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Shielding and Activation Calculations for the German Fusion Device WENDELSTEIN 7-X

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The shielding property of the hall walls of the new German fusion device Wendelstein 7-X was calculated using MCNP and ANISN while varying different parameters. Attenuation factors and dose rates for neutron and induced gamma radiation are presented. The resulting effective doses are compared with radiation protection limits, which led in some cases to changes in the planning. Weak points in the wall i.e. doors, ducts and channels were investigated with MCNP. Neutron streaming was observed in all those cases. The activation of the walls and of the door opening device was calculated with MCNP and GRSAKTIV for different irradiation patterns and different decay times.

KEY WORDS: Fusion device, stellarator, shielding calculation, wall activation, neutron streaming, MCNP, ANISN, GRSAKTIV, effective dose, dose limits, attenuation factors

I. Introduction

The device WENDELSTEIN 7-X[1], which is now under construction by the Max-Planck-Institute for Plasma Physics (IPP), is designed to demonstrate the optimized stellarator to be a viable fusion reactor concept. Stellarator fusion experiments confine the plasma in a magnetic field exclusively generated by external coils, thus affording the direct possibility of stationary operation. Major physical and technical objectives of Wendelstein 7-X are to demonstrate stationary operation and achieve plasma conditions, which though below ignition, allow good extrapolation to the properties of a future reactor-grade stellarator plasma. For the first time the magnetic field is generated with modular super conducting coils. The optimized stellarator overcomes the difficulties of previous stellarator concepts and achieves plasma equilibrium and confinement of a quality equal to that of a Tokamak. Operation is scheduled to begin in 2005. At the moment, buildings and sites are completed to 80% and the engineering installation has started.

Fusion reactions during pulses of about 10 seconds will produce high energy neutrons which have to be shielded. On the other hand activation of materials by thermalized neutrons will result in a constantly increasing gamma source. GRS was engaged to perform shielding and activation calculations for the planning of the stellarator hall and adjacent areas, in order to meet German[2] and EU[3] radiation protection standards.

The neutron source is a kidney-shaped plasma stellarator with 11 m in diameter placed on a table like concrete platform. The position in the hall is asymmetric. During operation neutrons with high intensity are streaming from the stellarator through differrent walls, openings and channels to the outside of the building producing activation of materials and radiation dose rates. In order to meet the dose limits for the public exposure the effective dose was aimed to be kept below 0.3 mSv/a. Three steps were necessary to achieve this goal:

- Shielding calculations of walls and doors penetrated by direct radiation.
- Shielding calculations of neutron streaming through ducts and channels.

Calculations of activated materials in the neutron field and its contribution to the radiation level.

II. Shielding Calculations

1. Source Term

The primary d-d fusion reaction produces neutrons with an energy of 2.45 MeV while neutrons from the secondary d-t fusion reaction have an energy of 14 MeV. The ratio of the intensity of the two reactions was predefined to be 200 to 1. The intensity of the neutron source was 7 x 10^{15} n/s during a pulse of 10 s. 1000 pulses per year were projected in the experimental phase, with a maximum limitation of the total number of neutrons per year to 3 x 10^{19} n/a.

2. Geometry and Materials

(1) Walls

Six different types of walls (see **Table 1**) were investigated with respect to shielding properties for the radiation of the fusion source in order to get a choice of adequate shielding possibilities in different situations. The thickness of the walls was varied from 0 to 200 cm by steps of 10 cm.

The designed thickness of the outer walls was 1.7 m. Because of the asymmetric position of the stellarator in the hall the distances of side walls are 7 , 9, 10 and 11 m, the distances to the ceiling is 12 m. The side walls have two steel reinforcements at a depth of 0.6 m and at 1.6 m.

(2) Doors

The stellarator hall has two large entrance doors made of concrete, the personnel door and the installation door. Both

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Table 1 Calculated attenuation factors, gamma and neutron dose percentages from the total dose rate and material properties of the planned stellarator walls

wall material	H_2O content l/m^3	density g/cm^3	boron ppm	attenuation factor 1 m	% n-dose 1 m wall	% γ-dose 1 m wall	attenuation factor 2 m	% n-dose 2 m wall	% γ-dose 2 m wall
concrete	60	2.3	0	1.8×10^3	74.1	25.9	2.6×10^6	25.3	74.7
concrete	100	2.3	0	4.3×10^3	66.2	33.8	7.8×10^6	12.2	87.8
concrete	100	2.3	400	9.8×10^3	87.3	12.7	6.1×10^7	40.2	59.8
baryte	165	3.25	0	1.6×10^4	77.1	22.9	2.1×10^8	42.0	58.0
sandwich	100/300	2.3/1.6	0	9.0×10^3	17.4	82.6	3.3×10^6	0.2	99.8
sandwich	100/300	2.3/1.6	400	1.6×10^4	15.2	84.8	4.8×10^6	0.1	99.9

doors are rail-borne and the opening and shutting device is integrated into the bottom of each door. While the upper part of both doors has the same thickness as the hall walls, the lower part of the doors has a thickness of only 1 m with a reduced shielding effect. Therefore, the insertion of baryte concrete into this door region was planned.

(3) Ducts , Gyrotron Channel

For the various monitoring, controlling and measuring devices ducts are planned to be drilled into the 1.7 m thick hall wall. Two ducts were investigated, both having diameters of 10 cm and being placed at the height of the neutron source. One duct is horizontal, while the other has an upward inclination and a length of 2 m.

The gyrotron channel is the largest opening in the hall floor. It holds the supply lines for the microwave heating of the plasma. The microwaves are generated in an adjacent building. The channel is 45 m long and extends horizontally underground at a depth of 8 m. It has concrete walls and a rectangular cross section of 2 m x 3 m. Beneath the stellarator the channel is divided into two vertical channels, each having a cross section of 2 m x 2 m.

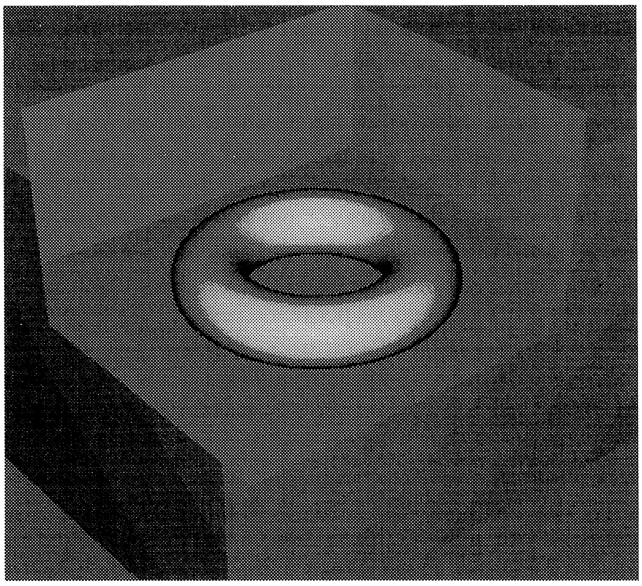

Fig. 1 3-dimensional MCNP model for the shielding calculations of the stellarator hall

3. Calculation Procedure

The attenuation factors of the 6 wall types according to table 1 were calculated with the 1-dimensional discrete ordinate code ANISN[(4)] in slab geometry.

For the determination of dose rates at the outside of the hall the shielding calculation problem was divided into two parts:

- A 3-dimensional calculation of the radiation field around the stellarator up to the inside of the building walls using the Monte Carlo code MCNP[(5)].
- A 1-dimensional shielding calculation through the walls using the GRS shielding system ANITABL[(6)] with the discrete ordinate code ANISN.

The advantage of this method is a very realistic model of the complex geometry in the area around the stellarator including the gyrotron channel, while the shielding calculation through the very thick concrete walls of simple geometry can be performed with high accuracy by the discrete ordinate procedure.

In the MCNP model the plasma was simplified to a torus ring, the solid material of the stellarator was neglected. A 3-dimensional view of the model used by MCNP is given in **Fig. 1**. ANISN used a cylinder geometry to calculate the radiation transport from the source through the walls to the outside of the building. The MCNP-dose rates at the inner surface of the walls were used to calibrate the ANISN dose rates gained from the ANISN geometric cylinder model from this point on outwards.

MCNP worked with point data from ENDF/B-VI[(7)] and ANISN with the 120 energy groups EURLIB[(8)] library. Dose factors of ICRP-74[(9)] were applied.

4. Results

(1) Walls

For the fusion neutrons the calculated attenuation factors of the 6 different wall types are given in table 1. The attenuation factors were determined as a function of wall thickness. They fall almost linearily with the wall thickness on a logarithmic scale and reach 6 to 8 orders of magnitude for a wall thickness of 2 m. The higher the water content in the concrete, the higher the attenuation factor.

Due to neutron capture gamma radiation is produced in the wall material. For standard concrete with 60 l/m^3 and 100 l/m^3 water content, the neutron dose is dominating at 1 m inside the wall, but at 2 m wall thickness the gamma dose exeeds the neutron dose. Since the moderation increases at higher water content, the neutron capture also rises, because of higher capture cross sections for thermal neutrons.

Adding boron increases the attenuation factor, because of the high capture cross section of the boron isotope ^{10}B. However in contrast to the other wall materials the reaction $^{10}B(n,\alpha)^{7}Li$ produces almost no gamma dose. Therefore, the percentage of the gamma dose drops.

For the sandwich wall the same arguments hold true, since the water content is high. However, since the moderation is very high due to gypsum, the addition of boron is not very effective. The low density of the gypsum results in a high gamma portion and a low attenuation factor.

The highest attenuation factors are achieved with baryte as wall material. Good moderation due to relatively high water content is effectively shielding the neutrons, while high density of the material weakens the gamma radiation.

None of the 6 wall types turned out to deliver a sufficient attenuation factor that was able to meet the dose limits for a wall thickness of 1.7 m as planned in the original construction design. Therefore, the boron content of the concrete wall was increased to 1000 ppm, the water content was elevated to 120 l/m^3 and the operation of the stellarator was confined from 7 x 10^{19} to 3 x 10^{19} total neutrons per year. These provisions lowered the total dose rate by a factor of 5. To provide a local dose below 0.3 mSv/a for the wall closest to the stellarator, the wall thickness had to be increased to 1.8 m.

(2) Doors

The calculated total dose behind the baryte concrete of the personnel door was 147 mSv/a without the contribution of the activation and with an actual water content of 135 l/m^3. This is far above the given limits. Baryte concrete is a good shielding material for gamma radiation. In this case, however, where neutrons are involved, the shielding is not sufficient and had to be reinforced. The problem was solved by an additional shielding panel of 35 cm polyethylene affixed to the inner side of the door wall infront of the door opening device. The calculated dose sank below 0.3 mSv/a.

(3) Ducts and Gyrotron Channel

The attenuation factor of the dose rate on the central axis before and after the ducts was 30 for the horizontal duct and 1000 for the inclined duct. This lead to a local dose rate more than four orders of magnitude higher than in the case of the unaffected wall. The dose rate was dominated by the neutrons, whereas the gammas did not play an important role. The ducts through the walls were quantitatively identified as weak points which require special precautionary measures.

In the horizontal part of the gyrotron channel the calculated neutron dose was 55 mSv/a at a distance of 33 m. The gamma dose was less than 10 % of the neutron dose. Because of the high dose in the channel, special precautions have to be taken during the operation of the stellarator.

III. Activation Calculations

Thermalized neutrons will activate irradiated materials and thus induce an additional gamma source which may enhance the dose at the outside of the building, but also may be a permanent source of irradiation of the personnel, when the stellarator is not in operation. Activation was calculated for a wall of the building and for the personnel door.

1. Irradiation Patterns

The gamma intensity as a function of decay time was calculated as a result of the activation for the following four irradiation patterns:

- One pulse irradiation lasting 10 s with an intensity of 7 x 10^{15} n/s.
- One week irradiation on 5 days, each day with 5 irradiations, each irradiation with 2 pulses, one pulse lasting 10 s.
- One year irradiation with 39 weeks (16 weeks shutdown time) resulting in a mean neutron intensity of 1.16 x 10^{12} n/s.
- Fifteen years irradiation according to the whole operation time with a mean neutron intensity of 8.7 x 10^{11} n/s.

2. Geometry and Materials

Geometry and materials of the walls shown in **Table 2** correspond to the configuration of the shielding calculations.

Table 2 Materials of the walls

wall material	concrete
density	2.3 g/cm^3
wall thickness	1.7 m
reinforcement	steel with 0.018 wt% Co
water content	120 l/m^3
boron content	1000 ppm

A weak point of the personnel door is the opening device with a thickness of 0.7 m consisting of different metals 98 wt% of which is iron. The activation in the door opening device at the inner side of the personnel door was calculated with and without the additional polyethylene panel. The cobalt content was assumed to be 300 ppm. The material as a whole was distributed evenly in the casing, resulting in a mean density of 3.1 g/cm^3.

3. Calculation Procedure

The activation calculation uses the combination of the codes MCNP, THERES(10) and GRSAKTIV(11). MCNP calculates the fluxes in each layer of the wall. The mean fluxes are condensed within the three corresponding ORIGEN(12) energy groups. The condensation is necessary, since the neutron capture cross sections of the ORIGEN library used for the activation calculation has this 3 group structure. THERES uses the mean fluxes to generate the three spectral ORIGEN indexes *therm, res* and *fast,* assuming a LWR-reactor-like neutron spectrum, using Bell's(12) method for the cross section condensing. This spectrum is different from a fusion spectrum. However, as MCNP calculations have shown, it is applicable, since neutron slowing down on the inner side of the walls of the hall alter the fusion spectrum considerably towards a LWR- spectrum. In addition the high water content of the concrete further enhances this effect, so that a LWR-like spectrum is already reached after 15 cm penetration into the wall. GRSAKTIV condenses the local cross sections to one total cross section, then ORIGEN solves the one-group rate equation. In a last step, GRSAKTIV calculates for desired decay times the activities and gamma powers corresponding to the given irradiation history, the materials and the mean neutron fluxes in the layers.

4. Results

The most important results achieved by activation calculations can be summerized as follows:

- Aside from the 60 isotopes existing in the wall materials, another 60 isotopes are created by neutron activation.
- Immediately after a 15 years irradiation time, the mean activity throughout the entire wall thickness is 1.6 Bq/cm^3 and decreases to 0.002 Bq/cm^3 after a decay time of 10 years.
- The inner concrete layer of the wall has 1 x 10^7 higher total activity than the one on the outside.
- Related to the whole thickness of the wall, the following isotopes have the highest activity:
  ^{28}Al for short decay times of seconds,
  ^{31}Si for decay times of hours,
  ^{37}Ar for days,
  ^{45}Ca for months,
  ^{55}Fe for years.
  Within the different material layers of the wall the ranking is different.
- ^{60}Co in the steel reinforcement of the wall has the highest gamma power of all nuclides
- For the door opening device without the polyethylene panel the mean specific activity after an irradiation of 15 years is 9.6 x 10^5 Bq/cm^3 at 1s decay time and 7.1 x 10^5 Bq/cm^3 after three hours decay time.
- After 15 years irradiation time the estimated upper limit of the additional gamma dose due to activation is about 20 mSv/a at the inside of the door opening device when no polyethylene panel is added. With polyethylene panel added the neutron flux is lowered by a factor of 250 approximately, resulting in a total activity lowered by a factor of 260. Thus the polyethylene panel will lower the gamma dose from 20 to about 0.08 mSv/a.
- The activation of the polyethylene itself is very low (7.7 Bq/cm^3) and dominated by ^{3}H and ^{14}C which both are low energy beta emitters. At the outside of the personnel door with the polyethylene panel the activation gamma dose is negligible, because there is 1 m shielding of baryte concrete towards the outside of the hall.

IV. Conclusions

In the phase of planning the new German fusion device Wendelstein 7-X shielding and activation calculations for the stellarator hall were performed. For the radiation source the neutrons of the d-d reaction were used. The attenuation factors of the shielding of 6 various wall configurations were calculated from 0 to 2 m thickness using a combination of MCNP and ANISN. High water and boron content in combination guaranteed the most efficient shielding. In order to meet German and EU dose limits the optimum wall was found to have a thickness of 1.8 m, made of ordinary concrete with 120 l/m^3 water content and 1000 ppm boron.

MCNP calculation in ducts and the gyrotron channel still showed high neutron doses on the outer side of the hall. Special provisions have to be taken during the operation. The shielding of the personnel and mounting door in the region of the opening device has to be fortified at easiest by a 35 cm polyethylene panel.

The neutron acitivation products in the walls and the opening device were calculated for irradiation and decay times up to 15 years using the activation code GRSAKTIV. An estimate of the dose caused by neutron activation showed that it is negligible in the case of the walls, but in the case of the inner side of the unshielded door opening device it is not negligible, because here a significant gamma source is created with increasing irradiation time.

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