Radiation Protection Aspects of the SPES Project at LNL

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Abstract. The SPES (Selective Production of Exotic Species) project will be built at the National Laboratories in Legnaro (Italy) of the National Institute of Nuclear Physics (INFN). Its goal will be the development of radioactive ion beams and the consequent re-acceleration with the existing linac to perform forefront research in nuclear physics. Radiation protection aspects are being considered at every stage of the project, e.g. civil construction planning, control system design and special technological plants. These aspects have been studied with the Monte Carlo transport code FLUKA and are presented in this paper.

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INTRODUCTION

The objective of the SPES project (see the layout in Fig. 1) is to produce radioactive neutron rich beams to be used in fundamental nuclear physics. The Radioactive Ion Beams (RIB) will be obtained by the proton induced fission on a uranium carbide target.

For the production of the primary proton beam, a proton cyclotron will be used to provide a beam in the energy range from 40 to 70 MeV and a current up to 750 μA. The proton beam will induce fission on a uranium carbide (UC_2) target at an expected rate of 10^{13} fissions per second [1]. All of the shielding aspects of the facility have been investigated with particular attention to the target hall. This study includes some preliminary considerations concerning the decommissioning of the facility and the dismantling of the shielding walls.

The activation of the materials interacting with the primary beam, as well as the dose rates in closed volumes, has been studied in order to plan maintenance activities and emergency access. Some evaluations have been made for the levels of radioactivity from activated air released to the environment, taking into account the recommendations of the Italian legislation. All of the calculations have been performed with the Monte Carlo code FLUKA [2,3].

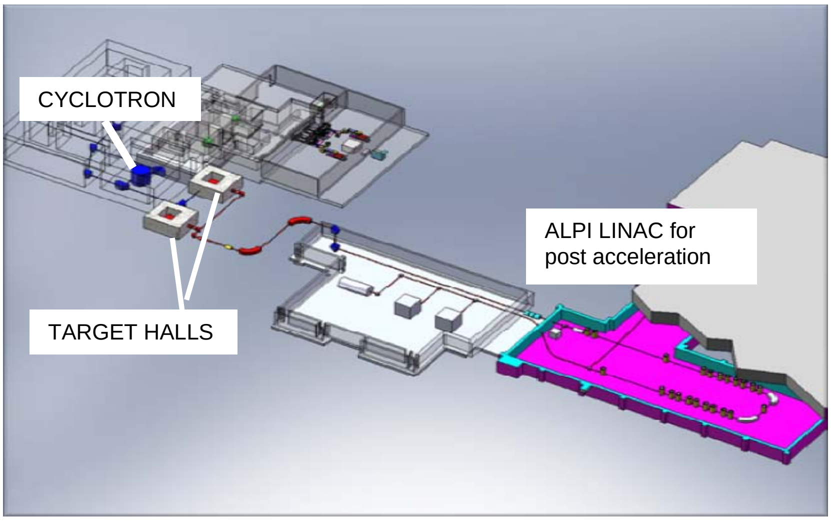

FIGURE 1. SPES layout: the ALPI linac already exists while the cyclotron vault and the target halls have to be built yet.

Shielding of the Target Hall

Two project dose constraints have been set for the shielding studies: 5 μSv/h for controlled classified areas and 0.3 μSv/h for non-classified areas. The source term for the shielding simulation is a proton beam of energy 70 MeV and current 300 μA impinging on 30 g of uranium carbide, and the irradiation period is 2 weeks (nominal shift time). The neutrons generated in the interaction of the beam with the target have an energy spectrum ranging from thermal energies to 60 MeV, peaking at 1-2 MeV. Thermal neutrons are produced through interactions with the air molecules in the target hall.

The neutron spectrum is attenuated in concrete, as shown in Fig. 2. Fast neutrons are slowed down more rapidly in the first 50 cm, with the consequence that the thermal group is enriched in the same layer. In layers deeper than 50 cm, the fast spectrum and the thermal one decrease exponentially with the same slope, as shown on the right in Fig. 2.

Figure 3 shows that the ambient dose equivalent due to neutrons during the irradiation at a distance of 1 m from the target is 10^{10} μSv/h. The attenuation that can be achieved with a 360 cm thick wall in the forward direction is a factor of 10^{8}. Considering that the target is 2 m from the wall, the ambient dose equivalent at 0° angle outside of the shielding is 10 μSv/h. During irradiation, access to the halls adjacent to the target room is prohibited.

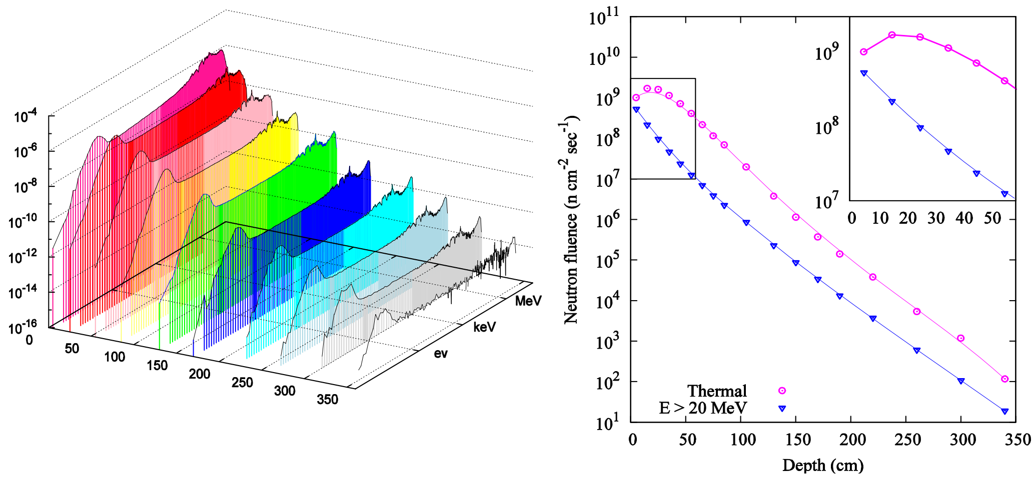

FIGURE 2. Left: neutron energy spectrum as a function of depth in concrete (n/cm^2/proton on target). Right: thermal (E <1 eV) and high energy neutrons (E >20 MeV) as a function of depth in concrete.

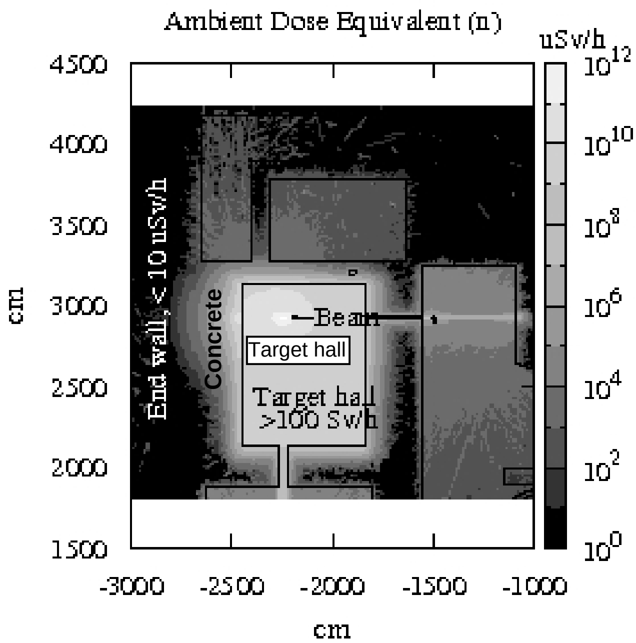

FIGURE 3. Ambient dose equivalent rate (μSv/h) due to neutrons in the target hall and adjacent rooms. The z axis represents the direction of the beam (from the right to the left) and the x axis represents the RIB extraction direction

The roof and the floor of the target room are 300 cm thick. This guarantees that the ambient dose equivalent rate is less than 5 μSv/h both outside of the roof where personnel access is prohibited during target irradiation, and in the ground below the floor, as shown in Fig. 4.

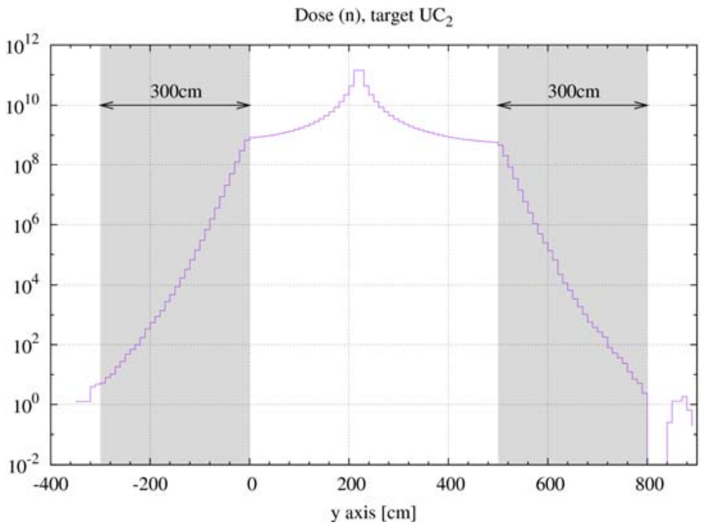

FIGURE 4. Ambient dose equivalent rate (μSv/h) due to neutrons in the vertical direction (roof and floor areas are highlighted).

Since the first phase of the SPES project will use conventional, non-fissionable targets, some evaluations for the shielding in this configuration have been done. In addition to the standard concrete wall, the shielding capability of other materials has been investigated. In particular, a sandwich-like composition has been studied with concrete as the container and gypsum (hydrated calcium sulfate, no impurities included) as the filling, with the results shown in figure 5. This structure has proven to be very effective in terms of neutron attenuation, due to the high hydrogen content in the gypsum composition; another advantage concerns the low activation after long irradiation periods. Nevertheless its use is quite impractical in view of the dismantling: being very dry and dusty, it could be easily spread and dispersed during demolition. The other option was a ferrous filling available as blast furnace waste, with a composition as given in Table 1. This content has a lower shielding efficiency and it would become more activated than concrete alone because of the metallic filling components.

TABLE 1: Sample composition of the blast furnace waste used to fill the sandwich-like shielding structure.

Compound	Partial density
CaO	26%
Fe	26%
Na_2O	45%
SiO_2	13%
Al_2O_3	6%
MgO	5%
Cr_2O_3	2%
MnO_2	0.6%
As, Cd, Co, Cu, Hg, Mb, Ni, Pb, V, Zn	<0.1%

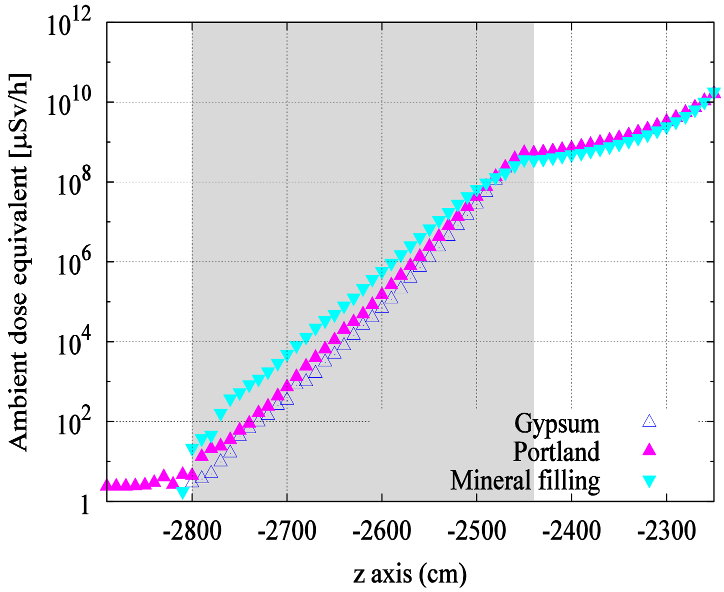

FIGURE 5. Comparison of the attenuation efficiency of concrete and sandwich-like structure with gypsum or blast furnace waste as filling. The irradiated target is made of SiC. The z axis represents the direction of the secondary particles (mainly neutrons) coming from the interaction of the proton beam with the uranium carbide target (from the right to the left). The white background in the picture indicates air while the grey background indicates the wall.

ACTIVATION SOURCES AND RELATED DOSES

Target

The irradiation of the UC_2 target with a 40 MeV proton beam at a beam current 200 μA will be done in 2 week cycles. The activity built up in the target at the end of one irradiation cycle will be 10^{14} Bq, with only 0.4% of the total activity due to nuclides with half lives longer than 1 month.

The ambient dose equivalent at 1 m distance from the target at the end of the irradiation cycle will be 9.8 $Sv{\cdot}m^2/h$, after one year of cooling time it will still be higher than 1 $mSv{\cdot}m^2/h$. These numbers serve as an indication of the high level of activation of the target and suggest that remote handling of the spent target is needed to move it from the irradiation hall to the dedicated repository outside. The exposure of personnel to the residual dose rate from the fixed aluminum target mounting structure during maintenance also has to be considered: at the end of the irradiation cycle the dose at 1 m is 0.7 Sv m^2/h and after 10 days of cooling time is 2.7 $mSv{\cdot}m^2/h$.

Cyclotron

The activation of the cyclotron structure has been evaluated: the protons lost during acceleration and extraction of the beam constitute the source term of the simulation, with an energy and current distribution specified in Table 2.

TABLE 2: Energy and current of the protons lost during acceleration and extraction in the cyclotron.

Energy [MeV]	Current
30	22.5 μA
40	22.5 μA
50	11.25 μA
60	11.25 μA
70	45 μA

At the end of an irradiation cycle (2 weeks), the residual dose in the cyclotron vault is less than 10 μSv/h at the distance of approximately 5 m after 10 days of cooling time: however, in the vicinity of the extraction point, which is considered to be the point of impact of the proton beam with the cyclotron's aluminum vacuum housing, the dose rate is 1 mSv/h. Long maintenance interventions must be preauthorized, planned and clocked in order to avoid excessive exposure to the operators.

Considering an irradiation period as long as 1 year, taking the buildup of residuals into account and 10 days of cooling time, it has been predicted that the dose rate in the cyclotron vault at distances up to 5 m from the casemate is on the order of 100 μSv/h, and close to the extraction point can reach 10 mSv/h. These doses are mainly due to the activation of the aluminum intercepting protons and the activation of aluminum and copper by secondary neutrons. The important residuals and their half lives are listed in Table 3.

TABLE 3: Residual nuclei and half lives in the cyclotron components.

Residuals from protons on Al	
Al-26	7.4×10^5 a
Na-24	14.96 h
Na-22	2.6 a
Be-7	53.29 d
Residuals from neutrons on Cu	
Zn-65	244.26 d
Cu-64	12.7 h
Co-60	1925.1 d
Fe-59	44.5 d
Co-58	70.82 d
Co-57	271.79 d
Co-56	77.27 d
Mn-54	312.12 d

Airborne Activity

The airborne activity has been evaluated in a 2-step approach: the particle fluence has been scored with FLUKA simulations and then folded with the cross sections for the production of the main radioactive nuclides in air [4,5].

Through the equation for the calculation of activation in the presence of a ventilation system, the amount of radioactivity released from operations with both fissionable (UC_2) and conventional (SiC) targets has been evaluated. According to the Italian law [6], the release to the environment of radioactive substances with certain characteristics must be authorized: in particular for those radioisotopes whose half life is shorter than 75 days, it must be guaranteed that the activity concentration is below 1 Bq/g in order to release it freely to the environment. For radioisotopes with half lives longer than 75 days, no authorization is required if the total effective dose equivalent to the public (TEDE) is below 10 μSv/a (this dose is considered to not to be relevant from a radiological point of view).

The equation used to calculate the activity exhausted in presence of ventilation is:

$$RA(t) = PR\lambda / (R + \lambda) \times (1 - e^{(-t(\lambda + R)}) ,$$

where P is the production rate (atoms/cm^3/s), λ is the decay constant (s^{-1}), R is the ventilation rate (s^{-1}) and t is the irradiation period (s). The ventilation rate is 50 m^3 per hour (the volume of the target room is 300 m^3) and it is supposed to compensate for the leaks of air from the door gaps or from the cables passages

These data have been used to give an estimate of the dose to the public due to inhalation of the radioactive gases and submersion in the exhausted plume (Total Effective Dose Equivalent). The TEDE has been calculated using the Hotspot code, using the recent ICRP coefficients for dose-activity conversion [7].

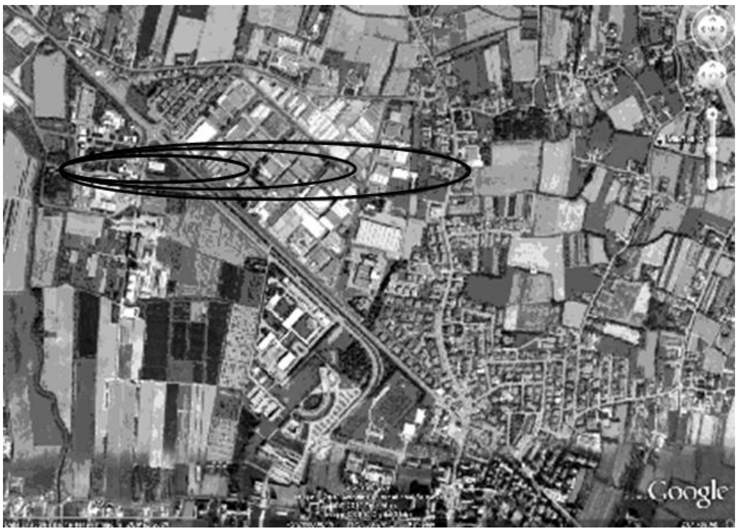

FIGURE 6. Realistic map of the SPES installation and release point. The contour curves give the dose received annually by the public: internal contour level (up to 600 m from the stack) more than 0.04 μSv, with a maximum at 30 m from the stack of 4.0 μSv; middle (up to 1 km from the stack) between 0.04 and 0.01 μSv, external (up to 1.5 km) between 0.01 and 2.5 10^{-3} μSv.

The annual activity released from irradiating a fissionable target is 7×10^{14} Bq. More than 99% is due to nuclides with half life shorter than 75 days (^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{41}Ar). A cooling time of about 2 hours is sufficient to reduce the activity concentration to 1 Bq/g, thus allowing release of the air to the environment without further authorization. In order to cool the continuous air flow pumped out of the irradiation room, a forced path with a dilution system to the stack is foreseen. For long half life nuclides (^{3}H, ^{14}C, ^{35}S), the TEDE to the population in the worst atmospheric conditions has been calculated, and it can be concluded that since this value is less than 10 μSv/a, the practice is not relevant from a radiological point of view.

The annual radioactivity produced in air from irradiating a non-fissionable target (SiC) is 5×10^{12} Bq. The concentration of short lived nuclides is less than 1 Bq/g at the exhaust, thus in principle, there would be no need for a dilution system to reduce the concentration further. For long lived nuclides, the TEDE is less than 1 μSv/a, thus as already pointed out, it is not relevant from a radiological point of view.

TABLE 4: Annual activity released and TEDE to the public due to the long lived radionuclides.

Nuclide	$T_{1/2}$	Activity release rate Bq/a		TEDE Sv/a	
		UC_2	SiC	UC_2	SiC
^{3}H	12.33 a	1.8×10^{9}	1.1×10^{8}		
^{14}C	5730 a	2.7×10^{8}	4.3×10^{7}	3.0×10^{-6}	3.0×10^{-7}
^{35}S	87.51 d	7.7×10^{8}	6.8×10^{6}		

CONCLUSIONS

The radiation protection aspects of the SPES project have been studied using the FLUKA code. Simulations have been run using nominal irradiation conditions in order to classify the areas close to the target irradiation room and the cyclotron vault during and after the irradiation of the target. In particular, an indication has been given of the remnant dose rate inside the irradiation hall and in the cyclotron vault after the beam has been stopped with some days of cooling in order to plan interventions on the equipment. The airborne activity has been calculated taking into account the ventilation system of the target room: the residual nuclei and their activity at the stack have been estimated in order to give a non-relevant dose to the population at any time.

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