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Activation and Shielding Analyses in Support of the GUINEVERE Project

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ABSTRACT

The **GUINEVERE** facility (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **RE**actor) must satisfy the nuclear safety criteria required by the Belgian safety authority to be licensed. The radiation dose and activation analyses for the nuclear safety assessment of the GUINEVERE project were performed at FZK. The concerted efforts of several European institutions were concentrated on the development and construction of a subcritical fast lead core based on the VENUS water moderated reactor at the SCK-CEN site in Mol, Belgium.

A Monte Carlo (MC) MCNP5 model was developed in accordance with the current design of the GUINEVERE fast lead core. The analytical MC method does not work for shielding analysis of the GUINEVERE building because of the large size of the rooms and thick concrete walls and floors. MC variance reduction techniques, such as particles splitting, Russian roulette, and point detectors were therefore applied. The JEFF-3.1 nuclear data library was used for radiation transport calculations. The activation analyses for the lead core and building materials were performed with the FISPACT-2005 inventory code and the EAF-2005 library. The neutron and photon dose rate maps were produced using MCNP track-length estimations, point detectors, and a mesh tally superimposed over the GUINVERE geometry. The effects of D-D and D-T fusion neutron sources were estimated.

1 INTRODUCTION

The GUINEVERE project is aimed at performing experiments on an Accelerator Driven System (ADS), which is a coupling of an accelerator, a neutron target, and a subcritical reactor core. The subcritical fast lead core is constructed on the premises of VENUS water moderated thermal reactor at the SCK-CEN site in Mol. The VENUS critical facility had a thermal core and was dedicated to a research programme on MOX fuels. The VENUS thermal core is being modified to the VENUS fast core, hereafter referred to as VENUS-F. The VENUS-F assemblies consist of 30% enriched uranium and lead rodlets, with radial and axial lead reflectors. A new GENEPI-C deuteron accelerator (from CNRS, Grenoble) operating in the continuous and pulsed mode will be designed to be coupled to the VENUS-F reactor. A more general overview for the GUINEVERE project is given in Ref. [1]. First, a critical core configuration of VENUS-F was investigated without an external neutron source from the D-T target. Next, the contributions of neutrons from the target and possible parasitic D-D nuclear reactions to the dose rate environment were estimated.

The modifications of the Monte Carlo (MC) MCNP5 model were implemented in accordance with the current design of the GUINEVERE fast lead core. The analytical MC method does not work for shielding analysis of the GUINEVERE building because of big size of the rooms 12x19x14 m^3 and thick (up to 1 m) concrete walls and floors. A Computer Aided Design (CAD) drawing of the building is presented in Figure 1. MC variance reduction techniques, such as particles splitting, Russian roulette, and point detectors were applied to deal with deep-penetrated radiation problems in the GUINEVERE building. The state of the art JEFF-3.1 nuclear data library was used for radiation transport calculations. Activation analyses of the lead core and building materials were performed by the FISPACT-2005 inventory code with the EAF-2005 nuclear data library. The irradiation scenario included 20 years of the GUINEVERE campaign with 1000 hours of operation per year. Time dependent dynamics of radioactivity was calculated for the GUINEVERE core and building materials, and the dominant radioisotopes were identified.

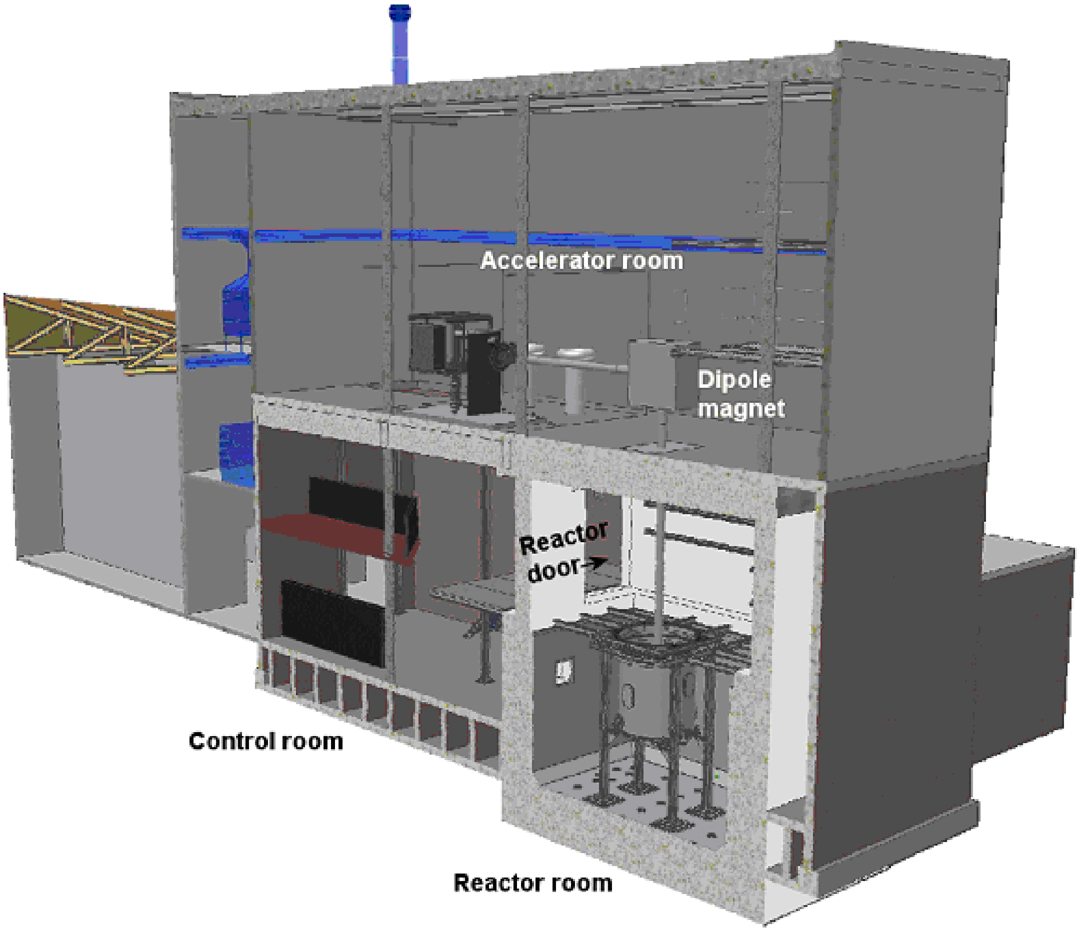

Figure1. General view of the CAD model of the GUINEVERE building containing the VENUS-F reactor.

The quality assurance of the MCNP5 models was done using the dosimetry measurement results obtained in previous experiments on the VENUS thermal light water core. It follows from the calculations that having the same 500 W of reactor power, the neutron dose in the control room is 3.0 - 4.5 times less in a fast core configuration than in the thermal one with which VENUS was operated before. However, the measured results were two times lower than the calculated ones in some detectors. This discrepancy was caused by differences between the models and the real experiment. Also, comparisons with results of MCNP5 calculations performed independently by FZD were done. The FZK results were about 10% higher than the FZD results. This can be attributed to differences in assumptions in the modeling.

It was realized that the neutron source from D-T fusion reactions on the tritium titanium (TiT) target inside the core causes doses in the control room one-two hundred times less than doses coming from the reactor operating at 500 W. That means the D-T source is negligible for the dose in the control room, and its contribution could add a a small amount to the dose on the accelerator room's floor. The effect of the parasitic D-D neutrons on the radiation environment in the GUINEVERE control room is negligible.

2 SHIELDING ANALYSES

The MCNP5 models were produced for the thermal VENUS and fast VENUS-F fission reactor cores based on the drawings of the GUINVERE building. Vertical and horizontal cuts of the MCNP5 models for the fast VENUS-F reactor are shown in Figures 2 and 3.

The dose rate results were normalized for 500 W of reactor power with the recent fast core design where number of source neutrons equaled 3.839934e13 n/s. This normalization was done for the absolute number of source neutrons with dependence on reactor power (P), average number of neutrons produced per fission (ν), recoverable energy per fission Q_{av}, and k_{eff} by the following Eq. (1):

$$\text{Norm\_fast\_factor\_500W} = \frac{\nu \cdot P}{(1.602 \cdot 10^{-13}\, J/MeV) \cdot k_{eff} \cdot Q_{av}} = 3.839934\text{e}13 \text{ n/s} \qquad (1)$$

Where: $P = 500$ W
$k_{eff} = 1.016$
$Q_{av} = 200$ MeV

The neutron and photon dose rate maps were produced using MCNP5 track-length estimations, point detectors, and a mesh tally superimposed over the GUINVERE geometry. Neutron dose rates were calculated using ICRP-74 flux-to-dose conversion factors with an ambient dose equivalent at 10 mm deep in human tissue. It was found that the total dose rate is dominated by the energy deposition from neutrons.

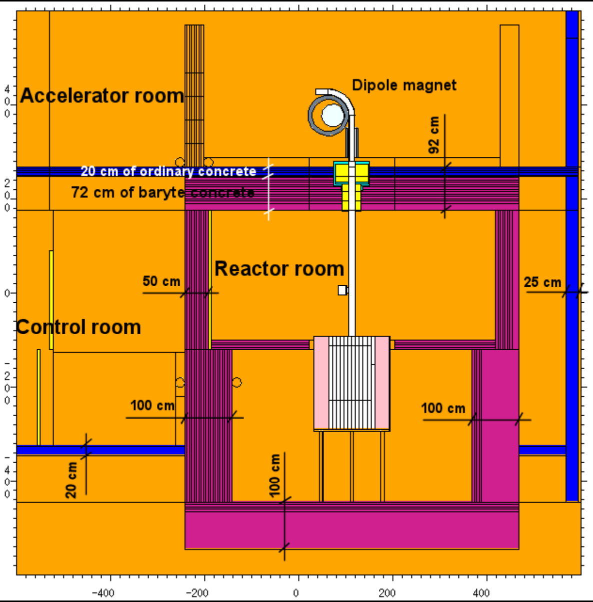

Figure 2. MCNP5 model: vertical cut through the GUINEVERE building with the fast core VENUS-F reactor. Wall thicknesses are depicted.

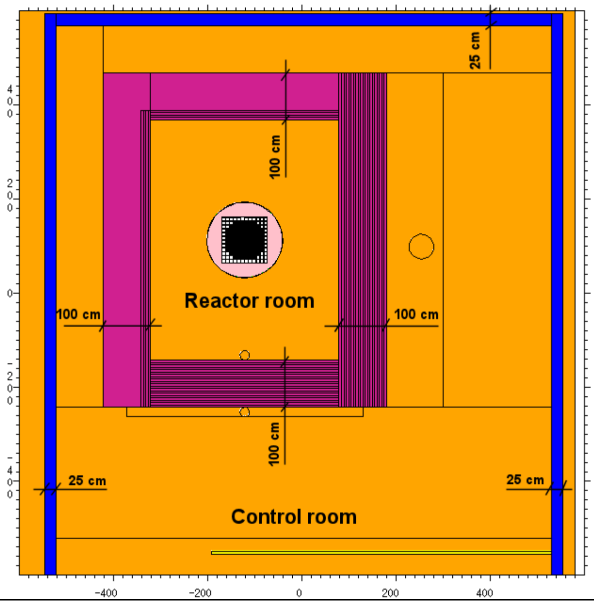

Figure 3. MCNP5 model: horizontal cut (at z = -70.4 cm) through the middle of the VENUS-F reactor inside the GUINEVERE building.

2.1 Radiation dose rates in the control room

The dose rate distributions were assessed in the GUINEVERE control room with the two types of the reactor cores: fast and thermal. For the both reactor types the results were normalised for 500 W of fission power. The dose rate was analysed behind the reactor room door by using a MCNP mesh tally, which was superimposed on the model geometry as plotted in Figures 4 and 5. The mesh-tally of neutron dose rate is presented in Figure 6. It was observed from the mesh tally maps that upper part of the room above the reactor was exposed to more radiation. The shielded reactor door nevertheless had some weakly protected areas, as shown in Figure 5, along the connecting edge between the door and wall. This results in asymmetry of the dose rate distribution behind the walls of the reactor room. Neutron dose at the top of the back side of the reactor door (see red spot in Figure 6) reaches 0.2 mSv/h normalized to 500 W of reactor power.

The resultant total dose rate maps for the control room are presented in Figures 7 and 8 for the vertical cut corresponding to X=-150 cm which was found to be the plane with the highest dose in the MCNP mesh-tally analysis. The thermal core produced total dose rate that was 5 times higher behind the door than the fast one. This difference is reduced to 3 times higher in case of thermal core than the fast one at the farther distances in the control room, compare the doses at the Z2 level and Y=6.8 m and Y=10 m in Figures 7 and 8.

In the thermal core the MOX fuel elements are longer than the uranium ones in the fast core, and a substantial part of the MOX rodlets protrude from the water of the reactor. Together with absence of reflector zones around the thermal core, these facts cause the higher neutron fields in the control room of the thermal reactor.

The radiation environment on the accelerator room's floor was also investigated. It has a hole for the deuterium beam propagation. The beam tube is shielded by the polyethylene (PE) plug, and above the hole the dipole magnet is situated which bends the D-ion beam from a horizontal direction to a vertical direction aimed toward the D-T target in the centre of the core. The dipole and plug arrangement is shown in Figure 9. The total (neutron and photon) dose rate (Sv/h) distribution on the accelerator room's floor is mapped in Figure 10.

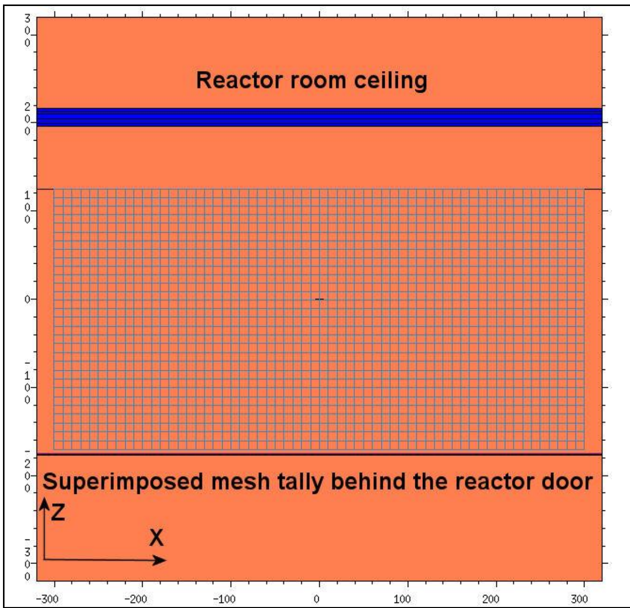

Figure 4: Mesh tally: XZ cut through Y= -410cm used for dose rate map behind the reactor door.

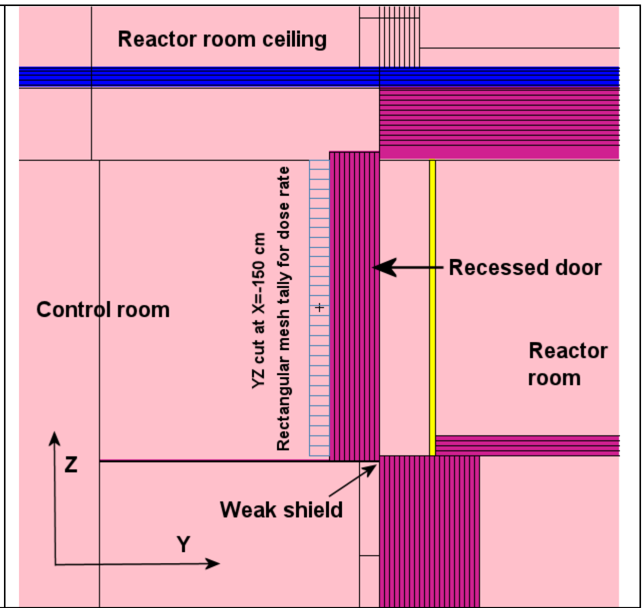

Figure 5: Mesh tally: YZ cut through X= -150cm used for dose rate map behind the reactor door.

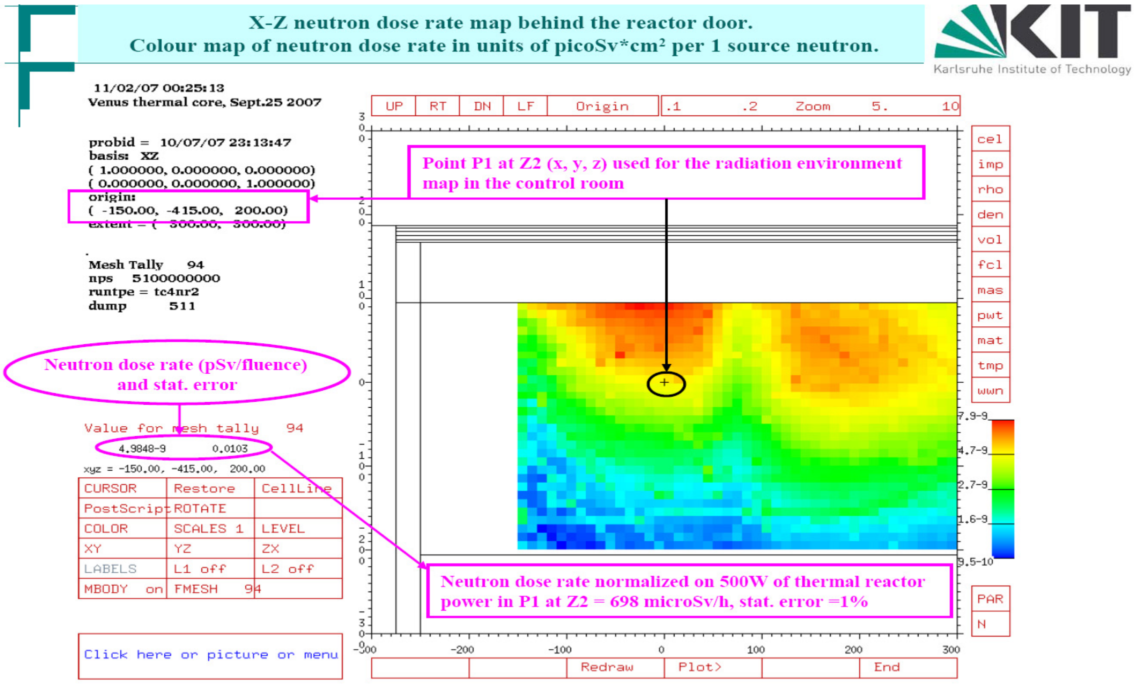

Figure 6: Neutron dose rate map behind the reactor door; variant of the VENUS thermal core.

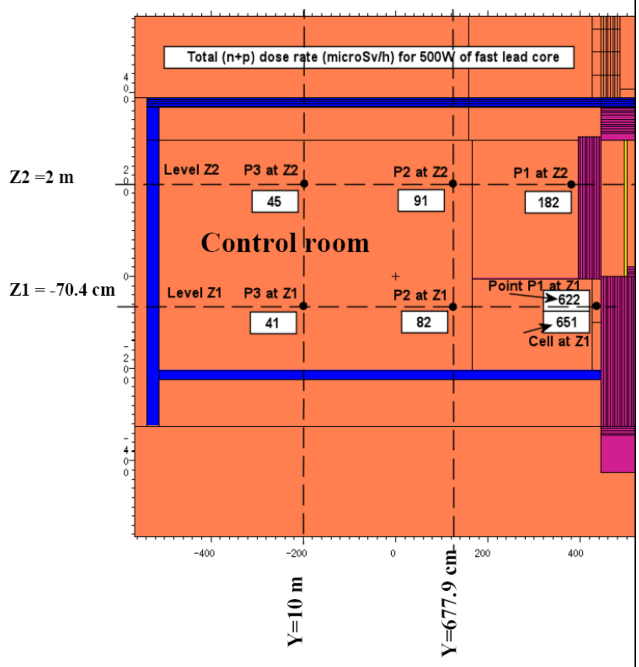

Figure 7: Total dose rate distribution in the control room of the fast core of the VENUS-F reactor.

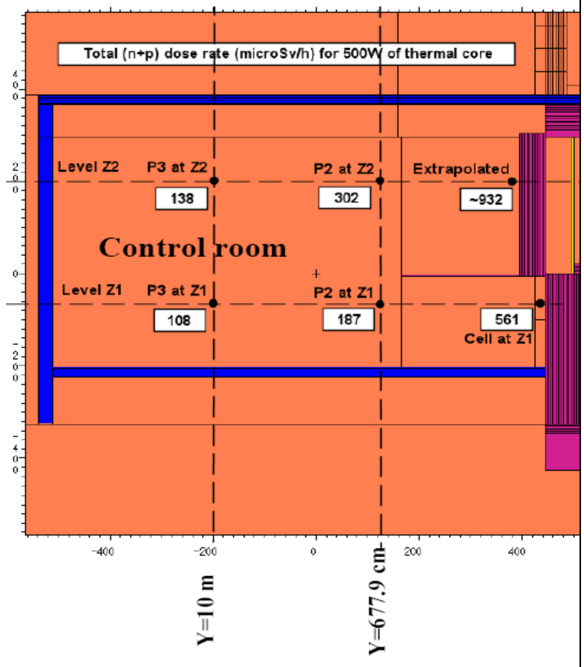

Figure 8: Total dose rate distribution in the control room of the thermal core of the VENUS reactor.

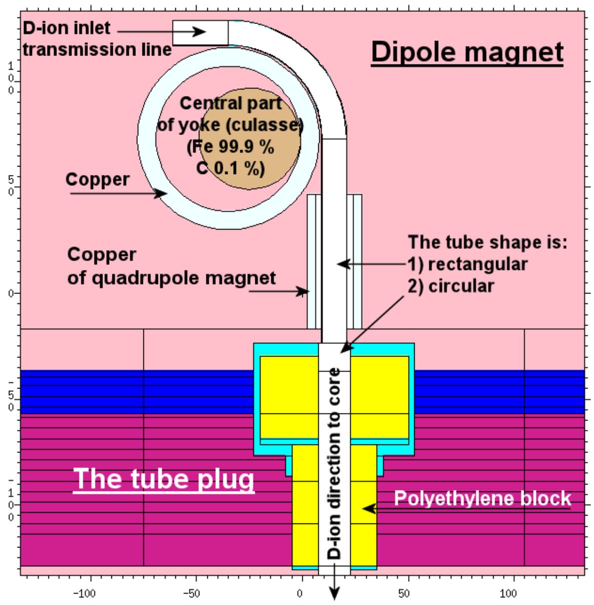	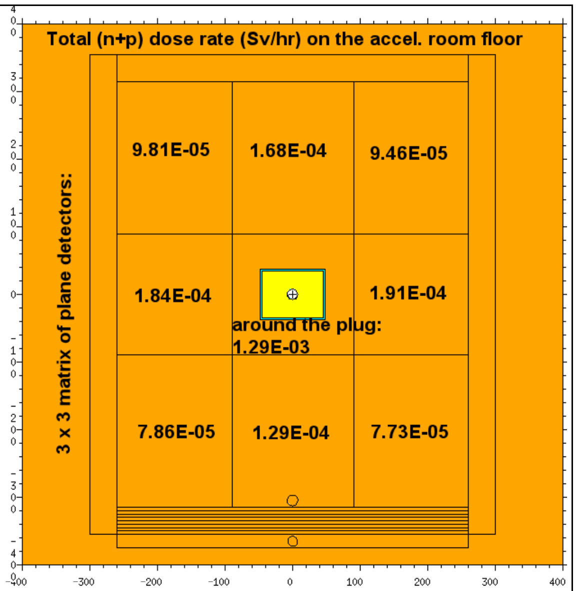
Figure 9: Dipole magnet configuration above the accelerator room's floor with the D-ion tube plugged around.	*Figure 10: Total (neutron and photon) dose rate (Sv/h) distribution on the accelerator room's floor.*

2.2 Dose rate contribution from the D-T neutron source

The contribution of neutrons coming from the D-T nuclear reactions occurring in the VENUS-F tritium titanium (TiT) target was estimated for the dose rate distributions on the accelerator room's floor and in the GUINEVERE control room. The estimations were done using MCNP5 radiation transport calculations with a point source emitting 14 MeV neutrons with an intensity of 5e10 n/s. The calculations were performed in the MCNP5 model of the GUINEVERE building presented in Figures 11 and 12 with the old type of fast lead core with a central void channel. The MCNP5 calculations were done using the "NONU" card, implying that no fission neutron is counted in the dose rates. Every other nuclear reaction causing neutron birth, like (n, 2n), was taken into account. The 14 MeV source point was located at the mid-plane of the central void channel of the VENUS-F lead core. The source position is also depicted in Figures 11 and 12.

The resultant total dose rate map on the accelerator room's floor is presented in Figure 13. The dose rate around the tube plug is 106 microSv/hr; in the peripheral cells of the 3x3 matrix the dose is ten times less, i.e. ~ 5-15 microSv/hr. Figure 14 displays the total dose rate in the control room induced by the D-T neutron source. The total dose rate behind the reactor door is (1.4 – 1.6) microSv/hr, and it falls to (0.2 – 0.4) microSv/hr in the control room.

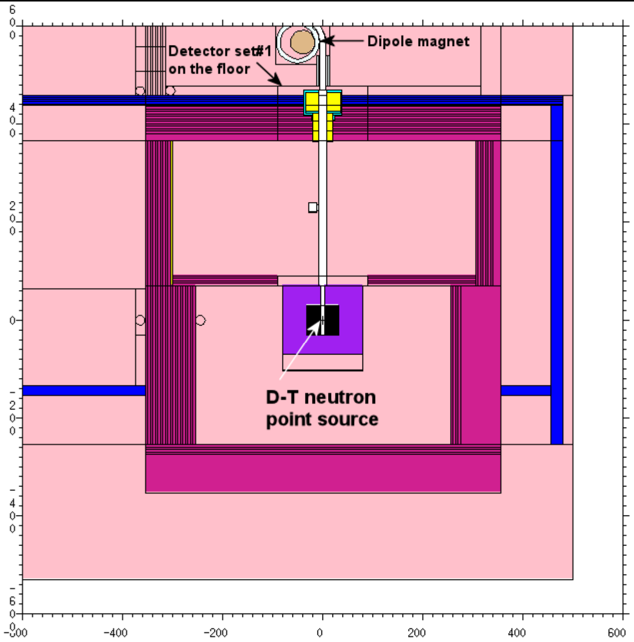

Figure 11: Vertical (Y-Z) cut through the GUINEVERE building with the D-T source of the TiT target in the middle plane (z = -70.4 cm) of the VENUS-F core.

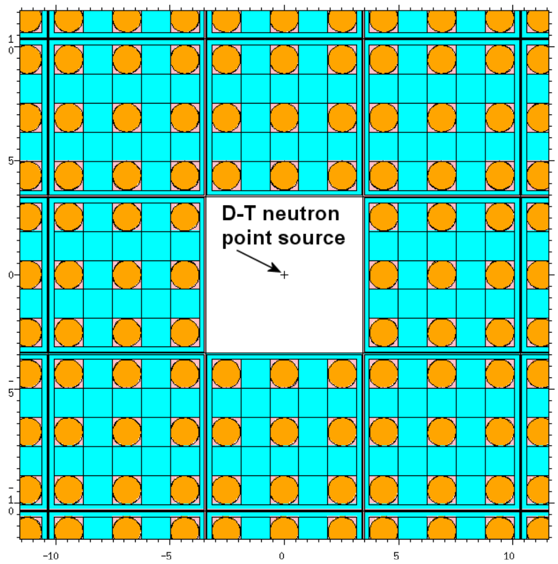

Figure 12: Horizontal X-Y cut through the middle of the VENUS-F core.

Analysis of the total dose rate on the accelerator room's floor in the cell around the tube plug indicates that the contribution from the D-T target source is ten times less than the dose induced by the VENUS-F operation at 500 W of the reactor power. Particularly, the total dose rate from the fission reactor power is 3.35e-3 Sv/h with the old-fast core model with a voided central channel, and 1.29e-3 Sv/h in the case of the new fast core without the central channel. The D-T source causes a dose rate of 1.06e-4 Sv/h in the same cell on the floor. The D-T source causes a dose rate in the control room one-two hundred lower than the doses coming from the reactor operation at 500 W power. This means the D-T source is negligible for the dose in the control room, and the contribution could add a small amount to dose on the accelerator room's floor.

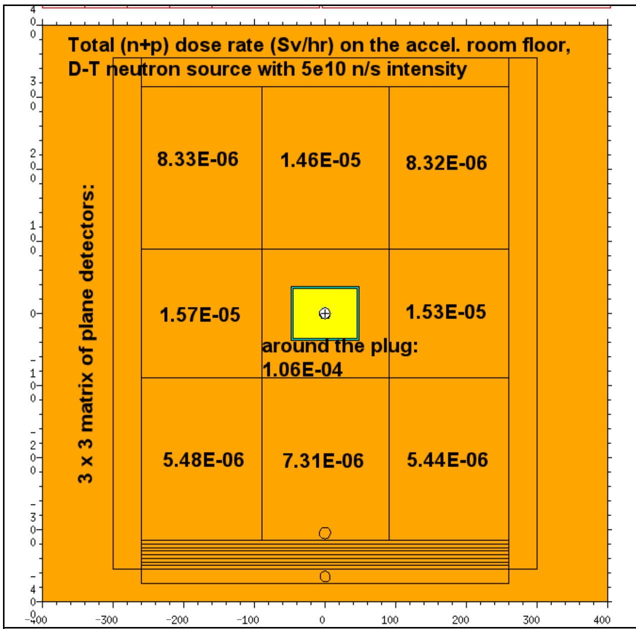

Figure 13: Total (neutron and photon) dose rate (Sv/h) on the accelerator room's floor caused by neutrons from D-T nuclear reactions in the VENUS-F reactor target.

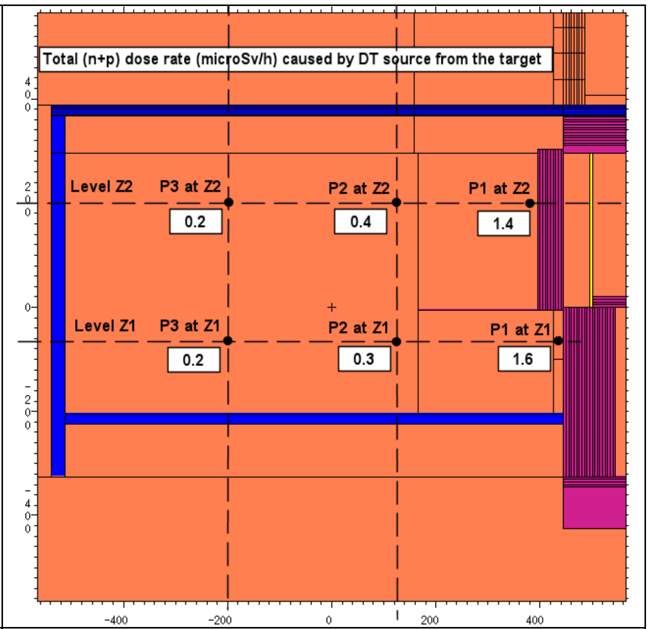

Figure 14: Total (neutron + photon) dose rate (microSv/h) in the GUINEVERE control room caused by a 5e10 n/s D-T neutron source from the reactor target.

2.3 Dose rate contribution from parasitic D-D neutron source

The influence of the parasitic D-D neutron source on the dose rate distributions on the accelerator room’s floor and in the GUINEVERE control room was estimated. The neutron emission is coming from the D-D nuclear fusion reaction at the bending place then the D-ion beam is curved by means of the dipole magnet system placed on the accelerator room’s floor, shown in Figures 15 and 16.

The estimations were done using MCNP5 radiation transport calculations with a point source emitting neutrons with 2.5 MeV energy and 1e5 n/s intensity. The calculations were performed in the GUINEVERE building presented in Figure 15. The spatial distribution of the neutrons coming from parasitic D-D nuclear reactions was modelled as a point source on the inner surface of the curved vacuum tube at the dipole magnet, depicted in Figure 16. The dipole magnet was surrounded by a polyethylene (PE) box with 5 cm thick walls. The D-D neutron source contribution to the total dose rate distribution on the accelerator room’s floor is presented in Figure 17. The doses are range from 0.1 to 0.2 microSv/h. The radiation environment in the control room caused by the parasitic D-D neutron source is depicted in Figure 18, and the total dose rates are range from 1e-4 to 3e-4 microSv/h.

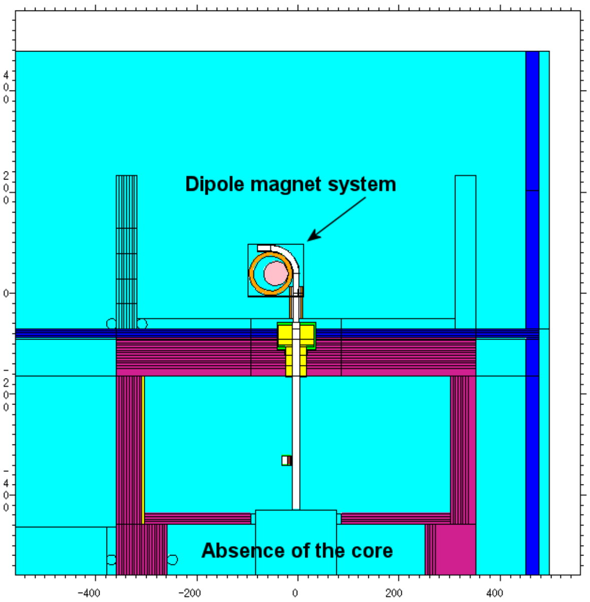

Figure 15: General view of the vertical Y-Z cut through the GUINEVERE building without the VENUS core.

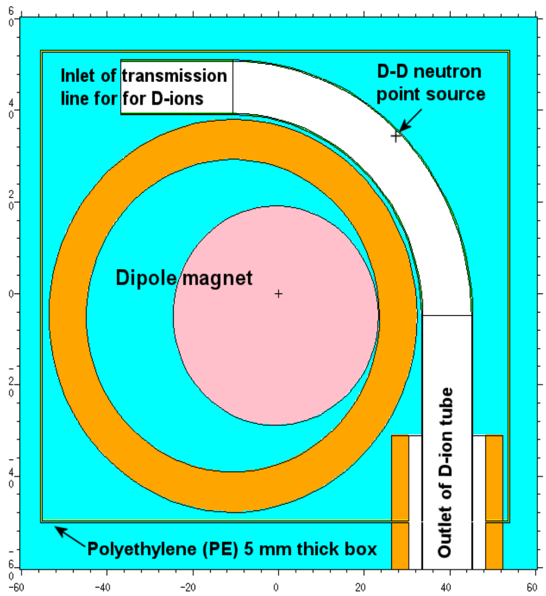

Figure 16: Enlarged view of the vertical Y-Z cut through the dipole magnet surrounded by the PE box with 5 mm thick walls.

The effect of the parasitic D-D neutrons on the radiation environment in the GUINEVERE control room is negligible; the total dose rate coming from the D-D source is 2e5 – 7e6 times less than the values from a configuration with the 500W fast lead core; that is enormous factor of difference. The contribution of the parasitic D-D nuclear reactions to the dose rate on the accelerator room's floor is also negligible, it is three orders of magnitude less than the operational dose.

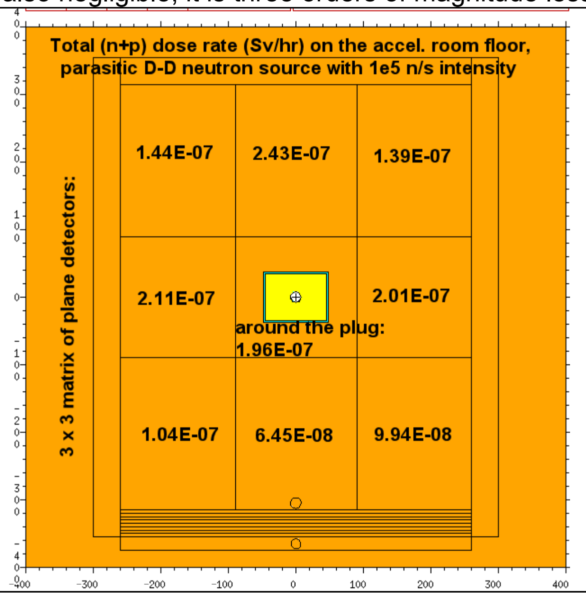

Figure 17: Total (neutron and photon) dose rate (Sv/h) on the accelerator room's floor.

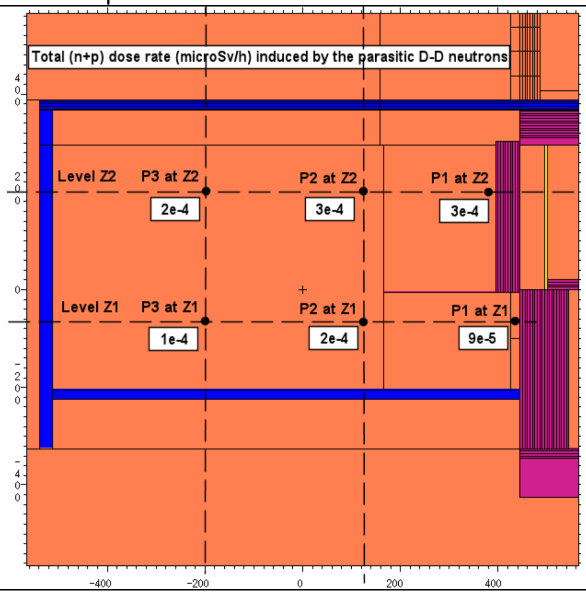

Figure 18: Total (neutron + photon) dose rates (microSv/h) in the GUINEVERE control room caused by a 1e5 n/s parasitic D-D neutron source.

3 ACTIVATION ANALYSES

The computational activation analyses were performed for various radioactive materials used in the components of the GUINEVERE building, including the concrete walls and the fast lead core. The analyses pertain to the problem of dismantling the building after completing the series of ADS experiments in the GUINEVERE project. The GUINEVERE campaign is supposed to span 20 years, in each year there are 1000 hours of operation and a the rest time of 7765.8 h. For a conservative analysis of the activation produced immediately after the reactor is shutdown, it is important that in the calculations the last year of 20 year campaign ends with 1000 hours of irradiation. Therefore a zero-cooling time goes immediately after the last 1000 hours of irradiation. The scenario includes a sequence of years with cooling (7765.8 h) and irradiating (1000 h) intervals, as it is depicted in Figure 19.

The activity density (Bq/kg) and shutdown contact dose rate were calculated for certain cooling times. The recent VENUS-F lead core configuration was used in the MCNP5 calculations of the neutron spectrums in the different GUINEVERE components. The results were normalized to 500 W fission power. The JEFF-3.1 nuclear data library was used in the MCNP5 transport calculations. The obtained neutron spectrums were supplied for the activation calculations done by the FISPACT-2005 inventory code which used cross-section data from the EAF-2005 European activation file.

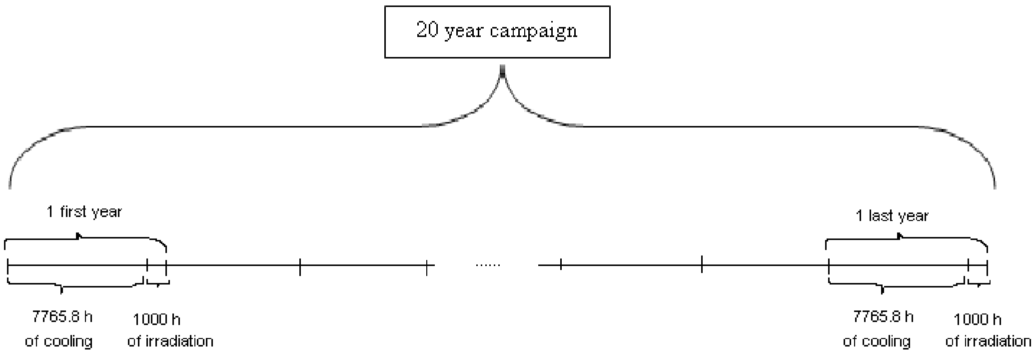

Figure 19: Irradiation scenario.

3.1 Radioactivity of the GUINEVERE components

The components considered in the analysis comprise the VENUS-F fast core, the concrete walls and ceiling. The fissile part of the core, named “fuel assembly”, consists of metallic uranium rodlets (see Position #1 of Figure 20) in a lead matrix (see cladded lead square bars in Position #4, and un- cladded lead bars in Position #5 in Figure 5). The lead is cladded by steel (shown in Position #3 in Figure 20). The fuel has a U235 mass content of 30%, and the fuel mass is 1.1 ton. The fuel is cylindrical and is 1.27 cm in diameter and 8 inches (20.32 cm) in length, and covered with nickel (Position #2 in Figure 20) that is about 70 microns thick. The lead is in square bars (1.27 x 1.27 cm) that are 4 inches in length (10.16 cm). The materials of the fissile assemblies are inserted inside a wrapper tube made of 304L steel, as well as large Pb blocks. The large Pb block claddings are shown in Position #7 in Figures 21 and 22. The fuel assemblies are surrounded by axial and radial reflectors made of lead. The radial-side reflector is shown in Position #8 in Figures 23 and 24. In this analysis there is no central channel for the D-T neutron generator. The whole core is filled by fuel assemblies and Pb blocks as shown in Figures 23 and 24. The core is arranged within a vessel 160 cm in inner diameter. The steel vessel cylinder is depicted in Position #9 in Figures 23 and 24. The activity density (Bq/kg) distributions have been calculated in all the core materials, as shown in Positions #1 - #9, and in the B4C control and safety rods. The results are presented in Tables 1 and 2. The parts of the concrete walls and ceiling, shown in Figure 25, were also used in activation analysis for the task of selecting appropriate waste management for the irradiated concrete. The activity distribution in depth of the reactor ceiling (see Figure 25) reveals the possibility to separate the final concrete waste in dependence on the remaining activity. The challenging task of waste management for the radioactive materials of the GUINEVERE components is still ongoing.

The most radioactive material in the fast core, accordingly to the results in Table 1, is the metallic uranium in Position #1 of the fuel rodlet. The fresh fuel consists of only two uranium isotopes: 30 wt.% of U235 and 70 wt.% of U238. During the reactor campaign the fuel accumulates fission by-products with α, β, and γ-emission. And after the discharge (“0” cooling time in Table 1) the spent fuel also includes other uranium isotopes, as well as plutonium, minor actinides, and fission products.

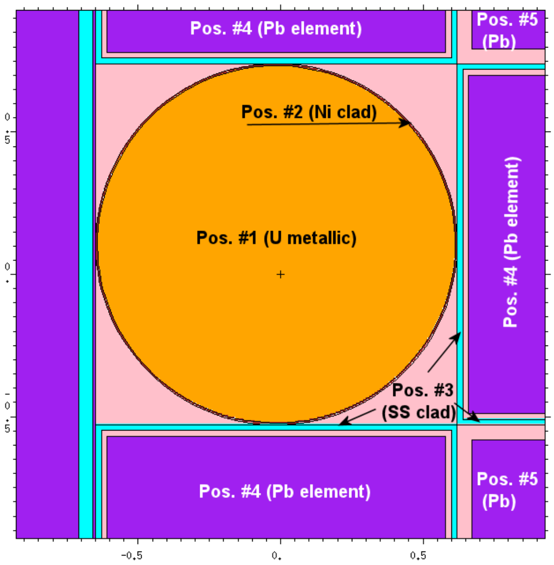

Figure 20: Metallic uranium fuel element.

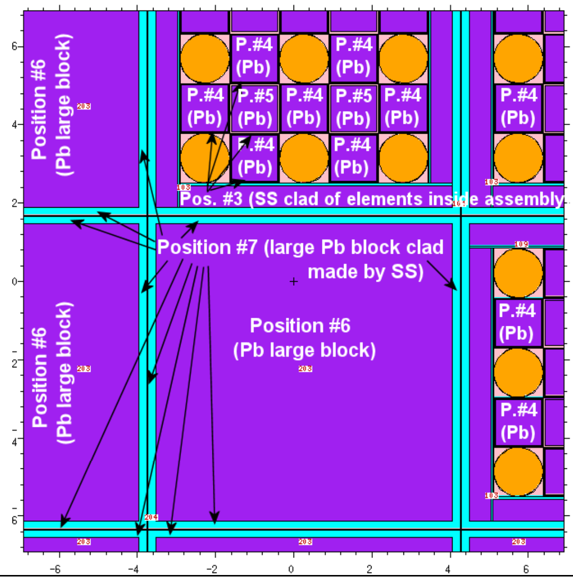

Figure 21: Close view of the fuel assemblies and Pb blocks.

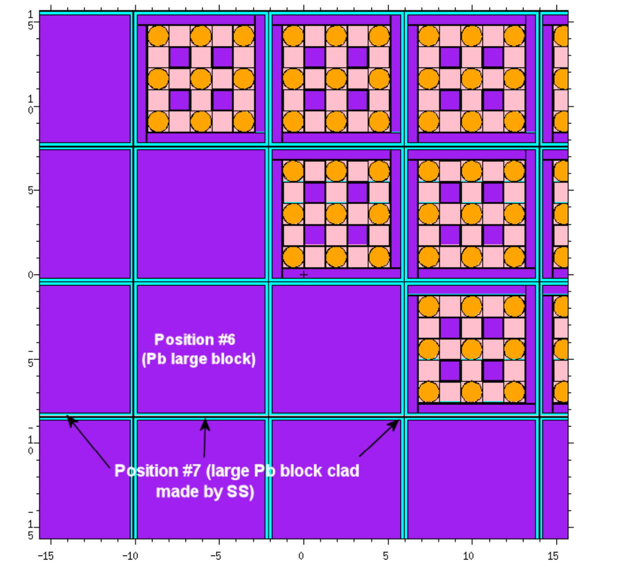

Figure 22: Distant view of the fuel assemblies and Pb blocks.

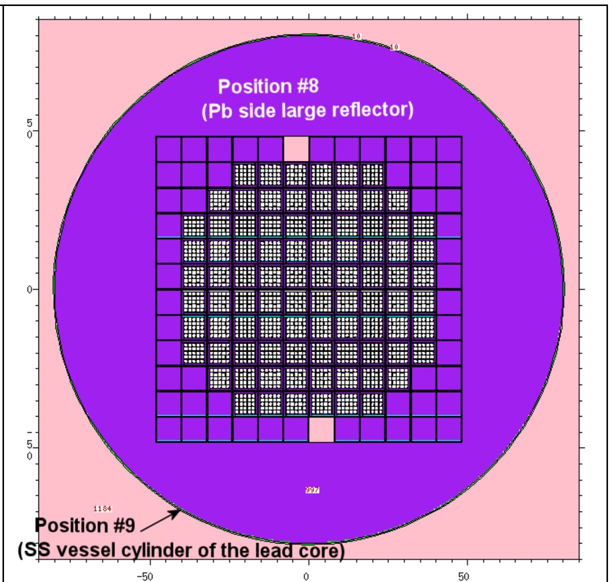

Figure 23: Distant view of the horizontal cut of the VENUS-F fast lead core.

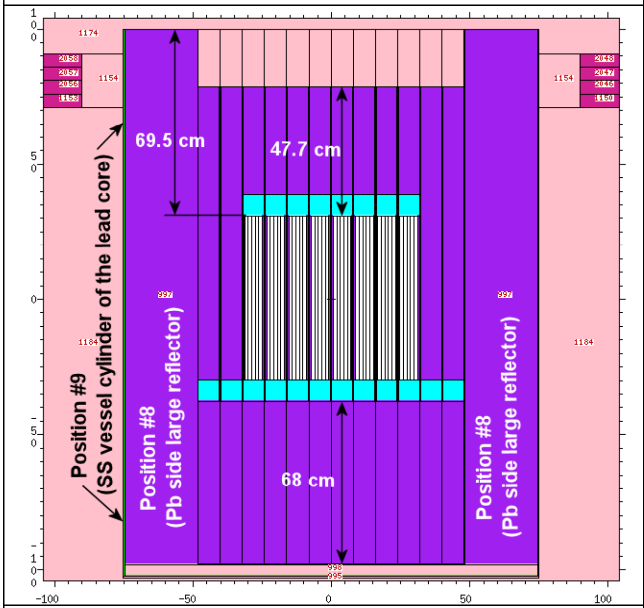

Figure 24: Vertical cut through the VENUS-F fast lead core.

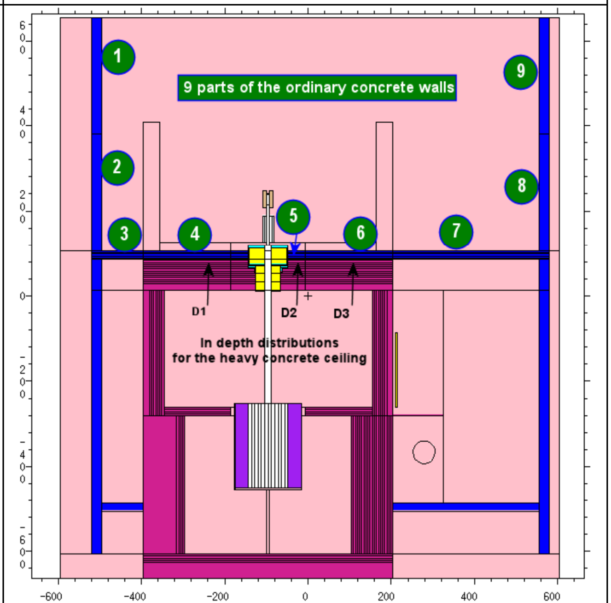

Figure 25: GUINEVERE parts of the concrete walls and ceiling used in activation analysis.

Table 1: Activity distributions in the fast lead core in Positions #1 - #6

Cooling time, years	Activity density in U metallic fuel (Pos.#1), Bq/kg	Activity density in nickel of fuel rodlet cladding (Position #2), Bq/kg	Activity density in SS clad (Position #3), Bq/kg	Activity density in Pb elements of cladded assembly (Position #4), Bq/kg	Activity density in Pb elements of un-cladded assembly (Position #5), Bq/kg	Activity density in large Pb block (Position #6), Bq/kg
0	8.35E+10	1.19E+09	1.85E+08	1.47E+08	1.47E+08	3.95E+07
1	3.72E+08	1.46E+08	2.30E+07	2.22E+05	2.25E+05	1.57E+05
3	2.39E+08	8.17E+07	1.20E+07	2.65E+04	2.68E+04	1.45E+04
5	2.10E+08	4.96E+07	6.99E+06	6.36E+03	6.39E+03	2.19E+03
10	1.85E+08	1.45E+07	1.99E+06	3.30E+03	3.30E+03	4.10E+02

Table 2: Activity distributions in the fast lead core in Positions #7 - #9 and the B4C control and safety rods, (continuation of Table 1)

Cooling time, years	Activity density in SS clad of large Pb blocks (Position #7), Bq/kg	Activity density in Pb side reflector (Position #8), Bq/kg	Activity density in SS vessel cylinder of the core (Position #9), Bq/kg	Activity density in B4C control rod, Bq/kg	Activity density in B4C safety rod, Bq/kg
0	9.72E+07	1.68E+07	4.81E+07	3.54E+04	2.51E+04
1	1.04E+07	7.55E+04	4.10E+06	3.35E+04	2.38E+04
3	6.09E+06	5.81E+03	2.50E+06	2.99E+04	2.12E+04
5	3.67E+06	7.71E+02	1.53E+06	2.67E+04	1.90E+04
10	1.08E+06	4.97E+01	4.79E+05	2.02E+04	1.43E+04

3.2 Activation and pathway analyses for the two variants of lead composition

In a first step of the activation analyses, a “guessed” composition of the fast core lead was used in the MCNP and FISPACT calculations. In order to realize the actual composition of lead, the composition was analysed by the company Ecometal AS, Estonia, which provided us with the specification of chemical elements in the lead. The lists of chemical elements for both “guessed” and certified leads are presented in Table 3. It was found that the certified lead is cleaner than was anticipated. The content of zinc and antimony in the certified composition was less than in the “guessed” by the three orders of magnitude. The copper in the certified lead was two times less. The difference in the amount of trace elements, caused the activity levels presented in Table 4 for both lead compositions, results in difference of the lead activities by a maximum factor of 44, occurring after 1 year of cooling time. The reason for the differences is explained by the results of the dedicated pathway analysis for the generation of the dominant radioisotopes in the both grades of the lead, the results of which are summarized in Table 5. In Table 4 five dominant radio nuclides are listed for certain times after the VENUS-F reactor shutdown. These times were set up by SCK•CEN as relevant for waste management concerns. For this concern the most important isotopes are the long-lived radioisotopes such as Zn65, Ag110m and Ni63, which have half-lives ($T_{1/2}$) presented in Table 6. The isotope with the longest half-life is Ni63. It is generated from copper in both lead grades by the Cu63 (n,p) Ni63 nuclear reaction. The short lived isotope Sb122 ($T_{1/2}$ = 2.8 days) would be important immediately after shutdown if antimony were to exist in the lead in a noticeable quantity, as predicted by the analysis of the “guessed” lead composition. It could be produced by a neutron capture reaction directly from Sb121, or through the isomeric transition (IT) to the ground state of Sb122.

Referring to Table 4, in the guessed lead the primary source of radioactivity in the period of 1 – 5 years after shutdown is zinc, in the initial amount of 0.2 wg.%, with the activity A1 from 4.5723E+04 to 7.2373E+02 Bq/kg. In the same period of time the certified lead composition demonstrates activity A2 from 1.4252E+03 to 2.4728E+01 Bq/kg which is coming from the decay of Ag110m, which has a half-life of ~250 days. This isotope is generated by the nuclear reaction Ag109 (n,g) Ag110m in silver which is 0.0024 wt.% of the certified chemical composition. The factor of total activities, F_t=A1/A2, presented in Table 4, is in the range of 44 – 10, meaning that the certified lead composition produces F_t times less activity than the “guessed” lead. The pathway analysis, the results of which are presented in Table 5, showed that the activity in the irradiated lead can be reduced by separating out the undesirable silver content.

Table 3: Initial chemical composition of the lead used in the MCNP model of the fast core

Chemical element name	Element Symbol	“Guessed” lead composition, wt.%	Certified lead composition, wt.%
Copper	Cu	0.1	0.043
Antimony	Sb	0.2	0.0001
Bismuth	Bi	-	0.0136
Silver	Ag	-	0.0024
Tin	Sn	-	0.0005
Zinc	Zn	0.2	0.0002
Arsenic	As	-	0.0001
Selenium	Se	-	0.0003
Sulphur	S	-	0.0001
Cadmium	Cd	-	0.0001
Nickel	Ni	-	0.0001
Tellurium	Te	-	0.0005
Gold	Au	-	0.0001
Iron	Fe	-	0.0001
Aluminium	Al	-	0.00005
Lead	Pb	99.5	99.940

Table 4: Activity densities for the lead with "guessed" and certified compositions irradiated by the VENUS-F spectrum in the side reflector (Position #8 in Figures 23 and 24)

Time after reactor shutdown	Factor of total activity (F_t=A1/A2)	"Guessed" lead composition in the side reflector			Certified lead composition in the side reflector		
		Nuclide	Activity, A1 (Bq/kg)	Percent of activity	Nuclide	Activity, A2 (Bq/kg)	Percent of activity
0 cooling time	4.6	Total	1.6825E+07		Total	3.6200E+06	
		Sb122	9.9838E+06	59.34E+00	Pb207m	1.2163E+06	33.60E+00
		Sb124	1.9847E+06	11.80E+00	Pb209	1.1590E+06	32.02E+00
		Pb207m	1.2110E+06	71.97E-01	Ag110	4.7254E+05	13.05E+00
		Pb209	1.1539E+06	68.58E-01	Cu 64	4.6197E+05	12.76E+00
		Cu 64	1.0784E+06	64.09E-01	Ag108	1.2738E+05	35.19E-01
1 year cooling time	43.9	Total	7.5454E+04		Total	1.7171E+03	
		Zn 65	4.5723E+04	60.60E+00	Ag110m	1.4252E+03	83.00E+00
		Sb124	2.9681E+04	39.34E+00	Po210	8.7971E+01	51.23E-01
		Ni 63	4.7635E+01	63.13E-03	Zn 65	4.5723E+01	26.63E-01
		Co 60	1.3063E+00	17.31E-04	Fe 55	4.2043E+01	24.48E-01
		Pb205	4.7302E-01	62.69E-05	Se 75	2.5367E+01	14.77E-01
3 years cooling time	21.8	Total	5.8076E+03		Total	2.6604E+02	
		Zn 65	5.7525E+03	99.05E+00	Ag110m	1.8773E+02	70.57E+00
		Ni 63	4.6972E+01	80.88E-02	Fe 55	2.5326E+01	95.20E-01
		Sb124	6.6382E+00	11.43E-02	Ni 63	2.0640E+01	77.58E-01
		Co 60	1.0042E+00	17.29E-03	Sb125	7.7828E+00	29.25E-01
		Pb205	4.7302E-01	81.45E-04	Cd113m	5.8261E+00	21.90E-01
5 years cooling time	9.7	Total	7.7130E+02		Total	7.9136E+01	
		Zn 65	7.2373E+02	93.83E+00	Ag110m	2.4728E+01	31.25E+00
		Ni 63	4.6319E+01	60.05E-01	Ni 63	2.0353E+01	25.72E+00
		Co 60	7.7202E-01	10.01E-02	Fe 55	1.5256E+01	19.28E+00
		Pb205	4.7302E-01	61.33E-03	Ag108m	5.4202E+00	68.49E-01
		Pb204	6.3519E-03	82.35E-05	Cd113m	5.2654E+00	66.54E-01
10 years cooling time	1.4	Total	4.9668E+01		Total	3.6054E+01	
		Ni 63	4.4726E+01	90.05E+00	Ni 63	1.9653E+01	54.51E+00
		Zn 65	4.0633E+00	81.81E-01	Ag108m	5.3754E+00	14.91E+00
		Pb205	4.7302E-01	95.23E-02	Fe 55	4.2968E+00	11.92E+00
		Co 60	4.0005E-01	80.54E-02	Cd113m	4.0886E+00	11.34E+00
		Pb204	6.3519E-03	12.79E-03	Sb125	1.3408E+00	37.19E-01

Table 5: Pathway for the generation of the first dominant radionuclides

Time after reactor shutdown, years	"Guessed" lead composition in the side reflector	Certified lead composition in the side reflector
0	Sb121 (n,g) Sb122 = 93.6% of Sb122 Sb121 (n,g) Sb122m(IT) Sb122 = 93.6% Sb122	Pb206 (n,g) Pb207m = 16% of Pb207m Pb207 (n,n') Pb207m = 84% of Pb207m
1	Zn64 (n,g) Zn65 = 100% of Zn65	Ag109 (n,g) Ag110m 100% of Ag110m
3	Zn64 (n,g) Zn65 = 100% of Zn65	Ag109 (n,g) Ag110m 100% of Ag110m
5	Zn64 (n,g) Zn65 = 100% of Zn65	Ag109 (n,g) Ag110m 100% of Ag110m
10	Cu63 (n,p) Ni63 = 100% of Ni63	Cu63 (n,p) Ni63 = 100% of Ni63

Table 6: Half-lives of the first dominant radionuclides

Time after reactor shutdown, years	"Guessed" lead composition in the side reflector		Certified lead composition in the side reflector	
	Radionuclide	Half-life, $T_{1/2}$	Radionuclide	Half-life, $T_{1/2}$
0	Sb122	2.8 days	Pb207m	0.8 seconds
1	Zn65	243.9 days	Ag110m	249.9 days
3	Zn65	243.9 days	Ag110m	249.9 days
5	Zn65	243.9 days	Ag110m	249.9 days
10	Ni63	96 years	Ni63	96 years

3.3 Estimation of the shutdown dose from the uranium fuel

The contact dose rate from the gamma-ray emission from the VENUS-F metallic uranium fuel after the reactor campaign was estimated by the FISPACT-2005 code using the EAF-2005 activation library. The approximation of a semi-infinite slab was used in the contact dose calculations, the results of which are presented in Table 7.

Table 7: Contact dose rate from the metallic U fuel discharged from VENUS-F

Cooling time, years	Contact dose rate, Sv/h
0	1.59E+01
1	5.33E-03
3	2.74E-03
5	2.53E-03
10	2.24E-03

The method of a semi-infinite slab is a conservative approximation for the contact dose calculations and is widely used in activation analyses. The measured gamma-dose could be less than was calculated here, because in reality the geometry effects will prevent some gamma-quanta from contributing to the dose. Of course, assuming if there are no other intensive sources exist nearby. The neutron spectrum, which was used in the shutdown dose rate estimation, was calculated as the average of all the rodlets in the VENUS-F core. Hence, the contact dose rate is related to the averaged value for all the uranium rodlets in the core.

4 CONCLUSIONS

The FZK organization provides support within the framework of the safety analysis and the core design of GUINEVERE. It was observed from the mesh tally maps that higher part of the room above the reactor is subjected to stronger radiation. The hottest spot of the neutron dose rate mapped behind the reactor door is located above Z=2 m from the core top, with maximum at X ~ -150 cm, hence the radiation environment in the control room was investigated at the plane of X = -150 cm.

The radiation environment comparison between the fast and thermal cores operated at 500W indicates that behind the door the thermal core produced a total dose rate of 1 mSv/h, which is 5 times higher than that produced by the fast core. The difference is reduced to 3 times higher at the farther distance deep in the control room, at Z=2 m and Y=6.8 m and Y=10 m. The higher radiation field around the thermal VENUS reactor is explained by the absence of radial and axial lead reflectors in the vessel and by the longer MOX fuel rodlets emerging from the water pool. The experience of the successful maintenance of the water-moderated VENUS thermal core gives safety margins for the operation of the VENUS-F fast lead reactor in less radioactive environment. The total dose rate in depth of the VENUS-F control room (Z=2 m, Y=10 m) is 45 microSv/h. It was decided to erect an additional concrete wall in the control room which will serve several purposes: additional support for the building roof, additional radiation shielding, and accidental fire spreading prevention. Such a wall will reduce the dose rate in the control room by a factor of few, the exact factor could be found after the final arrangement of the wall.

Thus, the exposure of personnel in the control room satisfies the SCK•CEN radiological regulations as predicated by the shielding analysis performed here.

The activation analyses concluded that the actual lead composition was purer than originally anticipated. The pathway analyses demonstrated that the radioactivity in the certified lead is caused by a few trace parent elements, particularly Ag and Cu, on which the long-lived isotopes of Ag110m and Ni63 are formed. Therefore, one way of minimizing the total radioactivity of nuclear waste is to reduce the content of the parent elements.

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