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Benchmark on computer simulation of radioactive nuclides production rate in lead target exposed to 660 MeV protons

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Abstract. The Benchmark on computer simulation of radioactive nuclides production rate and heat generation rate in lead target exposed to 660 MeV proton is part of IAEA Coordinated Research Project Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems, in the Joint Institute of Nuclear Research in Dubna (Russia). In the experiment absolute activities of several long-lived radionuclides, generated in lead target during its irradiation with 660 MeV proton beam, were determined to be compared with simulation predictions, based on different available codes and physical models. The paper shows the results obtained by us and compared among the participants as well as with the experimental results.

Keywords: Nuclear Engeneering, Experimental Benchmark, Accelerator Driven Systems, Lead Target
PACS: 28.41.-i, 28.50.-k

INTRODUCTION

The Accelerator Driven System (ADS), is an innovative reactor which is being developed as a dedicated burner in a Double Strata Fuel Cycle to incinerate nuclear waste [1]. The ADS system consists of a sub-critical assembly driven by accelerator delivering a proton beam on a target to produce neutrons by a spallation reaction. The physics and codes used for the design of ADS targets had been previously reported [2]. The spallation target constitutes the physical and functional interface between the accelerator and the sub-critical reactor. For this reason it is probably the most innovative component of the ADS. The target design is a key issue to investigate in the design of an ADS and its performances are characterized by the number of neutrons emitted per incident proton, the mean energy deposited in the target per neutron produced, the neutron spectrum and the spallation product distribution. To evaluate the present time international capability in design an ADS target, as well as the physical models used in the codes, an experimental benchmark on computer simulation of radioactive nuclides production rate and heat generation rate in lead target exposed to 660 Mev proton was proposed [3] as part of the IAEA Coordinated Research Project (CRP) "Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems" [4]. The benchmark was based in an early experiment conducted at Joint Institute of Nuclear Research in Dubna (Russia). In the experiment absolute activities of several

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long-lived radio nuclides, generated in lead target during its irradiation with 660 MeV proton beam, were determined to be compared with simulation predictions, based on different available codes and physical models. We participated in this Benchmark, and here we wish to report the results obtained by us compared with the results obtained by the participants as well as with the experimental results, divulgated by Dubna [5].

BENCHMARK EXPERIMENTAL SPECIFICATIONS

The Benchmark on computer simulation of radioactive nuclides production rate and heat generation rate in lead target exposed to 660 MeV proton had as specific objectives to calculate of the residual production of several nuclides during its irradiation and 200 days after irradiation in 32 samples located inside the target(^{46}Sc, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{75}Se, ^{83}Rb, ^{85}Sr, ^{88}Y, ^{88}Zr, ^{95}Nb, ^{95}Zr, ^{102m}Rh, ^{102}Rh, ^{110m}Ag, ^{121m}Te, ^{121}Te, ^{139}Ce, ^{172}Hf, ^{172}Lu, ^{173}Lu, ^{175}Hf, ^{183}Re, ^{185}Os, ^{194}Au, ^{194m}Ir, ^{195}Au, ^{203}Hg e ^{207}Bi.). Figure 1, illustrates the experimental target.

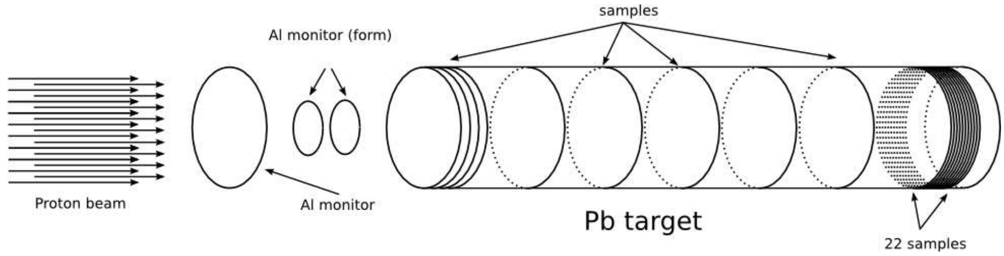

FIGURE 1. Lead Target Scheme

The target is assembled with several lead cylindrical pieces. Each cylindrical sample have 5 cm and 1 cm thickness and 32 pieces of 1 mm thickness. The diameter of these pieces is 80 mm. The total target length is 308 mm, with the last 5 mm composed of 22 samples of 1 mm thickness. The experimental parameters were: a) Proton Energy: $E_p = 660 \pm 4$ MeV; b) Maximum Proton current: $I_{p,max} = 3.0 \times 10^{10}$ p/s; c) Irradiation time: 530 minutes; d) Total number of Protons: $(2.6 \pm 0.2) \times 10^{14}$ protons.

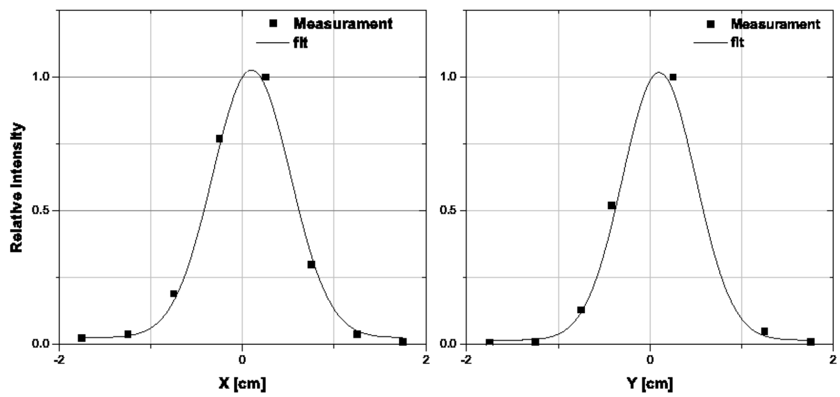

FIGURE 2. Proton beam distribution incident on the target surface (data from Ref. [3]).

The calibration of the intensity of the proton beam was made using an ionization chamber, calibrated with the reactions $^{12}C(p,pn)^{11}C$ and with Aluminum foils and the reactions $^{27}\mathrm{Al}(p,3n3p)^{22}\mathrm{Na}$, $^{27}\mathrm{Al}(p,n3p)^{24}\mathrm{Na}$ and $^{27}\mathrm{Al}(p,x)^{7}\mathrm{Be}$. Figure 2, shows the proton beam incident in the target surface.

CALCULATION METHODOLOGY AND RESULTS

The lead target was modeled and calculated using MCNPX 2.5 [6]. For the decay and residual production of the nuclides the code ORIGEN-S from SCALE 5.1 [7] was used.

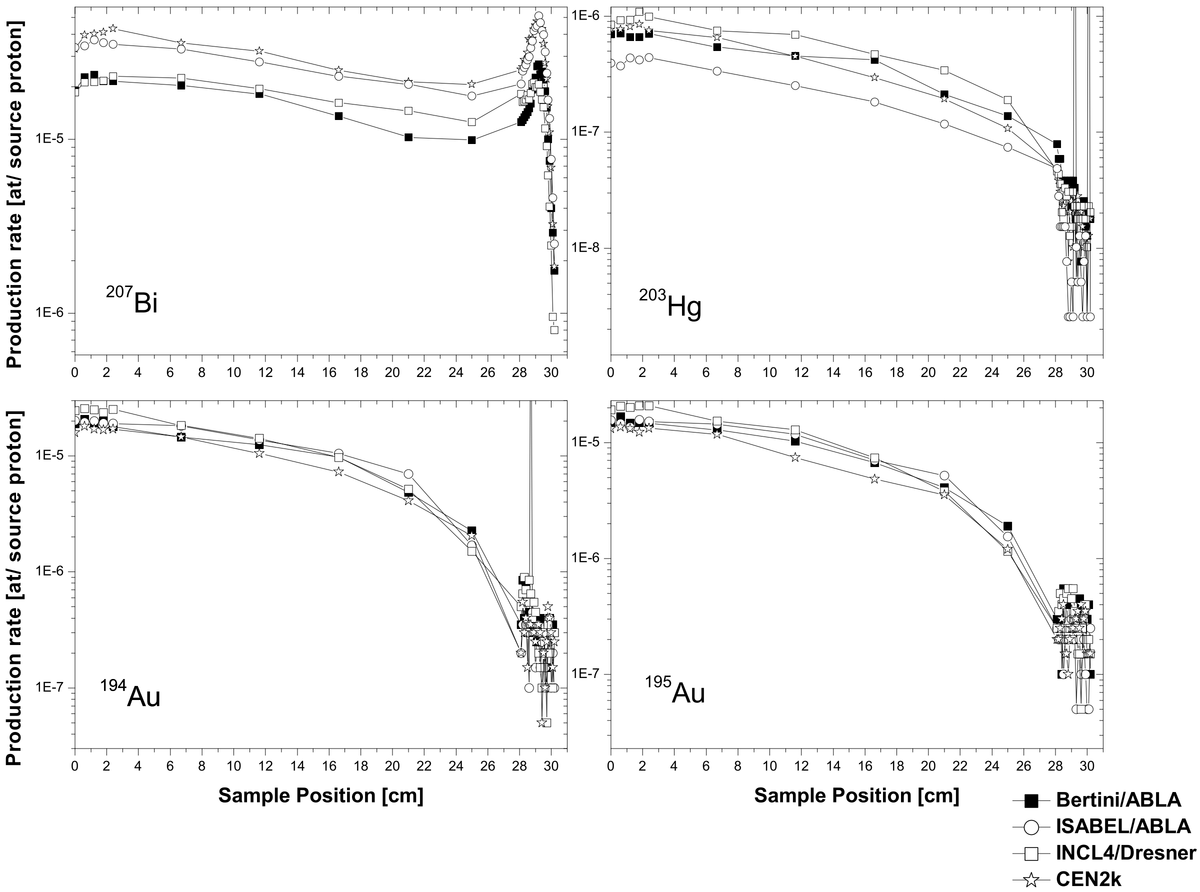

FIGURE 3. Distribution of the nuclides specific activity in function of the position

We have obtained all the results requested by the Benchmark coordinators, such as: a) the induced radioactivity and production rate for the nuclides listed before, at $x = y = 0$, and $z = 0$, 0.6, 1.2, 1.8, 2.4, 6.7, 11.6, 16.6, 21.0, 25.0, 28.1, 28.2, 28.3, 28.4, 28.5, 28.6, 28.7, 28.8, 28.9, 29.0, 29.1, 29.2, 29.3, 29.4, 29.5, 29.6, 29.7, 29.8, 29.9, 30.0, 30.1 and 30.2, having as reference the top of the target, as well as the integrated results for all target b) the fluxes, current and spectra for protons, neutrons and pions . Here we just wish to report some of most important results. In Figure 3, we show the comparison among several nuclear reactions models (BERTINI/ABLA, ISABEL/ABLA, CEM-2K, and INCL4/Dresner) available in MCNPX, for the isotopic production rate for the nuclides ^{207}Bi, ^{203}Hg, ^{194}Au, and ^{195}Au.

The total fluxes for pions, alpha, protons and neutrons are illustrated in Figure 4, using also several nuclear reactions models.

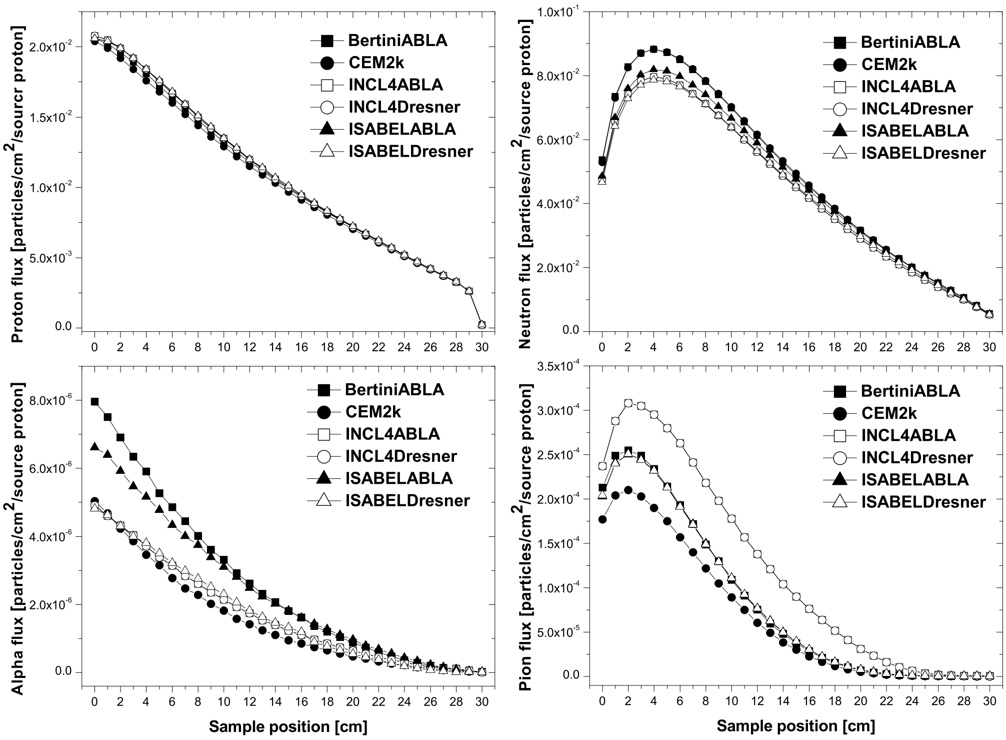

FIGURE 4. Total Fluxes for different models

Finally and most important we show in Figure 5, 6 and Table 1 , an inter comparison made by the Benchmark coordinator, during the final Research Coordinated Meeting held in Mumbay [8] of the results obtained by the participants of the Benchmark against the experimental results of the integrated activity 200 days after irradiation . We just illustrate the results for ^{207}Bi (Figure 5), and ^{203}Hg (Figure 6) and for several nuclides (in table 1). Our results are those indicated by index number 2.

CONCLUSIONS

The participation in the Benchmark was quite important for us, since allowed to assess our target calculation methodology. The result obtained by us allows concluding

TABLE 1. Comparative table for activity of the whole target with account of the decay during and after activation [calculated value per experimental data](from Ref. [8])

Participant No	C/E									
and	Nuclide									
model/code	^{60}Co	^{65}Zn	^{83}Rb	^{88}Y	^{102}Rh	^{173}Lu	^{175}Hf	^{185}Os	^{203}Hg	^{207}Bi
1-CEM-0301	0.65	1.67	1.4	1.31	-	1.58	1.70	1.06	0.55	1.42
1-CEM 2k	0.40	1.43	0.45	0.47	0.40	0.72	0.84	1.1	0.49	1.66
3-CEM	0.41	1.45	0.44	0.50	0.40	0.76	0.82	1.11	0.77	1.77
2-CEM2k	9.81	1.42	1.35	0.96	0.25	0.01	0.02	0.04	0.64	1.78
1-BERT/DRES	0.41	1.20	0.39	0.38	0.42	1.30	1.24	1.05	1.30	1.40
3-BERT/DRES	0.46	1.41	0.39	0.38	0.42	1.36	1.29	1.07	1.44	1.47
1-BERT/ABLA	0.43	0.61	0.44	0.38	0.67	0.99	1.07	1.16	1.32	1.06
2-BERT/ABLA	7.94	0.84	2.05	1.17	0.41	0.01	0.02	0.06	1.2	1.09
1-INCL4/ABLA	0.51	0.54	0.53	0.44	0.84	0.38	0.49	0.82	1.61	1.17
3-INCL4/ABLA	0.55	0.62	0.49	0.48	0.94	0.42	0.47	0.83	1.70	1.22
1-INCL4/DRES	0.51	0.47	0.57	0.45	0.89	0.38	0.48	0.82	1.62	1.17
2-INCL4/DRES	11.31	0.99	2.53	1.55	0.53	0.01	0.01	0.04	1.65	1.18
1-ISABEL/ABLA	0.39	0.58	0.48	0.45	0.85	0.65	0.75	1.08	1.02	1.85
2-ISABEL/ABLA	11.47	0.96	2.48	1.42	0.49	0.01	0.06	1.22	1.22	1.98
1-ISABEL/DRES	0.42	1.16	0.33	0.35	0.41	0.93	0.97	1.04	1.30	1.40
3–ISABEL	1.00	1.25	0.96	0.84	1.38	0.94	0.91	1.02	0.83	1.15

that still there are significant differences in the nuclear reactions models, which needs further investigations. Comparing our results with those obtained by others participants and with the experimental results, we notice that for ^{207}Bi everybody over estimated the calculated results, for the other nuclides there are a random inter comparison, and that it is impossible to conclude which one is the best. For ^{203}Hg, we obtained the closest results compared with the experimental results, but the divergences among the participants are visible. Finally the benchmark results shows that still there are many open questions to be solved, mainly related with the differences in the nuclear reactions models which show that the models available for calculating production rates are not satisfactory in most of the nuclides analyzed and form factor of distributions are well reproduced but the magnitude of the distribution shows significant deviations.

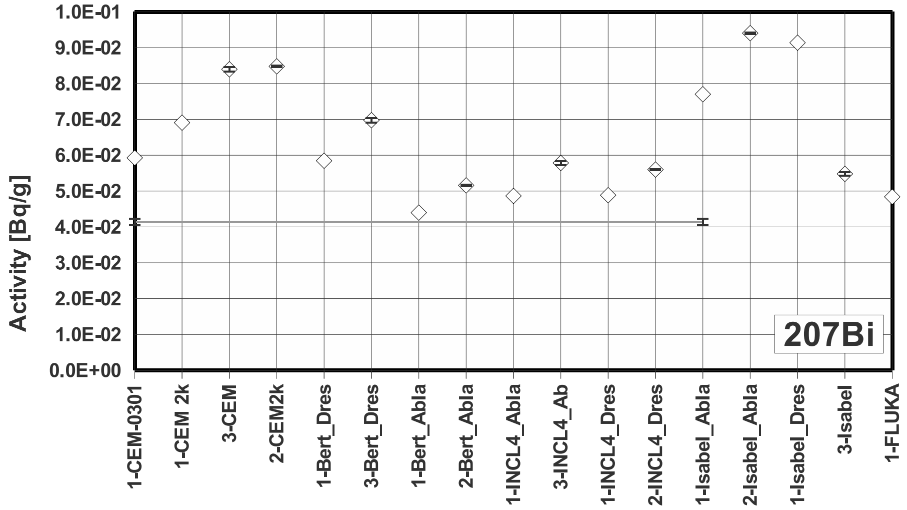

FIGURE 5. Integrated Activity of ^{207}Bi. Results obtained by the Benchmark Participants against the experimental results (line)

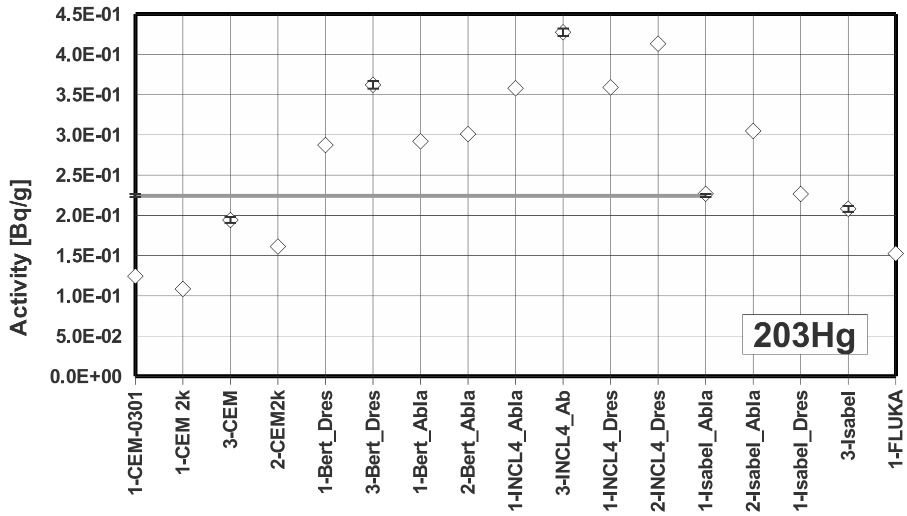

FIGURE 6. Integrated Activity of ^{203}Hg. Results obtained by the Benchmark Participants against the experimental results (line).

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