTRUM IN THE PTP OF THE HFIR (R = 5.38, Z = 31.75 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.861E-22	0.225E-22	0.414E-21
NI	0.975E-22	0.336E-21	0.530E-20
CR	0.980E-22	0.781E-23	0.118E-21
MN	0.127E-21	0.847E-23	0.916E-22
V	0.109E-21	0.144E-23	0.715E-22
NB	0.545E-22	0.566E-23	0.406E-22
MO	0.609E-22	0.537E-23	0.108E-22
TI	0.142E-21	0.108E-22	0.175E-22
ZR	0.763E-22	0.111E-24	0.231E-22
AL	0.165E-21	0.487E-22	0.278E-21
MG	0.166E-21	0.200E-21	0.835E-22
CU	0.118E-21	0.217E-22	0.126E-20
CO	0.160E-21	0.113E-22	0.203E-21
W	0.372E-22	0.0	0.271E-25
TA	0.443E-22	0.0	0.417E-23
BE	0.826E-22	0.199E-19	0.890E-25
SI	0.159E-21	0.225E-21	0.521E-21
C		0.122E-21	0.0
N		0.645E-20	0.109E-17
O		0.516E-21	0.153E-23
B10		0.228E-14	0.794E-22
B11		0.265E-23	0.151E-24
LI6		0.559E-15	0.559E-15
LI7		0.180E-20	0.180E-20

Table 8

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE ORR POSITION C3, 26.7 cm FROM HORIZONTAL MIDPLANE (221307)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.230E-21	0.652E-22	0.111E-20
NI	0.244E-21	0.926E-21	0.141E-19
CR	0.261E-21	0.238E-22	0.327E-21
MN	0.286E-21	0.258E-22	0.258E-21
V	0.283E-21	0.492E-23	0.199E-21
NB	0.152E-21	0.162E-22	0.114E-21
MO	0.163E-21	0.161E-22	0.313E-22
TI	0.363E-21	0.326E-22	0.531E-22
ZR	0.217E-21	0.455E-24	0.635E-22
AL	0.466E-21	0.148E-21	0.762E-21
MG	0.474E-21	0.563E-21	0.248E-21
CU	0.309E-21	0.640E-22	0.340E-20
CO	0.278E-21	0.334E-22	0.563E-21
W	0.764E-22	0.0	0.126E-24
TA	0.893E-22	0.0	0.112E-22
BE	0.230E-21	0.524E-19	0.469E-24
SI	0.456E-21	0.634E-21	0.144E-20
C		0.391E-21	0.0
N		0.174E-19	0.514E-18
O		0.140E-20	0.644E-23
B10		0.106E-14	0.218E-21
B11		0.969E-23	0.704E-24
LI6		0.261E-15	0.261E-15
LI7		0.485E-20	0.485E-20

Table 9

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE ORR POSITION C3, 16.5 cm FROM HORIZONTAL MIDPLANE (221311)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.266E-21	0.784E-22	0.135E-20
NI	0.281E-21	0.112E-20	0.171E-19
CR	0.302E-21	0.286E-22	0.395E-21
MN	0.326E-21	0.309E-22	0.311E-21
V	0.326E-21	0.589E-23	0.240E-21
NB	0.176E-21	0.195E-22	0.138E-21
MO	0.188E-21	0.193E-22	0.376E-22
TI	0.419E-21	0.391E-22	0.637E-22
ZP	0.251E-21	0.543E-24	0.771E-22
AL	0.537E-21	0.178E-21	0.920E-21
MG	0.545E-21	0.580E-21	0.298E-21
CU	0.357E-21	0.769E-22	0.409E-20
CO	0.310E-21	0.401E-22	0.673E-21
W	0.855E-22	0.0	0.151E-24
TA	0.982E-22	0.0	0.134E-22
BE	0.265E-21	0.640E-19	0.563E-24
SI	0.525E-21	0.763E-21	0.173E-20
C		0.469E-21	0.0
N		0.209E-19	0.425E-18
O		0.168E-20	0.770E-23
B10		0.872E-15	0.262E-21
B11		0.116E-22	0.842E-24
LI6		0.214E-15	0.214E-15
LI7		0.585E-20	0.585E-20

Table 10

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE ORR POSITION C3, 6.35 cm FROM HORIZONTAL MIDPLANE (221315)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APP4/UNIT FLUENCE)
FE	0.266E-21	0.782E-22	0.135E-20
NI	0.281E-21	0.112E-20	0.170E-19
CR	0.302E-21	0.285E-22	0.394E-21
MN	0.326E-21	0.309E-22	0.310E-21
V	0.326E-21	0.588E-23	0.240E-21
NB	0.176E-21	0.195E-22	0.137E-21
MO	0.188E-21	0.193E-22	0.376E-22
TI	0.419E-21	0.391E-22	0.636E-22
ZR	0.251E-21	0.542E-24	0.770E-22
AL	0.537E-21	0.178E-21	0.918E-21
MG	0.545E-21	0.678E-21	0.298E-21
CU	0.357E-21	0.767E-22	0.408E-20
CO	0.310E-21	0.400E-22	0.672E-21
W	0.854E-22	0.0	0.151E-24
TA	0.980E-22	0.0	0.134E-22
BE	0.265E-21	0.639E-19	0.562E-24
SI	0.524E-21	0.762E-21	0.173E-20
C		0.458E-21	0.0
N		0.209E-19	0.424E-18
O		0.168E-20	0.769E-23
B10		0.871E-15	0.262E-21
B11		0.115E-22	0.841E-24
LI6		0.214E-15	0.214E-15
LI7		0.584E-20	0.584E-20

Table 11

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE ORR POSITION C3, -3.9 cm FROM HORIZONTAL MIDPLANE (221319)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.265E-21	0.780E-22	0.134E-20
NI	0.280E-21	0.111E-20	0.170E-19
CR	0.301E-21	0.285E-22	0.393E-21
MN	0.325E-21	0.308E-22	0.309E-21
V	0.325E-21	0.586E-23	0.239E-21
NB	0.175E-21	0.194E-22	0.137E-21
MO	0.188E-21	0.192E-22	0.375E-22
TI	0.418E-21	0.390E-22	0.634E-22
ZR	0.251E-21	0.541E-24	0.768E-22
AL	0.536E-21	0.177E-21	0.916E-21
MG	0.544E-21	0.677E-21	0.297E-21
CU	0.356E-21	0.766E-22	0.407E-20
CO	0.310E-21	0.399E-22	0.670E-21
W	0.852E-22	0.0	0.150E-24
TA	0.977E-22	0.0	0.134E-22
BE	0.264E-21	0.538E-19	0.561E-24
SI	0.523E-21	0.760E-21	0.172E-20
C		0.467E-21	0.0
N		0.208E-19	0.429E-18
O		0.168E-20	0.767E-23
B10		0.880E-15	0.261E-21
B11		0.115E-22	0.839E-24
LI6		0.216E-15	0.216E-15
LI7		0.583E-20	0.583E-20

Table 12

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE NEUTRON SPECTRUM IN THE ORR POSITION C3, -14.0 cm FROM HORIZONTAL MIDPLANE (221323)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.268E-21	0.791E-22	0.136E-20
NI	0.283E-21	0.113E-20	0.172E-19
CR	0.304E-21	0.288E-22	0.399E-21
MN	0.328E-21	0.312E-22	0.313E-21
V	0.328E-21	0.594E-23	0.242E-21
NB	0.177E-21	0.197E-22	0.139E-21
MO	0.190E-21	0.195E-22	0.380E-22
TI	0.422E-21	0.395E-22	0.642E-22
ZR	0.253E-21	0.548E-24	0.778E-22
AL	0.541E-21	0.180E-21	0.928E-21
MG	0.549E-21	0.686E-21	0.301E-21
CU	0.360E-21	0.775E-22	0.412E-20
CC	0.312E-21	0.405E-22	0.679E-21
W	0.859E-22	0.0	0.152E-24
TA	0.983E-22	0.0	0.136E-22
BE	0.267E-21	0.647E-19	0.568E-24
SI	0.528E-21	0.770E-21	0.174E-20
C		0.473E-21	0.0
N		0.211E-19	0.425E-18
O		0.170E-20	0.777E-23
B10		0.872E-15	0.264E-21
B11		0.117E-22	0.850E-24
LI5		0.214E-15	0.214E-15
LI7		0.591E-20	0.591E-20

Table 13

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE
NEUTRON SPECTRUM IN THE ORR POSITION C3, 24.1 cm FROM HORIZONTAL MIDPLANE (221327)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.265E-21	0.780E-22	0.134E-20
NI	0.280E-21	0.111E-20	0.170E-19
CR	0.301E-21	0.285E-22	0.393E-21
MN	0.325E-21	0.308E-22	0.309E-21
V	0.324E-21	0.586E-23	0.239E-21
NB	0.175E-21	0.194E-22	0.137E-21
MO	0.187E-21	0.192E-22	0.375E-22
TI	0.417E-21	0.390E-22	0.634E-22
ZR	0.250E-21	0.541E-24	0.767E-22
AL	0.534E-21	0.177E-21	0.916E-21
MG	0.542E-21	0.676E-21	0.297E-21
CU	0.355E-21	0.765E-22	0.407E-20
CO	0.310E-21	0.399E-22	0.670E-21
W	0.850E-22	0.0	0.150E-24
TA	0.974E-22	0.0	0.134E-22
BE	0.263E-21	0.637E-19	0.561E-24
SI	0.522E-21	0.760E-21	0.172E-20
C		0.467E-21	0.0
N		0.208E-19	0.440E-18
O		0.168E-20	0.767E-23
B10		0.905E-15	0.261E-21
B11		0.115E-22	0.839E-24
LI6		0.222E-15	0.222E-15
LI7		0.583E-20	0.583E-20

Table 14

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE NEUTRON SPECTRUM OF ROW 2, 0. cm ABOVE THE MIDPLANE IN EBR-II (R = 5.2 cm, Z = 0.0 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.440E-21 (436) ^a	0.675E-22	0.129E-20
NI	0.483E-21 (480)	0.963E-21	0.173E-19
CR	0.506E-21 (505)	0.262E-22	0.356E-21
MN	0.517E-21	0.275E-22	0.270E-21
V	0.543E-21 (542)	0.594E-23	0.207E-21
NB	0.329E-21 (325)	0.169E-22	0.118E-21
MO	0.343E-21 (325)	0.170E-22	0.329E-22
TI	0.650E-21	0.337E-22	0.554E-22
ZR	0.497E-21 (491)	0.601E-24	0.714E-22
AL	0.107E-20 (106)	0.157E-21	0.780E-21
MG	0.120E-20	0.613E-21	0.255E-21
CU	0.632E-21 (627)	0.658E-22	0.434E-20
CO	0.487E-21	0.346E-22	0.659E-21
W	0.124E-21 (121)	0.0	0.364E-24
TA	0.126E-21 (121)	0.0	0.141E-22
BE	0.621E-21	0.655E-19	0.144E-23
SI	0.103E-20	0.623E-21	0.142E-20
C		0.445E-21	0.0
N		0.231E-19	0.217E-19
O		0.142E-20	0.982E-23
B10		0.971E-18	0.216E-21
B11		0.118E-22	0.114E-23
LI6		0.771E-18	0.772E-18
LI7		0.502E-20	0.503E-20

^aDoran and Graves, Ref. 7, to be read as 0.436×10^{-21} .

Table 15

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE NEUTRON SPECTRUM OF ROW 2, 60 cm ABOVE THE MIDPLANE IN EBR-II (R = 5.2 cm, Z = 60.0 cm)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM (APPM/UNIT FLUENCE)	HYDROGEN (APPM/UNIT FLUENCE)
FE	0.146E-21	0.226E-23	0.405E-22
NI	0.198E-21	0.270E-22	0.618E-21
CR	0.168E-21	0.814E-24	0.109E-22
MN	0.186E-21	0.931E-24	0.776E-23
V	0.217E-21	0.178E-24	0.608E-23
NB	0.120E-21	0.539E-24	0.348E-23
MO	0.123E-21	0.565E-24	0.105E-23
TI	0.252E-21	0.118E-23	0.194E-23
ZR	0.192E-21	0.137E-25	0.206E-23
AL	0.432E-21	0.557E-23	0.221E-22
MG	0.502E-21	0.169E-22	0.924E-23
CU	0.237E-21	0.234E-23	0.182E-21
CO	0.186E-21	0.119E-23	0.267E-22
W	0.448E-22	0.0	0.645E-26
TA	0.464E-22	0.0	0.534E-24
BE	0.394E-21	0.200E-20	0.251E-25
SI	0.384E-21	0.219E-22	0.478E-22
C		0.149E-22	0.0
N		0.997E-21	0.111E-19
O		0.369E-22	0.237E-24
B10		0.131E-16	0.729E-23
B11		0.337E-24	0.208E-25
Li6		0.367E-17	0.367E-17
Li7		0.139E-21	0.139E-21

Table 16

DPA AND GAS PRODUCTION RATES IN THE ELEMENTAL CONSTITUENTS OF FUSION CANDIDATE ALLOYS FOR THE NEUTRON SPECTRUM AT THE FIRST WALL OF A FUSION REACTOR (see Ref. 1)

ELEMENT	DISPLACEMENT DAMAGE (DPA/UNIT FLUENCE)	HELIUM ^a	HYDROGEN ^a
		(APPM/UNIT FLUENCE)	(APPM/UNIT FLUENCE)
FE	0.933E-21	0.967E-20	0.417E-19
NI	0.984E-21	0.360E-19	0.110E-18
CR	0.968E-21	0.903E-20	0.277E-19
MN	0.927E-21	0.739E-20	0.278E-19
V	0.953E-21	0.416E-20	0.217E-19
NB	0.592E-21	0.254E-20	0.922E-20
MO	0.610E-21	0.409E-20	0.597E-20
TI	0.129E-20	0.927E-20	0.138E-19
ZR	0.829E-21	0.811E-21	0.698E-20
AL	0.128E-20	0.279E-19	0.262E-19
MG	0.122E-20	0.406E-19	0.410E-19
CU	0.125E-20	0.881E-20	0.480E-19
CO	0.926E-21	0.640E-20	0.204E-19
W	0.279E-21	0.0	0.672E-21
TA	0.303E-21	0.0	0.366E-21
BE	0.489E-21	0.326E-18	0.522E-20
SI	0.125E-20	0.441E-19	0.825E-19
C		0.167E-18	0.0
N		0.568E-19	0.399E-19
O		0.326E-19	0.114E-19
B10		0.249E-17	0.796E-20
B11		0.653E-20	0.346E-20
LI6		0.851E-18	0.853E-18
LI7		0.997E-19	0.102E-18

^aMultiply by 3.6074×10^{14} to convert to DPA/sec/1 MW/m² or appm/sec/1 MW/m².

Table 17
DPA AND HELIUM PRODUCTION PER YEAR IN AN MFR AND IN FISSION REACTORS OF INTEREST
TO FUSION REACTOR ALLOY DEVELOPMENT PROGRAMS
(All calculations are for a plant factor of 1.0)

Element or Alloy	Reactor and Position							
	MFR		ORR		HFIR		EBR-II	
	First Wall ¹		C-3 ²		PTP ²		Row 2 ²	
	dpa	He (appm)	dpa	He (appm)	dpa	He (appm)	dpa	He (appm)
Fe	10.6	110.	7.1	2.1	30.9	8.6	37.3	5.7
SS-316 ³	10.7	155.	7.4	76.9 ⁶	32.2	2187. ⁶	39.2	15.1
PE-16 ⁴	10.8	228.	7.4	258. ⁶	32.4	7316. ⁶	39.5	37.0
Inconel 600 ⁵	10.9	332.	7.5	468. ⁶	32.8	13320. ⁶	40.4	62.0
Ni	11.2	409.	7.5	626. ⁶	33.1	17791. ⁶	40.9	81.6
Ti	14.7	105.	11.2	1.1	49.3	4.2	55.1	2.9
V	10.8	47.	8.7	0.16	38.2	0.55	46.0	0.5
Nb	6.7	29.	4.7	0.52	20.2	2.2	27.9	1.4

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¹ Wall loading 1 MW/m²

² Maximum flux position

³ Fe, 63.22; Cr, 19.21; Ni, 12.29; Mo, 1.49; Mn, 1.92; Ti, 0.06; Si, 1.58; C, 0.23; Atom %.
Effective Displacement Energy = 40 eV

⁴ Fe, 34.62; Cr, 17.77; Ni, 41.12; Mo, 1.87; Ti, 1.38; Al, 2.58; Si, 0.42; C, 0.24. E.D.E. = 40 eV

⁵ Fe, 6.84; Cr, 16.78; Ni, 74.87; Mn, 0.33; Ti, 0.22; Al, 0.15; Si, 0.57; C, 0.24; Atom %. E.D.E. = 40 eV

⁶ Calculated from Eq. (1) and does not scale linearly with time!

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