Overview on Neutronics, Safety and Radiological Protection of HiPER Facility

R. Juárez 1,2), J. Sanz 1,2), J. M. Perlado 2)

1) Departamento de Ingeniería Energética, UNED, Madrid, Spain

2) Instituto de Fusión Nuclear, UPM, Madrid, Spain

E-mail contact of main autor: rafael.juarez@upm.es

Abstract. The design of the HiPER facility is in its conceptual phase. The design of the facility includes different shields facing the dose rates that will arise from the operation. We have studied the implications of a preliminary proposal of design from the standpoint of shielding requirements. The reference case is considered to be the most exigent irradiation scenario conceived for HiPER 4a. 100MJ neutron yields per shot, with 100 shots at 10 Hz in a single burst, one burst every month. The expected lifetime of the facility for this scenario is 20 years. We have computed the prompt dose rates (PDR) and residual dose rates (RDR) delivered to the workers/public during the operation and in the period between bursts; we also computed the prompt dose delivered to the Final Optic Assembly (FOA), as a sensitive part of the facility. The shields that have been proposed behave reasonably well, creating free-restriction areas outside the target bay, and allowing manual maintenance 36 hours after the shutdown in some stays. The FOA receives a dose rate 30 times lower in the presence of the FOA shield. We compute the quantities with the same design undergoing a softer irradiation scenario, resulting a waiting time to access to the restricted area shorter than one day. The FOA receives 20 times lower dose rates. We have also considered different materials for the tubes which transport the beams, as they are the main responsible for the RDRs. The choice of material for the reaction chamber is discussed for commercial and reduced-activation steels, with regards to waste management performance.

1. Introduction

The HiPER project phase 4a is considered to become an engineering machine. The presence of neutrons derived from the experiments requires the study of doses and of the activation of the components of the facility to identify necessities of shields regarding with people and equipment.

The most exigent irradiation planning proposed has been 100 MJ of neutron yield per shot. Up to 100 shots could happen in a single burst at 10 Hz. With one month between bursts, up to 12 burst per years could be attained. The lifetime of the facility considered is 20 years for this irradiation scenario. It represents $1.2 \cdot 10^5$ MJ/yr, 1000 times higher than it is expected to happen in NIF [1]. The operation of the facility will spread neutrons and photons, giving rise to PDRs to people and equipment. Shields are placed within the target bay to protect people against the PDR, and a special shield is conceived to reduce the PDR delivered to the FOA. With this reference design, explained in section 2, we have also computed the activation of the components, and RDRs between bursts due to this activation. These results offer an idea of which could be the shield requirements

As some other irradiation scenarios are considered in HiPER, we have calculated the same quatities for another sequence of shots. A more realistic irradiation scenario consists in 20 MJ shots, with no more than 5 events with neutron generation in a 100 non-explosive shots burst. One burst would happen every week, limited to 50 bursts per year. 30 years of lifetime are assumed in the irradiation scenario, which accounts for $5 \cdot 10^3$ MJ/yr. For this softer scenario we have calculated the same quantities than for the exigent and reference one.

After this study, we focus on two specific problems: RDR to people (workers and public) inside the target bay and choice of material for the reaction chamber.

The RDR shows to be dominated by the activation of the tubes [2], so in order to reduce it, we have investigate different materials for these tubes, seeking a reduction of activation. The activation of the chamber is a quantity to consider to choice the material for the reaction chamber. We study the waste management of two different reaction chambers, one built of commercial stainless austenitic steel, and the other built of a reduced-activation ferritic steel (RAFS). Both compositions are assumed to present reasonable impurities concentrations.

2. Facility Design

The facility design consists in two groups of components: basic components and shields. The basic components are: reaction chamber, beam tubes, renewable optics and FOA. Given the necessity to protect some basic components and workers/public against radiation, several shields are placed to pursue a reduction of delivered dose.

2.1 Basic Components

Starting from the center of the facility, the first component that neutrons find is the reaction chamber. It is a spherical shell assumed to be made of SS304L steel [3]. This steel is commercial option of good welding capabilities. It has been considered for fusion before [4], and reasonable impurities concentrations are measured. It inner radius is 500cm and it is 10cm thick. It presents 48 cylindrical penetrations, distributed in 6 rings. In the section 4.4, there is a study on the impact of building the reaction chamber of EUROFER[5]. This RAFS is conceived to exhibit an attractive behavior from the waste management standpoint, giving rise to lower dose rates than commercial steels.

After the reaction chamber, there are the 48 beam tubes. They present a squared section of 100cm side and 1cm of thick. The vacuum is maintained inside these tubes to allow the beam to travel to the center of the reaction chamber. Two groups of tubes are separated by the FOA shield. Inside the first group of beam tubes, it is found the renewable lenses, and the second tubes, after the FOA shield, host the FOA, another group of lenses. The beam tubes are built of SS304L. The physical requirements for these tubes suggest the proposal of other materials as Al5083 [6] or PVC to build these tubes. It is sought to reduce the RDR between bursts, as some hours after the shutdown, the beam tubes are the main responsible for that dose [2]. Al5083 has been used in NIF to build the reaction chamber, and its radiological behavior has been studied before [7], being lower than that for SS304 in some periods of time after the shutdown. Its impurities level is well measured [6]. The PVC in its pure formulation is a very low activation material, due to the low Z number of its components [-CH2-CHCl-]n. Although the PVC requires additives to perform different tasks, we have assumed a pure PVC matrix as it is not defined which type of PVC would be suitable. If it were chosen, further analysis would be made on the impact of the additives.

The optics is divided in two groups: the renewable lenses, and the FOA. The renewable lenses face the detonations, so they undergo high radiation doses. They are expected to be replaced frequently. The lenses are 75cm side squares of 5cm thick. The FOA presents 6 optical elements per beamline, accounting for 288 elements. There mirrors, frequency converters and focusing lenses [8]. All the optical elements are made of pure silica. The disposition of the basic components can be found in figure 1.

2.2 Shields

The shields are added to protect against the radiation the people and the FOA. Starting from the center, the first one is the chamber shield. It is a 40cm thick spherical shell built of borated gunite. It is in contact with the chamber, and it is also present in NIF. It pursues to reduce the activation of components and the RDR derived from the activation of the chamber between burst. As the beams should go through, it presents the same penetration as the chamber does.

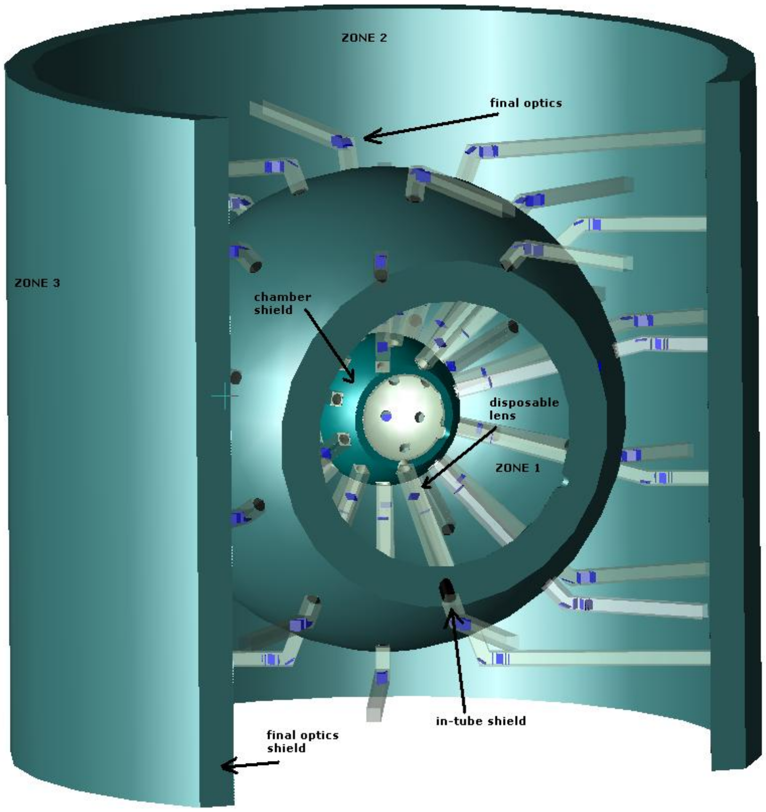

Figure 1: Preliminary proposal design of HiPER facility

At 16.5m from the center of the chamber, the beam presents a focus, and a beam spot of 2mm radius. There they are placed two different shields to protect the FOA with regards to the prompt dose. The first one is a 2 meter thick standard concrete [6] spherical shield, with 48 penetrations aligned with the beam tubes. Inside the penetrations, in-tube shields are placed. They are concrete cylinders of 50cm radius, presenting a pinhole of 2mm radius to allow the beam to cross through. The impact of the absence of this shield is studied in [2].

Finally, it is placed a bioshield which delimits the target bay. It consists in a 2 meter thick concrete cylindrical shell, with 25m of inner radius and 50m of height. All theses shields delimit areas where dose rates delivered to people will be computed to evaluate the shields. The areas will be named 1, 2 and 3 going from the inner part of the facility to the exterior. Thus, the zone 1 is the stay between the chamber shield and the FOA shield, where the chamber, the rims, the chamber shield, the tubes1 and the renewable lenses are located. After the FOA, but before the bioshield there is the zone 2, where tubes2 and FOA are located. The zone 3 stands for the two first meters after the bioshield and represents the exterior of the target bay. The disposition of shields is also found in figure 1.

3. Computational tools and methodology

The starting point is the geometry design, accomplished with MCAM [9]. Due the complexity of the geometry, an auxiliary code as MCAM has been necessary. The second one is performed with MCNPX [10] and the libraries la150n, endf60 and endl92, and fully corresponds to the operation of the facility. We transport the outcoming neutrons with a given spectrum [11] with MCNPX and compute the following quantities: PDR to people, PDR to the FOA and neutron fluxes with Vitamin-J energy structure. The dose rate to people is calculated with the flux-to-dose conversion coefficient given in ICRP74 for Ambient Dose Equivalent [12]. The PDRs to the FOA are calculated through the deposited energy.

With the neutron fluxes, we compute the activation of all the components of the facility for the exact pulsed irradiation scheme. It is performed with the isotopic inventory code ACAB [13] and the EAF libraries [14]. We also compute the parameters for the waste management: Waste Disposal Rate (WDR) [15], Contact Dose Rate (CDR), and Clearance [14]. This corresponds with the third step. Once the activation is known the fourth and last step starts. The resulting gamma decay computed with ACAB is transported with MCNPX, and the RDR (ICRP74) to people is calculated. This shows the time evolution of the dose rate levels within the zones delimited by the shields.

The limits for the dose rates to people are taken form ICRP90 [16]. For the workers, 20mSv/yr or 10μSv/h; for the public, 1mSv/yr. All the results expressed in this study are computed with a relative error lower than 2%. The RDR are computed as average doses in the whole stays where people could access, i.e., zones 1, 2 and 3.

4. Results and analysis

4.1 Reference Design

The problematic associated to the reference design with the reference and exigent irradiation scenario can be found extended in [2]. The PDRs to the people in the different areas and delivered to FOA are shown in table 1.

Table 1: PDR to people and FOA in the reference scenario and reference design

	Zone 1 (Sv/yr)	**Zone 2** (Sv/yr)	**Zone 3** (Sv/yr)	**FOA (Gy/yr)**
Neutrons	$3.46 \cdot 10^{5}$	32.0	$1.69 \cdot 10^{-7}$	34.1
Photons	$8.70 \cdot 10^{3}$	0.628	$1.88 \cdot 10^{-6}$	14.1
Total	$\mathbf{3.55 \cdot 10^{5}}$	**32.6**	$\mathbf{2.05 \cdot 10^{-6}}$	**48.2**

The zones 1 and 2 are areas of exclusion during the operation of the machine. The zone 3 fits the limit for the public, being free of restriction even during the operation. The RDRs in the zones 1 and 2 are depicted in the figure 2. The RDR in zone 3 is not shown because it is lower than workers limit from the shutdown. The time evolution of the RDR between bursts is shown after the 1st and after the 239th, the last burst. A difference of a factor of 4 is encountered [2]. The manual maintenance limit, 10μSv/h is never reached in zone 1, so only remote operation is allowed inside. In zone 2, after the first burst, 36 hours after the shutdown, this limit is reached, allowing the entrance of workers. As burst happens, radioisotopes accumulate. The limit is crossed, but given the assumptions and simplifications, it is though that manual maintenance will be allowed during the whole lifetime of the facility, after a careful study and planning. Details of the activities set in that stay are necessary and collective doses may be performed. The contribution of different components to the RDR is found in [2]

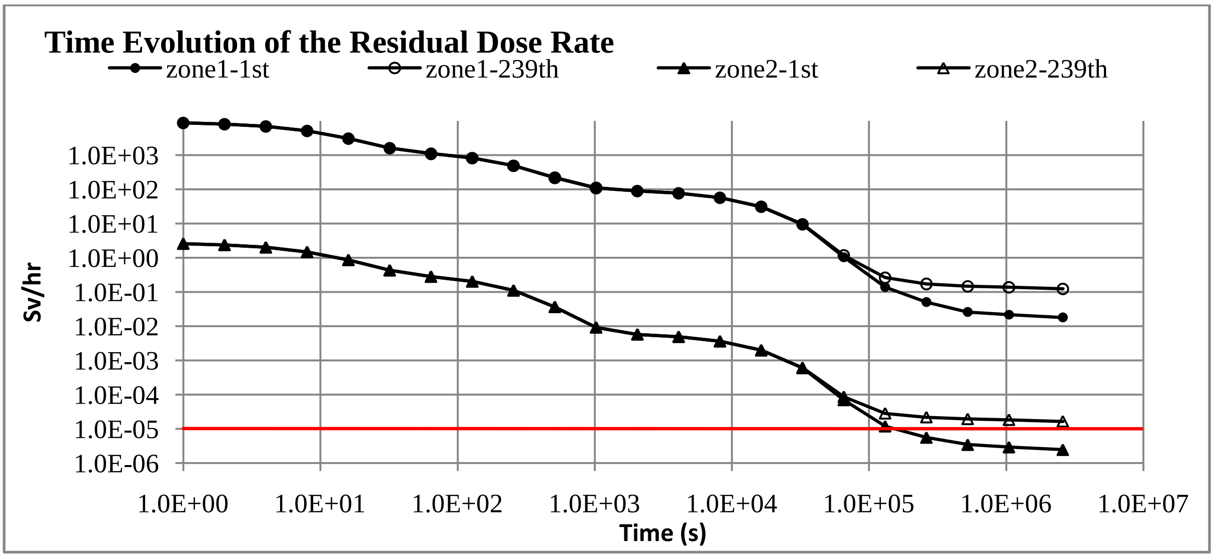

Figure 2: Time evolution of the RDR in the zones 1 and 2 in the reference scenario, after the first and the last burst

The RDR is so high in the zone 1 that is does not seem reasonable to try to reach the manual maintenance limit. In zone 2, from the shutdown to 10 minutes, the dominant contributor to the RDR is the FOA. After 10 minutes, the tubes are the main responsible for the RDR. This is the reason why, in order to minimize the RDR, the approach that we propose is to change the material for the tubes, trying to find a material which would result less activated in the 1 month time period between bursts.

4.2 Irradiation Scenarios

The reference irradiation scenario based on 100MJ-100shots-1month-20years is the most exigent scenario conceived up to the moment in the phase 4a of HiPER. However, there is a more realistic proposal of sequence of shots. It consists in 20MJ neutron yields, with 5 events in a 100 non-explosive shots per bursts at 10 Hz (explosions occur at 0.5 Hz). A burst happens every week, with no more than 50 bursts per year. The lifetime of the facility is assumed to be extended to 30 years. The consequences of the reduction of irradiation are explored in this subsection, by comparing with the reference case. The total PDR (neutrons and photons) to the people and optics is shown in table 2;

Table 2: Comparison of PDR to people and FOA with reference design and two irradiation scenarios

	Zone 1 (Sv/yr)	**Zone 2** (Sv/yr)	**Zone 3** (Sv/yr)	**FOA (Gy/yr)**
Exigent	**$3.55 \cdot 10^{5}$**	**32.6**	**$2.05 \cdot 10^{-6}$**	**48.2**
Soft	**$1.48 \cdot 10^{4}$**	**1.36**	**$8.55 \cdot 10^{-8}$**	**2.01**

The time evolution of the RDR is improved just in the zone 2. For the zone 1, even when reaching a lower level, it does not cross the limit for workers to enter. However, in the zone 2, the differences of around two orders of magnitude are significant. The waiting time is reduced to from 36 to 8 hours. Furthermore, the RDR bellow the manual maintenance limit is much lower than in the reference scenario, what guarantees a safe maintenance and less exposure planning.

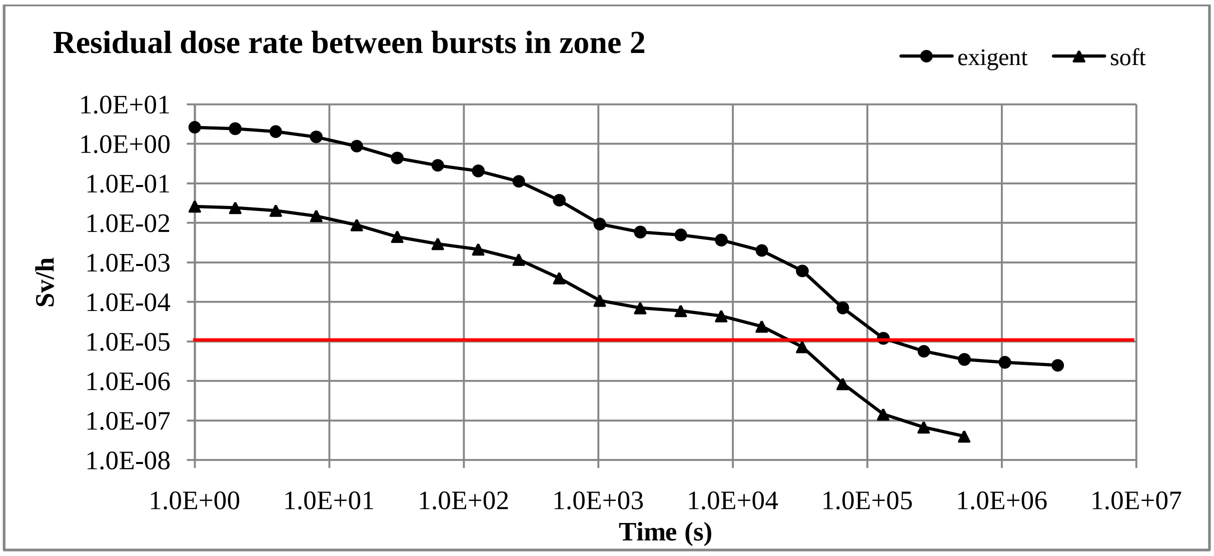

Figure 3: Time evolution of the RDR in zone 2 comparing two irradiation scenarios

4.3 Tubes Materials

When trying to reduce the RDR, we propose to explore different materials for the beam tubes. We have computed the RDR assuming tubes made of Al5083 or of a pure matrix of PVC. The results are depicted in figure 4. Al5083 in the tubes does not allow the entrance until 1 week after the shutdown. However, once the entrance is allowed one week after the shutdown, the workers would be exposed to a lower RDR than in the case of SS304L tubes. The PVC for the tubes reduces the waiting time to 15 hours, and then it allows working at lower RDR than in the case of SS304 and Al5083.

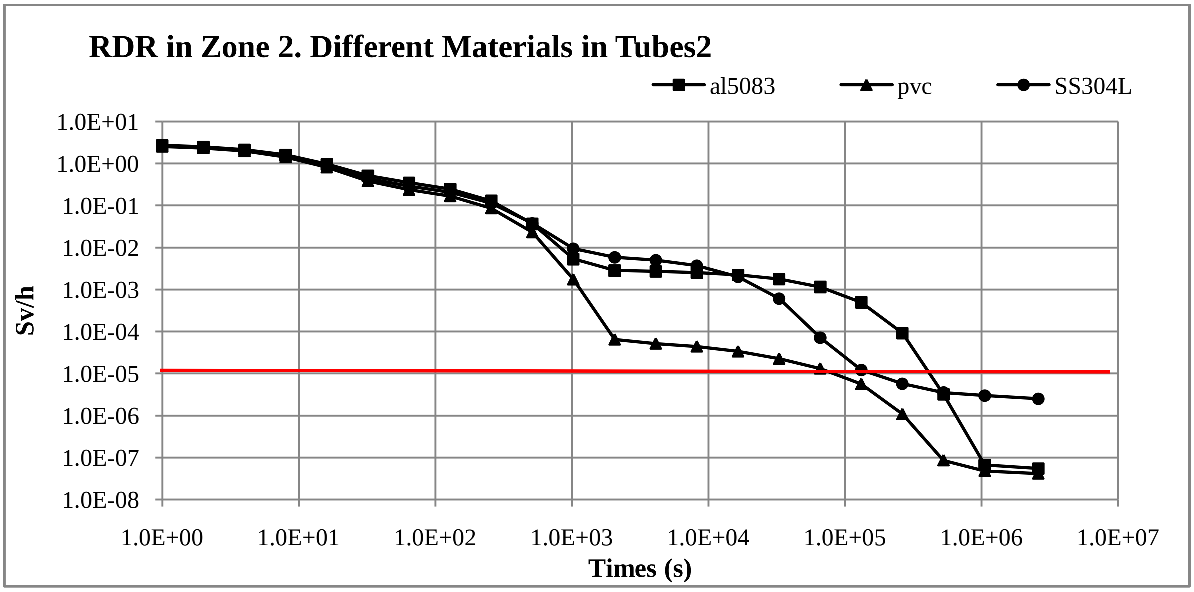

Figure 4: Time evolution of the RDR in the zone 2 in the reference scenario assuming tubes made of different materials

So, depending on the mechanical exigencies for the tubes, if possible, PVC would be a good choice. However, it has to be kept in mind that we have studied a pure PVC matrix. Additives could result in higher dose rates, and more detailed studies must be carried out. Al5083 forces to wait one week, against 36 hours of SS304L, but it results in a more confident safety once the entrance is allowed.

4.4 Reaction Chamber Material Choice

The material choice for the reaction chamber, from the standpoint of activation, should take into account the waste management assessment. Physical requirements indicate that the most likely material to constitute the reaction chamber is steel.

As EUROFER has been developed to be part of future DEMO reactor, having into account the waste management assessment, it is considered a candidate material. We have studied the waste management of EUROFER and SS304L to compare one another. A deeper analysis can be found in [7].

The results show that EUROFER is clearly overdeveloped for the HiPER purpose. It is conceived to be a RAFS in very exigent irradiation scenarios, usual in DEMO conceptions. But the irradiation level achieved in the most exigent scenario of HiPER does not explote the EUROFER advantages, because the long-term CDR is low enough also for a commercial steel, SS304L in this case.

Table 3: Waste Management quantities for chambers of SS304L and EUROFER after 20 years of life in reference scenario

	CDR (50yr)	CDR (100yr)	Clearance (100yr)	WDR
SS304L	$1.5 \cdot 10^{-5}$ Sv/h	$3.4 \cdot 10^{-8}$ Sv/h	10	$2.39 \cdot 10^{-5}$
EUROFER	$1.21 \cdot 10^{-7}$ Sv/h	$2.6 \cdot 10^{-9}$ Sv/h	5	$9.59 \cdot 10^{-6}$

5. Conclusions and ongoing work

With the actual proposal design, there are three different areas where people (workers and public) could stand, zones 1, 2 and 3. During the reference operation, zones 1and 2 are exclusion areas. The zone 3 is free of restriction as PDR is below the limit for public.

Between bursts, the zone 1 is also exclusion area, maintenance is forced to be performed remotely. Manual maintenance would be allowed 36 hours after the shutdown in zone 2. The zone 3 is free of restrictions.

The dose delivered to the FOA has been computed. The FOA shield reduces the PDR to the FOA in factor of 30. In future work, it will be studied with higher detail, as preliminary results indicate that the presence or absence of in-tube shields do not alter to whole FOA averaged PDR.

The residual dose rate could be significantly reduced by changing the material of which the tubes are made of. The studied alternatives, Al5083 and PVC show advantages with regards to SS304L. In future works, realistic compositions of PVC will be studied, as it seems a promising choice.

Accepting a reaction chamber made of steel, we find SS304L commercial steel an attractive option. EUROFER does not exhibit such a good behavior which could justify its choice before than SS304L. In future work, we will analyze different commercial steels, and will compare them with different RAFS and other metals, as Aluminum or Wolfram.

Acknowledgements

The authors gratefully acknowledge the support of the Fundings Agencies in undertaking this work (EC FP7 project number 211737): EC, European Commission, MSMT, Ministry of Education, Youth and Sports of the Czech Republic and STFC, Science and Technology Facilities Council of the United Kingdom. It has been also partially supported by Plan Nacional de I + D + I (2008 - 2011) Fusion Nuclear ENE2008-06403-C06-02 MICINN.

The authors also acknowledge Daniel López and Juan Pablo Catalán for their support in the coupling of codes MCNPX and ACAB.

References

[1] J.F, Latkowski. *Occupational Dose Estimate for the NIF*. UCRL-JC-133681 (1999)

[2] R. Juárez et.al., FUSENGDES-D-10-00575, SOFT 2010, OPORTO

[3] J.Sanz et al., Fusion Engineering and Design 75-79, 1157-1161 (2005)

[4] S. Reyes, et al., *Use of clearance indexes to assess waste disposal issue for the HYLIFE-II inertial fusion energy power plant design*, Fus. Engineering and Design 63-64 (2002) 257-261

[5] R. Lindau, et. al., *Present status of EUROFER and ODS-EUROFER for applications in blanket concepts*, Fusion Engineering and Design 75-79 (2005)

[6] J.F Latkoswki, J. Sanz, *Elemental Analysis of As-Build Concrete and Aluminum for the NIF and Their Effect upon Residual Dose Rates*, UCRL-JC-133680 (1999)

[7] R. Juárez et. al., *Advance in radiological analyses of candidates for HiPER reaction chamber material. DRAFT,* HiPER interim report (2010)

[8] Bruno Le Garrec's private communication

[9] Y. Wu, FDS Team., Fusion Engineering and Design 84, 1987-1992 (2009)

[10] D.B. Pelowitz. MCNPX User's Manual, LA-CP-05-0369 (2005) and extensions

[11] John Perkin's private communication

[12] ICRP publication 74. *Ambient Dose Equivalent flux-to-dose converison coefficients* (1996)

[13] J.Sanz et al. ACAB User's Manual v.2008. NEA-1839

[14] R.A. Forrest. EAF-2007 Clearance and transport libraries. UKAEAFUS 538 (2007)

[15] S. Fetter, E.T. Cheng and F.M. Mann, *Long term radioactive waste from fusion reactors: part II,* Fusion Engineering and Design 13 (1990) pp:239-246.

[16] ICRP publ. 60, Annals of the ICRP, Vol 21, nº1-3 (1990).