THE NUCLEAR ASPECTS OF A FUSION POWER PLANT: NEW CONSTRAINTS AND CHALLENGES

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Fusion would deliver a new source of energy from the mid of this century. But the fusion research has now to make an important step forward by switching from pure plasma physics, based on Hydrogen and Deuterium plasma, to burning plasmas, implying the use of radioactive fuel (the Tritium) and the production of intense neutron flux. These aspects bring with them the change of fusion devices from laboratory (or industrial) facilities to nuclear facilities, with all the necessary precautions which are involved. The nuclear aspects of fusion reactors and power plants have an impact on various domains of the facilities: the approach of safety, security and radioprotection, the resistance of materials to neutron bombardments, the activation of material and the needs of remote handling, the effects of radiations on instruments and functional components, and last but not least the impact on radioactive waste production and recycling. All these aspects will be handled shortly in this first approach of the "nuclearization" of fusion reactors and facilities..

I. INTRODUCTION

Fusion has been developed since several years in various countries in the world to be able to propose a new source of energy for mankind. Fusion being the process driving the sun and stars has demonstrated to be able to be a very important source of energy. But its control and confinement on Earth proved to be much more difficult than foreseen. The very high temperature or very high densities to be reached drove the focus of the research up to now on these aspects of high temperatures (for the magnetic confinement facilities: tokamaks and stellarators) or high densities (like in the inertial confinement fusion)[1] , and not on the nuclear aspects of the machines. Nevertheless, now that we are approaching the construction of reactors allowing "burning plasma", i.e. facilities which will produce large amount of fusion power, the nuclear aspects of the installations are becoming more and more important and have to be taken into account in the design and operation of such facilities.

This lecture will focus mostly on the impacts of the nuclear character of the future machines and will thus consider that the reader has already a sufficient knowledge of fusion facilities, and in particular of tokamak type installations. One considers also that a sufficient basic knowledge of nuclear physics is present, although some of the main phenomena will be reminded or shortly introduced.

Finally, this lecture is only an introduction to a very broad domain, which is currently studied and developed by a lot of scientists among the World. For further information or deeper analysis of the different areas which will be only superficially approached, the reader is sent to the literature on the different areas. The nuclear aspects of a fusion power plant are surely important features which need to be taken into account when one intends to design and build such a future source of energy.

II. THE REASONS OF THE NUCLEAR APPROACH

Fusion reaction is a nuclear process, involving the nucleus of the atoms; this is already a first reason to consider fusion as a nuclear process (the actual name of fusion being in fact "thermonuclear fusion"). Nevertheless, if the process did not involve radioactive materials, several aspects of the nuclearization would have been strongly simplified. Unfortunately, as in most nuclear processes and reactions, the fusion reaction implies the presence of radioactive isotopes and materials.

In fusion reactors, the presence of radioactive materials can be seen as having three main origins:

- the use of tritium as fuel, tritium being a radioactive species, with a rather short half-life;
- the activation of the materials facing the plasma or being exposed to neutrons coming from the plasma and the fusion reactions;
- the transport of radioactive contamination through the cooling fluids and in the air of the auxiliary buildings and areas.

The third origin is in fact more a consequence of the two other ones, but it brings the needs of precaution sometimes far away from the source of the activity.

[1] We will mostly base our analysis on magnetic confinement fusion, as this one is probably more advanced and closer to the production of energy, but the main data and information are valid also for inertial confinement, once D-T mixture will be used.

Let us try to have some facts and figures about the different nuclear aspects mentioned above and let us start with the tritium.

Tritium is an isotope of Hydrogen; but unlike the Deuterium (one proton, on neutron) which is a stable species to be found in seawater, tritium (1 proton, 2 neutrons) is radioactive, i.e. it disintegrates naturally by emitting a beta radiation (an electron) having a rather low energy (5.7 keV), to become an ^{3}He nucleus (2 protons and 1 neutron). The half-life of tritium (i.e. the time after which half of the original atoms have disintegrated) is about 12.32 years.

It is good to remember that after 5 half-lives the activity has decreased by a factor 32 (2^5), while after 10 half-lives the activity has decreased by a factor close to one thousand (2^{10}), and 20 half-lives divides the activity by a factor close to one million (2^{20}).

The mass of tritium is about three times the one of Hydrogen and 1.5 the one of Deuterium. This can play a certain role in the particles kinetics within the plasma. Finally the fact that tritium decays in Helium has also two important impacts: it creates He in the material in which it can diffuses, and it creates another source of He within the plasma, after the one of the fusion reaction itself:

$$D + T \Rightarrow {}^4He + {}^1n_0 \quad (1)$$

Another important aspect is the high diffusivity of tritium, which follows here the properties of its main element, hydrogen. Thus such an isotope can diffuse through solid materials (like steel or other metals) easily if the temperature is high.

Finally, for the aspect of safety and health effects, it is important to know the ratio between the tritium activity and the induced dose in the human body. This figure is very small and in the order[2] of 10^{-11} Bq/Sv:

Dose factor (radiotoxicity) of [1]:

Tritium (gaseous) = $1{,}8.10^{-15}$ Sv/Bq
Tritiated water (aqueous) = $1{,}8.10^{-11}$ Sv/Bq
Organically bound Tritium (OBT) = $4{,}1.10^{-11}$ Sv/Bq

This very small figure shows the low health impact of tritium on the body. Nevertheless, as for any other radioactive isotope, the ALARA principle must apply and the irradiation (mostly internal irradiation, by inhalation or ingestion) should be kept as small as reasonably possible. To have an idea of the activity content of tritium mass, one can also remember that 1g of T_2 gas represents about 10 000 Ci or 3.7 10^{14} Bq

[2] For those not very familiar with the Sievert, let us remind that the natural background of radiation fluctuates between 0.5 and tens mSv per year (thus around 1 µSv/h) and the max. occupational planned dose for a nuclear worker is set at 20 mSv/y [2].

The table 1 below gives a summary of the principal properties of tritium.

Property	Value	Unit
Half – life	12.32	year
Beta energy	5.7	keV
Atomic mass	3,0160492	a.m.u.
Tritiated water dose factor	$1{,}8.10^{-11}$	Sv/Bq

Table 1: main properties of Tritium

Let us now look at the activation aspect of materials facing the plasma or able to get some neutrons coming from the reaction. An important aspect is the neutron energy and the neutron flux (or better the so-called fluence, i.e. the integrated neutron flux over the time the material is exposed to the neutrons) which hits the various components of a fusion reactor. The most exposed components are indeed the plasma facing components or PFC. But as one can see on fig.1 (giving a developed view of the facing components of the research tokamak JET), the PFC can be very diverse, and one should not only focus on the blanket and first wall; heating antenna shields and limiters (if any), diagnostic windows or first mirrors, viewing systems, etc. are all facing the plasma, in a neutronic sense. If for plasma physics, a small geometrical recede changes strongly the plasma wall interaction, for neutrons, not influenced by the magnetic fields, this does not play any role.

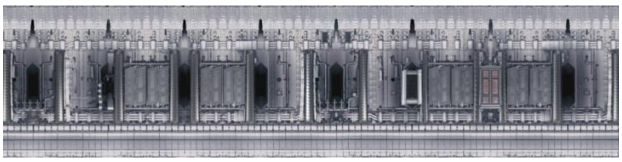

Figure 1: Outer wall of JET (developped)

The neutrons have several types of interactions with matter, which gives different macroscopic effects on components and systems. Neutrons can have elastic and inelastic interactions, knocking atoms from their original positions (often one single neutron induces a cluster of knocked atoms, and loses his energy by several elastic or inelastic interactions). Neutrons can also be absorbed by some atoms inducing transmutations of the original atoms. When the neutron is absorbed, it normally disappears, or can lead to an instable atom re-emitting one or several other neutrons. The transmuted nuclei are often radio-active, and their radioactivity can lead to the emission of a proton (leading to Hydrogen formation in the material) or to the emission of an alpha particle, leading to the creation of Helium inside the material. Finally the created radioactive species are often emitting gamma (or beta) rays leading to ionization and thus important influence on chemical bounds. The neutrons, by knocking atoms, by absorption or by the induced radioactivity are also producing heat in the material, (called "nuclear heating") which could be very significant for materials directly exposed to the neutron source. This is also the main route of transporting the created energy to the cooling fluid and subsequently to the turbine. Further analysis on this aspect will be done in the chapter IV.

Let us just still make a short comparison with fission neutrons, for having some ideas of the orders of magnitude and to feel a bit the importance of this aspect. In fission, each reaction creates about 200 MeV of energy, from which 2.5 neutrons are created in average, taking with them energy of around 2 MeV. This means that the neutrons take away about 2% of the total energy created, the remaining 98% being left in the fuel material by the recoils of the fissioned atoms. In fusion the situation is rather different! Each reactions produces around 17 MeV, from which the created neutron takes away around 14 MeV, or 82% of the total energy (the remaining 18% being transported by the alpha particle which stays in and gives its energy to the plasma). Comparing both situations, for the same overall energy production of the plant, the energy deposited by the neutrons is 33 times higher in fusion! The energy per neutron being about 7 times higher for fusion neutrons, the total number of neutrons for the same power is thus almost 5 times larger than in fission… Thus the total surface of the first wall of a fusion reactor gets 5 times more neutrons with an energy 7 times higher[3]. This gives only an idea of the issue at stake.

Finally, we should not forget the transport of activated materials through the cooling fluid and even by the atmosphere during maintenance and opening of the vacuum vessel. This transport, which is common and rather well known in fission reactors, depends a lot on the fluid physico-chemical conditions (temperature, pressure, purity, pH, oxygen content etc…) and is probably the main cause of activity dispersion in the plant. Moreover the transport and deposition of radioactive species induces exposition of workers to radiations, and is thus an important factor to consider. This topic will be analysed in chapter IV below.

III. THE NUCLEAR SAFETY AND CONFINEMENT, THE SECURITY AND THE RADIOPROTECTION

One of the first impacts of the presence of radioactive materials and species in a fusion power plant is surely the safety aspect and the radioprotection. Nuclear safety is of prime importance in a fusion power plant although the absence of fission fuel and its radioactive content reduces strongly the risks and source term in case of an accident compared to fission plant.

Nevertheless, the confinement of the radioactive species, present in a fusion reactor, in all cases of operation (up to the less credible accident) has to be assured in order to avoid any spread of radioactive contamination in the environment and to avoid absolutely any need of evacuation of the population in the surrounding of the plant in any case. This is probably one of the main objectives of the safety approach of a fusion power plant design. The aspects of radioprotection of the workers and operators will be analysed further.

The basis of the safety approach for a fusion power plant can be taken from the ITER Generic Site Safety Report [3]. Let us thus first define the safety objectives:

"ITER's safety objectives address the potential hazards in ITER from normal operation, accidents and waste:

(1) ensure in normal operation that exposure to hazards within the premises is controlled, kept below prescribed limits, and minimised;
(2) ensure in normal operation that exposure to hazards due to any discharge of hazardous material from the premises is controlled, kept below prescribed limits, and minimised;
(3) prevent accidents with high confidence;
(4) ensure that the consequences, if any, of more frequent events are minor and that the likelihood of accidents with higher consequences is low;
(5) demonstrate that the consequences from internal accidents are bounded as a result of the favourable safety characteristics of fusion together with appropriate safety approaches so that there may be, according to IAEA guidelines [IAEA96], technical justification for not needing evacuation of the public (external hazards are site dependent, but are considered for a generic site);
(6) reduce radioactive waste hazards and volumes."

One can also consider the safety principles used for the ITER GSSR [3], as basic principles for a fusion power plant (although the experimental character of ITER has also some specific aspects, which are not taken into account here):

<u>Defence-in-Depth</u>
All activities are subject to overlapping levels of safety provisions so that a failure at one level would be compensated by other provisions. Priority shall be given to preventing accidents. Protection measures shall be implemented in sub-systems as needed to prevent damage to confinement barriers. In addition, measures to mitigate the consequences of postulated accidents shall be provided, including successive or nested barriers for confinement of hazardous materials.

[3] To be more scientifically correct, we should speak about the neutron flux, for which the ratio is more complicated. This comparison is only given here to have some taste of the difference.

Passive Safety

Passive safety shall be given special attention. It is based on natural laws, properties of materials, and internally stored energy. Passive features, in particular minimisation of hazardous inventories, help assure ultimate safety margins. (…)"

Potential safety concerns that must be considered during the design process to minimize challenges to the public safety function of confinement of radioactive and/or hazardous materials include, but should not be limited to the following [4]:

a. ensuring afterheat removal when required;
b. providing rapid controlled reduction in plasma energy when required;
c. controlling coolant energy (e.g., pressurized water, cryogens);
d. controlling chemical energy sources;
e. controlling magnetic energy (e.g., toroidal and poloidal field stored energy);
f. limiting airborne and liquid releases to the environment.

Tritium

From the DOE Guidance [5], Tritium system design should include features which minimize the environmental release of tritium and exposure of personnel, minimize quantities of tritium available for release during accidents or off-normal events, and minimize the unintended conversion of elemental tritium to an oxide form. Consistent with facility safety analysis, design features should include:

1. Segmentation of the tritium inventory such that release of all tritium from the single largest segmented volume has acceptable consequences;
2. Confinement barriers to reduce tritium environmental release to an acceptable level;
3. Materials and equipment which are tritium compatible and minimize exposure of tritium to oxygen; and
4. Cleanup systems to recover gaseous tritium released within any confinement barrier or to process streams exhausting to atmosphere.

Aspects of Security

Beyond the safety aspects of a fusion plant, the security (i.e. the physical protection against unfriendly acts or terrorism) of the installation is also an aspect to be developed. The main item to defend is probably the tritium inventory (see below), but the diversion of activated or contaminated materials should also be taken into account as well as sabotage actions or even external attacks.

Fortunately, the "source term" in a fusion plant is limited to its activated (and contaminated) components and to the tritium inventory. As the activated species are mostly bound within solid components (first wall and blanket module; divertor, etc), except for the produced dust and for the components coolant, the main source of easily escaping radio-nuclide is the tritium inventory. That is why a particular attention is placed towards the monitoring and control of the tritium inventory, and to the separation of this inventory in small parts not possible to mobilize together.

The purposes of requirements placed on tritium control, accountability, and physical protection at fusion facilities are to [4]:

a. meet legal requirements for environmental releases, waste disposal, and transportation of tritium;
b. prevent the diversion of the material for unauthorized use;
c. gain knowledge of the process efficiency, that is, how much tritium is produced and used in processes under investigation;
d. meet the requirements of the safety authorities;
e. assure operational safety of the facilities by providing knowledge of the location and form of tritium;
f. prevent unwanted buildup of tritium within a facility; and
g. protect and control tritium commensurate with its monetary value.

Tritium is the predominant nuclear material used at fusion facilities. It is of interest because of safety concerns, its monetary value, and possible unauthorized diversion for other applications.

Other nuclear material that must be controlled and accounted for at fusion facilities includes depleted uranium (U-238) and deuterium. Depleted uranium is used for storage of tritium, fission chambers, and various radioactive check- and calibration-sources. The control and accountability of these materials is relatively straightforward and does not present significant problems for operating facilities. The scope and extent of the accountability program for these materials should be based on the monetary value of the material and should include inventories and some measurements.

ALARA and radioprotection optimization

The ALARA approach ("As Low As Reasonably Achievable") is not only an acronym but has led to a complete approach of the radioprotection optimization. Indeed the principle which is behind this acronym implies several aspects which should be taken into account. The term "Reasonably" for instance is probably one of the most important; it translates into 'reasonably' regarding the economic and social impact and constraints. Therefore this principle can almost be opposed to the "As Low As Technically Possible", which should also mean 'at every cost'! And this can have ethical implications. Indeed, one can protect anybody from even not harmful risks with high economic impact. But as the overall available money is always limited, for any type of project or practice, this means that this money (used for nothing) is no more available for other means (like e.g. modernizing a hospital or promoting R&D against cancer etc…).

On the other hand the radioprotection optimization approach under the ALARA principle should also take into account the whole lifecycle of the involved component or activity. As example, let us take the development of low activation materials (for facilitating the remote handling of the maintenance); this is good for the maintenance activity, but in the overall study one should also take into account the effects on the waste management and even the final effect after disposal… Moreover the ALARA approach can be done at the design phase of a facility as it allows to make large gains with limited (but smart) investments.

IV. THE NUCLEAR “CLEANLINESS” AND TRANSPORT OF RADIOACTIVITY

Materials exposed to neutron flux have to present a cleanliness above normal industrial standard, as the production of activated products often depends on trace impurities (in materials) or on traces of impurities on materials. In the case of fusion reactors, the components and materials situated inside the vacuum vessel and exposed to the plasma and to the low vacuum needed for operating the system, already imply a sufficient cleanliness of the exposed materials. Nevertheless, these components are not the only ones exposed to the neutron flux, and probably most of the difficulties will happen in the cooling circuits and any other loops allowing some fluid to circulate for a while in front of the neutron source. For instance, in fission power plant, most of the occupational dose is due to the contamination of the primary loop and the transport of radioactive species from the core of the reactor to the surface of the whole cooling loops. This will surely also happen in fusion power plant, where the exposed surface of the cooling fluid is rather important (although the mass of the cooling fluid is probably lower than in an LWR where the complete core and auxiliary are immersed in the primary water).

A. Contamination and Activated Corrosion Products (ACP)

One nuclear aspect, which forms an important factor for the exposure of workers and operators, is the radioactive contamination of cooling circuits. Moreover it can have also an impact on the waste management from fusion reactor decommissioning and large maintenance works. Therefore, it appears to be important to study this topic and take profit of the return of experience from fission.

Areas with large deposition surfaces and strong temperature gradients, like the heat exchangers and steam generators, constitute often large sources of radiations influencing the maintenance of the facilities. The main radio-isotope playing a role in fission plants in this domain is the Cobalt-60. With a half-life of 5.24 years and a double gamma-rays above 1 MeV, this radio-isotope represents, in fission reactors, one of the most important source of radiations originating from activation. In fusion reactors, where most of the water cooling loops are mostly foreseen in stainless steel, the presence of Cobalt in the water chemistry is quasi unavoidable. But one big difference is the neutron energy, as the production of Co-60 from the stable Co-59 has its largest cross-section for thermal neutrons. But other threshold reactions can happen at high neutron energy (above 1 MeV) and the neutron energy spectrum can be degraded when reaching the cooling fluids, which can even further slowdown the neutron flux.

Some of the potential radio-isotopes, presenting a role in radioactive contamination of the cooling circuits are given below.

Isotope	Type of radiation	Half-Life	Origin	Implication on	Specific Problem
Co-60	Gamma (strong)	5.25 y	Activation (neutron in steel)	Operations	Shielding
C-14	Beta	5730 y	Activation (neutron in graphite)	Contaminat°, Dispersion	Carbon chemistry
Nb-94	Beta Gamma	20 000y	Activation in steel	Waste	Long Half-life (present in steel)
Ni-63	Beta	100 y	Activation (in steel)	Waste	Stainless steel constituent
Eu-152 **Eu-154**	Beta-gamma	13.4 y 8.2 y	Activation (in concrete)	Contaminat°, Waste	Present in concrete

Table 2: some of the important radionuclides for radioprotection (ORE) and waste management aspects.

The actual rate of erosion/dissolution/deposition depends on a lot of other parameters, like the water chemistry, the local water velocity, the temperature differences, the solubility of various elements etc… which makes the modeling of this phenomenon rather complex. (see fig.2)

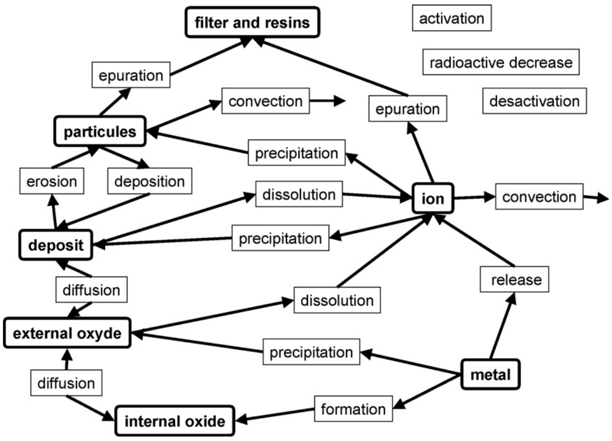

Figure 2: the various interactions and transport routes of radionuclides in cooling medias [6]

Nevertheless, based on fission experience, several aspects should be taken into account:

- envisage the possibility of decontaminating the loop during shutdown and maintenance periods;
- foresee sufficient shielding (or potential shielding space) around large exposed surface components (like heat exchangers);
- avoid spaces with stagnant fluid of with abrupt flow changes;
- keep the water chemistry under good control, and filter + purify water sufficiently (often, the filtration/purification loop is made on a by-pass of the main flow. Consider sufficient by-pass flow rate to avoid accumulation of ACP).

B. Airborne contamination and radioactive species transport during maintenance.

During shut down and maintenance outages of fusion plants, the vacuum vessel will be put at atmospheric pressure and can even be opened towards the external world for introducing remote handling inspection and repair machines. This opening brings the possibility of dispersing the existing contamination from the vessel internals towards the outside world. The main contamination sources being the tritium trapped in the metal structures and the dust deposited everywhere in the vacuum vessel. This dust is activated and can also contain some trapped tritium.

To mitigate as much as possible this source of contamination several processes can be put in place. The first one is indeed to collect the contaminants at the source; i.e. detriatiating as much as possible the vacuum vessel and its internals, and collecting or removing the dust as soon as the vessel is open. Nevertheless, none of these actions can insure 100% of removal. Therefore, when opening the vacuum vessel (including ports and neutral beam injectors) one should insure a pressure cascade between the outside atmospheric pressure and the inside pressure of the vessel, using adapted ventilation system. Several levels of the cascade should avoid or reduce the risk of contamination spread.

These effects have an impact on the occupational radiation exposure of the operators, but also on the consequences of an accident, on the waste management and on the needed handling systems for components replacement and repairs.

V. FUNDAMENTALS OF THE NEUTRONS INTERACTION WITH MATTER

Neutrons are, as indicated by their names, neutral particles, constitutive of the atom nucleus. Neutrons are ejected with high energy from the plasma (about 14 MeV or 1.93 10^8 m/s). But neutrons have various interactions with matter. Let us summarize the most important ones (see also fig. 3 below):

- it goes through the material without interactions; this can mostly happen as the neutrons are not charged, and if they have a high energy (or speed) most of them would not “see” the atoms of the matter;
- it can undergo elastic scattering against (mostly) light atoms, i.e. like bouncing of billiard balls, and sharing its energy between the neutron and the knocked atoms. This is for instance what is used for the slowing down of neutrons in thermal fission reactors;
- it can undergo what is called inelastic scattering, where the neutron is absorbed by the target atom, which re-emits another neutron with another energy;
- it can be absorbed by an atomic nucleus, leading to excitation and transmutation of the atom, and/or to several types of reactions implying the emission of other particles (n,p; n,α; n,γ; etc…); the n,γ reaction is also called "radiative capture";
- or it can induce fission of heavy nuclei (mostly of the actinides of the periodic table).

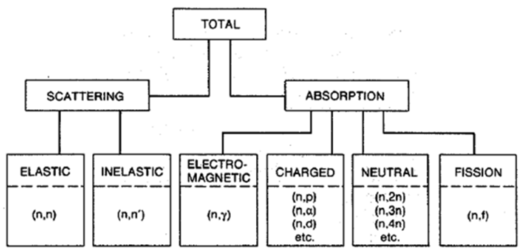

Figure 3: Various categories of neutron interactions. The letters separated by commas in the parentheses show the incoming and outgoing particles. [7]

The type of interaction strongly depends on the energy of the neutrons. Some reactions (mostly of absorption and re-emission of particles) have threshold energy under which the reaction does not appear; but a lot of them have a reaction rate (given in so-called "cross section") decreasing as 1/v, thus with much more probability at low (and very low) energy. At low energies, below 1 MeV, the elastic cross section is nearly constant, whereas the inelastic scattering cross section and absorption cross sections are proportional to the reciprocal of the neutron's speed (that is, 1/v).[7]

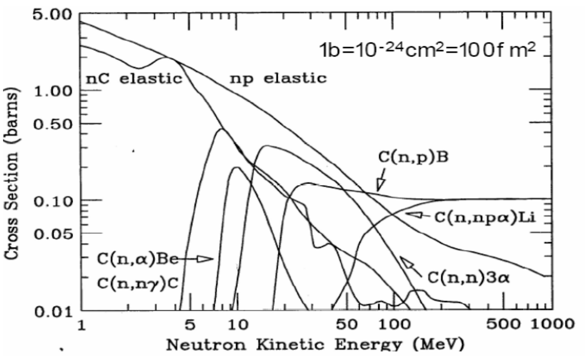

Figure 4: ex. of cross sections for Carbon, with elastic scattering in 1/v and threshold reactions (Univ. Rochester)

Moreover, due to the scattering of neutrons, their interactions can be spread to rather large volumes, away from the first knocked atom (see fig. 5 below).

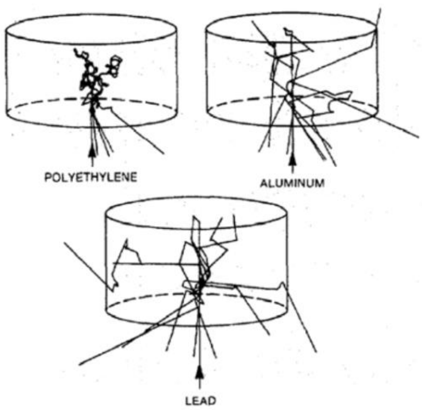

Figure 5: example of Monte-Carlo simulation of neutrons scattering in various materials [7]

These various interactions can lead to different macroscopic effects on the materials which are bombarded:

- Changes in mechanical properties by the formation of vacancies/interstitial atoms and the disorganization of the crystal structure;
- Activation of the elements and thus induced radioactivity (effects on the occupational exposure and on the waste management);
- Generated heat inside the material, often proportional to the material density (implying the need for cooling);
- Changes in electronic bonds and thus changes in the electric/thermal properties of the materials;
- Etc.

These effects and their implications for the design and operation of future fusion facilities and power plants will be shortly described in the following chapters.

VI. EFFECTS ON THE MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

The effects of neutrons on the mechanical properties of materials are very various and depend on the type of materials, on the present nuclei and isotopes, on the energy of the neutrons etc. In this chapter we will focus on the effects on structural materials, mainly concentrated on metallic materials. The effects on other materials, like beryllium or tungsten e.g. will also be tackled, mostly for the surface properties, as plasma facing components.

Neutrons can displace the atoms from their lattice position by elastic or inelastic scattering. This will indeed imply direct effects on the mechanical properties as it induce local defects that will be analyzed further. On the other hand, the n,p and n,α reactions involve the production of gas (H_2 and He) which can then diffuse through the material, aggregate and form gas bubbles which subsequently induce swelling.

As a general rule of thumb, for most of the metallic materials studied till now, the neutron irradiation induces an increase in the Yield Strength and the Ultimate Tensile Strength of the material with a parallel embrittlement (loss of ductility at high stress). At the same time, the fracture toughness is reduced and, due to the production of gas inside the material, swelling appears (at macroscopic level) and some effects on the creep resistance are often measured. However, these are only general trends, and each material shows specific influence depending also on the thermal treatments applied and on its crystal structure. These effects depend also strongly on the temperature range at which the material will be used (e.g. possibility of relaxation of some effects at high temperatures), on the physicochemical environment and sometimes on the stress or strain rate at which the material is submitted.

The in-depth study of the mechanical effects of neutrons on metallic materials is a domain of scientific knowledge in itself, and is rather complex to understand

and model. Most effects models are currently based on empirical equations tuned to fit the experimental results obtained in various types of irradiations conditions. The most known materials for high energy (> 1 MeV) neutrons effects, are austenitic stainless steels (type AISI 304, 316 and specific grades) which were developed for the fast breeder reactors and are also used as internals in the Light Water Reactors operated today.

Moreover, the effects of neutron irradiation are inherently multiscale, in space, time and number of atoms concerned. It varies indeed from instantaneous effects (ps) to long terms effects (Gs), from submicroscopic effects (Å, nm) to large macroscopic effects (m) and concerns small clusters from 10^2 to 10^{31} atoms … [8]

In the figure below are summarized some typical effects of irradiation on stainless steels.

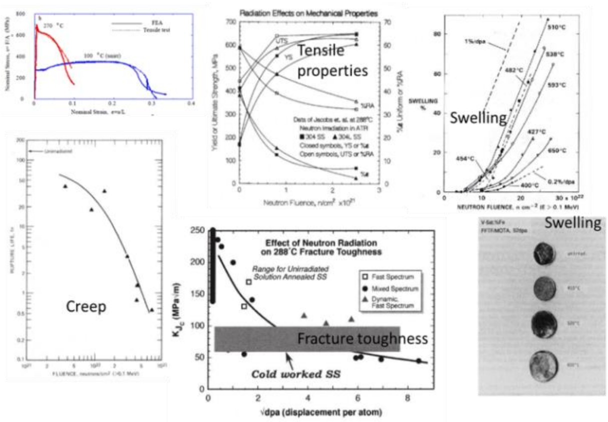

Figure 6: Typical effects of neutrons on austenitic stainless steels (example of effects on tensile properties, creep resistance, fracture toughness and swelling) [8]

The effects of the microstructure of the metals are also important factors to take into account. Metallic materials are often constituted of "grains" which consist of single crystals (bcc, fcc, hcp, …). The grains present different orientations and are separated by grain boundaries. Most of the metals used in structural materials (and in steels) are alloys which are composed of several alloying elements, and some impurities. For the neutron effects, even the impurities can have an important impact on the microstructure. Finally, for modeling and understanding of the phenomena happening in the microstructure of the materials, one has to take into accounts the defect structures: dislocations, gas bubbles, cavities (voids), vacant lattice sites (vacancies), interstitials.

Point defects (vacancies and interstitials) are created by the radiations. They undergo reactions and aggregations (clustering), as they can move and diffuse in materials. The modeling of these effects and of their diffusion and effects on the macroscopic properties of the materials is currently a subject of a lot of research (see e.g. [9]).

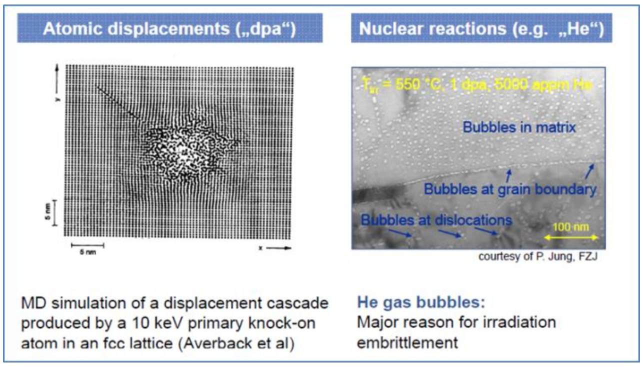

Figure 7: view of the effects of "damages"(dpa) and gas formation in metallic materials (A. Möslang, 2009)

Finally, the choice of the alloying elements (and of the following impurities) is very important also for the activation of the components, with implications on remote handling constraints and waste management. Fusion reactors being often much larger (in volume) than fission reactors, and the replacement of the Plasma Facing Components (PFC) being foreseen at rather high frequency (e.g. replacement every 3 or 5 years of the divertors) this aspect of low activation or reduced activation material is very important for the overall environmental impact of fusion. Therefore the selection of the alloys and alloying elements is also constraint by this aspect [10] (e.g. one should avoid Re as alloying element as it gives rise to long lived radionuclides). See also the chapter IX below.

The current R&D on structural material in magnetic fusion mostly focuses on the ferritic/martensitic steel, more particularly to the reduced activation alloy called "Eurofer".

A second aspect, which should also be looked at, is the effect of neutron irradiation on plasma facing components. Here the material challenge is still more severe: the material must be compatible with the high thermal heat flux (up to 10 MW/m² on the divertor), the sputtering and blistering due to particles impacts, the compatibility with the plasma (low Z material), together with the radiation damages and transformations. Moreover, the PFC must present a low tritium trapping behavior to avoid tritium inventory buildup in the plasma facing materials and in flakes and dust.

All these qualities together do not lead to a lot of remaining materials. For plasma compatibility (low Z) and high heat flux (and high temperature) resistance, the Carbon composites seems to give the most interesting answers, but they show a tendency to have a high tritium retention. For plasma compatibility and sputtering, this is the case for Beryllium; but this element has bad sputtering resistance qualities and is not very well fitted for high heat flux; it is moreover toxic and thus difficult to handle. Vanadium and Vanadium alloys seems to present some potentiality but their radiation induced damages are precluding their use. Finally, today the R&D focuses mostly on Tungsten and Tungsten alloys for its high heat flux resistance, low sputtering behavior and relatively good behavior towards the neutron irradiation which compensates for its high Z property. Silicium Carbide fibers in Silicium Carbide matrix (SiC/SiCf) seems also promising but is far to be developed sufficiently.

An example is the sputtering rate: for low Z material like Carbon, the erosion is of the order of 3mm/burn-year while for Tungsten it is around 0.1 mm/burn-year [Wirth].

VII. THE RADIATION RESISTANCE OF DIAGNOSTICS AND FUNCTIONAL COMPONENTS

The effects of neutrons on organic or amorphous materials is also important for diagnostics, instrumentation and remote handling components. Changes in the insulation resistance of insulators, darkening of glass and optical components, changes in the lubricating properties of oils or embritlement of the components can play an important role in the design and selection of materials for the measuring instruments or functional materials of fusion facilities.

Functional components are concerned by the neutron irradiation and the impact on their operation and "function". We will focus here mostly on diagnostics and instrumentation components and equipment. Up to now this equipment, to measure the various plasma parameters, was designed to resist to the high vacuum and sometimes high temperature environment, plus the presence of strong electro-magnetic fields.

The nuclear environment adds another difficulty to these components. First of all, the presence of neutrons and of strong gamma field (due to the radioactive decay of neutron activated metallic component in the vacuum vessel) precludes the use of most organic materials as insulator. In high radiation environment, only mineral insulation (like MgO or Al_2O_3) ceramic insulation materials can be used.

The use of semi-conductors must also be done with care, and high electronic circuit integration in high level radiation field is not advisable.

The use of optical components (windows, fiber optics, even mirrors) can also be influenced by the presence of radiations and the selection of the specific materials and assembly process must be done with great care and after intensive testing in similar conditions.

Several studies have been carried out during the last 10 to 20 years to develop and test radiation hardened components and systems. Nevertheless, sophisticated systems and highly integrated circuits tends to show strong sensitivity to radiations.

One can give here some generic and simplified trends shown by various components under radiation (but for more details, please refer to the literature):

- In high radiation fields, use mostly mineral; insulators instead of organic ones;
- Semi-conductors can be sensitive to radiations and circuits have to be designed fault-tolerant if used in semi-hard radiation fields (never directly in the strong neutronic field);
- Optical instruments (and their bonding system) tends to be radiation sensitive if not selected carefully; the presence of impurities in the glass can have dramatic impact on the properties;
- Fiber optics show in general the same trend as optical glasses, but some typical fiber types can resist to some radiation levels allowing to use them in specific locations.

There is a range of effects on insulating and functional materials that one can summarize in the following list :

- Radiation-induced conductivity (RIC);
- Radiation induced electrical degradation (RIED);
- Radiation-induced electromotive force (RIEMF);
- Radiation-induced thermo-electric sensitivity (RITES);
- Radiation induced absorption (RIA) for optical components;
- Radioluminescence (RL or RIE) e.g. in fiber optics
- Nuclear heating;
- Change in other properties such as activation, transmutation and swelling.

For further details on the impact on diagnostics and remote handling, see also the lecture of A. Donné.

VIII. THE ACTIVATION OF MATERIALS AND THE REMOTE HANDLING

The activation of materials has been described above. The very high activation level (giving up to tens of kGy/h radiation field) of the plasma facing components induces the impossibility to have human intervention in the plasma chamber after the D-T reactions. Moreover, the rather long distance of actions of neutrons and the transport of activated product also preclude human intervention in the vicinity of the vacuum vessel and of the neutral beam lines.

The principal elements that are leading to activation in the metallic parts (first wall, shielding, divertor, blanket,…) surrounding the plasma are the nickel, chromium, iron, cobalt and copper leading to the production of Co-60, Mn-54, Cr-51, Cu-64… Other isotopes are also produced, depending on the alloying elements used and the impurities present in the metals. The activation data is a rather complex topic as it depends on the local neutron flux, the operation and exposure data, the presence of impurities in the metals etc. The activation leads e.g. to high requirements in the purity of the metals (removal of several important impurities [10]) but also on the potential alloying elements. As example, there is currently an optimization study for the tungsten alloy to be used for power plant divertors. Beyond the mechanical and thermal behavior in irradiated situation, the used alloying elements should not lead to high activation for handling purposes, but also for waste management and environmental impact aspects (see chapter IX below).

Therefore, remote handling has to be used for all inspection, maintenance and repair works to be carried out in these areas, as well as for decommissioning. Remote handling is thus a real challenge for these activities, as it has to work in a rather harsh environment (high radiations, temperature, vacuum for some case). Moreover, the geometry and the available space for maintenance and repair are also rather complex and limited leading to challenging operations and complicated movements.

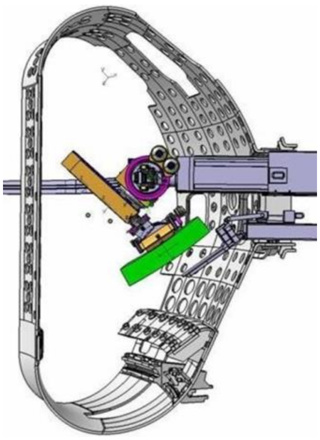

Figure 8: remote handling of ITER shielding block (ITER.org)

Several R&D works are currently on going for developing the needed equipment and testing the components in the foreseen environment. A first trial was already made at JET, for replacing remotely the complete first wall.

Several aspects need to be taken into account for the design of remote handling systems:

- the accessibility of the component to replace (some "tiles" or first wall components in the torus are not easily accessible);
- the weight of the heaviest component or tool to be handled by the RH system (some pieces can be very heavy: the divertor cassettes in ITER for instance are already weighing more than 10 tons);
- the limited access through narrow ports;
- the potential contamination by dust (from beryllium, tungsten or carbon, with tritium content and activated products);
- the high to very high gamma radiation field (more than 30 kGy/h);
- the unavailability of direct viewing conditions (only televisual connection);
- the ultra-high vacuum and nuclear cleanliness requirements.

The main impacts of the nuclear aspects of a fusion plant concerns the resistance to radiations of all components (actuators, motors, sensors, …) and the necessary cleanliness and easiness to wash the potential contamination of the manipulators and vehicles.

The resistance to radiations can lead to special developments of the whole systems (like e.g. the use of water instead of oil for hydraulic high payload manipulators) [11] , to the use of radiation resistant sensors and vision systems (this implying the same approach as for the diagnostics systems - see chapter VII above) and the development of actuators and motors with limited (or even no) organic content and specific insulation and lubricant materials.

The development of such remote handling system, with strong request and resistance to severe and harsh environment is also a technical challenge for today's technology.

IX. THE RADIOACTIVE WASTE AND RECYCLING

Even if fusion would not produce long lived radioactive waste, regarding the high volume and mass surrounding the plasma chamber, fusion will probably produce, by far, much more quantity of short lived waste than any other facilities. But the quantity and mostly the "quality" of the generated radioactive waste (i.e. its radioactive lifetime and its possibility to be recycled) depends strongly on the individual constituents of the materials facing the plasma (incl. impurities).

Therefore, it is of very high importance for the design and selection of the materials facing the plasma but also likely to be bombarded by neutrons, to take these aspects of waste management and recycling into consideration.

Several studies have already been carried out in this domain (see e.g. [12, 13, 14]) but a lot remains to be done to develop the necessary process and infrastructure allowing to dismantle, condition and recycle the materials generated by the regular maintenance and replacement of a fusion plant.

To give some idea of the magnitude of the problem, the structural and functional metallic material situated around the plasma in one of the European fusion power plant conceptual design (PPCS-AB) had a mass of about 97,000 tons! This represents 13 times the mass of the Eiffel tower… And the mass of the replaceable components in ITER (divertors and first wall) represents a (potentially activated) mass of about 800 tons (above 2000 with the shielding).

Once again the first mitigation technique of this issue is to treat the problem at the source; i.e. developing materials without isotopes leading to long-lived radionuclides [waste1] and developing materials with a strong control on the impurities level (often the impurities, even at trace levels, can have an impact on the long lived waste stream). Moreover, the design of the components has to be such that their dismantling and the separation of the different constituents (made of different materials) must be easy to carry out remotely.

On the other side, methods and process for recycling/reuse of material have to be developed, to avoid generating too much waste for disposal. Recycling and reuse means to handle, work on and refabricate (slightly) radioactive materials into new elements for re-use in fusion reactors or recycle within the nuclear industry. Clearance and free release is another way of disposing materials, if the remaining radioactivity (after decay storage) is low enough to have negligible effects on the populations and environment.

The question is whether it is feasible to fabricate the complex units of a fusion plant under remote control conditions. Indeed, for the higher activity pieces it will not be possible to reuse highly activated materials for shielding or other "simple" purposes, unless radioisotopes are removed during reprocessing. Reuse of these materials in a fusion power plant or an advanced fission next-generation reactor seems the only option. Therefore, sophisticated fabrication and testing processes have to be looked at in detail and limits must be defined if applicable. The use of refractory materials (such as Nb, Mo,Ta, W, Re) may need innovative approach.

This would lead to a material cycle approach, as follows, if all the steps can be developed on time and with the available technology:

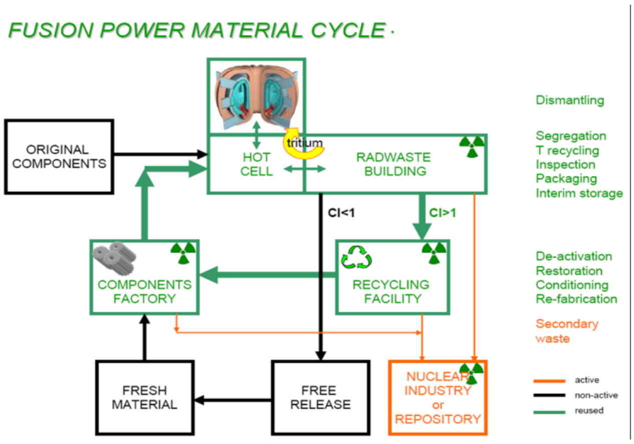

Figure 9: Fusion power potential material cycle [11]

To summarize this topic, there are still some open questions, which have to be solved or answered in order to reduce the generated waste amount and tend towards a low radioactive waste production (and thus low environmental impact) from fusion energy production:

- Definition of undesirable alloying elements;
- Assessment of radioactivity build-up by repeated reuse of structural materials;
- Dismantling and separation of different materials from complex components: different steps to follow and impact on design requirements;
- Developing processes for the production of material suitable for recycling;
- Fabrication of complex components using recycled materials by remote handling and related design approach;
- Acceptable limits for processing of radioactive materials in foundries;
- Study of (Li-Pb) breeder refurbishment by chemical process for reuse.

The back end of material re-use is thus an important factor in preparing the future of fusion power.

X. CONCLUSIONS

The nuclear aspects of a fusion power plant are rather new to tackle. Up to now, only very few machines (JET, TFTR) in the world have worked in D-T plasmas, with very limited amount of tritium (the total amount in JET was 20 g, to be compared with the 3 kg foreseen in ITER) and a very low neutron flux on the walls and in-vessel components compared to the ones expected in ITER and future fusion power plants.

The nuclear aspects of a plant are various and must be taken into account in parallel with other issues; moreover, the experience gained in fission power plant can be very valuable for drawing lessons and taking the best solutions for different aspects.

Beside the safety aspects (including the radioprotection of the workers and population), one can understand that the aspects of materials properties and the impact of neutrons and the nuclear environment on these materials are of prime importance.

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