The radiological source terms in a nuclear fusion experimental facility

Sandri S.[1*], Contessa G.M.[1], Guardati M.[1], Mariano G. [1], Villari R.[1]

[1]*ENEA - Italian national agency for new technologies, energy and sustainable economic development, Via E. Fermi 45, 00044 Frascati, Rome, Italy*

*Corresponding author's e-mail: sandro.sandri@enea.it

Abstract. A thermo-nuclear fusion experimental reactor produces a large amount of energy that is mainly transported from the plasma by neutrons and deposited in the machine components, generating nuclear activation. One of the elements used in the fusion reaction is tritium, the radioactive isotope of hydrogen, but in many instances, experimental facilities are based on deuterium only reactions and do not use tritium as fuel. High temperatures in the plasma-facing components and in other parts of these facilities require specific cooling systems that are subject to the neutron activation and that transport the radioactivity into their loops and components. Because of the above considerations, the radiation sources in an experimental fusion machine could be:

- the primary neutronic field resulting from the fusion reactions occurring in the reaction chamber,
- the gamma radiation generated from neutrons' interaction with the machine components,
- the X and gamma radiation due to the plasma currents,
- the gamma radiation emitted by activated products in the machine components
- loose contamination from activated dust generated in the machine components,
- activated corrosion products generated in the cooling loops after the activation of the inner wall of cooling water pipes,
- activation of the cooling water,
- tritium used as fuel for the fusion reaction or produced in the D-D fusion reactions,
- wastes, still containing tritium and gamma emitters,
- activated air produced in the main hall atmosphere and released to the environment,
- neutrons and secondary gamma radiation generated in Neutral Beam Injectors.

The current analysis is a brief review of the studies on the subject, aimed to define the radiation protection approach to be applied to the next fusion experimental machines. Specific reference will be made to the DTT experimental fusion device which is in an advanced design phase in Italy.
Activities developed at different experimental fusion machines, like TFTR in the USA, JET in England, JT60 in Japan, together with some minor experiments implemented in Italy, will be the basis for identifying the typical radiological source terms. Finally, the studies performed for designing the international project ITER and the Italian DTT will be considered for providing qualitative and quantitative information about the radiological source terms and the potential radioactive waste produced and released to the environment.

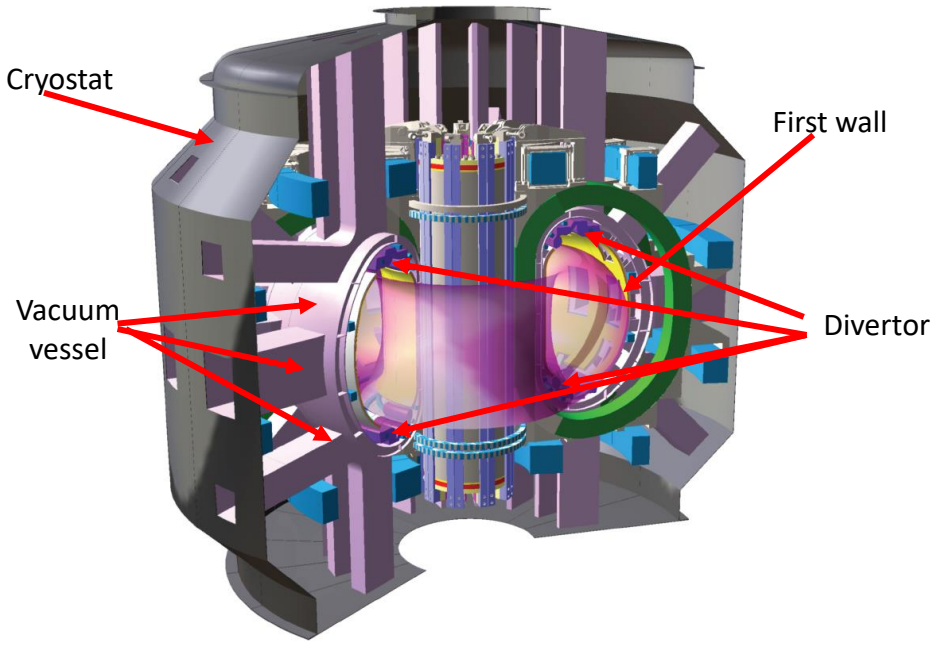
KEYWORDS: Nuclear fusion, Fusion facilities, radiological source terms.

1 INTRODUCTION

Nuclear fusion experimental facilities are a very promising solution for energy production. They are less hazardous than the fission nuclear reactors and do not have the same problems related to the long-lived radioactive waste. However, the intense, high energy neutron radiation produced by DD and DT fusion reactions represents a challenge for the radiation protection of the workers and the population. Neutrons from fusion reactions produce an additional intense gamma radiation field and activate the materials that are around the core of the facility. The typical radiological sources of these devices are therefore of a different kind and must be distinguished in order to provide the correct protection approach to each one of them. Some previous experimental facilities have given the opportunity to test equipment and procedures, however, their power and workload were very low if compared with those of the future devices now under construction, like ITER in Europe and JT60-SA in Japan. Also, intermediate power facilities like DTT (Divertor Tokamak Test) in Italy could be considered as further training opportunities toward the improvement of the radiation protection approaches.

Following the guidelines described within the European Fusion Road Map [1], the DTT facility, now in an advanced design phase, has been charged with the challenge to test the science of tokamak alternative divertor concepts under integrated physics and technical conditions that can reliably be extrapolated to DEMO [2, 3], the last step before the first fusion power reactor. The DTT cross section is reported in figure 1. In a magnetic fusion device, the divertor is the system where energy and particles, transported out from the plasma through non-neutronic channels, are collected. The baseline solution to the exhaust issue consists in a metal divertor operating in a plasma fully detached condition. However, as widely illustrated within the European Fusion Road Map, the baseline solution might not fit the needs of DEMO and of a future reactor. The plasma exhaust issue needs therefore to be solved with great urgency and strength in order not to cause delays to the development of fusion. In this effort a key aspect will be the availability of DTT scenarios [4], with high-performance core plasma properties. Testing the alternative divertor configurations in different scenarios will provide the whole set of information needed to choose the right solution for DEMO.

Figure 1: DTT cross section and main components



DTT project, with its intense maximum neutron flux of more than 10^{17} n s^{-1}, is a challenge for the radiation protection. It will not use tritium as fuel, however, it will have all the different kind of radiological sources typical of the experimental nuclear fusion facilities, as listed below:

- Direct radiation produced during plasma operation,
- Gamma radiation emitted by activated products in the machine components,
- Loose contamination from activated dust generated in the machine components,
- Activated corrosion products and activated water generated in the cooling system,
- tritium produced in the D-D fusion reactions,
- wastes, still containing tritium and gamma emitters,
- activated air produced in the main hall atmosphere and released to the environment,
- neutrons and gamma radiation generated from the auxiliary devices, like Neutral Beam Injectors.

2 DIRECT NEUTRON AND GAMMA RADIATION

Radiations emitted by devices that use nuclear fusion reactions are generally very similar and often have comparable characteristics. In most cases, these systems are based on deuterium-deuterium (D-D) and/or deuterium-tritium (D-T) reactions, according to the following main relationships:

$^{2}H + {}^{3}H => {}^{4}He + n$
$^{2}H + {}^{2}H => {}^{3}He + n$
Neutron production is present in both cases. These fast neutrons have high initial energy, about 14 MeV in the D-T reaction, and about 2.4 MeV in the D-D reaction. In D-D systems there is a production of tritium due to the concurrent reaction:
$^{2}H + {}^{2}H => {}^{3}H + p$
The absence of an energy threshold for these reactions implies that a high acceleration of deuterium is not necessary. Typically, some hundreds of keV are enough to allow the crossing of the Coulomb barrier and to make effective the reaction that is always exothermic.
DTT facility is based on DD fusion reactions [5], it does not use tritium as fuel, however, its neutron yield during the 28 years of experimental campaigns will be quite intense. It will increase in the first years and will reach a total neutron production as high as 3.73 10^{22} n/year at the end of DTT life, as shown in figure 2 [6].
The neutron field is always accompanied by a gamma radiation field, mainly due to the prompt radiation following the neutron interactions. In DTT, at its maximum performance, during plasma burning neutron and gamma fluxes inside the cryostat would have the trends reported in figure 3 [6].
The results reported in the figure 3 [6] show the neutron and prompt gamma fluxes in high performance operations (i.e. for a DD Neutron yield of 1.5x10^{17} n/s and 1% DT neutrons due to triton burn-up) assessed with Monte Carlo N-Particle (MCNP5) code [7]. It is able to simulate the transport of neutrons, photons and electrons in an arbitrary three-dimensional geometry and it is the most used and validated code for fusion neutronics. MCNP use pointwise cross section data point and therefore there is no approximation or averaging in the cross-section data and hence a very good representation of transport is maintained. For the present application FENDL2.1 libraries have been used [8]..

Figure 2: DTT annual neutron production

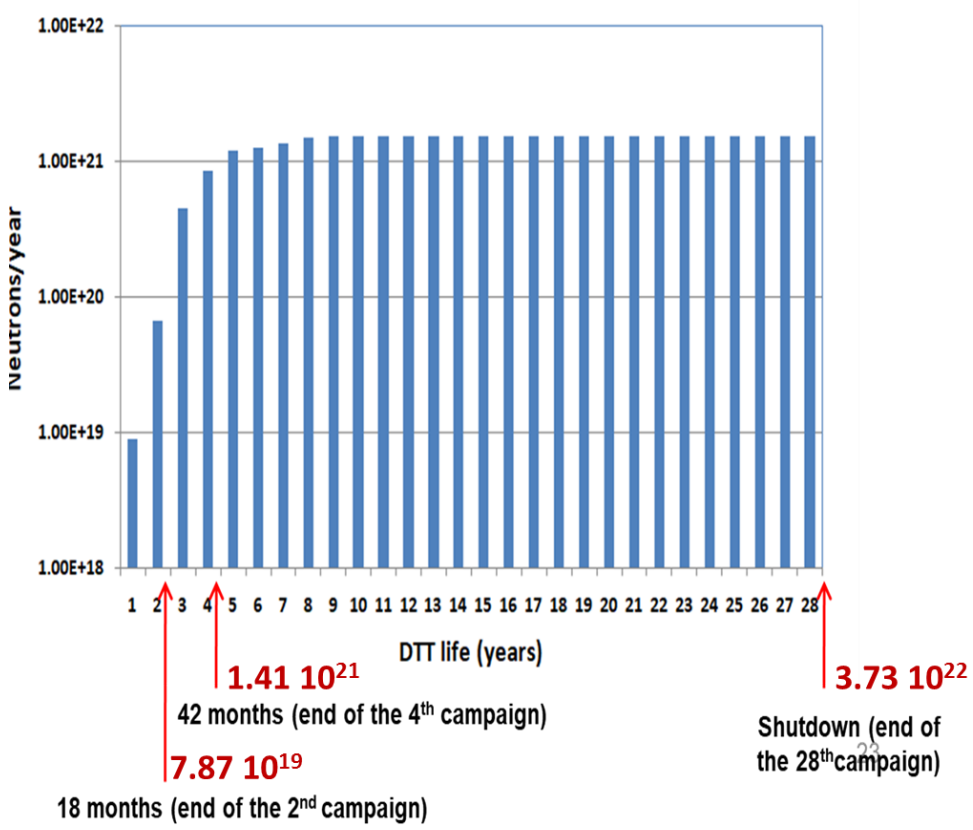
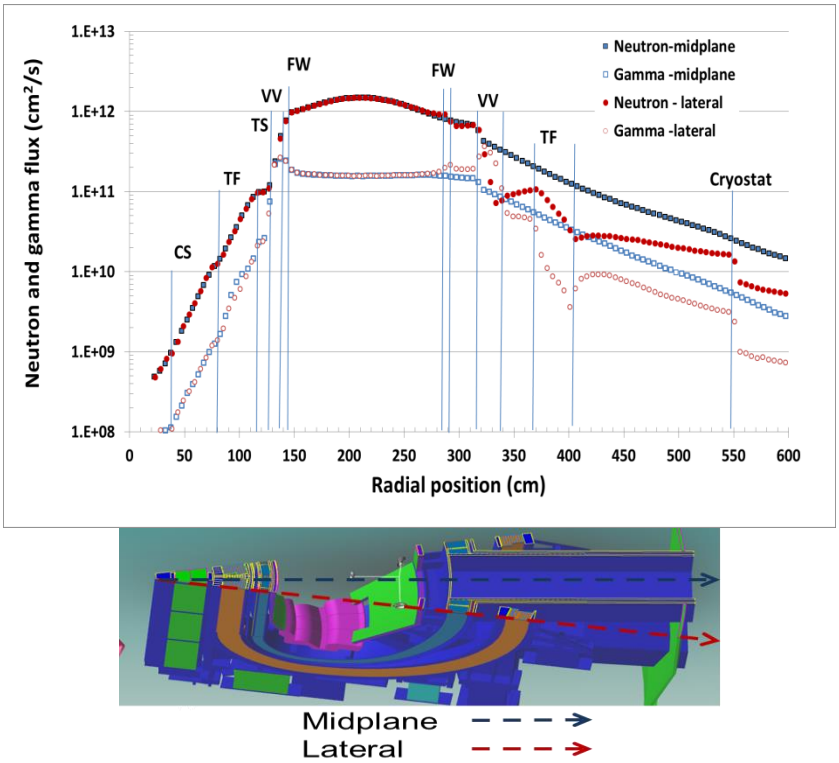


Figure 3: DTT neutron and gamma fluxes radial distribution at the midplane in high performances operations [6]



3 NEUTRON ACTIVATION

The radioactive residues and the consequent contamination are essentially due to the action of the neutron fields that activate the materials determining the formation of different radionuclides in the structures of the machines themselves and in the surrounding environment, including atmospheric air.
When materials are irradiated by neutrons a number of reactions are possible such as capture reactions (n,γ), (n,α), (n,p). A large number of reactions can occur such that after a long irradiation period many different radioactive isotopes can be generated.
Due to the high number of isotopes, the possible decay pathways, and the analytically unsolvable reactions, a consistent and reliable computational scheme must be found. There are several nuclear inventory codes worldwide that provide possible solutions to this kind of problem. Each code has benefits such as speed of processing, accuracy of calculation etc. One of the codes that show good balancing for features and accuracy in the fusion applications is FISPACT (FISsion Products and ACTivation) [9]. FISPACT is now the nuclear industry standard in the UK and is part of the ITER benchmark code suite for activation calculations and is the only code to include cross section uncertainties in the final activity.
Considering the DTT facility, the FISPACT code was used to assess the radioactive inventory and the contact dose rate in the machine components after shut-down, using the neutron spectra calculated with MCNP in 3-D DTT geometry. Three scenarios were considered for the calculation (see figure 2) taking into account the time from the beginning of the operations, the accrued activation, and the related increase of the neutron flux. In figures 4 and 5 [6] the FISPACT code results are reported, respectively in terms of radioactivity concentration and contact dose rate, for the scenarios after 18 months, 42 months, and 28 years of DTT operation. These results show that the neutronic activation is the real challenge for the radiation protection at the experimental fusion facilities, both for a) the important inventory of radioactive material produced and b) for the high dose rate after shut-down around the internal components. The first aspect could represent a concern for the release of the waste materials during the operation of the machine and is the principal issue in the decommissioning of the facility at the end of its life. The dose rate is indeed a limiting factor for the hands-on maintenance

(workers intervention) that should be avoided beyond 100 µSv/h [10], a value that for DTT at the shut-down will be exceeded for some component also after the first years of operation. The dose rate will decrease after the shut-down, due to the radioactive decay, but for the inner components it will remain higher than 10 µSv/h (the generally acceptable threshold for the free access of exposed workers) for some months after the first two or three years of operation and for some years at the end of DTT life.

Figure 4: DTT activity concentration in the in-vessel components versus time after irradiation

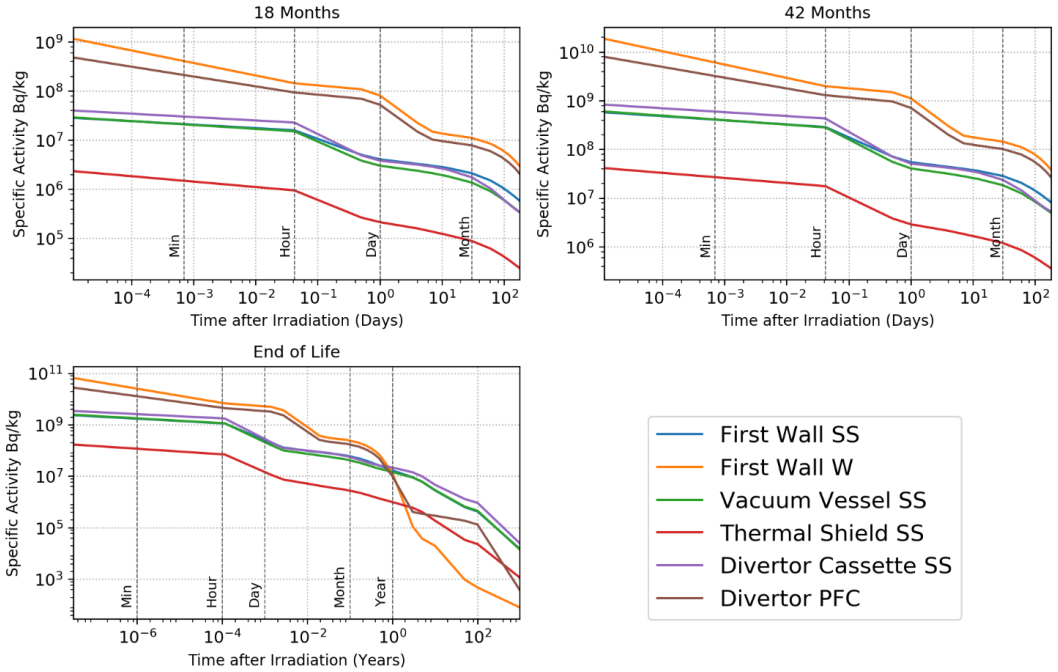
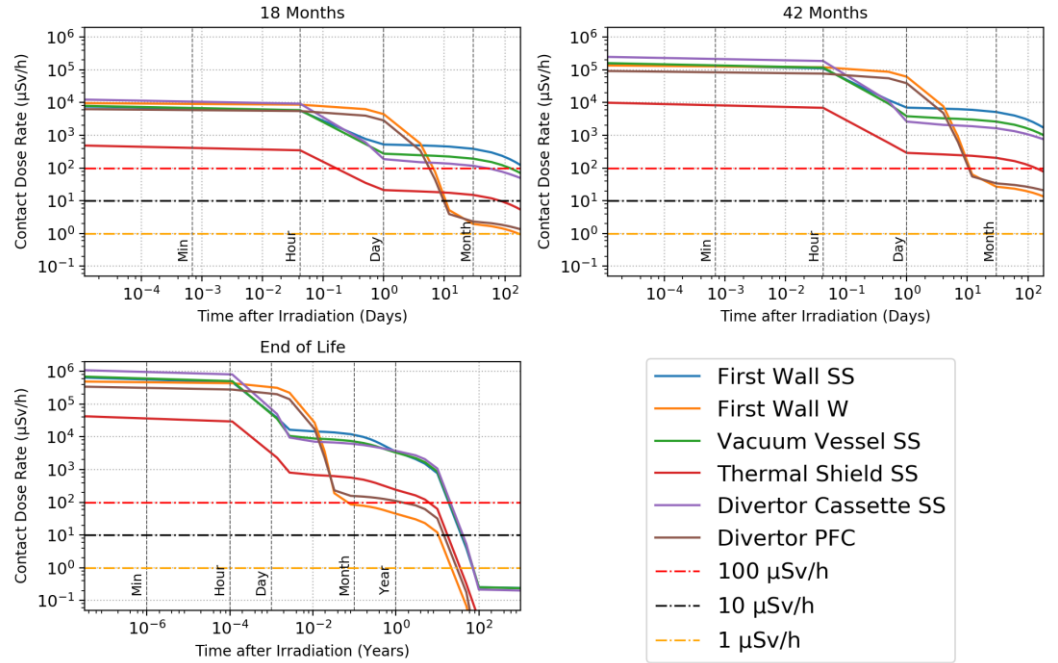


Figure 5: DTT contact dose rate from the in-vessel components versus time after irradiation



In some tokamak devices, like in ITER, the first wall is composed also of beryllium, and, in this case, there is a shutdown neutron field [11]. However, it is usually responsible for a dose rate lower than the one due to the shutdown gamma field. This residual neutron field is produced by Be (γ,n) reactions in the first wall and is proportional to the shutdown gamma-ray field, so it shows a time dependence similar to the shutdown gamma-ray field.

4 CONTAMINATION, DUST AND AIR ACTIVATION

In the experimental nuclear fusion devices, the choice of materials is a crucial issue, mainly for the in-vessel components, and especially for the Plasma Facing Components (PFCs). The combination of very high temperatures, high radiation levels, intense production of transmuting elements and high thermomechanical loads requires very high-performance materials. Corrosion and erosion processes determine the production of activated dust and its resuspension in case of LOss of Coolant Accidents (LOCA) and LOss of Vacuum Accidents (LOVA) [12]. Dust is produced by the surface interactions of the energetic plasma. The dust may contain tritium, may be radioactive from activation products, and may be chemically reactive and/or toxic. Possible accidents in large fusion reactors could mobilize the dust and threaten occupational and public safety.
The activation of the air surrounding a device based on nuclear fusion reactions, following the interaction with the neutrons that are produced, involves the production of some radionuclides, among which the main ones are: ^{3}H, ^{11}C, ^{13}N, ^{16}N, ^{14}O, ^{15}O, ^{37}S, ^{37}Ar, ^{41}Ar, ^{39}Cl, and ^{40}Cl. Those who generally contribute the most to the dose and need to be considered for the evaluation of releases in the environment are: ^{15}O (for a 30%), ^{11}C, ^{13}N, ^{41}Ar (over 50%), ^{39}Cl and ^{40}Cl. Generally, the reaction that determines the need to size the ventilation system and that requires the demonstration of respect for the impact on the population is the ^{40}Ar(n,γ)^{41}Ar [13]. However, the activation of air in these plants does not usually affect operational scenarios as releases in the environment are responsible for very low doses and below the exposure constraints for the population both in the case of normal activity and as a result of accidental releases, as it was assessed during the design of DTT facility [14].

5 RADIOACTIVITY IN THE WATER-COOLING SYSTEMS

The water cooling systems (WCSs) of the nuclear fusion facilities could be one of the critical exposure sources for the personnel when the plasma facing components need to be cooled. Indeed, the working activities for routine inspection and maintenance at the WCS are highly person power consuming and frequently require tight contact with the main system components.
From the radiological point of view, the risk at the WCS mainly comes from the activated corrosion products (ACPs) that are generated in the regions of the system under the flux and are moved in the remainder of the loops. The ACPs are corroded and eroded by the coolant from the inner walls of the pipes and are then diluted in the coolant itself. The cooling water moves the ACPs along the whole cooling loops and releases them on the inner surface of the system components, such as heat exchangers, pipes, valves, pumps, and filters [15].
Usually the coolant content of ACPs is lower than that of the surfaces, or at least this is the situation after some operative cycles. However, the radiation produced by the ACPs on the inner surface of the WCS are less shielded, on the average, than those coming from the ACPs diluted in the coolant and therefore they are more relevant from the radiological protection point of view. The dose rate assessment around the loop components requires an adequate analysis of the ACPs and the evaluation of the ACPs inventory on the inner surface of the WCS components.
The cooling water istself can be activated by 14 MeV neutrons, and in this case it emits both high energy gamma radiation from ^{16}N and delayed neutrons from ^{17}N. The isotopes ^{16,17}N are produced through the ^{16}O(n,p)^{16}N ($T_{1/2}$ = 7.13 s) and ^{17}O(n,p)^{17}N ($T_{1/2}$ = 4.1 s) reactions, respectively. These sources of radiation may represent an issue for workers's safety and can have an impact on the design of the machine and on the qualification of components. However, the energy thresholds of the above reactions are higher than 9 MeV, making them impossible for neutrons produced by the DD reactions. For DTT the lower energy of neutrons from DD reactions and the limited impact of the secondary DT

reactions guarantee a low influence of these radiation sources on the workers safety. On the other end, this aspect represents a radiation safety concern at the facilities based on DT fusion reactions, like ITER [10].

6 TRITIUM

Tritium is a beta emitter frequently used as fuel in the more advanced experimental nuclear fusion facilities. It decays to ^{3}He by emitting a beta particle (electron) and an antineutrino from one of the neutrons in the nucleus. No gamma radiation is released. The generally accepted value for the half-life of tritium is 12.323 ± 0.004 years (4500.88 ± 1.46 days). The energy of the beta particle varies from 0 to 18.6 keV with an average energy of 5.69 keV. The range of the tritium beta particle is low, about 6 mm in air and 0.005 mm in water or soft tissue. Human skin is composed of the epidermis, 20-100 μm thick, and the dermis, 1-3 mm thick. The target cells for skin cancers and skin damage of other types are present at the basal layer of the epidermis and in the dermis. Thus, electrons emitted from tritium outside of the body hardly could reach these targets. In other words, electrons from tritium can inflict damage on humans only when tritium is present inside the body. Exposure to tritium is primarily in the form of HT gas or HTO water vapor, although T_2 and T_2O may be present. Only about 0.005 percent of the activity of inhaled HT gas is incorporated into lung tissue, and most is exhaled. In addition, tritiated water can be absorbed through the skin or wounds unless protective equipment is used. Low penetration of tritium beta emission also implies that most commonly used monitors such as film badges, thermoluminescence dosimeters or pocket ionization chambers are ineffective for detection of tritium in the body and that bioassay by liquid scintillation counting of urine, blood, or water vapor from expired air is the means to monitor tritium in the body.
As mentioned, Current designs for DT nuclear fusion devices call for the use of tritium and deuterium as the fuel for the energy producing fusion reactions. But the tritium fuel injected in the vacuum vessel to trigger the fusion reaction burns partially (0.3%) in the plasma [16]. A large fraction of the unburnt DT fuel is extracted from the Vacuum Vessel (VV) by means of the tritium extraction system and sent to the fueling system in which the tritium and the impurities are separated. This part of the tritium inventory is well controlled in normal operation. Only in accident conditions it can be a concern for the worker and public safety. The tritium spare part remains in VV, trapped in the materials. After that, it outgasses from in-vessel materials and diffuses into cooling systems. Therefore, the tritium in the DT fusion devices is present in the VV, in the bulk and in the PFCs, in the Rad-Waste areas, in the materials transferred in the buildings, in the cooling system and in the tritium plant. However, in the DD facilities the tritium inventory due to the nuclear reactions among deuterium particles only is considerably lower and can be easily controlled to reduce its safety impact on the workers and the population [16].

7 CONCLUSION

The present study is an analysis of the sources of ionizing radiation that could be present in a typical nuclear fusion facility. The main source of radiation has been proved to be the high-energy neutron field produced during nuclear fusion reactions. However, with few exceptions, the experimental machines currently in operation worldwide have usually low neutron production and seldom use tritium as fuel. The activation induced by neutrons is important in machines like DTT, which, even if it is based on DD fusion reactions, is expected to produce more than 10^{17} n/s in high performance operations and more than 10^{22} neutrons over his lifetime. The problems related to materials activation are more significant in future tokamak machines operating in DT like ITER and DEMO and these will have further critical issues like cooling water activation, ACPs and radioactive dust release in case of LOCA accidents as well as on rad-waste management. Therefore, the studies and developments aimed at reducing the impact of radiological source terms at the nuclear fusion facilities have to be intensified in order to apply the best radiation protection solutions at the future high-power Nuclear Fusion Reactors that will be constructed after the DEMO plant.

8 REFERENCES

[1] F. Romanelli, et al., Fusion Electricity – A Roadmap to the Realisation of FusionEnergy, FDA, 2012 (and) https://www.euro-fusion.org/wpcms/wpcontent/uploads/2013/01/JG12.356-web.pdf.

[2] M. de Baar, et al., A strategy to address exhaust issues in the EU Fusionprogramme, in: 2nd IAEA DEMO Programme Workshop, Vienna, 18.12.2013.

[3] R. Wenninger, et al., Advances in the physics basis for the European DEMOdesign, Nucl. Fusion 55 (2015) 063003.

[4] R. Albanese, A. Pizzuto. The DTT proposal. A tokamak facility to address exhaust challenges for DEMO: Introduction and executive summary, Fusion Engineering and Design, Volume 122,2017, Pages 274-284

[5] DTT, Divertor Tokamak Test facility – Interim Design Report ("Green Book"), https://www.dtt-project.enea.it/downloads/DTT_IDR_2019_WEB.pdf, April 2019.

[6] R. Villari, et al., Nuclear design of Divertor Tokamak Test (DTT) facility, Fusion Engineering and Design 155 (2020) 111551

[7] X-5 Monte Carlo Team: MCNP - A General Monte Carlo N-Particle Transport Code, Version 5, LANL report LACP-03-0245, (2005).

[8] FENDL-3.1d: Fusion Evaluated Nuclear Data Library ver.3.1d, https://www-nds.iaea.org/fendl/, (2018).

[9] R A Forrest, *FISPACT 2007: User manual*, UKAEA Fusion, Culham Science Centre, Oxfordshire, OX14 3DB, 2007.

[10] Maubert, H. et al., Radiological protection in ITER. RADIOPROTECTION – VOL. 42 – N° 4 - pages 519 - 534 (2007)

[11] Khripunov, V., "The ITER first wall as a source of photo-neutrons", *Fusion Engineering and Design*, vol. 56-57, pp. 899 – 903, 2001.

[12] Malizia, A. et al., A Review of Dangerous Dust in Fusion Reactors: from Its Creation to Its Resuspension in Case of LOCA and LOVA. Energies 2016, 9, 578; doi:10.3390/en9080578.

[13] NCRP. Radiation Protection for Particle Accelerator Facilities; Report No. 144; NCRP: Bethesda, MD, USA, 1977.

[14] Sandri, S. et al., A Review of Radioactive Wastes Production and Potential Environmental Releases at Experimental Nuclear Fusion Facilities. Environments 2020, 7, 6; doi:10.3390/environments7010006.

[15] Lu Li et al., Evaluation of ACPs in China Fusion Engineering Test Reactor Using CATE 2.1 Code. Science and Technology of Nuclear Installations, Volume 2017, Article ID 2936069, 7 pages, https://doi.org/10.1155/2017/2936069.

[16] Tosti S., Ghirelli N., 2013. Tritium in Fusion: Production, Uses and Environmental Impact. Nova Science Pub. Inc.