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Doses and fluxes in the proton-irradiated Big Target: A MARS15 analysis[1]

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Abstract

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Doses and fluxes in the proton-irradiated Big Target: A MARS15 analysis

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This work is aimed at determination of secondary particle fluxes, prompt and residual doses as well as energy deposition in and around the Big Target, a 20-tonnes cylindrical target made of natural uranium with the lead core and a stainless-steel yoke, which is being considered to be irradiated by a 0.16-μA 600-MeV proton beam of the JINR Phasotron accelerator. The simulations were performed with the use of the MARS15 particle transport code employing the LAQGSM and CEM generators and based on the ENDFB-VIII neutron cross section library. The calculations for 12-hour, 100-hour, and 3-day irradiations with the aforementioned conditions indicate that temperature rise due to the beam does not require target cooling, the target can be safely handled soon after the end of irradiation, and its decommissioning is possible three years past the irradiation.

Introdiction

Studies of the Accelerator-Driven Systems (ADS) have a long story [1], and have been conducted at Joint Institute for Nuclear Research and many world accelerator centers for several decades [2]. Recent and ongoing ADS-related programs at world laboratories (at LANL, CERN, PSI, KEK, JINR) aimed at high-precision measurements of relevant cross sections as well as prototype experiments include, for example, [3-7]. Natural uranium as the prospective material of subcritical reactor cores have been investigated both experimentally and theoretically since 1970s at FNAL and JINR [8-10]. Recent simulations in the broad energy range have shown that while the proton beam energy in the 2-4 GeV range is still optimal for energy production and fission, the 660-MeV beam results in the energy amplification decrease by 20% [11]. Therefore, the 660-MeV beam option is almost as feasible as that in the few-GeV range.

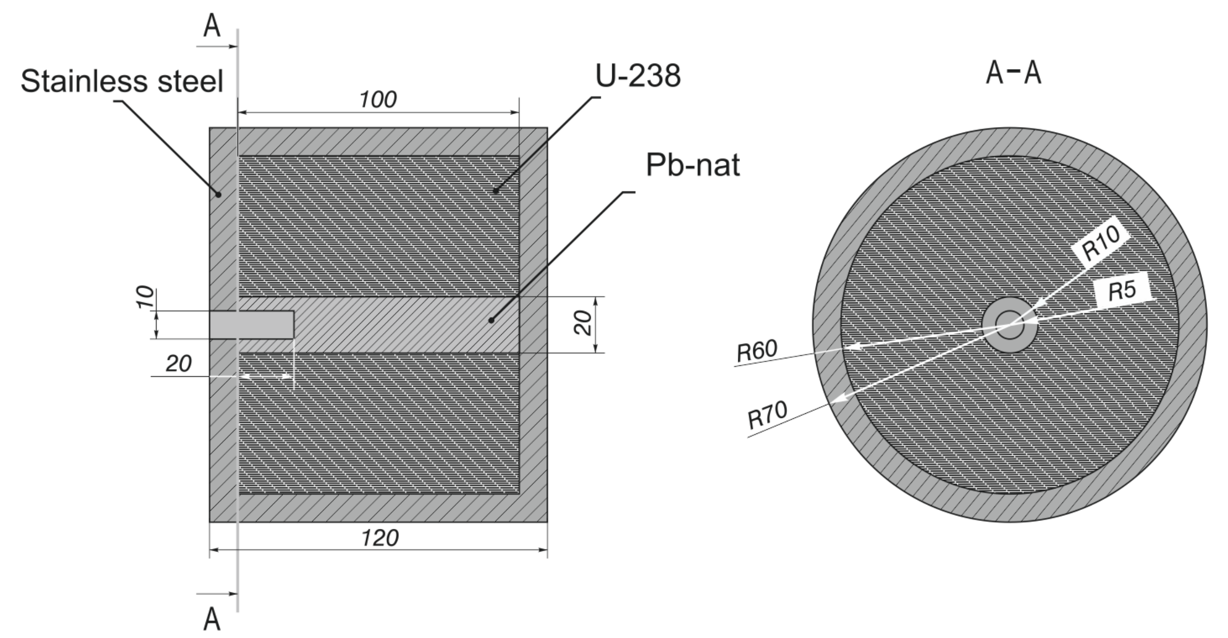
Depleted uranium is an abundant waste of the uranium enrichment industry and has been accumulated in large amounts worldwide. Therefore, the ways of its peaceful utilization are of big demand. Besides its broad application in energy production systems, depleted uranium has been successfully utilized in high-energy physics experiments. For example, in the D0 experiment [12], ^{238}U plates with the total mass 144.4 tons, were employed in the hadron calorimeter [13]. Depleted uranium, having the 4.5-million-year half-life, emits α, β, and γ-radiation, however, due to self-attenuation in bulk material, despite large quantities, emission of radiation outside is quite modest because the detector mass eliminates any radiation exposure concerns. Also, uranium oxidation is seriously limited by inert gas atmosphere under which the D0 detector plates are stored. Hence, depleted uranium even in significant quantities was found to be a feasible material for long-term accelerator-based physics experiments.

There are several nuclear interaction and particle transport Monte Carlo codes that are widely used in the domain of ADS simulations, among most popular and well-developed are Geant4 [14], FLUKA [15], PHITS [16], MARS15 [17], MCNPX [18]. In this work, we utilize the MARS15 code, which shows one of the best results not only in ADS studies but also in various shielding application for accelerator-based experiments [19, 20], to simulate particle fluxes, energy deposition, and residual doses in the Big Target [2]. In what follow we describe the simulation model of the Big Target setup, model settings of the MARS15 code, and discuss the results obtained.

Description of the setup

The Big Target MARS15 model represents itself a 1-meter-long cylinder with the radius of 60 cm made on ^{238}U surrounded by a 10-cm-thick stainless yoke from all sides. At the center of the target at its Z-axis, a one-meter-long cylindrical lead target with the radius of 10 cm is placed. At the beam entrance to the target, a 10-cm in radius hole is made that penetrates the yoke as well as goes 20 cm deep in the target along its Z-axis (Figure 1). The beam strikes the upstream edge of the lead core of the Big Target inside the hole.

Figure 1. The scheme of the MARS15 model of the Big Target.



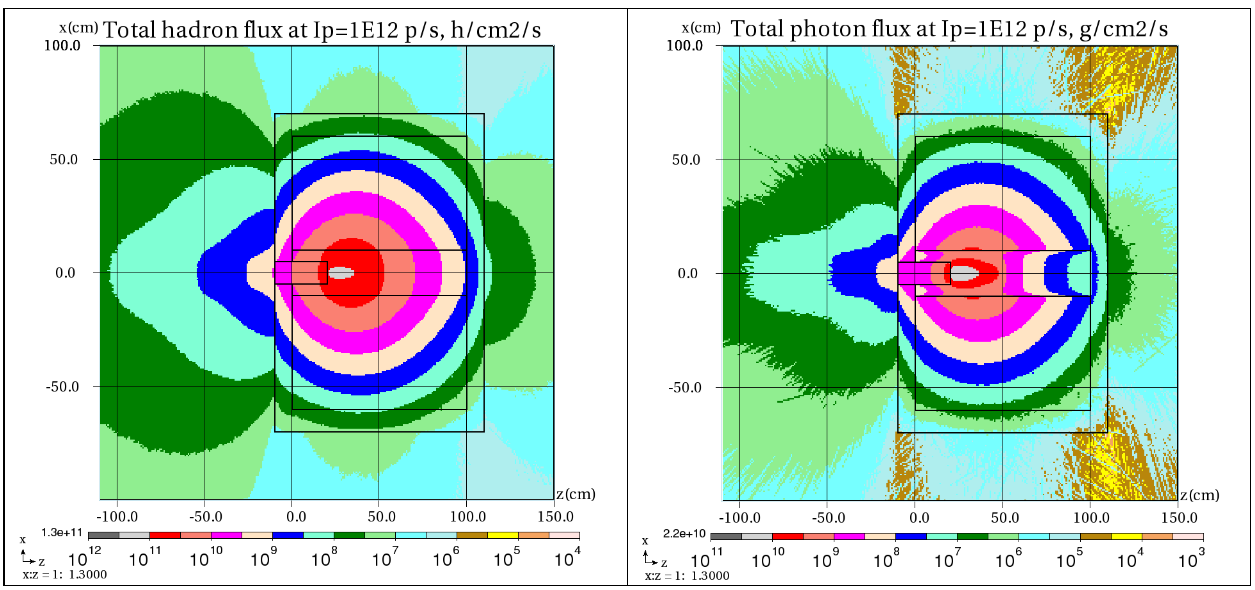
Simulation methods

The simulations have been performed using the multipurpose transport code MARS15 [17]. In the calculations, the proton beam with the energy of 660 MeV was utilized, beam intensity was assumed to be 10^{12} p/s, the isotopic composition of the target was ^{238}U for the main cylinder, natural lead for the target, and stainless steel for the yoke. A combination of the built-in CEM and LAQGSM [21] event generators was deployed in the MARS15 simulations in order to determine outcomes of the hadron-nuclei interactions in the range few MeV to 660 MeV. In the case of pions, the aforementioned generators were engaged between 0 and 660 MeV. For neutron interactions, both elastic and inelastic interactions are taken into consideration. The ENDFB-VIII neutron cross section library mode with the neutron transport threshold was set to 10^{-12} GeV whereas for the transport of charged particles the energy threshold was 100 keV.

Simulation results

The proton beam intensity was assumed to be 10^{12} p/s, which represents realistic irradiation conditions for the Big Target at the JINR Phasotron accelerator at the 660 MeV proton energy. Such an intensity corresponds to 0.16 μA and the beam power of 106 W, and represents realistic conditions of irradiations at Phasotron. Total hadron flux at the hottest location of the target is as high as ~10^{11} hadrons/cm^2/s but because the target is a full absorption one, the hadron flux is at the level of 10^7 hadrons/cm2/s on sides. The flux beyond the target can reach 10^8 h/cm^2/s, and the albedo flux in front of the target can be as high as 10^9 h/cm^2/s. The photon flux on sides is by an order of magnitude lower than the hadron one.

An important task of the simulations was to estimate the prompt dose and energy deposition in the Big Target (Figure 2). The total prompt dose (due to all secondary particles) is estimated to be ~3 Sv/hr on the sides on the target, ~30 Sv/hr behind the target, and ~1 kSv/hr in front of it, which means that the target has to be surrounded by shielding walls to protect personnel during irradiation. The peak energy deposition at the target core is ~6.5 mW/g and rapidly falls off toward surface, therefore, no special measures for the target heating is required.



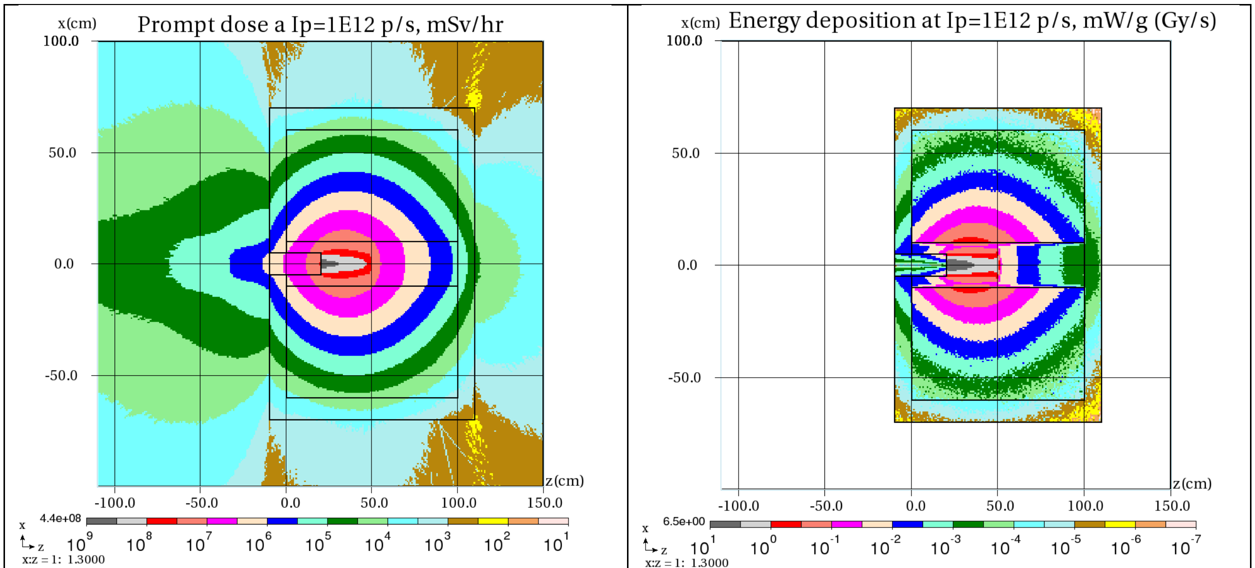


Figure 2. Top left. Total hadron flux in the Big Target and its vicinity, h/cm^2/s; Top right. Total photon flux in the Big Target and its vicinity; Bottom left. Prompt dose in the Big Target and its vicinity, mSv/hr; Bottom right. Energy deposition in the Big Target, mW/g (Gy/s).

One of the central aims of the works is to assess by MARS15 simulations the residual dose on contact with the target and its yoke after irradiation (Figure 3). For the sake of the convenience of comparison with planned irradiation conditions at Phasotron, the irradiation times were chosen to be 12 hours, 100 hours, and 30 days. Simulation results show that immediately after the irradiation, the residual dose on contact with the target yoke is less than 1 mSv/hr, i.e. its handling can be performed very soon after the exposure. In less than a day after end of irradiation, the dose on contact becomes lower than 0.05 mSv/hr, i.e. smaller than the one for The 30-d irradiation time corresponds to an unrealistic condition, which, however, models the use of the target in the long run mode that can be important to estimate its thermal map in equilibrium with the air and other surroundings. Calculations show that even after a 30-d exposure and 1-d cooling, side surfaces of the target yoke exhibit the peak contact doses below 1 mSv/hr, which makes it transportable from the accelerator channel to the storage at least within the Phasotron premises. The Figure 3 (bottom) indicates that after 3 years after irradiation, the contact dose on surface drops below 1 mSv/yr, which enables its decommissioning and safe transporting outside the Phasotron complex.

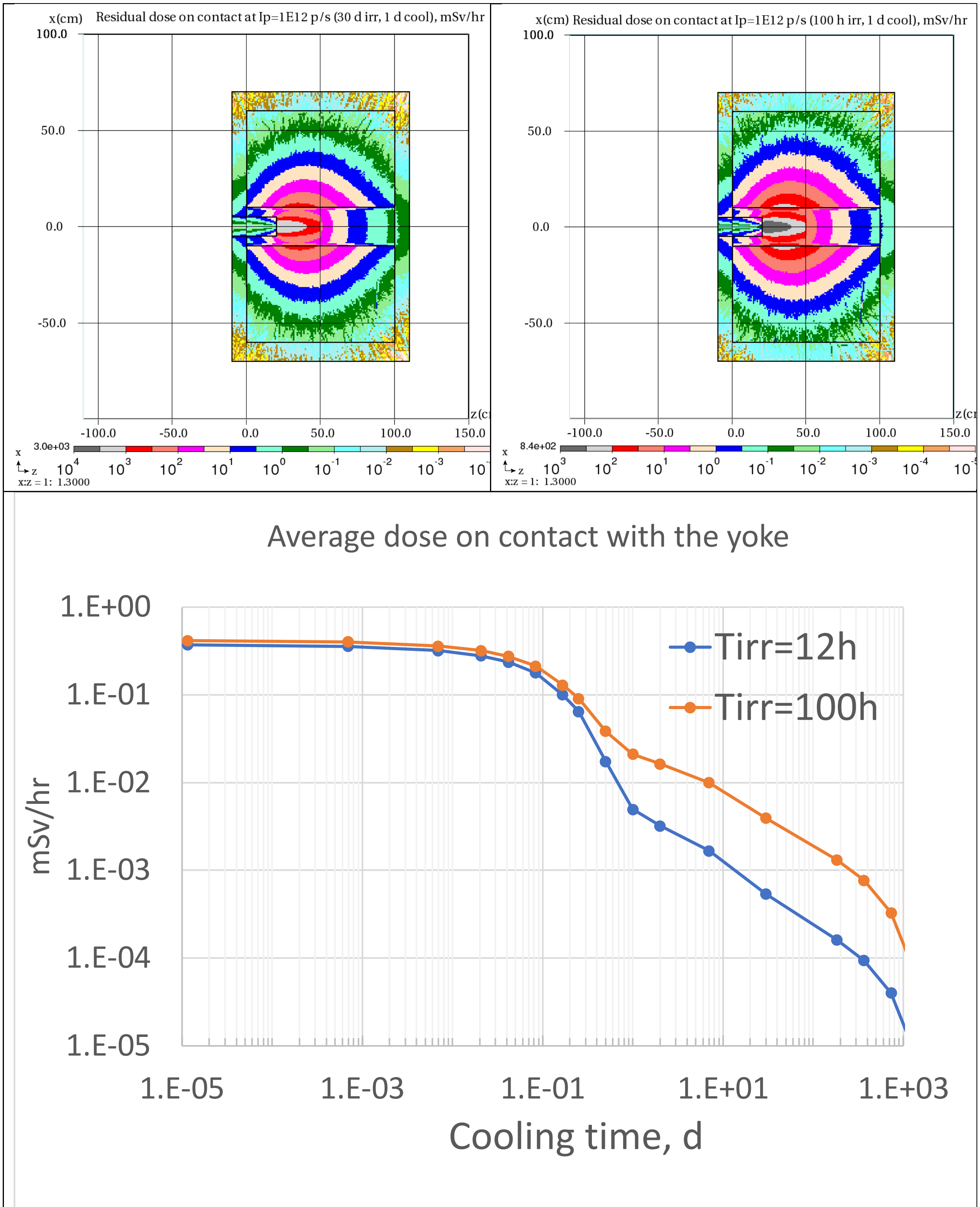


Figure 3. Top left. Residual dose on contact with the Big Target after 30 days of irradiation and 1 day of cooling, mSv/hr; Top right. Residual dose on contact with the Big Target after 100 hours of irradiation and 1 day of cooling, mSv/hr; Average residual dose on contact with yoke

Conclusions

The simulation of the Big Target activation and energy deposition has been performed using the MARS15 code. The calculations allowed us to determine the hadron and photon fluxes in and around the Big Target, energy deposition in, and prompt dose around the setup. Residual doses on contact for a numbers of irradiation times as well as the residual dose curve as a function of cooling time in the range from 1 second to 3 years have been simulated. Average doses at the yoke surface have been found to be at the level of 0.4 mSv/hr immediately after the irradiation, and goes down to below 0.05 mSv/hr after a day of cooling, which makes it suitable to handle soon post irradiation. In addition, after three years of cooling the contact dose falls off to below 1 mSv/yr, and therefore, becomes transportable in the course of anticipated decommissioning.

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