COMMISSION OF THE EUROPEAN COMMUNITIES

nuclear science and technology

RECOMMENDATIONS ON THE MEASUREMENT OF IRRADIATION RECEIVED BY THE STRUCTURAL MATERIALS OF REACTORS

by

J.P. GENTHON, B.W. HASENCLEVER, P. MAS, W. SCHNEIDER, S.B. WRIGHT and W.L. ZIJP

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Following an explanation of some theoretical aspects, practical guidelines for neutron metrology on irradiation of graphite and of metals are given. A thorough knowledge of the spectrum of the incident neutrons is required for a proper interpretation of the results of irradiation experiments.

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SUMMARY

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I. INTRODUCTION

During its meeting at Petten on 9.3.71, under the chairmanship of Prof. U. Farinelli (Casaccia), the Euratom Working Party on Dosimetry of Reactor Radiations decided to tackle the problem of measuring irradiation received by structural materials.

Approved at a plenary meeting of the Euratom Working Party on Dosimetry on 15.3.74 at Brussels, this recommendation replaces those already issued ([9] and [10]). It is an updated and completed synthesis of them.

It must be made clear that our primary concern was to finalise a number of standards on which there could be general agreement now, even if at the cost of updating later on, having regard to the development of knowledge on radiation-induced damage in materials. Certain choices of model, or of a constant may very well be quasi-arbitrary, when there does not appear, at this time, to be any major physical reason to choose one rather than the other. We therefore used that which was most suited, in practice, to general agreement.

As a general rule, the choice made was the measurement of irradiation received in accordance with the number of displacements induced in the solid under consideration.

The Dosimetry Group of the I.A.E.A. adopted [11] a recommendation which is compatible with this one in almost every case.

II. PRINCIPLE OF DEFINITION OF FLUENCES

II.1 GENERAL PRINCIPLES

It is known that the effect of irradiation of a solid in a reactor is to modify its physical properties.

At the origin of these changes in physical properties, there are:

- on the one hand, neutron collision reactions which, by the transfer of kinetic energy, displace atoms directly or indirectly, and thus alter the structure of the solid. These atom displacements can occur in various groups, and there will accordingly be several possible changes of structure;

- on the other hand, nuclear neutron reactions which, by transmutation, change the actual nature of the nuclides which are subjected to the reaction; foreign atoms are thus introduced. Furthermore, when these new nuclides are formed, they are usually endowed with enough kinetic energy to displace atoms and thus bring about structural changes as previously.

Various changes of crystal structure and modification of atomic nature are likewise events making up what we shall call the Source of changes[1]. This Source s is distributed according to the various types i of events, whose number is s_i, per unit time and volume.

A neutron flux density ϕ - with a spectrum distribution $\phi(E)$ - is thus the cause of a source of changes, s.

The accumulation of events from the Source, and their regrouping of annihilation etc., lead to a state of microscopic equilibrium d made up of new modifications j in the solid, more complex and usually of greater size, whose number is d_j per unit volume.

New physical properties of the solid correspond to its new microscopic state, and these constitute radiation-induced damage.

The various types of event i from the Source have, for a given variation of physical property D, an incidence which varies from one type of event to another. To simplify this here, an approximation will be made according to which only one (or two) types of event, k, have an influence on the given variation D.

It is thus the appropriate Source s_k which well characterises the irradiation received as far as D is concerned, and not the neutron flux. The origin of s_k matters little, whether it is a question of reactor neutrons of some energy or

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(1) - that is to say rate of changes.

another, or even of ions in an accelerator, etc., once s_k is well defined.

For this reason the fluences received on irradiation will be defined on the following principles, with regard to a given physical effect D:

a) choice of type (or types) of event k of prime importance as regard the effect D;

b) calculation of number of events $\int s_k dt = S_k$;

c) choice of a practical scale of fluence, expressing a fluence proportional to the quantity S_k. If two types of event, i and k have had to be considered (e.g. helium produced and induced atom displacements), two fluences must be determined, proportional - even equal, according to the unit chosen - to S_i and S_k.

II.2 VARIOUS TYPES OF EVENT CONSTITUTING THE TERM "SOURCE"

II.2 a) Modification of the nature of atoms (nuclear reactions):

Creation of gas by (n,α) or (n,p) reactions, introduction of chemical impurities etc. The calculation of these foreign atoms is a pure neutron physics problem; it is a problem of knowledge of the cross sections of the appropriate reactions; we shall not mention them any more here.

II.2 b) Structural modifications of the solid:

A neutron collision reaction, whether elastic or inelastic, imparts a kinetic energy of greater or less significance to the atom collided with. A nuclear reaction leads to one or more new nuclei which are themselves given kinetic energy; moreover, the excited nuclei which will be formed will be endowed with kinetic energy on their return to the stable state. Changes in the structure of the solid are induced by the collision of these initial atoms, called primaries, and the transformation of their kinetic energy.

Definition of the kinetic energy E_p of the primary atom is again a neutron physics problem of knowledge of the cross sections of the appropriate reactions.

Change in the structure of a solid by the action and transformation of the kinetic energy of the primary is no longer a neutron physics problem of nuclear collision, but one of atomic collision.

In more detail, it is known that a neutron with energy E_n can collide with a nucleus in the irradiated solid, and impart to it a kinetic energy E_p; if for example E_n = 1 MeV, for a nucleus of middle atomic number we shall have $E_p \sim 40$ keV; this value E_p is much higher than the energy E_d needed to strip

an atom away from its crystal structure ($E_d \sim$ some tens of eV); the first atom (primary atom) is therefore set in motion in the solid. It is an atom and no longer a neutron; its slowing down will be caused by electrostatic (and quantum) interaction with the higher or lower charged particles which make up the solid (electrons and ions).

Various mechanisms tend to appear: distribution between electron and atom collisions; cascade of atomic collisions; channelling, focussing, creation of vacancy-interstitial pairs, and creation of various defect zones:

b.1) Slowing down by electrons and atoms: Excitation of electrons by collisions with the incident primary atom does not effect the structure of the solid; consequently the associated events take no part in the constitution of the term Source defined earlier. A first problem, therefore, is to take into consideration the energy transferred in electron collisions E_i which does not concern us, and that transferred in atom collisions E_r.

A fairly high energy can put in question the integrity of an atom by stripping away some of its orbiting electrons (electron collisions). On the other hand, atomic interactions will be proportionately greater as the energies transferred are lower, and insufficient for such electron stripping.

Moreover, at a given neutron energy E_n, the energy E_p of the primary is proportionally smaller as the mass number A of the irradiated solid is greater; we have, for example, in the case of a simple elastic collision, as a mean:

$$E_p = \frac{2A}{(A+1)^2} E_n$$

E_n = energy of the initial neutron;

E_p = energy of the atom collided with by the neutron (the primary atom); E_p varies as E_n and as A^{-1} where A is the mass number of the atom.

E_i = energy transferred in electron collision (ionisation);

E_r = energy transferred in atomic collision (energy transferred to the lattice.

E_r/E_p increases as E_r/E_i increases

i.e. as E_p^{-1},

i.e. as A.

It will suffice to conclude this very simplified scheme on this essential fact:

the part of the energy transferred to the lattice, E_r (atomic collision) is proportionately greater than the ionisation part E_i (electron collision), as the atomic number of the irradiated solid is greater, and as the neutron energy is lower.

At present, the universal Lindhard model [1] provides the best theoretical treatment for most cases.

It is expressed according to: (see [2])

$$E_r = \frac{E_p}{1 + k\, g(\varepsilon)}$$

where ε is a reduced expression of energies E : $\varepsilon = E/e$

$$\text{with} \quad e = 86.93\, Z^{7/3} \text{ eV}$$

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

$$k = 0.1337\, Z^{2/3}\, A^{-1/2}$$

Z = atomic number A = mass number

(N.B. In the case of mixtures or alloys of nuclides with adjacent atomic numbers (steel), mean values of Z and A can be used; the approximation is very good. On the other hand, in the case of mixtures of nuclides with greatly differing atomic numbers, e.g. metal oxides, these relations are excluded. The full calculation must be undertaken, using the Lindhard slow-down powers [1].

As will be seen in the case of graphite, a more empirical model was preferred, which, on the one hand was that generally used for graphite, and on the other hand appeared to be better proved by experiment.

b.2) Collision cascade:

The primary atom set in motion in the solid can collide with another atom, giving it sufficient energy to be itself set in motion; then these two moving atoms can each collide with another one and set it in motion; in the same way those 4 moving atoms displace 4 others, then the 8 will displace others, and so on. There is cascade multiplication of displaced atoms until, following successive bipartitions of energy at each multiplication - and losses through electron collisions accompanying this atomic collision mechanism - the energy per moving atom becomes close to the minimum displacement energy E_d.

Figure 1 shows this collision cascade. Each atomic position left empty by the expulsion of its atom is a vacancy; each excess atom, at the end of a cascade, is an interstitial.

Actually, the situation at the end of the cascade is not so simple as the above description may leave one to think.

A more precise description calls for a quick consideration of the laws of electrostatic interaction: a charged particle in motion can approach the objective charged particle more closely as its kinetic energy increases; in particular the minimum approach distance can be defined; it is, in a head on collision, the minimum approach following which the incident particle rebounds by electrostatic repulsion. The "hard spheres" approximation describes the collision by considering the interaction of two hard spheres of radius equal to the minimum approach distance. The continuously variable repulsive electrostatic potential is then replaced by a jump potential, varying from 0 to infinity at the minimum approach distance.

It can be seen that the hard spheres approximation considers the interaction of particles as the collision of 2 spheres whose radius increases as the energy decreases. This approximation is sufficient to bring out here some phenomena which complicate the slowing-down cascade.

b.3) Displacement zones [3]:

The sphere equivalent to the particle sees its radius grow progressively as it slows down until it attains dimensions comparable to interatomic distances, from and below a kinetic energy limit E_s. Collisions then occur involving atoms which are very close to each other, too close to be considered separately.

Their grouping delineates a zone in the solid which we shall call the displacement zone: it is no longer possible to speak of a cascade of independent collisions within this zone.

Many characteristics must be considered with regard to the displacement zone:

- an energy limit higher than the primary E_s[(2)], below which the collisions most probably induce a zone; E_s increases when the atomic number of the nuclide under consideration increases. For graphite, for example, $E_s \sim 1$ keV; for iron, $E_s \sim 75$ keV; for gold, $E_s = 1$ MeV (see [3]).

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(2) marked as E_0 in [3].

- a lower energy limit E_m, below which the zone created is unstable. We have, for iron $E_m \sim 3$ keV (see [4]). A value formerly used was $E_m = 0.4$ keV (see [5]); it is no longer used to-day.

- recombination in the zone: an interstitial atom, created by a branch of the cascade, can end up, inside a zone, in the vicinity of a vacancy left by another branch. There is, then, reciprocal annihilation by recombination of these two defects.

In fact, within the zone, the rate of such combinations will be significant; it is above all the interstitials projected into a periphery distant from the vacancies, especially by focussing (see below), which escape these recombinations, which reduce the number of defects remaining by a factor of about 2.

- The zone accordingly consists of a central zone, essentially of vacancies, surrounded by a peripheral interstitial zone. The number of vacancy-interstitial pairs is appreciably less there (a factor of 2?) than if the slowing down were the result of a cascade of collisions which are separate from each other and independent (i.e. without recombination).

b.4) Focussing and channelling [6]:

Channelling is a high energy phenomenon, where the particle, of small radius, follows a path almost parallel to the atom lines in the crystal, equidistant from these lines and channelled by them. As the particle has a small radius, there are few interactions.

In focussing, on the other hand, it is a question of a large radius low energy particle, which hits a line of atoms in their direction of alignment. Here there can be step by step substitution of atoms, and/or step by step energy propagation along this line in quasi-adiabatic conditions. Channelling and focussing imply a large distance covered by the particle without apparent displacement of atoms, either because there may not actually have been any displacements induced (channelling), or because all the collisions were of replacement type, where there is atom substitution, that is to say, as regards results, apparently no displacement (focussing).

A primary cannot be found at the start on a channelable path; it is at the outset a crystal atom, i.e. an atom situated on a line. It is only after collision that its path will merge into a channel. It will then already have lost energy, and grown larger (radius of the equivalent sphere) and will therefore be less subject to channelling. Channelling is therefore a phenomenon of small importance so far as radiation damage by neutrons is concerned.

As to focussing, it is liable to play a significant part in the analysis of radiation-induced damage in steels. It permits long distance transfer of atoms - the crowdion - and, through this mechanism, leads to interferences between zones.

A law of saturation of effect could be established from zones and crowdions [7].

b.5 Independent displacements. Independent vacancy-interstitial pairs

An interstitial is very clearly associated somewhere with each vacancy. In the case where the collision cascade does not cause the occurrence of displacement zone phenomena, i.e. in the case where the distance between collisions is large by comparison with the atomic distance, there is no interaction between defects created; it can be said that they are independent.

At the start of slowing down ($E_p > E_s$), the primary could either induce such independent vacancy-interstitial pairs (low energy transfer), or induce zone generating secondaries (high energy transfer). Actually, it is fairly difficult and probably illusory to wish to make an exact count of independent defects produced by neutron irradiation. They are undoubtedly a minor phenomenon in relation to the zone phenomenon.

Nevertheless, it can be said qualitatively that independent defects are especially related to the $E_p > E_s$ area, i.e. a region of high energy and/or a low atomic number of the particle.

Figure 4 summarises all these phenomena.

II.2 - c) Conclusion

Types of event concerned in the constitution of the term Source:

We have seen that it may be useful to consider focussing and the number of crowdions.

It may be useful to consider the number of stable zones created. In particular, as regards mechanical properties of metals, it can be said that the "impurity" which constitutes a zone plays a part analogous to that played by a carbon impurity in iron converted into steel.

If we ignore the possible effect of zone size, and assume that each primary having energy higher than E_m forms one zone, and one only (which is very debatable!), then it is sufficient to consider the number of a primary whose energy is $E_p > E_m$; we have seen, for iron: $E_m = 3$ keV (and formerly 0.4 keV).

If, on the other hand, we wish to consider, on the grounds of fairness, all the zones which may be created (and not just one alone, by the primary), and if we make the hypothesis, certainly more arguable, of a zone effect more or less proportinal to its size, it is then sufficient to consider the total size of the zones created, i.e. the total number of displacements induced by a primary as zone phenomena.

As a general rule, the simplest and undoubtedly the fairest way in the present state of knowledge, is to consider the total number of displacements assumed to be induced in a cascade of defects which are all independent.

We are not looking here for an absolute number of displacements; a relative value, containing an unknown constant coefficient k is sufficient. Focussing may occur at the end of a cascade to stop chain multiplication of atoms; in this case it is taken into account in k.

If the quasi-totality of the cascade then produces the zone mechanism, there is a reduced number of displacements, by a factor which can again, as a first approximation, be assumed to be constant; it is taken into account in k.

On the other hand, it must be said that too high a proportion (though unlikely) of truly independent displacements, with high primary energy, could lead to a variation of the k factor with the energies.

Channelling can be ignored. Ionisation must certainly be considered (see above).

It is atom displacements, assumed to be all independent, which, as a general rule will constitute the retention component s_k of the term "Modification Source". It is the number of these displacements (or any proportional quantity) which will define the irradiation fluence. Along with this main fluence, other fluences may be expressed according to the case, proportional to a number of transmutations, to a number of zones of such and such a size, to a number of crowdions, etc.

We shall find, particularly in [8], a detailed description of displacements assumed to be independent, for various bodies.

Finally, and to allow for the possible use of other models (a more sophisticated model in the future, for example), it is necessary to retain, alongside the fluences defined above, all possible information on the neutron spectrum, and on the total flux and neutron fluence relating to the irradiation.

III. QUANTITIES USED

The following quantities and their corresponding notations are defined:

III.1 DAMAGE FUNCTION AND DAMAGE CROSS SECTION

The damage function w(E) expresses, by definition, a quantity of radiation-induced effects (energy transferred, number of atoms displaced, etc.) per unit of fluence at an energy E.

The damage cross section $\sigma_w(E)$ is the cross section for a given quantity of radiation-induced effect. If for example we call this conventional quantity q, we have:

$$w(E) \equiv q\, \sigma_w(E).$$

III.2 FISSION FLUENCE AND RAPID FLUENCE

The fission fluence Φ_x^f (or in brief, Φ_x) is the equivalent fission fluence as far as it concerns a given reaction governed by a cross section $\sigma_x(E)$ (or $\sigma_{wx}(E)$, or a damage function $w_x(E)$)

$$\boxed{\Phi_x^f = \frac{1}{\sigma_x^f} \int_0^\infty \sigma_x(E)\Phi_E(E)dE} = \Phi_x \text{ (in brief)}$$

where $$\sigma_x^f = \int_0^\infty \sigma_x(E)\chi_E(E)dE$$

$\chi_E(E)$ = normalised fission spectrum: $\int_0^\infty \chi_E(E)dE \equiv 1$

The same definition can be made from the functions $\sigma_w(E)$ or w(E), used in place of $\sigma(E)$ (the notation σ_w^f or w(E) then takes the place of σ^f).

N.B. Two representations of $\chi_E(E)$ will possibly be used later, either $\chi_E(E) = 0.77\, E^{0.5} \exp(-0.775\, E)$ (the Leachman formula), or $\chi_E(E) = 0.484 \exp(-E) \sinh \sqrt{2E}$ (the Watt formula) where E is expressed in MeV.

The rapid fluence Φ^r is the fluence of neutrons with an energy above a certain threshold E_{min}, whatever the reaction x or any other means used to determine it may be.

$$\Phi^r = \int_{E_{min}}^{\infty} \Phi_E(E)dE$$

(in English, we shall speak of "rapid fluence" and not "fast fluence", which would lead to the notation Φ^f, already used for "fission fluence".)

The value chosen for E_{min} must be specified in each case; present values are 1 MeV and, even better, 100 keV.

The systematic use of the notations Φ^f and Φ^r is recommended to avoid any ambiguity between fission fluence and rapid fluence (their ratio varies in proportions which may be large, and confusion is frequent).

III.3 DENSITY OF FISSION FLUX AND OF RAPID FLUX

Their definition is analogous to that of fluences:

fission flux ϕ_x^f (or ϕ_x in brief)

$$\phi_x^f = \phi_x = \frac{1}{\sigma_x^f} \int_0^{\infty} \sigma_x(E)\phi_E(E)dE$$

rapid flux ϕ^r

$$\phi^r = \int_{E_{min}}^{\infty} \phi_E(E)dE$$

III.4 SPECTRUM INDICES

If i is a reaction governed by a cross section $\sigma_i(E)$, or a damage function $w_i(E)$, and if j is another reaction governed by $\sigma_j(E)$ or $w_i(E)$, the index can be defined:

$$\rho_{ij} = \Phi_i^f / \Phi_j^f = \phi_i^f / \phi_j^f$$

If i is a damage reaction and j is an activation reaction, we can define a more explicit notation DA of ρ_{ij}

$$DA = \frac{\text{Damage}}{\text{Activation}} = \Phi^f_{\text{Damage}} / \Phi^f_{\text{Activation}}$$

by detailing in the text the nature of the damage and activation reactions considered.

We can also write: $\Phi_{Damage} = DA \cdot \Phi_{Activation}$

III.5 QUANTITIES RELATIVE TO EFFECTS (Source terms)

Energy transferred to lattice, E_R

$$\boxed{E_R = \int w(E)\,\Phi_E(E)\,dE}$$

$$\text{with } w(E) = c \sum_i \sigma_i(E) \int_{E_{p\,min}}^{E_{p\,max}} E_r(E_p) P_i(E,E_p)\,dE_p$$

where the summation Σ_i is extended to all neutron reactions liable to lead to transference of energy (elastic and inelastic collisions, etc.) and where:

E_p = energy transmitted during the reaction i;

$E_{p\,max}$ and $E_{p\,min}$ = upper and lower limits of possible values of E_p during the reaction i;

$P_i(E,E_p)$ = probability of a given value E_p per unit energy;

E_r = energy transferred to lattice by a primary having energy E_p (§II.2 - b.1);

c = number of target atoms considered.

Number of displacements, d, or N_d:

We assume (see [2]):

$$\boxed{d = E_R/E_0 = N_d}$$

where E_0 is a conventional value[3] (E_0 = 100 eV, except for graphite, as will be seen later).

Furthermore, d will always be given as the number of displacements per target atom (i.e. c will always be taken as equal to 1).

III.6 PRACTICAL QUANTITIES

Practical quantities exist, especially for graphite, established by usage

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[3] $E_0 = 2\,E_D/0.8$ where E_D, the displacement energy, is taken as equal to 40 eV and where 0.8 is an effectiveness factor.

and/or by the practical selection of a reference material taken as a standard.

This question will be dealt with further in the appendix, for the case of graphite (Para. VI).

IV. APPLICATION TO METALS

Quantities used to express irradiation fluences.

IV.1 We recall (§II.2 - c) the value of providing, as often as possible, all information regarding spectra, flux and neutron fluences.

IV.2 BASIC QUANTITY: energy E_R and displacements d.

The quantity recommended for use is the energy E_R transferred to the lattice, or even, according to applications, the number d of displacements induced.

The energy E_R transferred to the lattice constitutes the basic measurement of the fluence received. It leads directly to the number d of displacements induced, which is itself strictly proportional within the framework of selections made here (§III.5).

It is, then, a question of an energy fluences (or of a displacement fluence), and no longer of an equivalent neutron fluence as in the case of graphite. It did not seem realistic to wish to alter the practices simply for the sake of uniformity. In any case, it is always possible to talk about energy or displacement fluence in the case of graphite (§V.3) or of equivalent neutron fluence in the case of metals (§IV.3); these quantities are, by definition, strictly proportional.

The calculation of energy E_R is that from §III.5, using the Lindhard model (§II.2 - b.1). The number of displacements, d, is deduced from it (§III.5).

$$E_R = \int w(E)\Phi_E(E)dE$$

$$d = E_R/E_0 \quad \text{with, by agreement} \quad E_0 = 100 \text{ eV}$$

The use of E_R and/or d is recommended for all applications to irradiation of metals. It should be noted that the I.A.E.A. recommendation [11] suggests empirical damage functions in so far as the mechanical properties of a USA steel are concerned. The results obtained are in practice very similar to those from the present recommendation.

IV.3 OTHER QUANTITIES: EQUIVALENT FLUENCE Φ_Z^f :

$$\text{if } w_Z^f = \int_0^\infty w_Z(E)\chi_E(E)dE \qquad \text{(see §III.2)}$$

we can define Φ_Z^f, the equivalent fission fluence for a metal Z (according to §III.2)

$$\Phi_Z^f = \frac{1}{w^f} \int_0^\infty w_z(E)\Phi_E(E)dE$$

IV.4 NUMERICAL VALUES

Table 2 shows:

- a distribution w(E) to be used when there is no special reason to use a given library of neutron cross sections[4];

- corresponding values for w^f; for the forms of $\chi_E(E)$ set out in §III.2;

- the values w corresponding to thermal neutron nuclear reactions (n,γ), and, in brackets, the corresponding recoil energies;

- the number P_Z of atoms per gram.

The values of w are given in keV per gram for 1 $n.cm^{-2}$ from which

$E_R = \int w(E)\Phi_E(E)dE$ is obtained in $keV.g^{-1}$

$d = \frac{1}{E_O P_Z} E_R$ is obtained in atom displacements

$\Phi_Z = \frac{1}{w^f} E_R$ is obtained in $n.cm^{-2}$

---

[4] If necessary, fuller and more detailed information can be found in [8], which is consistent with that given here.

V. APPLICATION TO GRAPHITE

Quantities used to express irradiation fluences.

V.1 We repeat the necessity (§II.2.c) of providing, whenever possible, all information on spectra, flux and neutron fluences.

V.2 BASIC QUANTITY

V.2 a) Principle:

The damage function recommended is that from the Thompson-Wright model [12]. More empirical, and undoubtedly less satisfactory on the theoretical plane than the universal model suggested in II.2 - b.1, for graphite it is shown to be better confirmed by experiment than the latter (see [13] especially). The Thompson-Wright function expresses a number of atoms displaced per target atom in graphite; if w(E) is this number of displaced atoms, we can write:

$$w(E) = \sigma_s(E)d(E)$$

$\sigma_s(E)$ being the scattering cross section of graphite

and $d(E)$ the number of atoms displaced as a result of a neutron collision.

We recommend the use of the equivalent fission fluence Φ_G^f (§III.2):

$$\Phi_G^f = \frac{1}{w^f}\int_o^\infty w(E)\Phi_E(E)dE = \Phi_G \quad \text{in brief}$$

where $$w^f = \int_o^\infty w(E)\chi_E(E)dE$$

We also recommend the use of the equivalent fission flux density ϕ_G^f (§III.3):

$$\phi_G^f = \frac{1}{w^f}\int_o^\infty w(E)\phi_E(E)dE = \phi_G \quad \text{in brief}$$

V.2 b) Numerical values

Table 3 gives the distribution d(E) to be used. Table 4 suggests in addition a relative distribution of $w_G(E)$, to be used in the case where there is no special rason to use a given library of the cross section $\sigma_s(E)$ of graphite. The cross section for atom displacement $\sigma_w(E)$ is numerically

confused here with w(E). (w and σ_w are defined in §III.1).

It seems useless, for graphite, to specify $\chi_E(E)$ among the possible forms of fission spectra; the distribution w(E) is here such that w^f is insensitive to the choice of representation of $\chi_E(E)$.

At better than 1%, we have:

w_G^f = 720 x 10^{-24} displacements per target atom for 1 neutron per cm^2;

σ_w^f = 720 barns, for graphite.

V.3 OTHER THEORETICAL QUANTITIES

Energy transferred E_R and number of displacements d (§III.5)

The conventional energy E_0 is taken as equal to 120 eV in the Thompson-Wright usage [12]. It was not considered worthwhile to modify this value. Φ_G, d and E_R are linked by the relations (§III).

$$E_R/E_0 = d = w_G^f \Phi_G$$

with, here, E_0 = 120 eV and w_G^f = 720 x 10^{-24} displacements per atom for 1 $n.cm^{-2}$.

V.4 PRACTICAL QUANTITIES

Various practical quantities are used with regard to graphite: equivalent fluence for nickel, equivalent fluence for High Temperature Reactor, response of a graphite standard characteristic of any reactor position, etc.

These quantities are set out in the Appendix which follows (Para. VI).

VI. APPENDIX - Practical quantities - Graphite

VI.1 Principles

Every practical quantity must be defined by its theoretical value and/or by its practical reference:

its theoretical value: the value, in atoms displaced, of the quantity considered. Let $\Phi^{practical}$ be this quantity; which is, in other terms, the number of atoms displaced $w^{practical}$ such that:

$$d = w^{pract.}\ \Phi^{pract.}$$

its practical reference: according to one, at least, of the two following references:

- full definition of the location taken as standard;
- definition of measuring equipment (standard graphite) and of its response as a function of the quantity considered.

VI.2 Equivalent fluence for nickel, DIDO: Φ^{DNE}_{G} or Φ^{DNE}

A theoretical definition of Φ^{DNE} was adopted, and the use of the value w^{DNE} is recommended as the most generally used, that is to say:

$$w^{DNE} = 1300 \times 10^{-24} \text{ displacements per atom for 1 n.cm}^{-2}$$

(i.e., $\sigma^{DNE}_{w} = 1300$ barns)

$$d = w^{DNE}\ \Phi^{DNE}$$

(N.B. we have seen, above, $w^{f} = 720 \times 10^{-24}$ displ. for 1 $n.cm^{-2}$).

VI.3 Equivalent fluence for High Temperature Reactor: $\Phi^{0.18}$ or Φ^{HTR}

This is the fluence equivalent to the fluence of a neutron having energy higher than 0.18 MeV in an HTR (i.e. in a spectrum characteristic of HTR.)

We suggest the theoretical definition:

$$w^{0.18} = w^{HTR} = 900 \times 10^{-24} \text{ displacements per atom for 1 n.cm}^{-2}$$

$$d = w^{HTR} \Phi^{HTR}$$

(N.B. We have seen above, $w^f = 720 \times 10^{-24}$ displ. for 1 n.cm^{-2}).

VI.4 Practical reference (standard graphite)

The use [13] of a well defined standard graphite permits very accurate measurement of an experimental index r

$$r = \frac{\text{damage response of standard graphite}}{\text{activity response of nickel}}$$

More precisely $r = 10^{-1}\ \delta/A$ where δ and A are the effects induced by the simultaneous irradiation at a very low fluence of a standard graphite sample and a nickel sample.

δ is the relative variation of graphite $\Delta R/R$, corrected (for saturation, temperature, etc.).

A is the reaction number Ni^{58} (n,p) per nickel target nucleus.

Measurement of the index r under the physical conditions of the standard location of a given practical quantity, constitutes a definition of this quantity.

Table 5 shows measurements made.

The values in Table 5 are typical values; r can vary according to the measuring position and the local loading. We find, for example: r = 3.95 in PLUTO with a loading of graphite and aluminium, and r = 4.0 in FRJ2 with a loading of heavy water and aluminium among others; and we calculate that r would be 3.3 without any load (void).

In RAPSODIE, r may vary by a factor of 2 according to the position of measurement within the core-reflector boundary. The presence of beryllium, in the H_2O reactor, can cause r to increase by more than 20%, and so on. (For more details, see, among others, [13]).

The value $r^f = 2.0$ in Table 5 explains the standardisation of measurement, resulting from a great many comparisons between calculations of Φ_G/Φ_{Ni} and measurements of r.

The measurement r^i in a given location in a neutron spectrum i permits the determination of the index $DA = \Phi^f_G/\Phi^f_{Ni}$ (§III 4) relating to this location, and if required, determination of the equivalent nickel flux characteristic of the spectrum i, Φ^{ENi}:

$$r^i/r^f = DA = \rho_{G,Ni} = \Phi^f_g/\Phi^f_{Ni}$$

and $$r^i/r^f = w^{ENi}/w^f = \Phi^f_G/\Phi^{ENi}$$

We obtain, with $r^{DIDO} = 3.6$ the value w^{DNE} seen above which corresponds to DA = 3.6/2 = 1.8.

If, on the other hand, we consider by way of example, an OSIRIS type location in which r = 3.41, we can calculate:

$$(DA)_{OSI} = 1.71$$

$$w^{ENOSI} = 1230 \times 10^{-24} \text{ displ. per atom cm}^2$$

$$\Phi^{ENOSI} = 0.61\, \Phi^f_G$$

*
* *

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(These are all in French, except for [1], [4], [5] and [12], which are in English).

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Physical phenomenon	Physical quantity	Dimension
Neutron flux ϕ	Number of neutrons per unit area per unit time	$L^{-2}\ T^{-1}$
↓		
Modifications source s	Modifications per unit volume per unit time	$L^{-3}\ T^{-1}$
↓		
Action of ϕ, then of $\underline{s}$ during a given period		
↓		
Microscopic equilibrium $\underline{d}$	Modifications per unit volume	L^{-3}
↓		
Variation of physical properties D	Property studied	?

TABLE 1 - Synoptic of damage produced by neutrons.

Group	Energy lower limit of group	Δu	w (keV.g^{-1} . cm^2)					
			Fe	Ni	Zr	Mo	Cr	Al
	14 MeV							
0	10 MeV	0,338	2,400	1,973	1,990	1,720	2,650	3,199
1	7,788 MeV	0,25	2,091	1,659	1,422	1,280	2,272	2,912
2	6,0653 MeV	0,25	1,896	1,518	1,165	1,094	2,139	3,082
3	4,7237 MeV	0,25	1,807	1,385	1,006	0,978	1,938	2,964
4	3,6788 MeV	0,25	1,608	1,324	0,885	0,867	1,764	3,045
5	2,8650 MeV	0,25	1,501	1,195	0,731	0,750	1,611	2,994
6	2,2313 MeV	0,25	1,270	1,139	0,625	0,649	1,482	2,950
7	1,7377 MeV	0,25	1,048	0,986	0,565	0,549	1,351	2,669
8	1,3533 MeV	0,25	0,798	0,843	0,506	0,468	0,860	2,279
9	1,0540 MeV	0,25	0,588	0,820	0,470	0,441	0,830	2,255
10	0,8208 MeV	0,25	0,395	0,570	0,471	0,383	0,646	1,660
11	0,6393 MeV	0,25	0,504	0,485	0,452	0,352	0,586	1,963
12	0,4979 MeV	0,25	0,280	0,384	0,411	0,310	0,413	1,509
13	0,3877 MeV	0,25	0,386	0,394	0,373	0,276	0,365	1,451
14	0,3020 MeV	0,25	0,252	0,355	0,287	0,237	0,278	1,083
15	0,2352 MeV	0,25	0,187	0,347	0,237	0,197	0,183	0,884
16	0,1832 MeV	0,25	0,229	0,278	0,190	0,166	0,188	0,934
17	0,1426 MeV	0,25	0,157	0,289	0,152	0,138	0,318	1,399
18	0,1111 MeV	0,25	0,119	0,166	0,122	0,109	0,224	0,441
19	86,52 keV	0,25	0,116	0,154	0,099	0,083	0,260	0,954
20	67,38 keV	0,25	0,169	0,201	0,079	0,062	0,051	0,469
21	40,87 keV	0,50	0,071	0,109	0,057	0,043	0,097	0,159
22	24,79 keV	0,50	0,180	0,100	0,035	0,026	0,038	0,346
23	15,03 keV	0,50	0,008	0,198	0,022	0,015	0,021	0,018
24	9,11 keV	0,50	0,015	0,109	0,013	0,008	0,026	0,016
25	5,53 keV	0,50	0,029	0,024	0,008	0,007	0,044	0,014
26	3,53 keV	0,50	0,009	0,032	0,007	0,003	0,030	0,008
27	2,04 keV	0,50	0,006	0,013	0,004	0,001	0,006	0,005
28	1,235 keV	0,50	0,004	0,007	0,002	0,001	0,003	0,003
29	0,724 keV	0,50	0,002	0,003	0,001	0,001	0,001	0,001
30	0,455 keV	0,50	0	0	0	0	0	
31	0,276 keV	0,50	0	0	0	0	0	
thermal neutrons (0,025eV)			0,011	0,027	0,00025	0,025	0,014	0,004
NB: energy per collision (eV)			(389,2)	(567)	(201)	(148,5)	(389,1)	(771)
w_Z^f (keV.g^{-1} . cm^2) Leachman			0,879	0,843	0,555	0,518	1,036	2,255
Watt			0,905	0,859	0,564	0,529	1,063	
$10^{-20}.P_Z$ atoms.g^{-1}			108	103	66	63	115	223

TABLE 2 - w_Z functions

Energy (MeV)	d(E)	Energy (MeV)	d(E)	Energy (keV)	d(E)
14,00	550,3	1,169	316,4	94,02	73,0
12,88	540,4	1,036	304,0	83,39	66,0
11,42	531,4	0,9192	291,0	73,96	60,0
10,13	521,4	0,8152	279,0	65,59	53,8
8,987	510,2	0,7231	265,0	58,18	49,0
7,970	500,2	0,6413	250,6	51,60	43,6
7,069	490,1	0,5688	236,4	45,76	39,2
6,270	480,4	0,5045	222,4	40,59	35,0
5,561	468,6	0,4474	209,8	36,00	32,0
4,932	459,6	0,3968	197,0	31,93	28,6
4,374	448,0	0,3519	185,0	28,32	26,0
3,880	437,6	0,3121	174,2	25,12	23,2
3,441	427,0	0,2769	162,0	22,28	21,0
3,052	415,0	0,2455	515,0	19,76	18,8
2,707	404,4	0,2178	139,2	17,52	17,0
2,401	392,6	0,1932	129,4	15,54	15,2
2,129	384,0	0,1713	118,2	13,78	13,4
1,888	366,5	0,1519	108,0	12,23	12,2
1,675	354,0	0,1348	96,60	10,84	10,8
1,485	341,0	0,1195	88,40	10,01	10,0
1,318	328,8	0,106	80,60	<10	~ E KeV

TABLE 3

Function d (E) as number of displacements per neutron collision.

Group	Energy	Δu	w/w_f
0	14 - 10 MeV	0,338	0,853
1	10 - 7,88 MeV	0,25	0,905
2	7,788 - 6,0653 MeV	0,25	0,830
3	6,0653 - 4,7237 MeV	0,25	0,787
4	4,7237 - 3,6788 MeV	0,25	1,155
5	3,6788 - 2,8650 MeV	0,25	1,231
6	2,8650 - 2,2313 MeV	0,25	0,917
7	2,2313 - 1,7377 MeV	0,25	0,941
8	1,7377 - 1,3533 MeV	0,25	0,973
9	1,3533 - 1,0540 MeV	0,25	1,038
10	1,0540 - 0,8208 MeV	0,25	1,086
11	0,8208 - 0,6393 MeV	0,25	1,096
12	0,6393 - 0,4979 MeV	0,25	1.071
13	0,4979 - 0,3877 MeV	0,25	1,021
14	0,3877 - 0,3020 MeV	0,25	0,961
15	0,3020 - 0,2352 MeV	0,25	0,884
16	0,2352 - 0,1832 MeV	0,25	0,789
17	0,1832 - 0,1426 MeV	0,25	0,684
18	0,1426 - 0,1111 MeV	0,25	0,571
19	111,1 - 86,52 keV	0,25	0,473
20	86,52 - 67,38 keV	0,25	0,390
21	67,38 - 40,87 keV	0,50	0,287
22	40,87 - 24,79 keV	0,50	0,187
23	24,79 - 15,03 keV	0,50	0,121
24	15,03 - 9,11 keV	0,50	0,075
25	9,11 - 5,53 keV	0,50	0,046
26	5,53 - 3,35 keV	0,50	0,027
27	3,35 - 2,04 keV	0,50	0,019
28	2,04 - 1,235 keV	0,50	0,007
29	1,235 - 0,742 keV	0,50	0,006
30	0,742 - 0,455 keV	0,50	0,004

$720 \times 10^{-24}\ w/w_f$ = w displacements for 1 n. cm^{-2}

$720\ w/w_f = \sigma_w$ barns

TABLE 4 - Damage function w for graphite

	Reactor	r
D_2O	Type DIDO : PLUTO (Harwell), FRJ2 (Jülich)	3.60*
G	" BR1 - moderator - core (Mol)	7.25
	" DRAGON (HTR) - fuel - core (Winfrith)	5.65
	" BEPO (TE 10)	8.20
H_2O	" HFR - core (Pretten)	3.62
	" MELUSINE - core (Grenoble)	2.93
	" OSIRIS & ISIS - core (Saclay)	3.41
	" BR2 - core (Mol)	3.42
	" PEGASE - reflector loop (Cadarache)	3.54
	" TRITON - reflector (Fontenay aux Roses)	2.46
Fast Reactor	" RAPSODIE - core-reflector boundary (Cadarache)	12**
Fission spectrum	Interpretations calculated	2.0

* measurements corrected and reduced to the definition here recommended of the Φ^{END} ($w^{END} = 1300 \times 10^{-24}$ displacements for 1 n. cm^{-2}

** very variable according to position.

TABLE 5 - Characteristic values of r, measured graphite/nickel index.

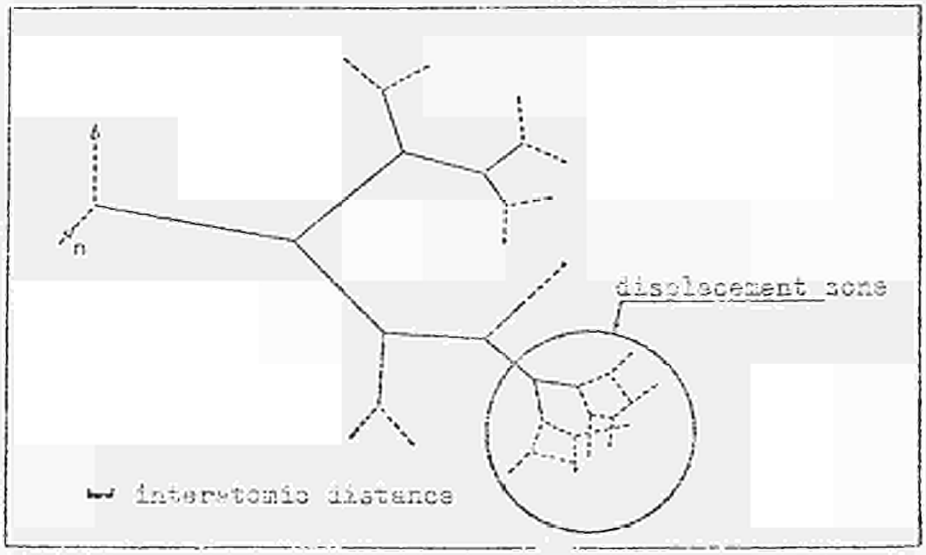

FIGURE 1 : slowing-down cascade.

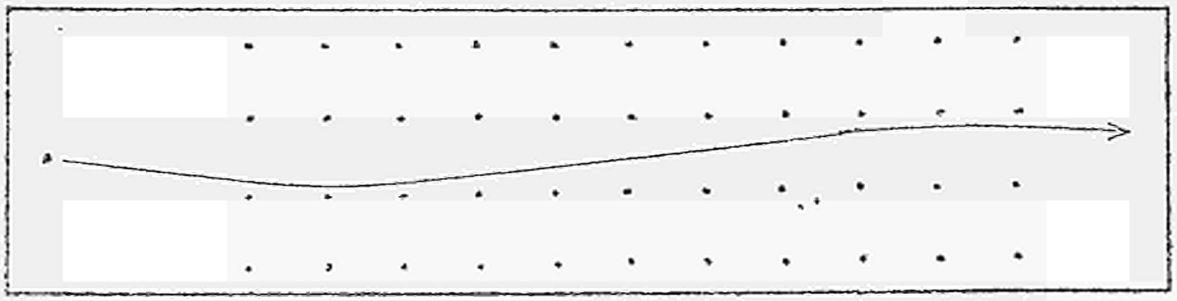

FIGURE 2 : channelling (a high energy phenomenon)

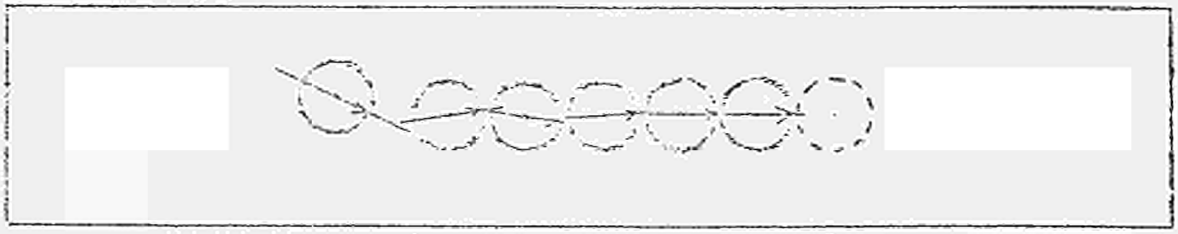

FIGURE 3 : focussing (a low energy phenomenon)

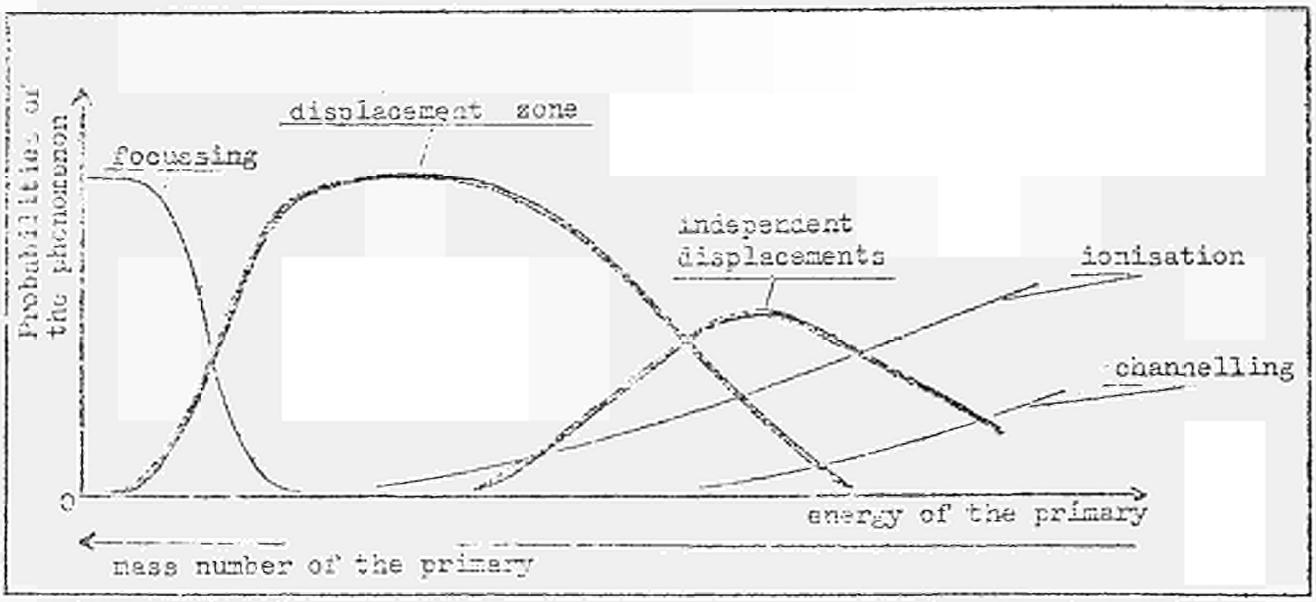

FIGURE 4 : The different slowing down phenomena of a primary (qualitative aspects)

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