Shielding and Activation Analyses for Inboard Region of FESS-FNSF Design

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November 2015

UWFDM-1423

Abstract

Radiation shielding requirements for fusion devices present different problems than those facing fission reactors. Fusion devices, especially the inboards of tokamaks are constrained and present a challenge for accommodating an effective shielding. This report discusses some developments and optimization of FNSF design components from the first wall to the low temperature shield, examining the structural ring and permanent component constituent based on the radiation damage to the magnet, evaluating the peak radiation damage to the FS structure, and eventually demonstrating the neutron and gamma ray fluxes. Radiation transport calculations are required for predicting and affirming the nuclear performance of the design. Fusion devices offer the great advantage that the main source of radioactivity is mainly generated from the activation of the plasma facing components (first wall and blanket). This process depends on a careful selection of the materials, alloying elements and impurities, which could significantly influence the radioactive inventory in any fusion device. This report documents the results of 1-D shielding and activation analyses that provide the basis for future two and three-dimensional analyses doing the final 2016-year of the FNSF study.

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Introduction

FNSF (Fusion Nuclear Science Facility) is viewed as an essential element of the US fusion roadmap that displays a strategic pathway from ITER, to US DEMO, and eventually to the first commercial power plant [1]. Shielding for tokamak depends on the operating parameters and some limitations that should be followed. Designing the shielding is influenced by the geometry of the device. The evaluated nuclear parameters in this report are the nuclear heating distribution and the radiation damage to the inboard (IB) region of the FESS-FNSF design. It is shown in Figure 1 with a major radius of 4.8 m and minor radius of 1.2 m. The peak IB neutron wall loading (NWL) is 1.4 MW/m^2. The plant lifetime is 8.5 full power year (FPY) and the fusion power is 526 MW. The radiation damage helps to determine the best filler of the permanent components and the composition of LT shield. The activation analysis is also presented in this report as it compliments the shielding analysis. It basically determines some activation parameters (such as specific activity, decay heat, waste disposal rating, recycling dose rate, and clearance index) to characterize the materials resulting from the neutron activation and to show how the FNSF inboard components decay with time after shutdown. The activation analysis also classifies the waste and determines the clearability as well as the recycling potential of the IB region components. A summary of FNSF shielding and activation assessments is presented in this report. A similar analysis has been performed for the outboard region as documented in Reference [2].

The feasibility of fusion energy depends on developing advanced structural materials that can sustain extended component lifetimes in an ultra-severe environment, including up to 200 displacements per atom (dpa) and 2000 apm He [3]. Different irradiation schedules are used for the groups with different lifetimes. The irradiation schedule for the component is summarized in table 1.

Table 1 Irradiation schedule of the components

Group	Components	Irradiation Schedule
1	FW/blanket	3 years with 15% availability (0.45 FPY) in phase 3. +5 years with 25% availability (1.25 FPY) in phase 4.
2	Structural Ring	3 years with 15% availability (0.45 FPY) in phase 3. +5 years with 25% availability (1.25 FPY) in phase 4. +5 years with 35% availability (1.75 FPY) in phase 5.
3	VV, LT Shield and Magnet	3 years with 15% availability (0.45 FPY) in phase 3. +5 years with 25% availability (1.25 FPY) in phase 4. +19 years with 35% availability (6.65 FPY) in phase 5,6,7.

Codes and Analysis

Four codes have been used in this shielding analysis:

- DANTSYS discrete ordinate neutral particle transport code (developed by Los Alamos National Laboratory) [4] and its multi-group FENDL-2.1 cross section data library [5] to calculate the neutron and gamma flux throughout all components perform LT shield optimization, and plot the nuclear heating distribution.
- KaleidaGraph to generate the data necessary to plot the spectra at any radial location and the activation analysis data.
- Grace to plot the data of the neutron and gamma fluxes generated by DANTSYS.
- ALARA activation code (developed by the University of Wisconsin) [6] with the IAEA FENDL-3 data library [7].

The shielding analysis determines:

- Shielding of permanent components (for protection against radiation)
- The best filler for the permanent components.
- The impact of each filler on peak damage at the inboard midplane:
    - ➢ Radiation damage to ferritic steel structural materials (dpa, He production, etc.)

– The optimization of the low temperature (LT) Shield using the chosen filler.

The activation analysis determines:

– Specific activity
– Waste disposal rating
– Decay heat
– Recycling dose to equipment
– Clearance Index.

Radiation Shielding and One-Dimensional Modeling

Radiation shielding for fusion reactors is affected by geometry constraints that complicate disposition of fully effective shielding. It also depends on the total shield thickness that it is determined by the radiation limits of the coils shown in Fig.1. Scoping calculations for preliminary neutronics information are most readily performed using one-dimensional transport methods. One-dimensional codes are used to calculate the radial dependence of the neutron and gamma ray flux in the machine components. They are also used to optimize the LT shield of the inboard side using the best filler of the permanent components.

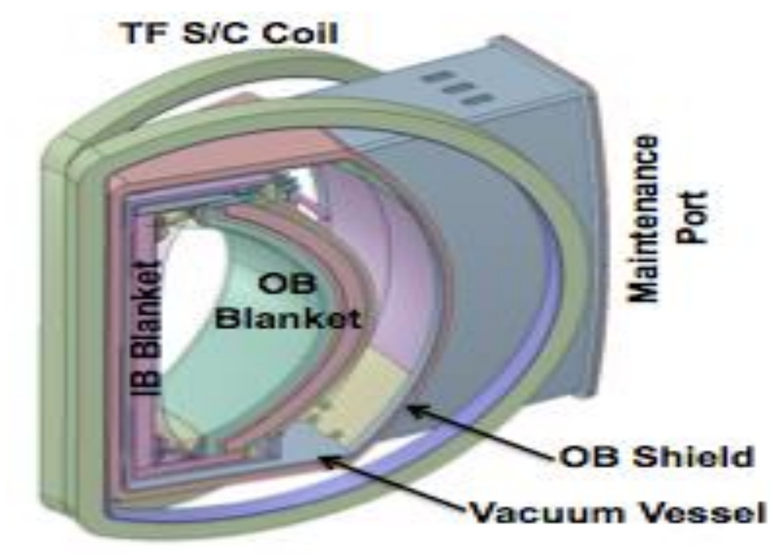

Figure 1 Fusion Energy System Study (FESS) – FNSF Design.

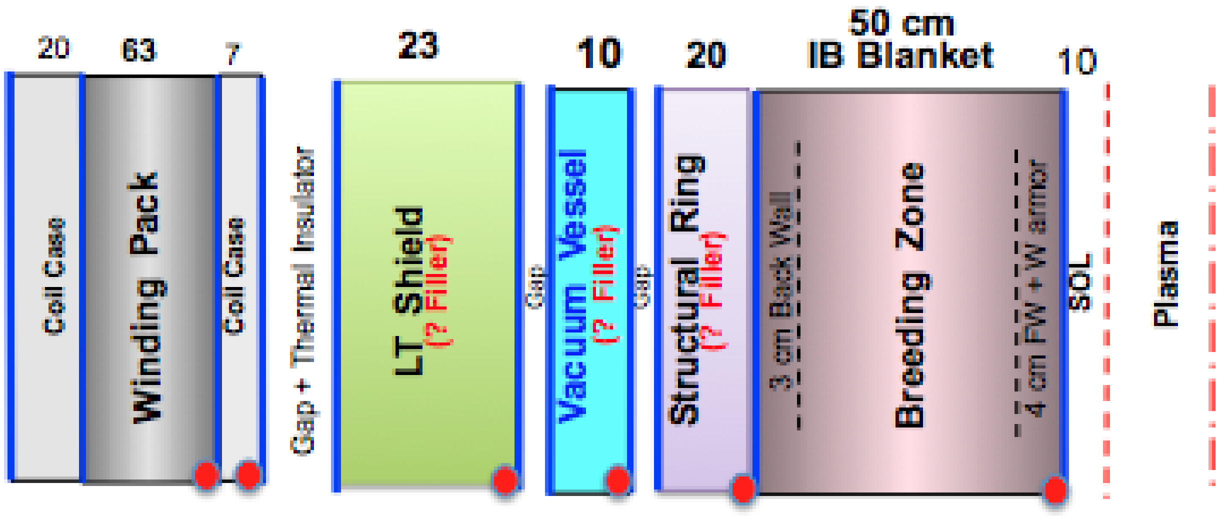

Figure 2 FESS-FNSF Inboard Radial Build at the midplane.

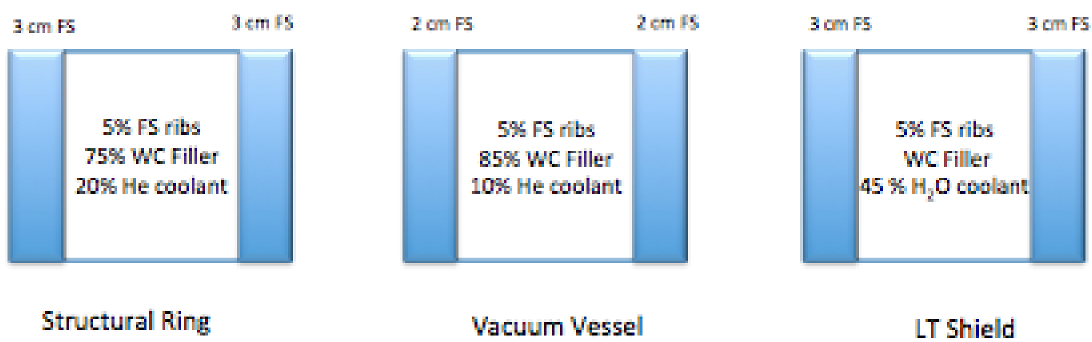

Figure 3 The layut of LT Shield, VV and SR

A representative radial build for the LiPb/FS/He blanket concept is illustrated in Fig. 2. The inboard shield dimensions are constrained by the available space between the plasma and the inboard TF coil dictating a careful design of the blanket and shield thickness and their composition. Although there is more space available for shielding on the outboard side of the plasma, the presence of the large ports reduce the shielding effectiveness and particular care must be paid to shielding each major penetration, such as the neutral beam injection ports. Fig. 3 shows that the VV and SR are He-cooled while the LT whiled is water-cooled.

Shielding Analysis

The shielding system is an important element of the tokamak core and it consists of several components that provide an important shielding function. The basic function of the shield is radiation protection of the magnet. It contains 10% of the thermal power, which means that it has to be recovered and preserved to enhance the overall power balance. In this shielding analysis, we have considered a safety factor of three to account for neutrons streaming through the assembly gaps between the blanket and structural ring, as will be discussed later.

- **Examination of the three fillers:**

All the specialized components such as structural ring, vacuum vessel, and LT shield should provide shielding function to collectively satisfy the radiation limits so searching for a filler that satisfy the radiation protection was made in this analysis. Several fillers have been identified for examination: MFH82H (Modified Ferritic Steel), B-FS (Borated Ferritic Steel), and WC (Tungsten Carbide). The comparison was made based on that the material should have an enough radiation attenuation to achieve the magnet protection by minimizing the following:

- Peak nuclear heating at the winding pack (< $1 mW/cm^3$)
- Peak nuclear heating at the coil case (< $2 mW/cm^3$)
- Peak dpa to Cu stabilizer (< 10^{-4} dpa)
- Peak dose to electric insulator (< 5×10^{10} rads)
- Peak fast neutron fluence to ternary Nb_3Sn super conductor (< $3 \times 10^{18} n/cm^2$).

Nuclear heating deposited in magnets causes a temperature increase that requires removal, resulting in a higher cryogenic load. The major design impacts are economics and changes in superconductor parameters as a result of temperature change.

The amount of normal metal needed for safe operation increases with increasing the resistivity. The design of a large composite superconducting magnet for fusion devices will depend on increases in resistivity of the Cu stabilizer produced by irradiation during its lifetime (8.5 FPY). The magnet will be rated for safe operation according to a stabilizer resistivity value, which cannot exceed certain limit.

The following visual graphs display the effect of the three filler in SR, VV, and LT shield on magnet damage. As shown in Figs. 4, 5, 6, 7, and 8. The magnet damage reaches its minimum when WC is used as filler in SR, VV, and LT shield. Tungsten Carbide has the ability to reduce the magnet heating, insulator dose, Cu stabilizer, and fluence by almost 90-95% compared to other fillers. Also, WC has high radiation attenuation and is endowed with several superior material properties, such as high melting point (~2750 °C) (LOCA accidents), high resistance to oxidation and corrosion, and high hardness that is useful to reduce the mechanical degradation of the material due to displacement of atoms caused by neutron radiation.

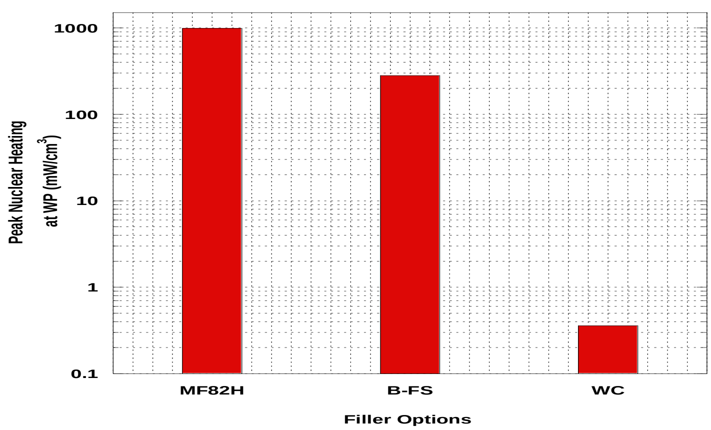

Figure 4 Bar Chart showing the peak nuclear heating at WP for different fillers

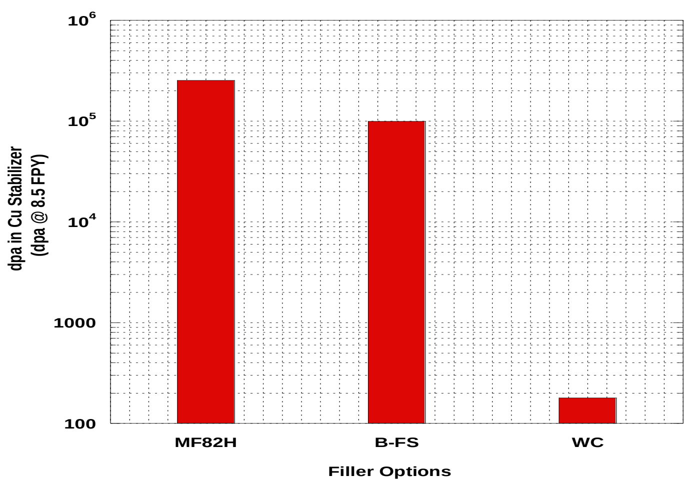

Figure 5 Bar chart showing the dpa to Cu stabilizer for different fillers

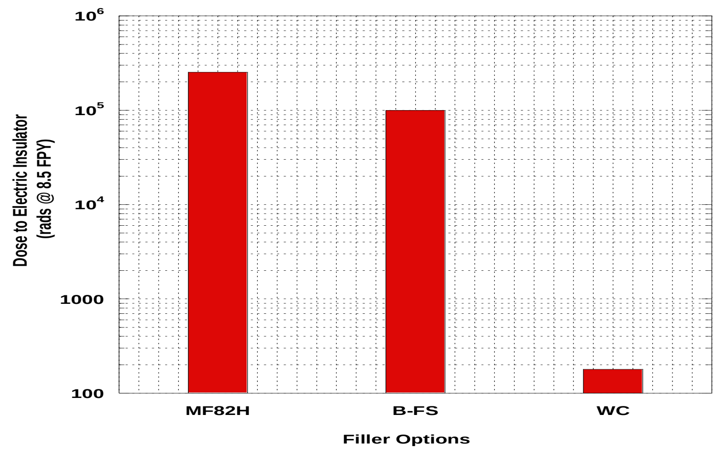

Figure 6 Bar chart showing the dose to electric insulator for different fillers

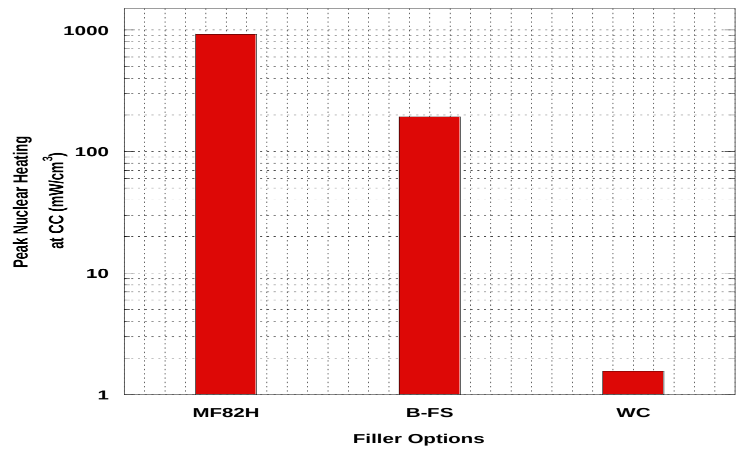

Figure 7 Bar chart showing the peak nuclear heating at CC for different fillers

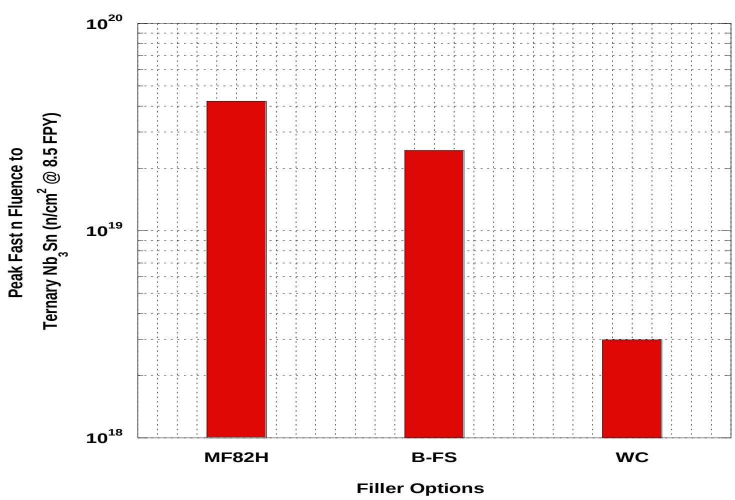

Figure 8 Bar chart showing the peak fast n fluence to ternary Nb_3Sn for different fillers

- **Radiation Damage to LT Shield**

The first wall and blanket are replaceable components that will be replaced every few years due to radiation damage considerations. The shield protects the externals and recovers the leaked energy. The total cost of all items external to the shield is minimized under the constraints that magnet radiation effects do not exceed limits set by technical considerations. Also, being the closest component to the magnet, the composition of LT shield influences the radiation damage at the magnet. Enhancement to the shielding performance by optimizing its composition will determine the attainable limits. The LT shield is composed of water-WC mixture (composition). The optimum composition should meet the requirements for magnet protection. The FNSF radiation limits of LTS magnet are shown in Table 2.

Table 2 FNSF Radiation Limits

LTS Magnet (at 4K)	Value
Peak fast n fluence	$3e^{18}$ n/cm^2
Peak nuclear heating at WP	1 mW/cm^3
Peak nuclear heating at CC	2 mW/cm^3
Peak dose to electric insulator	$5e^{10}$ rads
Peak dpa to Cu stabilizer	10^{-4} (Too Low); consider $6e^{-3}$ dpa

Note that the dpa to Cu stabilizer limit was taken from the ARIES design; its value in FESS-FNSF design is too low.

The following visual graphs show the radiation effect at the magnet for different WC-water mixtures in the LT shield

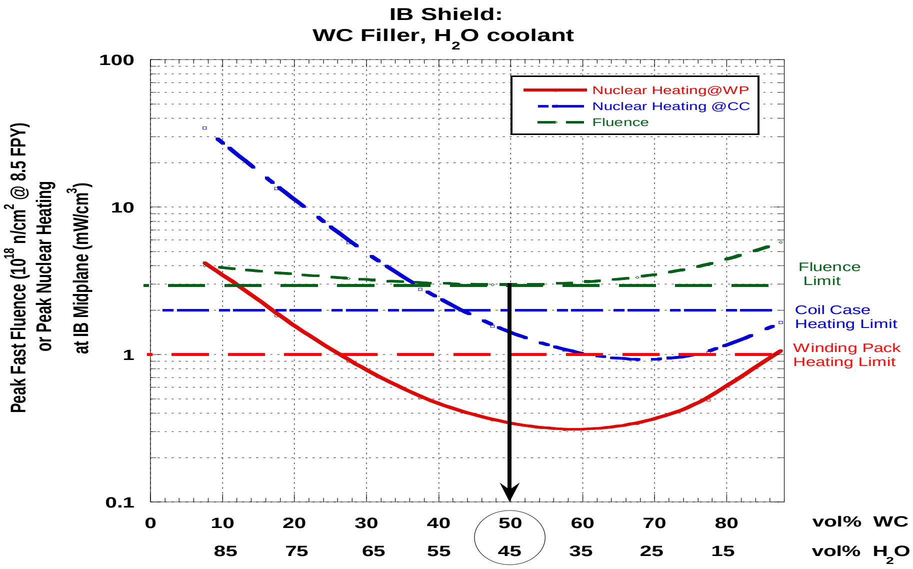

Figure 9 Sensitivity of peak radiation effects at magnet to LT shield composition

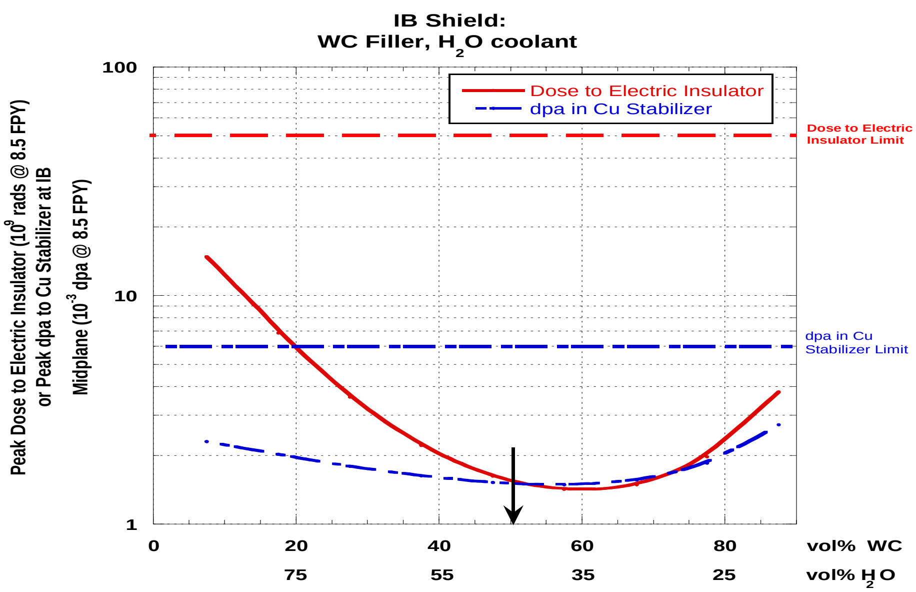

Figure 10 Sensitivity of peak radiation effects at magnet to LT shield composition

- **Discussion and Main Findings:**

  - The fluence is minimized when the LT shield material composition is 50% WC and 45% H_2O.
  - The nuclear heating at the coil case and winding pack minimizes at higher WC content than 50%, so selecting 50% WC will increase the heating slightly.
  - The dose to electric insulator and dpa to Cu stabilizer are found to be well below their limits at a composition of 50% WC and 45% H_2O.

Therefore, water comprises 45% of volume and WC is 50%, while the remaining 5% left is FS-3Cr steel ribs in the middle region of the LT shield. This material composition minimizes the radiation damage effects at the magnet. Table 3 shows a comparison between FNSF radiation limits for LTS magnet and their values using the optimized LT shield, while Table 4 lists the composition of all components.

Table 3 FNSF Radiation Limits and the Radiation Results in LT Composition

LTS Magnet (at 4K)	Limits values	At optimum composition
Peak fast n fluence	$3e^{18}$ n/cm^2	$3e^{18}$ n/cm^2
Peak nuclear heating at WP	1 mW/cm^3	0.34 mW/cm^3
Peak nuclear heating at CC	2 mW/cm^3	1.45 mW/cm^3
Peak dose to electric insulator	$5e^{10}$ rads	$1.55e^{9}$ rads
Peak dpa to Cu stabilizer	10^{-4} (Too Low) … $6e^{-3}$ dpa	$1.50e^{-3}$ dpa

- **Radial Distribution of Nuclear Heating at Inboard Midplane:**

The blanket/shield surrounding the plasma converts around 99% of the fusion energy into heat. The nuclear heating at the first wall is the highest, while it reaches the minimum at the back of LT shield. The nuclear heating shows a radial dependence of the inboard region. The safety factor of 3 is included in heating of components outside the blanket (LT shield, VV, and SR) to account for higher damage due to neutron streaming through assembly gaps between 16 toroidal modules. The inboard components are marked clearly on the graph as shown in Fig.11.

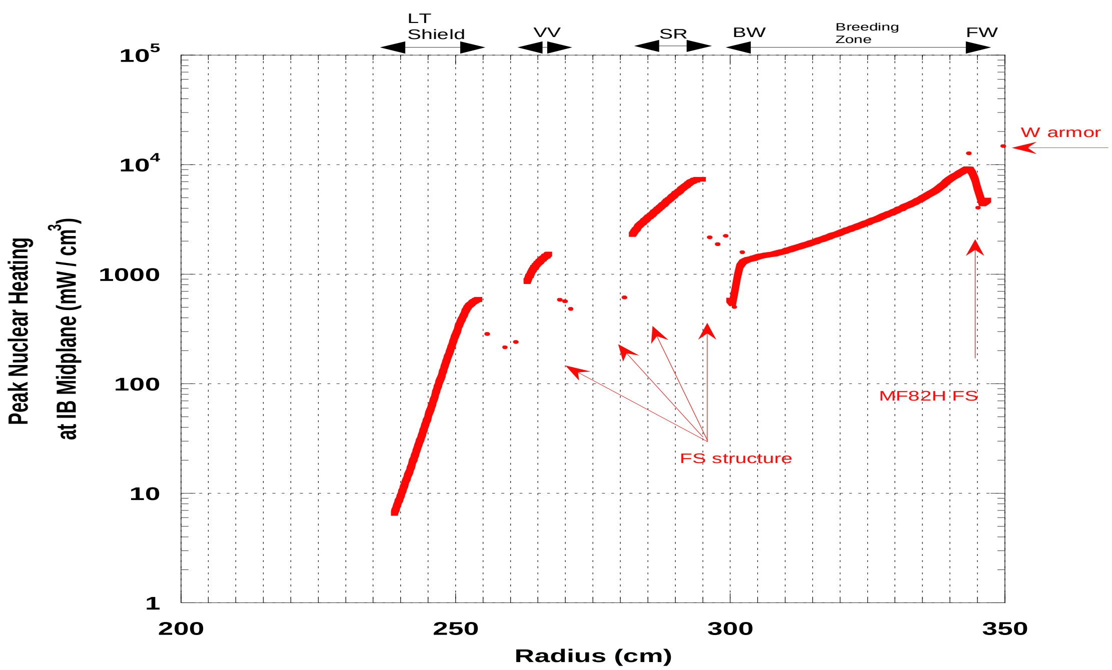

Figure 11 Radial distribution of nuclear heating at inboard midplane

Table 4 Compositions of FNSF Components (in Vol%)

50 cm	**2 mm W armor**	91.3% W, 8.7% void
	3.8 cm FW	34% FS (MF82H) structure, 66% He
	43 cm Breeding Zone	80% LiPb (90% Li-6), 12% He/void, 5% FS, 3% SiC
	3 cm Back Wall	80% FS (MF82H) structure, 20% He
	20 cm Structural Ring*	5% FS (MF82H) structure, 20% He, 75% WC Filler
	10 cm VV*	5% 3Cr-FSstructure, 85% WC Filler, 10% He
	23 cm LT Shield*	5% 3Cr-FS structure, 50 % WC Filler, 45% H_2O
	Coil Case	100% SS-316LN
	Winding Pack	30% JK2LB Steel, 25% Cu, 25% Ternary Nb_3Sn, 10% Hybrid Electric Insulator, 10% Liquid He

*Middle region. Filler type and content are determined by optimization analysis.

- **Radiation Damage to Ferritic Steel structure of IB Region:**

The first wall (FW) and the breeding blanket components will be exposed to plasma particles and EM- radiation and will be irradiated by 14 MeV neutrons. The high-energy neutrons will produce displacement damage and gases (He\ H atoms) due to transmutation of the structural materials that degrade the material properties [8]. Evaluating the radiation damage to FS-based components in the presence of the IB assembly gaps is required. There are 2 cm wide radial assembly gaps separating the 16 toroidal modules. The safety factor of 3 is included in the calculations of radiation damage in three components to account for the increase in damage due to neutron streaming through assembly gaps between modules. The results presented in Figs. 12, 13, and 14 show a radial dependence of dpa, He production, and H production in FS structure. He and H production drops faster radially than the dpa due to higher threshold energy for He and H production. The peak values of dpa, He, and H at the main components of the IB are shown in table 5.

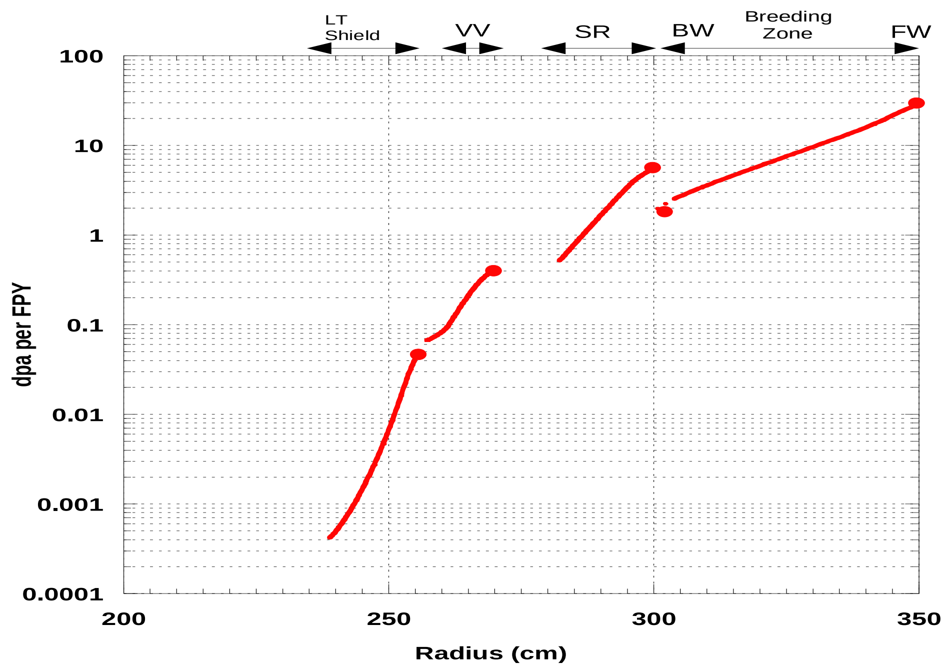

Figure 12 Radial Distribution of atomic displacement at the Inboard Midplane

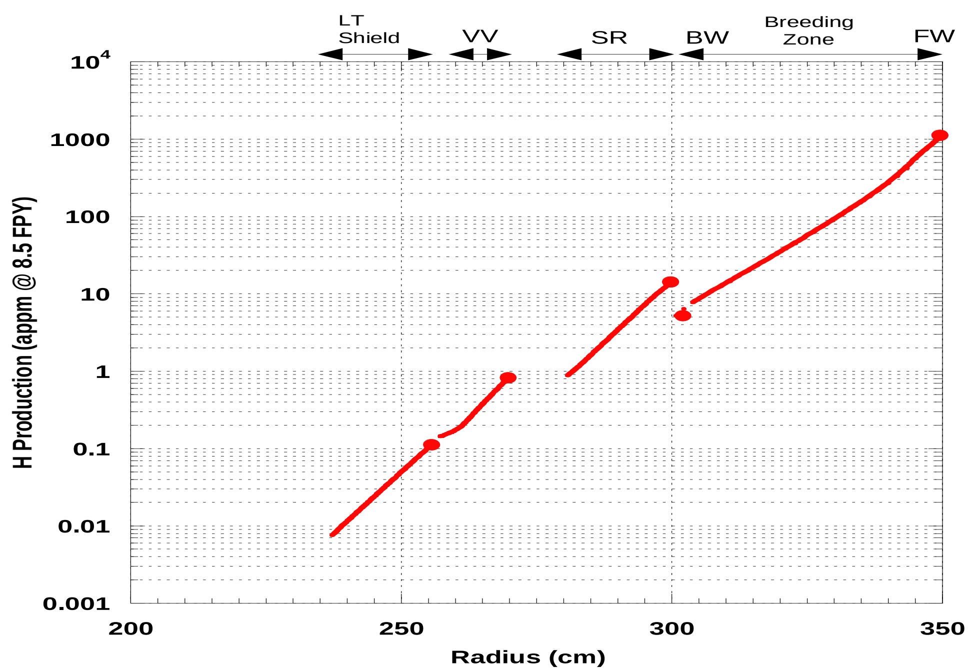

Figure 13 Radial Distribution of Hydrogen Production at the Inboard Midplane

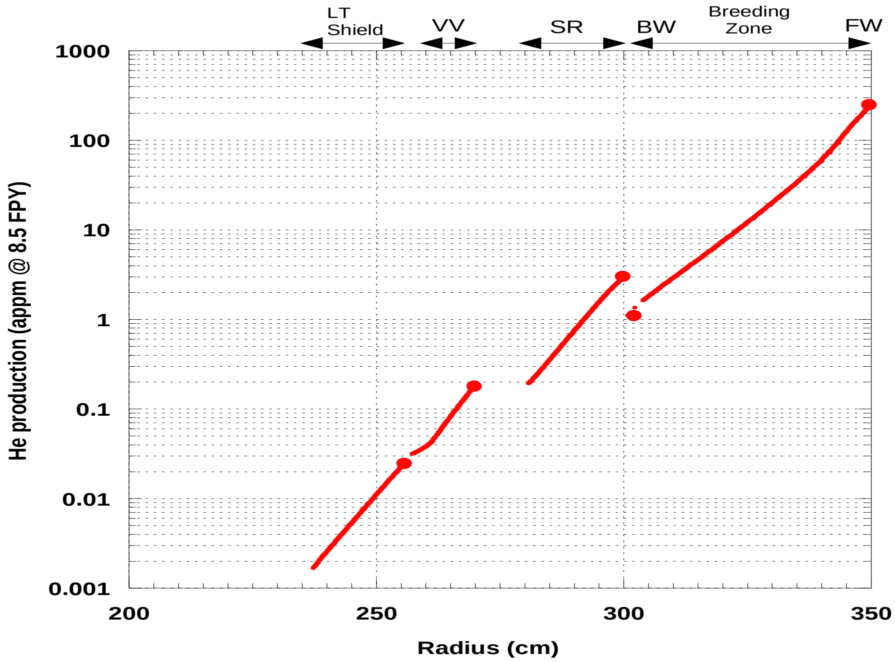

Figure 14 Radial Distribution of Helium Production at the Inboard Midplane

Table 5 Peak Radiation Damage to FS Structure

	Dpa (dpa)	He production (appm)	H production (appm)	He / dpa ratio
FW	29.3	246	1100	8.3
SR	5.56	2.98	14.1	0.54
VV	0.415	0.182	0.83	0.44
LT shield	0.051	0.0251	0.114	0.5

- **Neutron and Gamma fluxes:**

An important feature of the D-T fusion reaction is the generation of 14 MeV neutrons. These neutrons gradually slow down by scattering events within the materials surrounding the plasma and migrate through the components depositing energy and producing secondary gamma rays, which eventually influence the performance of the magnet. The flux distributions are plotted as a function of energy in Figs. 15 and 16. They show the total neutron and gamma-ray fluxes, the neutron flux >0.1 MeV, the thermal neutron component, and the 14.1 MeV neutron value.

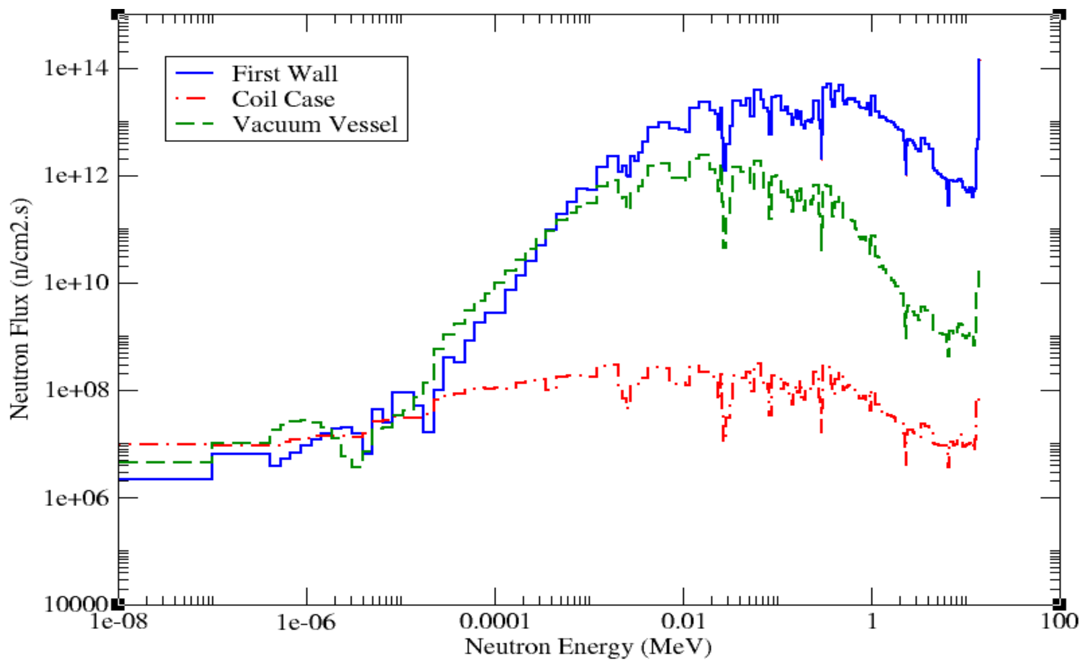

Figure 15 The neutron flux as a function of neutron energy at different regions of the inboard

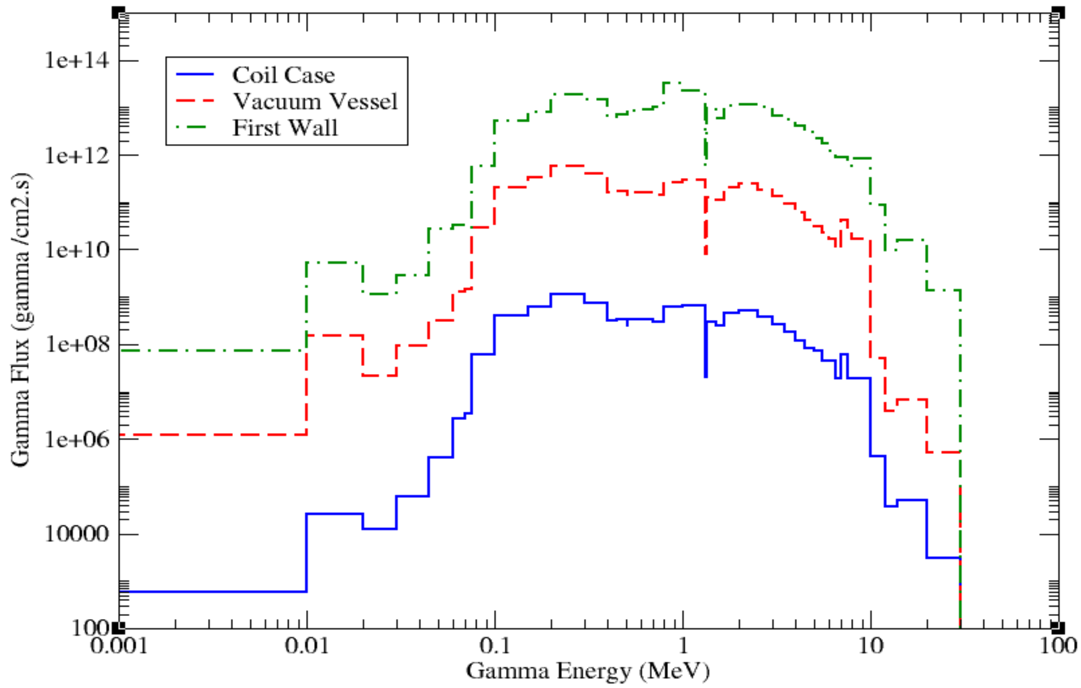

Figure 16 The gamma flux as a function of gamma energy at different regions of the inboard

Main Findings

Figs. 15 and 16 show:

1. The neutron and gamma fluxes a radial dependence throughout the inboard components.
2. The first wall has the highest neutron flux while the magnet has the lowest. This is due to radiation attenuation within the IB blanket and shielding components.
3. The source of gamma-rays is the IB components from (n,γ) reaction, not from the plasma. The neutrons number decreases with radius, gamma-ray intensity follows and shows a radial dependence as well.

Activated Materials Management Strategy

The minimization of active and decommissioning wastes of fusion power plants is the main goal of any fusion design to reduce:

- Radioactive releases during normal and abnormal operations
- Long-term environmental impact
  - No high-level waste (HLW)
  - Only low-level waste (LLW)
- Radwaste volume.

By application of smart waste management strategies, it is possible to limit the volume of material, which ultimately becomes classified as HLW requiring long-term storage or disposal in a deep geological repository. This is important for future generations and public acceptance of fusion, in order to maintain a positive perception, in the face of the likely competition between fusion and other "clean" energy sources. The feasible options for managing the radwaste are the geological disposal, recycling, and clearance. Recycling and clearance are easy to apply from the science perspective, but they still face a real challenge from policy, regulatory, and public acceptance in the US.

A. Geological disposal

The concerns of the geological disposal are that the geological conditions could change over millennia to the extreme that even the hardest rock may behave like a dynamic liquid. Also, the water is a prime carrier for wastes and if it infiltrates, it will corrode waste packages. Radioactive materials could leak and contaminate the groundwater, in which it will danger the health of humans and other living beings. To achieve a safe waste disposal, the repository licensees must provide evidence that pathways will not result in excessive doses of radioactivity to workers and public. Further, the power rate of fusion facilities tends to generate large amounts of LLW compared to fission. For these reasons, this option of radwaste management should be eliminated and replaced by recycling and clearance.

B. Reuse and Recycling

Recycling or reprocessing means reuse the radioactive materials within the nuclear industry. The reuse usually happens after a decay period up to 50 years to keep the materials out of the waste streams [8]. These reprocessed materials such blanket, shield, and magnet materials, concrete of bioshield, and all types of steels may be used to fabricate components for further fusion power plants that help in resourcing certain elements [8].

- The recycling criteria include:
    - Dose to remote handling (RH) equipment
    - The efficiency of detritiation system
    - Decay heat level during reprocessing
    - Economics of fabricating complex shapes remotely
    - Physical properties of recycled products
    - Acceptability of nuclear industry to recycled materials.

C. Clearance

The clearance is the unconditional release of slightly radioactive materials to the commercial market to fabricate as consumer products or dispose of in non-nuclear landfill [9]. This is feasible for components exposed to very low neutron flux such as bioshield and cryostat. The clearable materials are different from the recycled materials since clearables are handled as if they are no longer radioactive, reused without restrictions, and recycled into consumer products such as bridges, dams, and concrete walls. They are also safe because they contain less than 10 μS/y, which is less than 1% of background radiation. Clearance offers a useful means of reducing the volume of active waste from a fusion plant, but first the principle must be accepted by regulators and embodied in national regulations. In 2003, NRC declared that materials with a low concentration of radioactivity could be deregulated and issued the clearance limits for 115 radioisotopes of alloys such as steel, copper, aluminum, and concrete. In 2004, IAEA also published clearance standards for 277 radionuclides. Although NRC and IAEA declared most of the radioisotopes, some of those resulting from the fusion are still missing from the declared radioisotopes. US industries expressed serious concerns that the presence of radioactive materials in their products could damage their markets, erode people confidence in the safety of their products, and negatively affect their sales due to public fear. Currently, clearance is performed on a case-by-case basis for US nuclear facilities [10].

Nuclear Activation Analysis

The energetic 14 MeV neutrons emitted from the plasma are slowed down and absorbed by surrounding components. The interactions between neutrons and components result in producing radioactive materials. To eliminate the high-level long-lived waste, the option of low activation materials has been chosen. For all fusion designs, neutron activation analysis evaluates the concentration of radionuclides in plasma surrounding components that is determined the neutrons intensity. This analysis utilizes the ALARA code and accurate activation method applicable for a large number of elements comprising the FNSF components.

This analysis will discuss five parameters:

- Specific Activity
- Waste Disposal Rating
- Decay Heat
- Recycling Dose Rate
- Clearance Index

A. Specific Activity

The specific activity is the source term for the parameters mentioned above and defined as the amount of radioactivity or the decay rate of a particular radionuclide per unit mass of that radionuclide (Ci/m^3). In this report, the specific activity calculations are made for all inboard components

As shown in Figs. 17, 18, and 19, the IB FW and its armor have the highest activity at shutdown. The specific activity drops at 1day after shutdown by a factor of 2-10. This drop is a result of the decay of short half-life radionuclides. Figure18 shows the specific activity for the magnet region. The outer coil case has the lowest specific activity and that is due to the low neutron fluence in this last component of the inboard region. In general, the magnet has the lowest activity, producing no radiological hazard in the design.

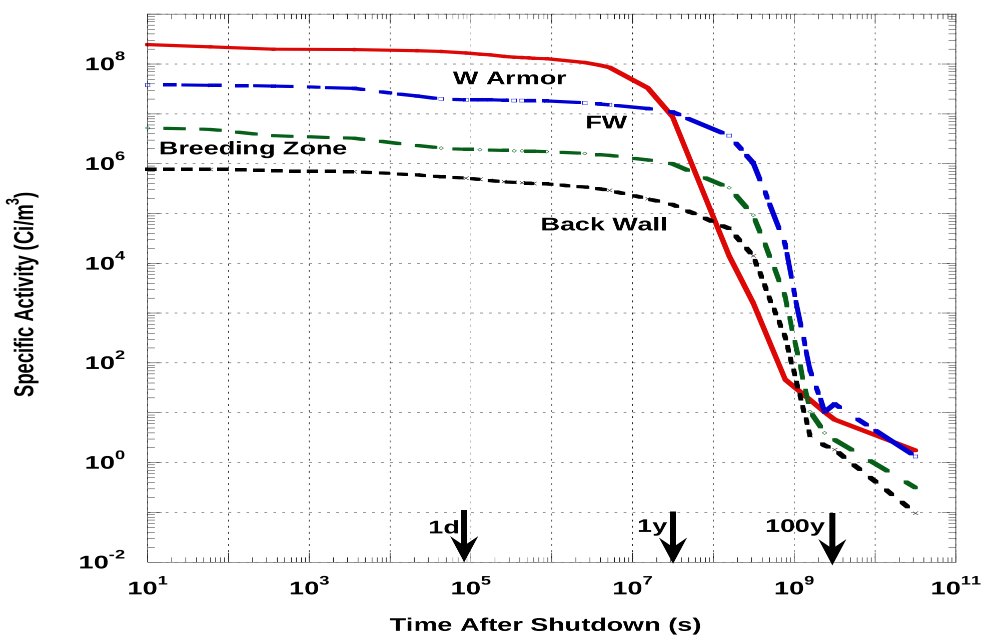

Figure 17 Specific activity of FNSF IB blanket

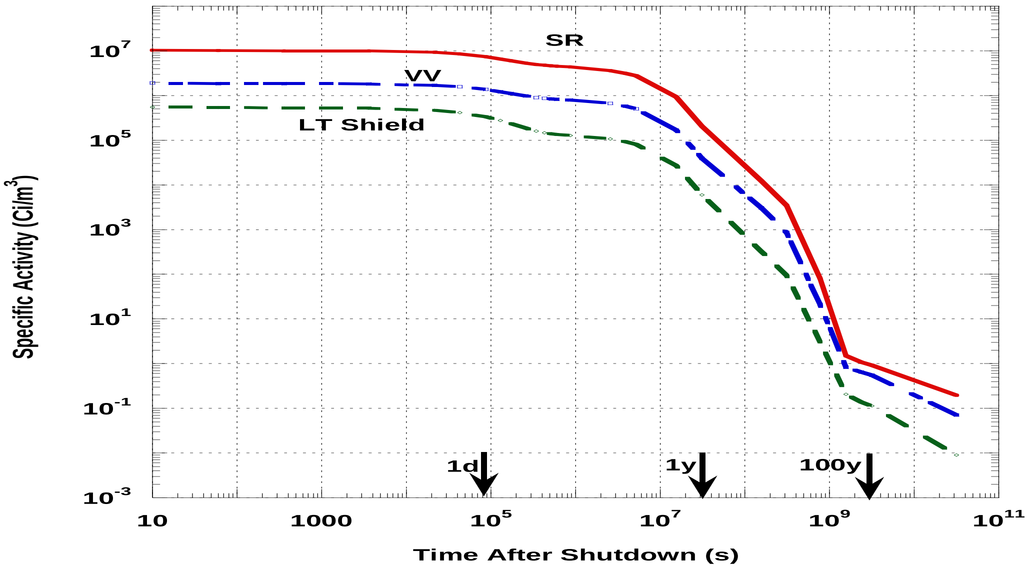

Figure 18 Specific activity of FNSF IB SR, VV, and LT shield

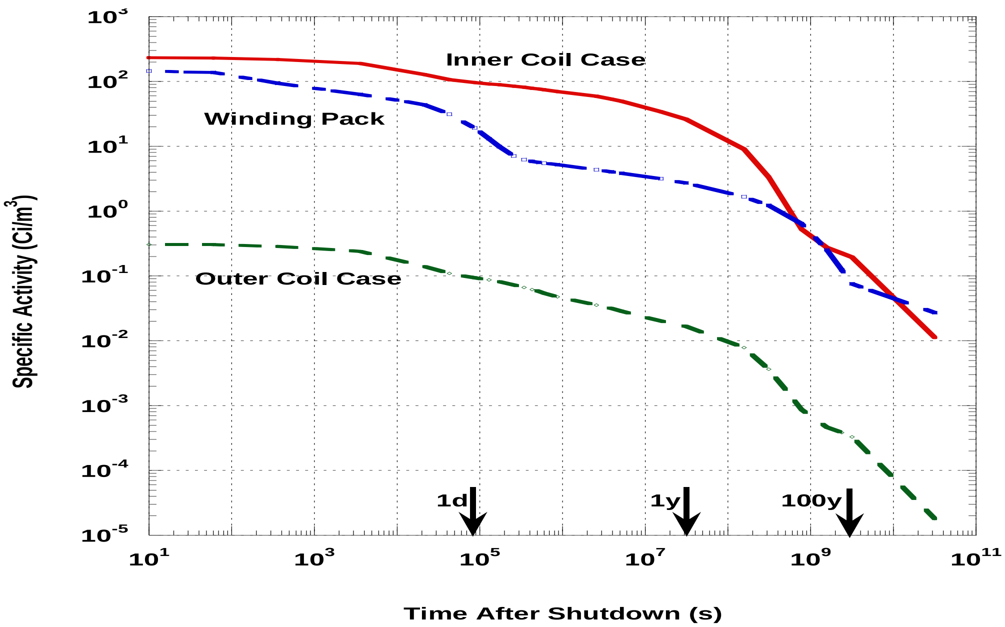

Figure 19 Specific activity of FNSF IB magnet

Table 6 provides the main radioisotopes that contribute to the specific activity of IB components at shutdown and at one year after shutdown.

Table 6 Main Contribution of Specific Activity of FNSF IB Region

Specific Activity (Ci/m^3) of IB Zones	At shutdown	At 1 year after shutdown
W Armor	2.85e8 (32% w-185, 18.3% W-187, 18.1% W183m. 15.4% W-181, 12.9% W-185m)	8.83e6 (61.6% W-181, 35.9% W-185, 1.11% Ta-182)
First Wall	3.86e7 (44.3% Mn56, 33.5% Fe-55, 8.92% Cr-51, 4.21% Mn-54, 2.66% V-52, 1.16% W-185, 1.1% W-187)	1.09e7 (92.6% Fe-55, 0.3% W-181)
Breeding Zone	5.36e6 (26.5% Al-28, 28% Mn-56, 21.7% Fe-55, 5.97% Cr-51, 3.20% W-187, 2.69% W-185, 2.14% V-52, 1.17% W-183m)	9.94e5 (90.9% Fe-55, 0.5% W-185)
Back Wall	8.05e5 (21.5% W-187, 15.4% W-186, 22.09% Fe-55, 14.36% Mn-56, 9.37% Cr-51, 5% V-52, 2.18% Mn-54)	1.52e5 (91.7% Fe-55, 5.15% Mn-54)
Structural Ring	1.12e7 (46.6% W-187, 41.4% W-185)	2.04e5 (78.5% W-185, 16.3% Fe-55)
Vacuum Vessel	2.05e6 (47.6% W-187, 41.1% W-185, 8.25% W-183m)	3.96e4 (74.6% W-185, 21.9% Fe-55)
LT Shield	5.87e5 (66.2% W-187, 23.1% W-185)	5.94e3 (79.2% W-185, 14.2% Fe-55)
Inner Coil Case	2.35e2 (42.5% Mn-56, 9.44% Fe-55, 6.95% Co-58, 5.4% Mo-99, 4.75% Tc-99m, 4.28% Co-58m, 3.03% Co-60m, 2.34% Mn-54, 1.88% Co-60, .98% Cu-64, 1.77% Co-57, 1.62% V-52, 1.29% Mo-101, 1.29% Tc-101,)	2.63e1 (65.3% Fe-55, 14.7% Co-60, 6.23% Co-57)
Winding Pack	1.47e02 (45% Nb-94m, 30.2% Cu-64, 11.4% Mn-56, 5.96% Cu-66,)	2.73e0 (57.3% Nb-93m, 16.4% Fe-55, 7.7% P-34, 2.62% Co-60, 2.52% Sn-119m, 1.69% Ni-63, 1.15% Co-57, 1.10% Nb-94, 1.03% Sn-113)
Outer Coil Case	3.06e-1 (53.3% Mn-56, 9.19% Mo-99, 6.83% Cr-51, 3.3% Fe-55, 3.21% Cu-64, 2.75% Co-60, 2.18% Tc-101, 2% Ta-182)	1.67e-2 (47% Fe-55, 44.2%, Co-60, 3.66% Ni-63)

B. Waste Disposal Rating

The waste disposal rating (WDR) is the ratio of specific activity to allowable limit summed over all radioisotopes. US fusion designs, the WDR is based on both Fetter's and NRC limits. It is divided into three categories:

- If WDR is greater than 1, it means HLW or GTCC (greater than class C waste)
- If WDR is less than 1, it means LLW (Class C)
- If WDR is less than 0.1, it means waste may qualify as Class A LLW

LLW is generated anywhere radioisotopes are produced or used in nuclear industries, university research laboratories, hospitals, and food irradiation facilities. It contains alpha, beta, and gamma emitters. The NRC classified the LLW into three classes (A, B, and C), according to the type of radioisotopes and specific activity level.

- Class A is the least hazardous type of waste, its containers are placed at ~5 m deep in the ground.
- Class C contains some long-lived radioisotopes; its containers are placed at a greater depth than 8 m in the ground.

In general, fusion reactors designers should avoid generally HLW, minimize the Class C LLW, tolerate any Class A LLW, and develop low activation materials with impurity control. The impurities play an important role in the activation analysis. They should be included in the analysis to assure accurate and precise results. The impurities control and the selection of low activation materials could qualify the waste as Class A LLW. Our results show that all IB components qualify as Class A LLW since their WDR is less than 1 using NRC-A limits, meaning no modifications impurity control are needed for IB components. The main contributors of the WDR are listed in Table 7. The activation of the MF82H steel is within certain acceptable limits without additional control of impurities. Since Nb-94 is the main radioisotope contributing to the WDR of MF82H-FS, keeping its impurities at 3.3 wppm is essential to control the WDR. The parent nuclide that is responsible for the production of Nb-94 is Nb-93. The contribution of Nb-94 to the WDR of FW\blanket exceeds 80%.

Table 7 The Main Contributors of the WDR of FNSF IB Region

IB Zones	Fetter-Hi	Fetter-Lo	NRC-C	NRC-A
W Armor	0.046 (50.8% Re-186m, 22.3% Tc-99, 15.7% Nb-94)	0.140 (74% Tc-99, 16.8% Re-186m, 3.25% Nb-91)	0.009 (81.2% Nb-94, 15.9% C-14, 2.43% Tc-99)	0.097 (74.3% Nb-94, 14.5% C-14, 7.89% Ni-63)
FW	0.2 (84.7% Nb-94, 6.97% Ho-166m, 3.21% Tc-99)	0.25 (65.7% Nb-94, 24.9% Tc-99, 5.41% Re-186m)	0.17 (98% Nb-94, 1.07% Ni-63)	2 (81.5% Nb-94, 17.7% Ni-63)
Breeding Zone	0.076 (89.2% Nb-94, 7.28% Ho-166m, 2.16% Tc-99)	0.091 (74.5% Nb-94,18% Tc-99, 6.09% Ho-166m)	0.07 (96.6% Nb-94, 2.29% C-14)	0.76 (88.6% Nb-94, 8.68% Ni-63, 2.1% C-14)
Back Wall	0.078 (91.3% Nb-94, 1.8% Tc-99)	0.091 (78.6% Nb-94, 15.5% Tc-99)	0.072 (99.2% Nb-94, 0.37% Ni-59)	0.77 (93.3% Nb-94, 6.31% Ni-63)
FW/Blanket/BW/W Armor	0.099	0.123	0.088	0.99
Structural Ring	0.042 (62.1% Nb-94, 27.9% Ag-108m)	0.063 (41.9% Nb-94, 18.9% Ag-108m, 2.92% Ho-166m)	0.028 (92.6% Nb-94, 6.5% C-14)	0.30 (87% Nb-94, 6.38% Ni-63, 6.11%C-14)
Vacuum Vessel	0.025 (72.6% Nb-94, 17.9% Ag-108m, 4.85% Ho-166m)	0.035 (51.5% Nb-94, 32.1% Tc-99, 12.7% Ag-108m)	0.018 (96.8% Nb-94, 2.42% C-14)	0.20 (90.6% Nb-94, 6.73% Ni-63)
LT Shield	0.0028 (60.2% Nb-94, 26.5% Ag-108m, 7.06% Ho-166m)	0.0042 (39.1% Nb-94, 38.6% Tc-99, 17.2% Ag-108m)	0.0018 (94.6% Nb-94, 3.92% C-14)	0.02 (81.6% Nb-93, 14.4% Ni-63, 3.38% C-14)
Inner Coil Case	0.0014 (49.8% Tc-99, 48.5% Nb-94, 2.18% Nb-94	0.0063 (90.8% Tc-99, 8.85% Nb-94)	0.00063 (88.3% Nb-94, 4.11% Ni-63, 3.	0.011 (49.6% Nb-94, 46.2% Ni-63, 1.84%
Hybrid Insulator 2	0.0000014 (72% Al-26, 28% C-14)	0.000005 (79.6% C-14, 20.4% Al-26)	0.00003 (100% C-14)	0.0003 (100% C-14)
Winding Pack	0.14 (99.9% Nb-94)	0.14 (99.9% Nb-94)	0.14 (100% Nb-94)	1.4 (99.9% Nb-94)
Hybrid Insulator 1	0.0000000014 (82.4% C-14, 17.6% Al-26)	0.000000012 (97.9% C-14, 2.1% Al-26)	0.000000084 (100% C-14)	0.00000084 (100% C-14)
Outer Coil Case	0.0000025 (51.1% Tc-99, 48.6% Nb-94)	0.000014 (91.3% Tc-99, 8.67% Nb-94)	0.0000013 (91.3% Nb-94, 3.37% Ni-63)	0.000022 (55.7% Nb-94, 41.1% Ni-63, 1.17% Tc-99)
Magnet	0.083	0.083	0.083	0.83

C. Decay Heat

Decay heat is an important feature for safety and also in determining whether cooling is necessary during reprocessing or accidents. Figs. 20, 21, and 22 show the time-dependence behavior of IB components indicating a notable drop in decay heat at one day after the shutdown. As for the specific activity, the magnet presents in Fig. 22 has the lowest decay heat.

Table 8 lists the main contributors to the decay heat at shutdown and one day after shutdown the most important for controlling and avoiding any severe accident. At 1 day after the shutdown, the dominant isotopes in W armor layer are W-187 with a contribution percentage of 51.6% and 30.6% of W-185. For the FW/ blanket region, the contributors are W-187 and Mn-56.

Intermediate radioactivity can be reduced with what is known as isotopic tailoring. It is defined as the removal of certain naturally occurring isotopes from alloying elements [11]. It can reduce the decay heat of W. The parent nuclide producing W-187 is W-186. Isotopic tailoring of W can lead to a reduction in the decay heat and improve the design safety.

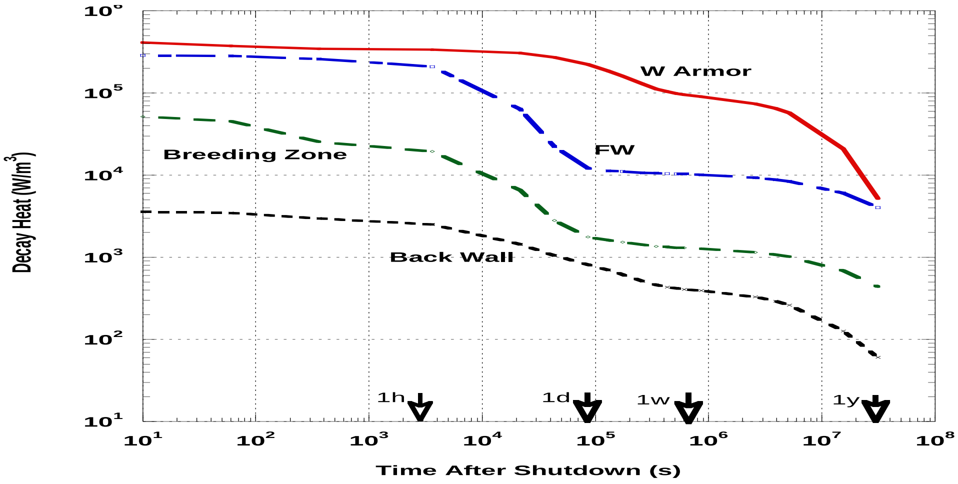

Figure 20 Decay heat of FNSF IB Blanket

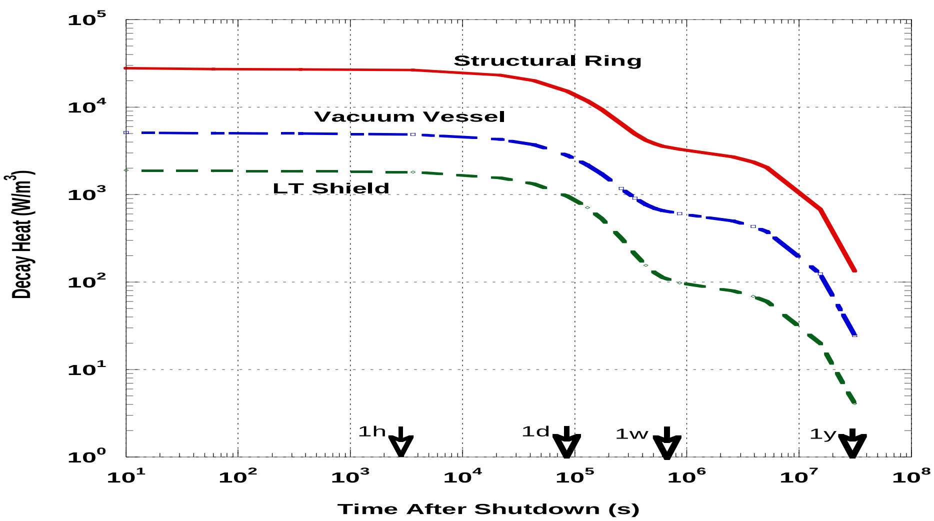

Figure 21 Decay heat of FNSF IB SR, VV, and LT Shield

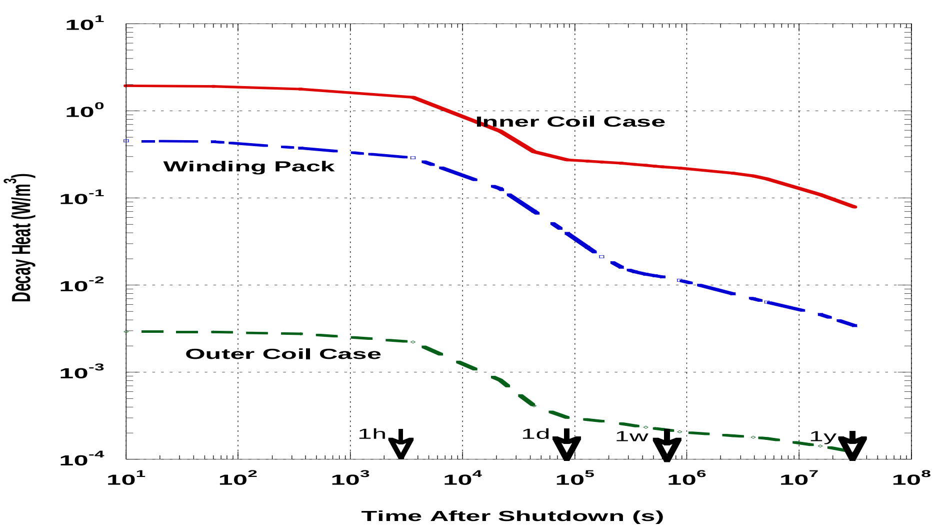

Figure 22 Decay heat of FNSF IB magnet

Table 8 The Main Contributors of the decay heat of the FNSF IB Region

IB Zones	At shutdown	At 1 day after shutdown
W Armor	4.85E5 (47.4% W-187, 19.5% W-183m, 14.2% W-185, 8.88% W-185m, 2.88% W-181, 2.05% Re-186, 1.62% Ta-182, 1.43% Re-188, 1.14% Re-184)	2.22E5 (51.6% W-187, 30.6% W-185, 6.27% W-181, 3.72% Re-186, 3.53% Ta-182, 2.64% Re-184, 1.18% Re-188)
FW	2.88E5 (88.9% Mn-56, 5.3% V-52, 2.8% Mn-54)	1.12E4 (66.9% Mn-54, 7.73% w-187, 3.82% w-185, 3.60% Fe-55, 3.39% Mn-56, 2.35% Ta-182, 2.26% Fe-59,1.02% Co-58)
Breeding Zone	5.33E4 (47.7% Al-28, 42.2% Mn-56, 3.20% V-52, 1.65% Mn-54, 1.42% W-187)	1.77E3 (49.5% Mn-54, 21.2% W-187, 6.4% Fe-59, 5.75% Ta-182, 2.2% Fe-55, 2.03% Mn-56)
Back Wall	3.65E3 (47.4% Mn-56, 20.9% W-187, 16.4% V-52, 2.93% Fe-59, 2.55% W-185, 2.4% Mn-54, 1.72% W-183m)	8.15E2 (46.6% W-187, 13.6% Ta-182, 12.9% Fe-59, 11.3% W-185, 10.7% Mn-54)
Structural Ring	2.92E4 (78.5% W-187, 11.9% W-185, 6.05% W-183m, 1.32% Re-188)	1.52E4 (74.8% W-187, 22.5% W-185, 1.1% Re-186)
Vacuum Vessel	5.36E3 (79.8% W-187, 11.9% W-185, 5.76% W-183m)	2.81E3 (75.7% W-187, 22.3% W-185)
LT Shield	1.97E3 (86.9% W-187, 5.17% W-185, 4.66% W-183m, 1.94% Mn-56)	9.64E2 (88.3% W-187, 10.4% W-185)
Inner Coil Case	1.94 (76.9% Mn-56, 5.02% Co-58, 3.5% Co-60, 2.9% V-52, 2.09% Mo-99, 1.81% Mo-101, 1.41% Mn-54, 1.28% Al-28, 1.05% Ta-182)	0.275 (35.2% Co-58, 24.7% Co-60, 11.5% Mo-99, 9.9% Mn-54, 7.38% Ta-182, 2.89% Tc-99m, 2.24% Fe-59, 1.39% Cr-51, 1.28% Co-57)
Hybrid Insulator 2	0.219 (43.8% Al-28, 33.9% N-16, 16.5% Na-24,)	0.0119 (100% Na-24)
Winding Pack	0.458 (55% Mn-56, 18.2% Cu-64, 13.1% Cu-66, 4.06% Nb-94m, 3.31% Cu-62, 1.42% Nb-92m)	0.0391 (57.4% Cu-64, 15.5% Nb-92m, 6% Mn-54, 4.8% Co-58, 1.65% Sn-121, 1.54% Sn-117m, 1.51% Sn-125, 1.49% In-113m, 1.1% Mo-99, 1.03% Mn-56)
Hybrid Insulator 1	0.000251 (75% Al-28, 9.92% N-16, 8.68% Si-31, 1% Mg-27)	0.00000409 (99% Na-24)
Outer Coil Case	0.00292 (83.7% Mn-56, 4.43% Co-60, 3.09% Mo-99, 2.66% Mo-101, 1.86% Ta-182 1.1% Tc-101)	0.000302 (42.8% Co-60, 23.2% Mo-99, 17.9% Ta-182, 5.85% Tc-99m,3.97% Fe-59, 1.29% Mn-56, 1.12% Co-58)

D. Recycling Dose Rate

Fusion produces large amounts of LLW due its large volume. So, recycling is the preferred option for all fusion designs. The most important criterion in recycling is the dose to remote handling equipment. When the FNSF materials are irradiated by high flux of 14 MeV of neutrons, RH will be required to change any components exhibiting high dose equipment rates. The dose determines handling process with hands-on, conventional, or advanced equipment and the interim storage period required to meet the dose limit. All FNSF components can be recycled using advanced RH equipment with a storage period less than 1 year as in previous studies [12]. The first wall shown in Fig. 23 has the highest dose to RH equipment. Storing the materials for a period of time will drop the dose by few orders of magnitude before their recycling. For recycling, the materials of each component should be separated to determine if individual materials are recyclable. In Figs. 26, 27, 28, 29, and 30, all with individual materials in SR, VV, LT shield, and winding pack are recyclable with advanced RH equipment in less than 1 day. The dose of SiC in the breeding zone is slightly above the advanced RH equipment right at shutdown, but rapidly with time. At 100 years after shutdown, all the materials can be recycled using conventional RH equipment. The hybrid insulator in WP can be recycled using hands-on procedure in less than 1 year of storage. The main contributors of the recycling dose rate are shown in Table 9.

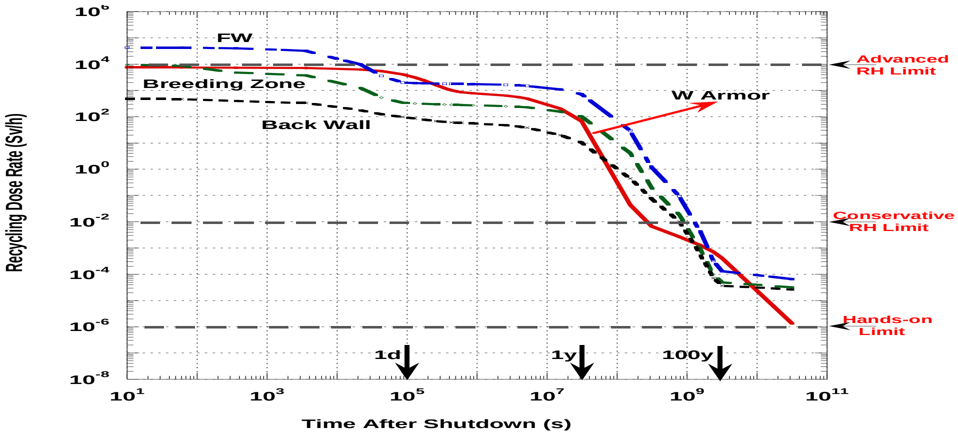

Figure 23 Recycling dose rate of FNSF IB blanket

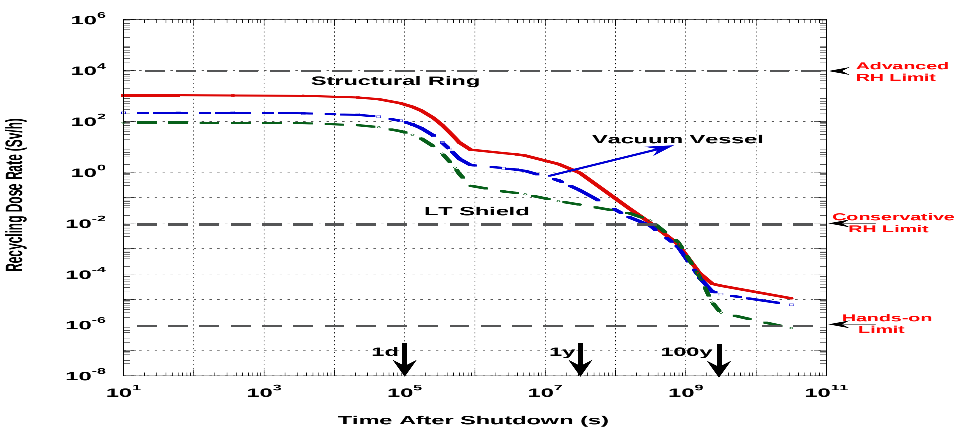

Figure 24 Recycling dose rate of FNSF SR, VV, and LT shield

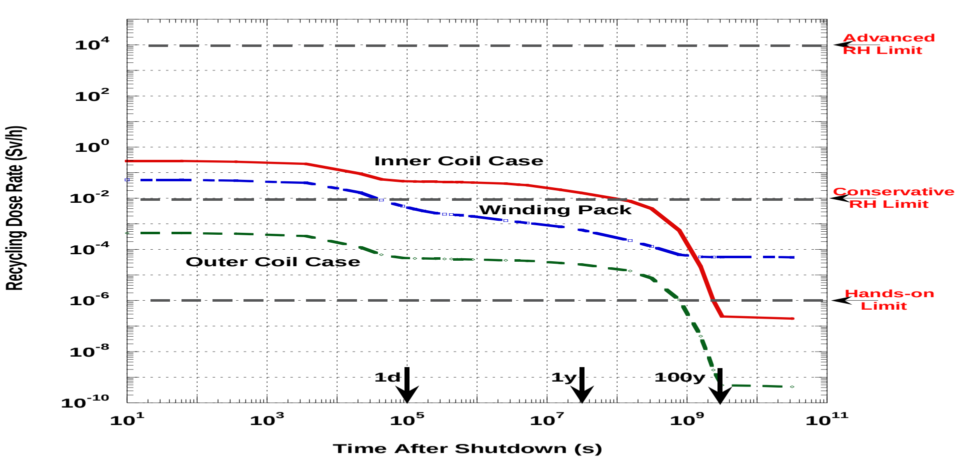

Figure 25 Recycling dose rate of FNSF IB magnet

Table 9 Main Contributors of Recycling Dose Of FNSF IB Region

IB Zones	At shutdown	At 1 year after shutdown
W Armor	7.45E3 (86.5% W-187, 6.86% Ta-182, 4.45% Re-184)	6.73E1 (84.2% Ta-182, 11.1% Re-184, 3.26% Re-184m, 1.10% W-181)
FW	4.31E4 (90.1% Mn-56, 4.78% V-52, 3.7% Mn-54)	7.19E2 (98.7% Mn-54)
Breeding Zone	9.83E3 (47.4% Al-28, 44.2% Mn-56. 2.97% V-52, 2.24% Mn-54)	1.01E2 (96.9% Mn-54)
Back Wall	4.80E2 (54.7% Mn-56, 16.8% V-52, 15.3% W-187, 4.47% Fe-59, 4.04% Ta-182, 3.6% Mn-54)	1.02E1 (75.8% Mn-54, 21.2% Ta1-82, 2.2% Co-60)
Structural Ring	1.07E3 (96.8% W-187, 1.38% Mn-56)	9.37E-1 (54.7% Mn-54, 39.5% Ta-182, 3.33% Co-60)
Vacuum Vessel	2.18E2 (96.9% W-187, 1.14% V-52)	1.97E-1 (52.1% Ta-182, 32.4% Mn-54, 12.7% Co-60, 1.35% Fe-59)
LT Shield	8.79E1 (95.2% W-187, 4% Mn-56)	5.37E-2 (77.5% Co-60, 15.2% Mn-54, 2.59% Ag-110m)
Inner Coil Case	2.91E-1 (77.4% Mn-56, 6.16% Co-58, 5.03% Co-60, 2.59% V-52, 1.84% Mn-54, 1.83% Mo-101, 1.21% Ta-182)	1.62E-2 (79.3% Co-60, 14.7% Mn-54, 2.42% Ta-182)
Hybrid Insulator 2	1.54E-1 (38.3% N-16, 36.9% Al-28, 21.7% Na-24, 2.01% Mg-27)	1.30E-9 (100% Al-26)
Winding Pack	5.33E-2 (73.1% Mn-56, 15.2% Cu-64, 2.01% Cu-62, 1.67% Cu-66)	5.81E-4 (42.1% Co-60, 36.2% Mn-54, 9.89% Sb-125, 8.74% Nb-94, 1.74% Co-58)
Hybrid Insulator 1	1.44E-4 77.2% Al-28, 13.7% N-16, 7.88% Na-24)	3.09E-13 (100% AL-26)
Outer Coil Case	3.32e-4 (85.4% Mn-56, 6.47% Co-60, 2.73% Mo-101, 2.18% Ta-182)	2.57E-5 (95.5% Co-60, 4.06% Ta-182)

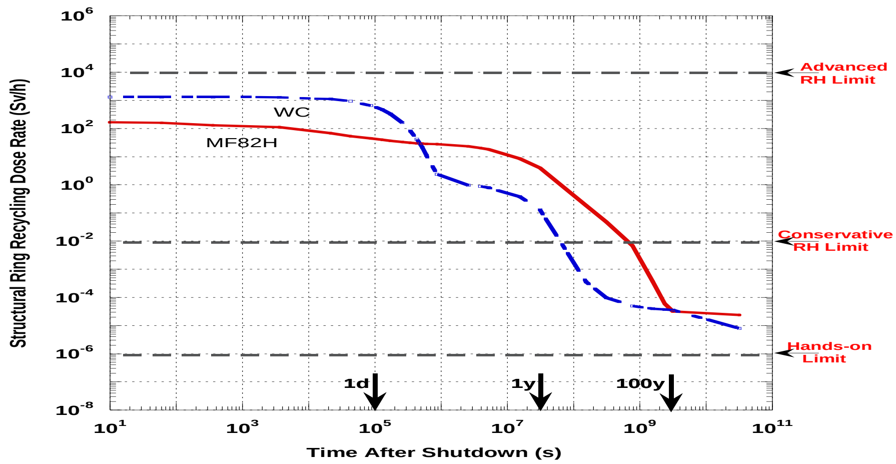

Figure 26 Recycling dose rate of FNSF SR

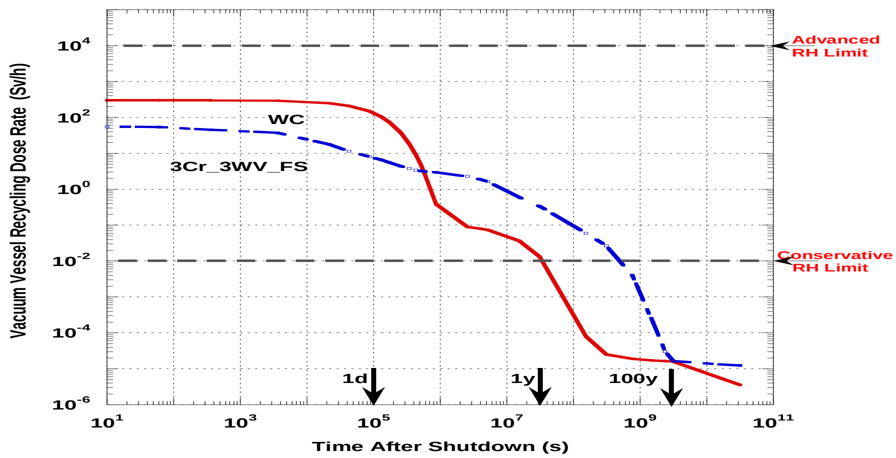

Figure 27 Recycling dose rate of FNSF VV

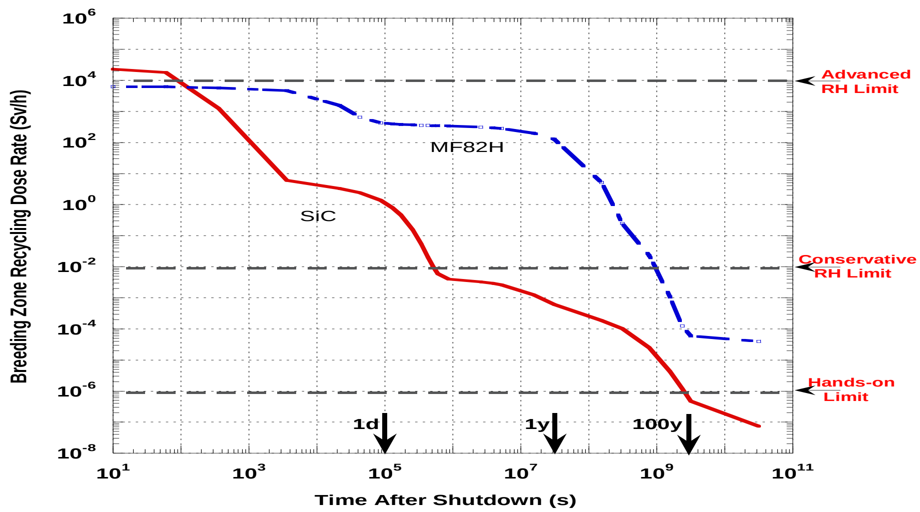

Figure 28 Recycling dose rate of FNSF BZ

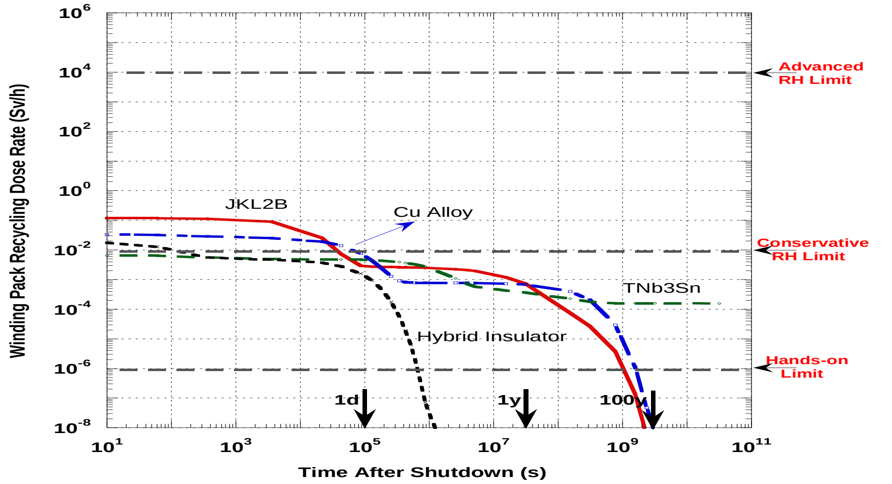

Figure 29 Recycling dose rate of FNSF WP

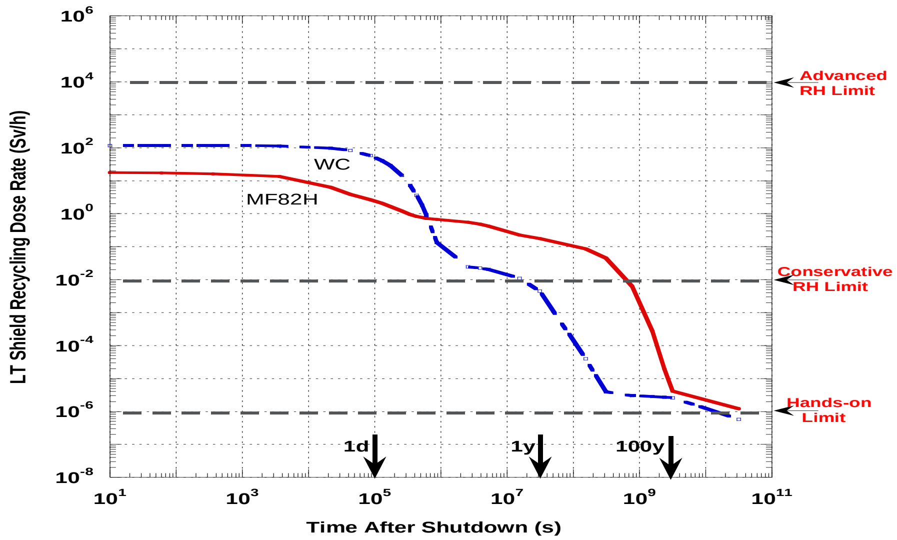

Figure 30 Recycling dose rate for FNSF LT shield

E. Clearance Index

Clearance is the unconditional release of materials from radiologically controlled areas to the commercial market at the end of a specific interim storage period. Individual materials could be stored for a certain period of time (< 100 years), and then released to the commercial market if the clearance index falls below the limit of 1 [13]. The clearance is feasible for components exposed to very low neutron flux. The two options for clearable materials is either disposal as a non-active waste, known as clearance with disposal or recycling outside the nuclear industry as a non-active recyclable material in which it's referred as clearance with recycling. In the FNSF IB region, no component is clearable except the outer coil case (CC) of the magnet since it's exposed to very low neutron flux. The main contributors to the clearance index of Outer CC are Co-69 (94%) and Ni-63 (3%). The other components are not clearable as indicated in Figs. 31 – 33. The winding pack contains four materials (hybrid insulator, JK2LB, Nb3Sn, and copper) and none of them is clearable (refers to Fig. 34). The individual materials of SR, VV, and LT Shield are not clearable as shown in Figs. 35, 36, and 37. The vacuum vessel can be cleared if it's composed of pure Fe, and that is confirmed in Fig. 38. However, this is impractical. Basically, the bioshield and cryostat in the outboard region are the only components that have low neutron flux and thus are clearable [2].

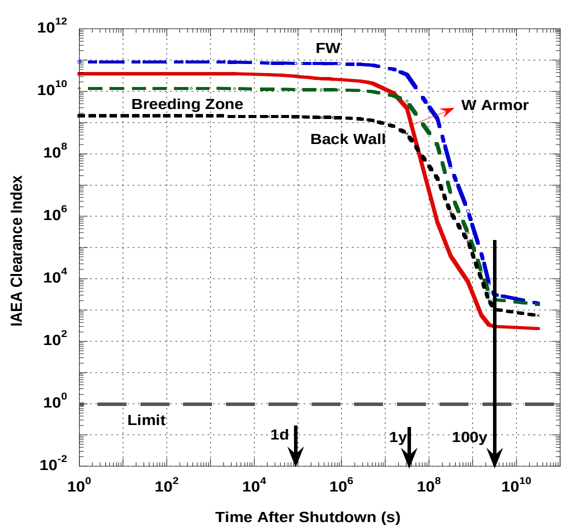

Figure 31 Clearance index of FNSF blanket

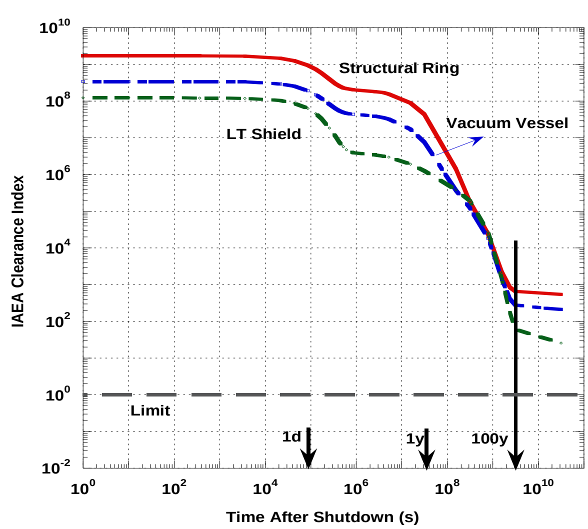

Figure 32 Clearance index of FNSF SR, VV, & LT shield

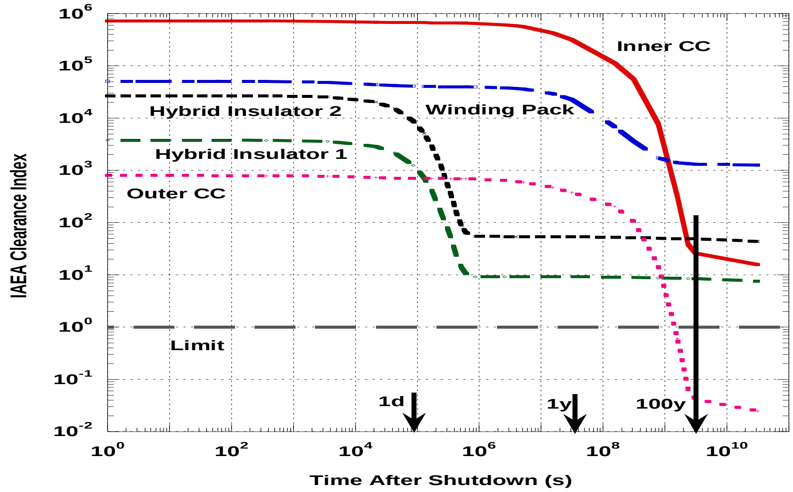

Figure 33 Clearance Index of FNSF Magnet

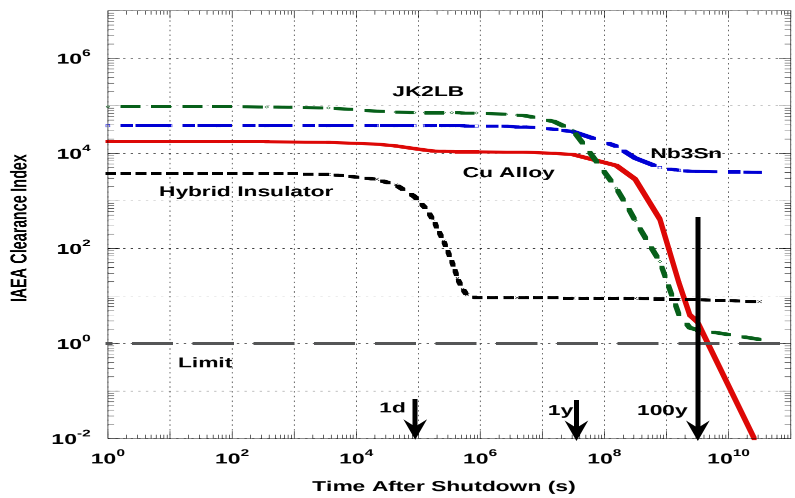

Figure 34 Clearance Index of FNSF WP

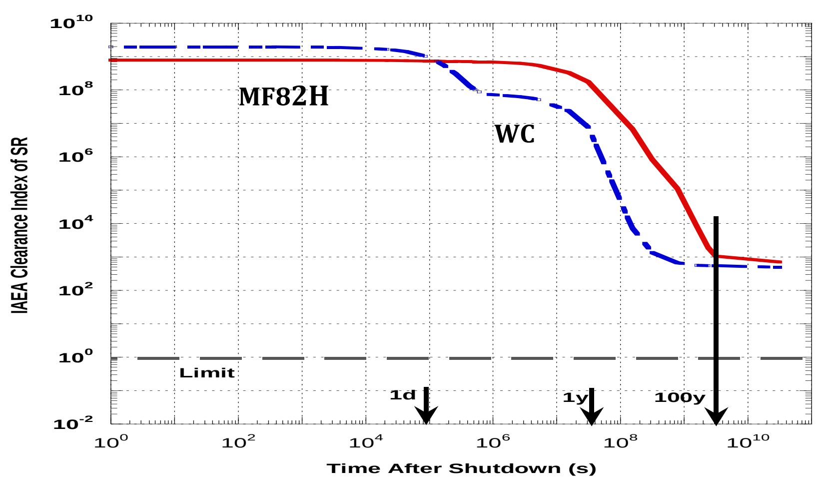

Figure 35 Clearance Index of FNSF SR

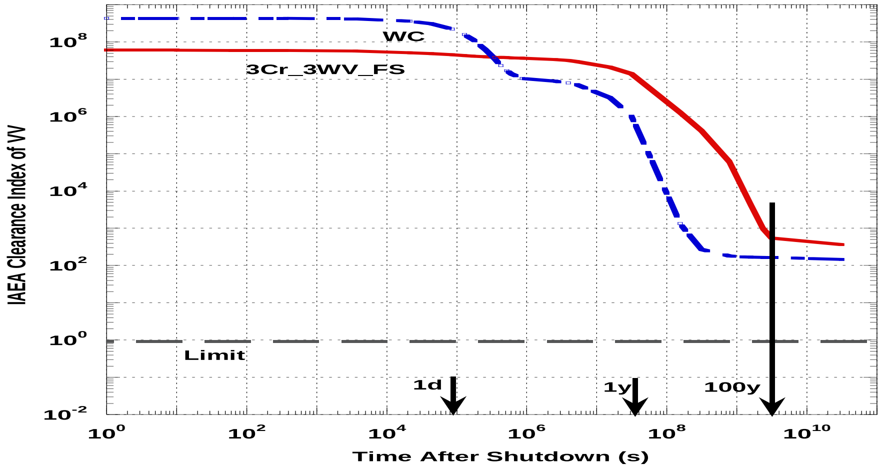

Figure 36 Clearance Index of FNSF VV

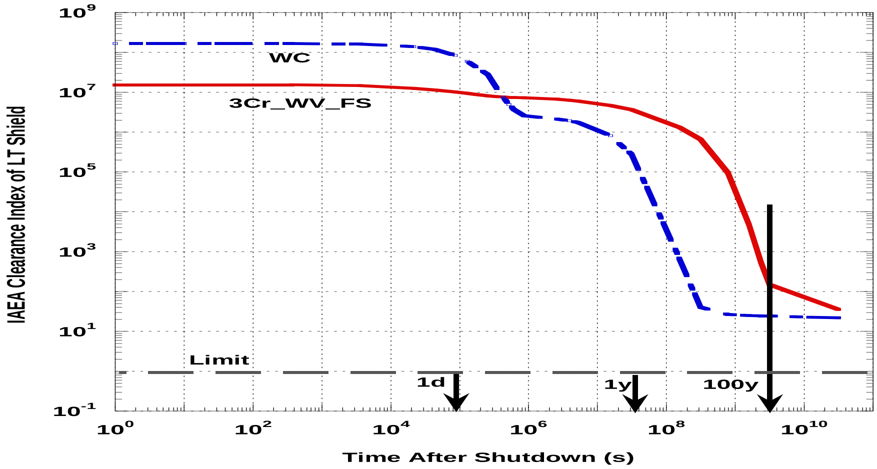

Figure 37 Clearance Index of FNSF LT shield

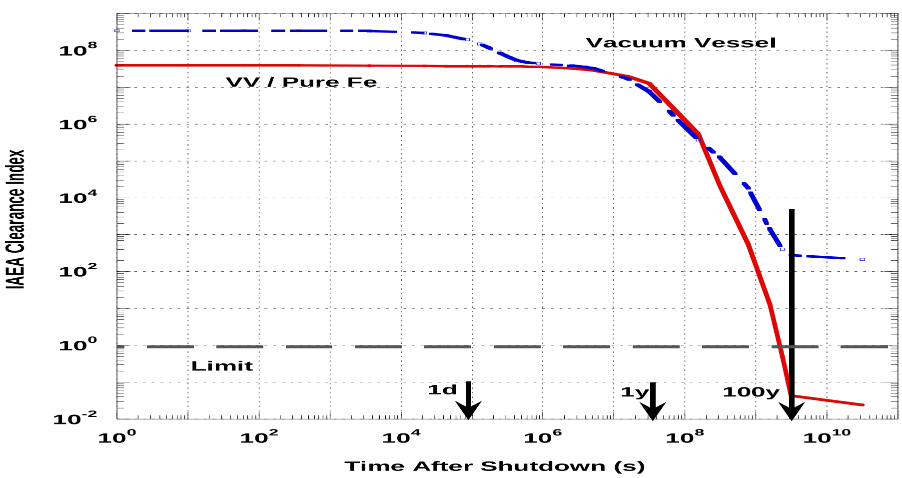

Figure 38 Clearance Index of FNSF VV

Conclusions

This report focuses on the shielding requirements to minimize the magnet radiation damage to the inboard magnet of the FESS-FNSF design. Magnet radiation shielding is required to limit the nuclear heating, fast neutron fluence, dose to insulator, and Cu stabilizer of the magnet. An optimum shield composition was found to minimize the magnet damage with 50% WC and 45% water with 5% FS ribs by volume. The fast n fluence has an important role in the shielding analysis and influences the LT shield composition. A safety factor of three was included in the shielding analysis to account for neutrons streaming through the assembly gaps between modules reaching the SR, VV, LT shield, and magnet. The 103 cm thick inboard blanket, SR, VV, and LT shield provides adequate protection for the magnet.

Detailed activation calculations for the inboard region of the FNSF design were also performed to evaluate the specific activity, decay heat, waste disposal rating, recycling dose rate, and the clearance index. The WDR indicates that all components qualify as Class A LLW using NRC limits, thus no modifications to the F82H FS composition are needed. Advanced RH equipment can recycle all IB components after a short storage period less than 1 year. The outer coil case is the only clearable component at 50 y after shutdown since it’s exposed to very low neutron flux.

Acknowledgment

This work has been supported by the FESS-FNSF project, funded by the US Department of Energy. The authors would like to express their appreciation to Profs. Mohamed Sawan, Douglass Henderson, and Paul Wilson (UW) for their unlimited support designing this study.

References

1. L. El-Guebaly, S. Malang, A. Rowcliffe, L. Waganer, "BLANKET/MATERIALS TESTING STRATEGY FOR FNSF AND ITS BREEDING POTENTIAL," Fusion Science and Technology, Vol. 68, No. 2, 251-258 (September 2015).

2. M.T. Elias and L. El-Guebaly, "Shielding and Activation Analyses for Outboard Region of FESS-FNSF Design,"University of Wisconsin Fusion Technology Institute Report, UWFDM-1424 (November 2015). Available at: http://fti.neep.wisc.edu/pdf/fdm1424.pdf.

3. OAK RIDGE NATIONAL LABORATORY, "FUSION MATERIALS SEMIANNUAL PROGRESS REPORT FOR THE PERIOD ENDING", April 2011, Page 90.

4. DANTSYS: A Diffusion Accelerated Neutral Particle Transport Code System, Los Alamos National Laboratory Report, LA-12969-M (1995).

5. L. ALDAMA and A. TRKOV, "FENDL-2.1 Update of an Evaluated Nuclear Data Library for Fusion Applications," International Atomic Agency Report INDC(NDC)-467 (2004).

6. P. WILSON and D. HENDERSON, "ALARA: Analytic and Laplacian Adaptive Radioactivity Analysis: A Complete Package for Analysis of Induced Activation," University of Wisconsin Fusion Technology Institute Report. Volume I - UWFDM-1070. Volume II, UWFDM.1071 (1998). ALARA user's guide: https://trac.cae.wisc.edu/trac/svalinn/wiki/ALARAInputFileSyntax.

7. FENDL3 Activation Library: https://www-nds.iaea.org/fendl3/000pages/StarterLib/2011-12-01/.

8. L. El-Guebaly, R. Raffray, S. Malang, J.F. Lyon, L.P. Ku, the ARIES Team, "BENEFITS OF RADIAL BUILD MINIMIZATION AND REQUIREMENTS IMPOSED ON ARIES COMPACT STELLARATOR DESIGN," Fusion Science and Technology, 47, No. 3, 432-439 (2005).

9. N.P. Taylor, E.T. Cheng, D.A. Petti, M. Zucchetti, "Overview of International Waste Management Activities in Fusion," Fusion Technology 39, 350-356 (2001).

10. L.A. El-Guebaly, L. Cadwallader, "Integrated Management Strategy for Fusion Activated Materials: US Position and Regulations," University of Wisconsin Fusion Technology Institute, UWFDM 1373 (July 2009). Available at: http://fti.neep.wisc.edu/pdf/fdm1373.pdf

11. T. Lechtenberg, "Minimum activation martensitic alloys for surface disposal after exposure to neutron flux," Department of Energy, US, US4533406 A, (1985)

12. L. El-Guebaly, “Evaluation of Disposal, Recycling, and Clearance Scenarios for Managing ARIES Radwaste after Plant Decommissioning,” Nuclear Fusion 47, 485 -488 (2007).

13. L. El-Guebaly, P. Wilson, and D. Paige, “INITIAL ACTIVATION ASSESSMENT OF ARIES COMPACT STELLARATOR POWER PLANT,” Fusion Science and Technology, 47, No. 3, 440-444 (2005).