IAEA coordinated research project (CRP) on "Analytical and experimental benchmark analyses of accelerator driven systems"

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Abstract

In December 2005, the International Atomic Energy Agency (IAEA) has started a Coordinated Research Project (CRP) on "Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems". The overall objective of the CRP, performed within the framework of the Technical Working Group on Fast Reactors (TWG-FR) of IAEA's Nuclear Energy Department, is to increase the capability of interested Member States in developing and applying advanced reactor technologies in the area of long-lived radioactive waste utilization and transmutation. The specific objective of the CRP is to improve the present understanding of the coupling of an external neutron source (e.g. spallation source) with a multiplicative sub-critical core. The participants are performing computational and experimental benchmark analyses using integrated calculation schemes and simulation methods. The CRP aims at integrating some of the planned experimental demonstration projects of the coupling between a sub-critical core and an external neutron source (e.g. YALINA Booster in Belarus, and Kyoto University's Critical Assembly (KUCA)). The objective of these experimental programs is to validate computational methods, obtain high energy nuclear data, characterize the performance of sub-critical assemblies driven by external sources, and to develop and improve techniques for sub-criticality monitoring. The paper summarizes preliminary results obtained to-date for some of the CRP benchmarks.

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1. Introduction

The CRP on "Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems" is implemented within the framework of the Technical Working Group on Fast Reactors (TWG-FR) of IAEA's Nuclear Energy Department. Currently, 27 institutions in 18 IAEA Member States and two international organizations are participating in this CRP.

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The specific objective of the CRP is to improve the present understanding of the coupling of an external neutron source [e.g. a spallation source in the case of the accelerator driven system (ADS)] with a multiplicative sub-critical core. As outcome, the CRP aims at advancing the efforts under way in some IAEA Member States towards the proof of practicality for "transmutation machines" (e.g. ADS based transmutation concepts) by providing an information exchange and collaborative research framework needed to ensure that the tools to perform the detailed analyses of sub-critical systems driven by external neutron sources are available.

The participants are performing computational and experimental benchmark analyses using integrated calculation schemes and simulation methods. To reach the CRP's objectives, experimental benchmarking is of paramount importance. ADS constitute the main thrust of the CRP which is addressing all major physics phenomena of the spallation source and its coupling to the sub-critical core. However, transmutation concepts based on sub-critical cores driven by non-spallation neutron sources are also considered – in particular as regards the experimental benchmarking activities of the CRP, since there are a series of experimental demonstration projects using non spallation targets [e.g. (D,D) or (D,T) neutron sources, and photon-neutron sources based on electron accelerators].

In a first stage of the CRP, the participants agreed to perform benchmark exercises in eight areas, *viz.* YALINA-Booster, Kyoto University Critical Assembly (KUCA) sub-critical experiments, Pre-TRADE experiments, FEAT and TARC experiments, Kharkov Institute for Physics and Technology (KIPT) electron accelerator based neutron source, ADS kinetics analytical benchmark, Actinides cross sections, Spallation targets, and ADS performance.

The paper summarizes the overall status of the CRP activities and presents the major results obtained so far.

2. YALINA-Booster

YALINA-Booster is a sub-critical assembly driven by an external Cf, (D,D) or (D,T) neutron source. It has a fast spectrum ("booster") zone in the centre (lead sub-assemblies fuelled with highly enriched metallic uranium and uranium oxide), surrounded by a thermal zone (polyethylene subassemblies fuelled with low enriched uranium oxide). The "booster" zone multiplies the source neutrons through the fission reactions in the highly enriched uranium and the (n,xn) reactions in lead. Between the fast and the thermal zones, there is a "buffer" zone that consists of one layer of natural metallic uranium rods and one layer of boron carbide rods that allows for fast neutron leakage into the thermal zone, and at the same time reduces thermal neutron leakage into the fast zone. In the radial direction and axially, the sub-critical assembly is surrounded by a graphite reflector and by borated polyethylene, respectively.

Practically all measurements for the YALINA-Booster reference configuration with 1141 EK 10 fuel rods in the thermal zone (Stanculescu, 2007) have been performed. As an example, the results of ^{3}He detector count rates obtained in six different YALINA-Booster experimental channels (EC) (Stanculescu, 2007) are shown in Fig. 1. In this example, the ^{3}He detector count rates were measured over 20 ms) after a 5 µs (D,T) neutron pulse insertion.

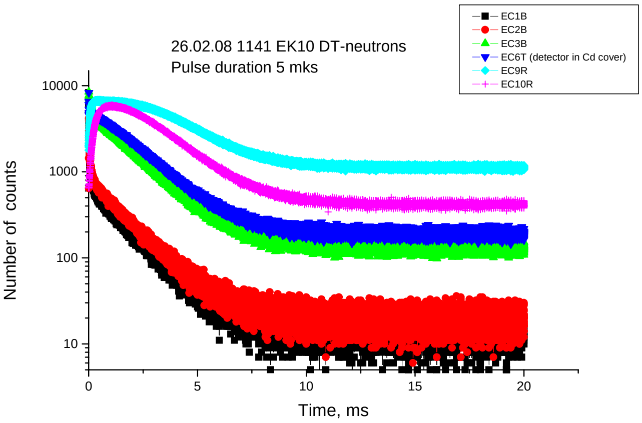


Fig. 1. YALINA-Booster reference configuration, 3He count rates after 5 µs (D,T) neutron pulse.

The benchmark participants are calculating for various configurations axial and radial reaction rate distributions, normalized to one external source neutron and to one atom of the respective detector isotope. Further, participants are calculating the neutron energy spectra at the various EC locations. The neutron flux is calculated (over a period of 20 ms) as function of time after a (D,D) or (D,T) 5 µs neutron pulse insertion, based on the measurements obtained from ^{3}He(n,p) and ^{235}U(n,f) detectors. Finally, the participants are calculating, for various configurations, the usual kinetic parameters, i.e. the effective and source multiplication factors, the mean neutron generation time, the prompt and mean neutron lifetime, and the delayed neutron fraction. While major efforts are ongoing, some preliminary results have been obtained by the Belarus, US and Brazilian groups.

Table 1
Calculated criticality parameters for the YALINA-Booster reference configuration

Code	XS Library	β (pcm)	k_{eff}	k_{source} (D-D)	k_{source} (D-T)
MCNPX 2.6b	ENDF VI.6	760± 8	.97972± .00004	.98683	.99148
MCNP5	ENDF VI.6	766± 18	.98016± .00009	—	—
MCNP 4c3	ENDF VI.6	747± 15	.98004± .00007	—	—
MCNP 4c3	ENDF VI.0	765± 16	.98097± .00008	—	—
MCB2	JEF-2.2	699± 17	.98318± .00009	.98856	.99291
MONK 9a	JEF-2.2 BINGO	—	.9836± .00020	.98980± .00020	.99320± .00020
MONK 9a	JEF-2.2 DICE	—	.9824± .00020	.98910± .00020	.99310± .00020
MONK 9a	ENDF VI.6 DICE	—	.9773± .00010	.98610± .00020	.99060± .00020
MONK 9a	ENDF VI.6 WIMS	—	.9844± .00020	.99260± .00020	.99300± .00020

Table 1 summarizes results obtained by ANL for β_{eff}, k_{eff} and k_{source} for the YALINA-Booster reference configuration with Monte Carlo codes [MCNPX, various MCNP versions, MCB, and continuous (BINGO), quasi-continuous (DICE, 13193 energy groups) as well as multi-group (WIMS, 172 energy groups) MONK9a] using different nuclear data libraries (various ENDF/B-VI and JEF versions). Deviations between calculated and experimental (based on measurements in three different experimental channels) k_{eff} values for the YALINA-Booster reference configuration, are shown in Table 2. Preliminary inter-comparison results for the calculated effective and prompt criticality, delayed neutron fraction and lifetime are shown in Figs 2 - 5.

Table 2
Average deviation between calculated (Talamo and Gohar, 2008) and measured YALINA-Booster reference configuration k_{eff}

	Experimental channel EC5T	Experimental channel EC6T	Experimental channel EC7T
ρ/β_{eff} (\$)	-3.3627± 0.0077	-3.4088± 0.0069	-3.5198± 0.0081
β_{eff}	0.00760	0.00760	0.00760
k_{eff} (measured)	.97508±.0022	.97475±.0020	.97395±.0022
E-C(pcm)			
MONK	222	255	335
MCNPX	464	497	577

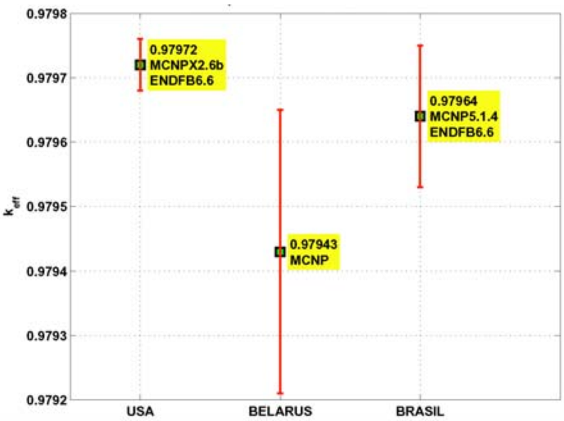


Fig. 2. YALINA-Booster reference configuration, k_{eff} inter-comparison.

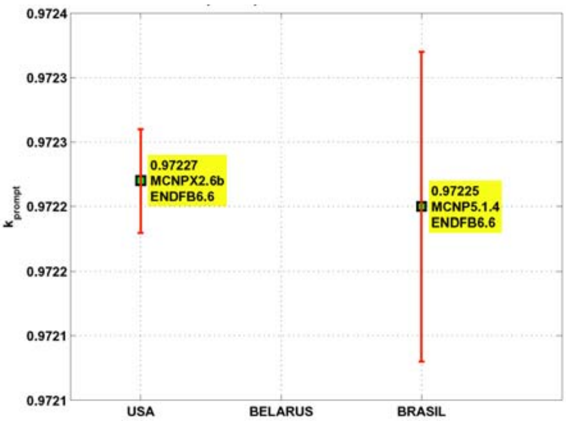


Fig. 3. YALINA-Booster reference configuration, k_{prompt} inter-comparison.

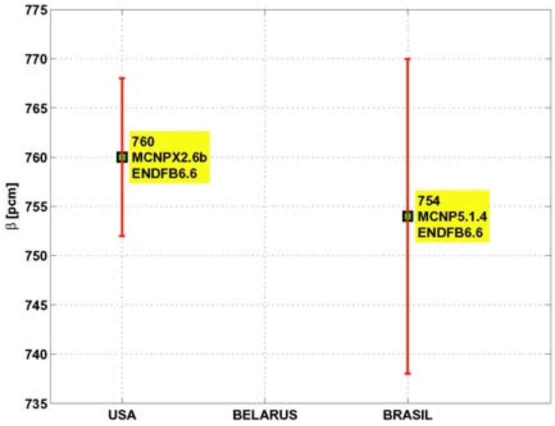


Fig. 4. YALINA-Booster reference configuration, delayed neutron fraction inter-comparison.

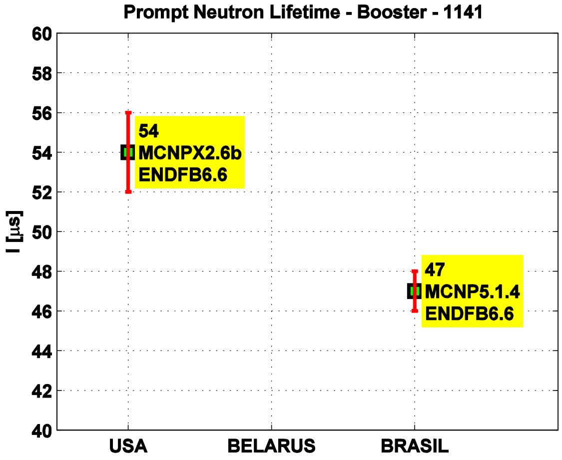


Fig. 5. YALINA-Booster reference configuration, prompt neutron lifetime inter-comparison.

3. KUCA sub-critical experiments

The first stage in the KUCA experimental program comprised experiments based on a sub-critical KUCA core and a 14.1 MeV (D,T) pulsed neutron source. The main objective of these experiments was to study the sub-critical static neutronics characteristics (neutron spectrum, reaction rates distributions) and validate appropriate measurements techniques. The experimental configurations are assembled with various combinations of highly enriched ^{235}U, ^{232}Th, and natural uranium fuels, as well as polyethylene, graphite, aluminium, and beryllium reflector materials. The first experiments consisted in reaction rates measurements made in the centre of a thermal core and close to the tritium target for three different sub-criticality levels (approximately 870, 1230, and 1750 pcm), using the foil activation method. The following reactions were considered: ^{115}In(n,n')^{115m}In, ^{56}Fe(n,p)^{56}Mn, ^{27}Al(n,α)^{24}Na, and ^{92}Nb(n,2n)^{92m}Nb. Participants perform calculation vs. experiment comparisons using various codes and data libraries. First results indicate satisfactory agreement (within 10%) for ^{27}Al reaction rates in the core, regardless of the sub-criticality level (the discrepancy is higher, up to 26%, for positions close to the target). Very large discrepancies and a strong dependency on the sub-criticality level are found for ^{115}In, ^{56}Fe and ^{93}Nb reaction rates. The second stage, based on the same experimental program, comprises kinetics benchmarks focusing on various sub-criticality measurement methods. Measurements use an optical fibre detection system based on LiF (^{6}Li(n,α) reaction for thermal neutrons) and ThO$_2$ (^{232}Th(n,f) reaction for fast neutrons). Preliminary results indicate that sub-criticality levels can be satisfactorily evaluated by the pulsed neutron method (see Fig. 6).

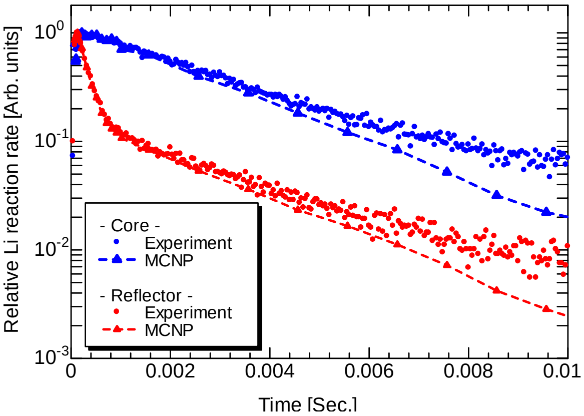


Fig. 6. KUCA LiF fibre detector response in the core and reflector (experiment vs. MCNP results).

Sub-criticality levels were also measured by the source multiplication method (^{252}Cf source, BF$_3$ detectors located at various positions). Preliminary results show a strong dependency of the E/C discrepancy on the detector position: varying from -4.2% to +20.8% for Monte Carlo, and from -6.9% to +18.1% for deterministic calculations. The third stage will consist in benchmarks based on static and dynamic spallation target KUCA experiments (coupling of KUCA to a 150 MeV FFAG proton accelerator).

4. Pre-TRADE

The Pre-TRADE experimental benchmark is focused on the evaluation, via computation, of the spatial-energy correction factors to be applied to some reactivity estimates measured under sub-critical conditions in the RC-1 TRIGA reactor located at the ENEA-Casaccia research centre near Rome. These measurements, performed within the framework of the TRADE program (Monti et al., 2003), are based on the so-called Area-ratio and Source Multiplication methods, and are relative to three different sub-critical "clean" (control rod free) core configurations, namely SC0 (~ -500 pcm), SC2 (~ -2500 pcm) and SC3 (~ -5000 pcm). A typical core loading, relative to the SC3 configuration, is shown in Fig. 7.

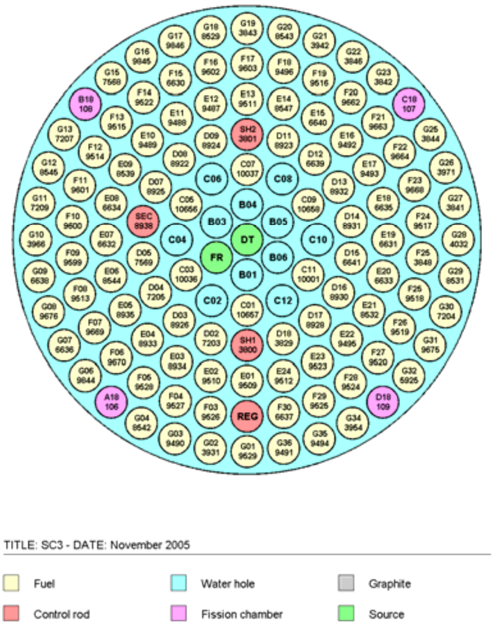


Fig. 7. RC-1 TRIGA, SC3 configuration.

To prepare the fuel element compositions for the benchmark specifications, the RC-1 TRIGA fuel burnup distribution was re-evaluated. In the past, estimates of the TRIGA RC-1 burnup were made on the basis of approximated "plant formulas" based on a detailed calendar (since the 1960's when the reactor was built) of the total thermal energy produced by each configuration loaded into the core. Given that the previous estimate does not satisfy the energy balance constraints for each core configuration, it was decided to calculate the energy produced by each element of the TRIGA RC-1 configurations by means of the TRIGLAV spatial diffusion code (Persic et al., 2000), thus obtaining the cumulative energy produced by each element loaded in the particular benchmark configuration. On the basis of this fuel element energy mapping and with the help of the ERANOS code (Rimpault et al., 1997), the relative fuel pin composition (plutonium, minor actinides and fission products) was calculated. Then, isotope build-up curves in function of the energy produced by the element were prepared. These curves were normalized, in the case of ^{235}U, ^{236}U and fission products, to the initial ^{235}U content of the fuel element, and, in the case of ^{238}U, ^{239}Pu and ^{240}Pu, to the initial ^{238}U content. These build-up curves formed the basis for the evaluation of the fuel element compositions for the benchmark configurations. As an example, Fig. 8 shows the plutonium build-up curves for a particular fuel element.

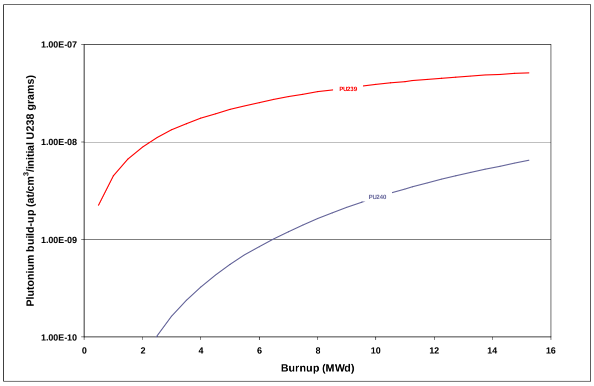


Fig. 8. Example of RC-1 TRIGA plutonium build-up.

5. TARC and FEAT benchmarks

The TARC experiment (Abánades et al., 2002) was specifically proposed as an experimental study of the neutron Adiabatic Resonance Crossing (ARC) moderation in a large lead block. The experiment was set up at the CERN Proton Synchrotron (PS). Even though the main goal of TARC was to demonstrate the efficiency of ARC in the transmutation of long lived fission products (^{99}Tc, ^{127,129}I), the experiment was designed in such a way that several basic processes involved in ADS R&D could be studied in detail, and therefore has deserved its consideration as a worthy set of data for the CRP. Among the excellent data obtained it is worthwhile emphasizing the measurement of neutron production rates by GeV protons hitting a large lead volume, the study of neutron transport on distance scales relevant to industrial application, and of the efficiency of long-lived fission products transmutation in a neutron field produced by spallation neutrons. The CRP benchmark activity is in progress with the analysis of neutron fluence measurements with several complementary techniques, in the energy range from thermal up to a few MeV, and of neutron capture rate measurements for ^{99}Tc (both differential and integral) and on ^{129}I and ^{127}I (integral measurements).

The FEAT experiment (Andriamonje et al., 1995) was done in an already existing sub-critical system made of natural uranium and light water that was exposed to a low intensity proton beam from the CERN PS at several kinetic energies from 600 MeV to 2.75 GeV. Specifications are being prepared for a proposal to benchmark the energy gain vs. the proton energy and the spatial distribution in a deep sub-critical configuration (k_{eff}~0.895).

6. Actinides cross sections

The CRP participants are analyzing integral fission cross section measurements (^{235}U, ^{239}Pu, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{241}Pu, ^{242m}Am, ^{243}Cm, ^{245}Cm, and ^{247}Cm) performed within the framework of the ISTC Project #1145 at the Institute's for Theoretical and Experimental Physics (ITEP), Moscow, MAKET heavy-water critical facility. The actinide samples were placed into special channels inside the cylinder-shaped $0.52NaF+0.48ZrF_4$ solid salt melt blanket "micro-model" (SBM) at different distances from its axis (Stanculescu, 2007). To evaluate the neutron spectra in the SBM channels, the ^{235}U(n,f), ^{238}U(n,γ), ^{55}Mn(n,γ), ^{63}Cu(n,γ), ^{176}Lu(n,γ), ^{197}Au(n,γ), ^{115}In(n,n'), ^{27}Al(n,α), and ^{64}Zn(n,p) reaction rates were measured using gamma-spectrometry. Preliminary comparisons between the MAKET experimental results and calculations (Titarenko et al., 2001) show that the required uncertainties of the actinide cross sections for various applications (Fomushkin et al., 2001) are not attained (C/E discrepancies in the range 4% to 60%). Currently, the CRP participants are setting up Monte Carlo models for the simulation of these experiments.

7. Spallation targets

The participants are performing several benchmark exercises addressing the validation and verification of data and codes used to calculate spallation reaction yields. The experimental data is provided by various experiments performed at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow within the framework of ISTC projects, and also at laboratories of the Joint Institute of Nuclear Research (JINR) Dubna.

7.1. ITEP benchmarks

The ITEP experiments consisted in the irradiation of various spallation target and structural materials in the 300 MeV – 2.6 GeV proton field of the U-10 accelerator. The aim of these experiments was to determine the yields of the different radioactive nuclides produced in those materials. The CRP participants are analyzing, in a first stage, the yields obtained from the irradiation of thin natural iron targets, and of thin natural tungsten targets.

The yields from ^{nat}Fe(p,x) reactions were determined by γ-spectrometry after irradiation with 0.3, 0.5, 0.75, 1 and 2.6 GeV protons. A total of 221 independent and cumulative reaction products were identified, with half-lives in the range 6.6 minutes to 312 days. The irradiation results were compared with inverse kinematics experimental results obtained at GSI Darmstadt (Villagrasa-Canton et al., 2007). Preliminary results obtained, so far, by one CRP participant indicate that the most significant C/E discrepancies are obtained for light nuclei yields (A<30).

The irradiation of ^{nat}W is particularly relevant for ADS studies, due to the formation of the α-emitter ^{148}Gd ($T_{½}$=74.6 yrs) (a residue obtained in all heavy target materials irradiated with protons above 0.5 GeV). Preliminary experimental results, which show satisfactory agreement with previous measurements at 0.6 GeV and 0.8 GeV (see Fig. 9) (Kelley, K.C. et al., 2005) were compared with calculations performed, so far, by one CRP participant (Titarenko et al., 2008) (see Fig. 9). The conclusion to-date is that the theoretical predictions based on the models considered (see legend in Fig. 9) provide, at most, only a qualitative description of the ^{148}Gd formation from ^{nat}W(p,x) reactions in thin targets. Contributions by other CRP participants and the planned irradiation of ^{181}Ta targets are expected to improve these preliminary findings.

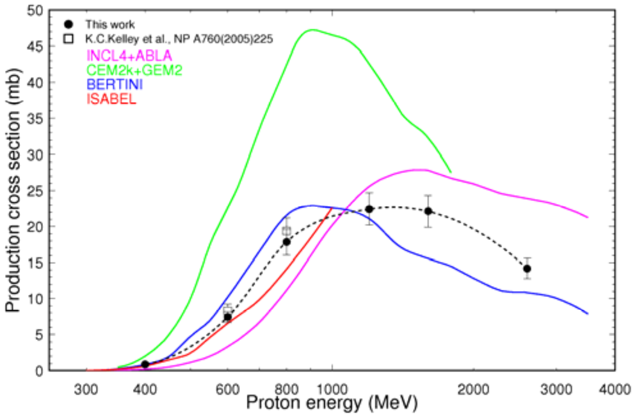
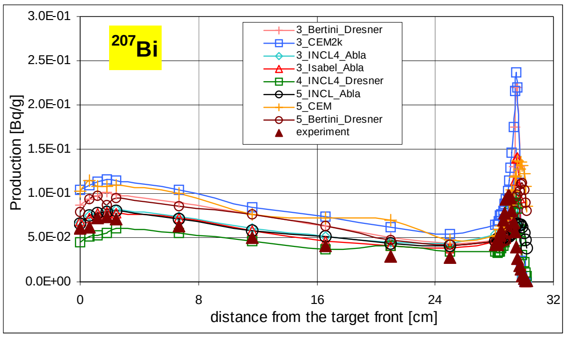


Fig. 9. Experimental and calculated ^{148}Gd production from ^{nat}W(p,x).

7.2. JINR Dubna benchmarks

The first benchmark exercise relying on JINR experimental data was proposed by the AGH University of Science and Technology, Kraków, Poland, is based on lead target irradiation experiments performed at JINR's Dzhelepov Laboratory of Nuclear Problems of the Joint Institute of Nuclear Research Dubna. The measurements consisted in determining the axial distribution of long-lived residual isotopes production rates in 32 lead samples irradiated over 530 minutes with 660 MeV protons. The description and specifications of the benchmark are given in Pohorecki et al., 2008. First results (see Fig. 10, results obtained for 4 residues) obtained by the CRP participants for the production rates show rather large discrepancies between experimental and calculated values. A somewhat better agreement is obtained for heavier residues (A>170, e.g. Au).

The second JINR benchmark is based on experiments carried out at the Veksler and Baldin Laboratory of High Energies. The experiments are performed in the GAMMA-2 target, an experimental facility for the measurement of integral data from transmutation reactions of spallation neutrons that are produced by high-energy protons (0.53–7.4GeV) in a lead target and then partially thermalised in a



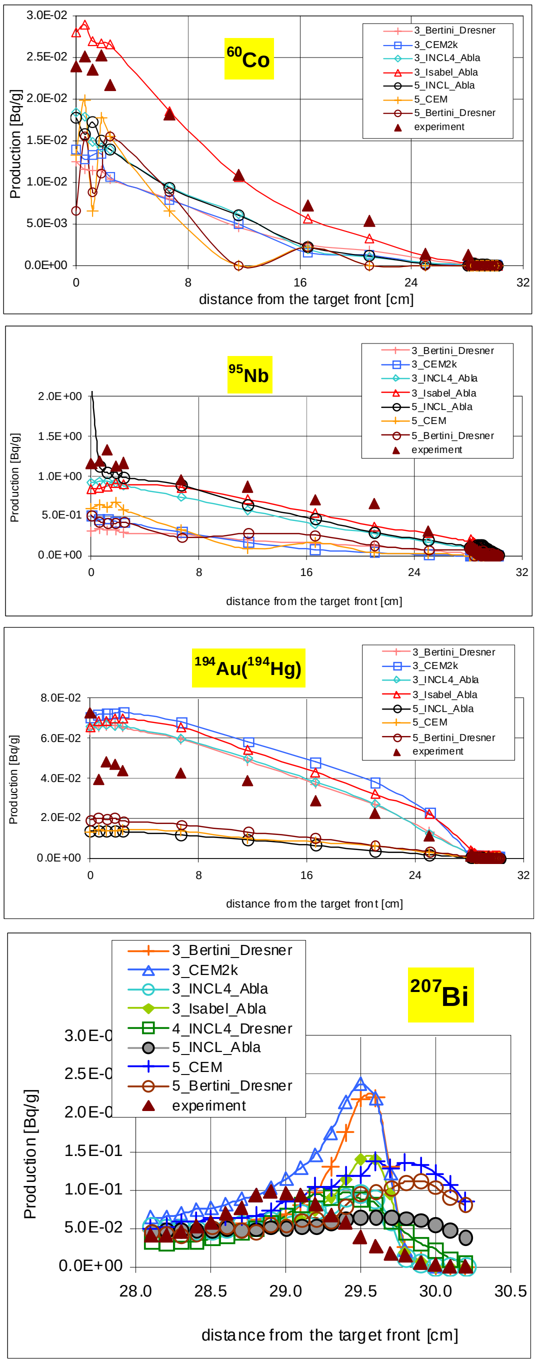


Fig. 10. Calculated and measured ^{207}Bi, ^{60}Co, ^{95}Nb, and ^{194}Au (^{194}Hg) production rates.

paraffin moderator. The CRP participants are computing ^{129}I and ^{237}Np reaction rates, and the spatial distribution of low-energy neutrons, which is measured using the indicator nuclide ^{139}La. The GAMMA-2 target is a lead (96% Pb and 4% Sb) core of 8 cm diameter and 20 cm length. The lead core is surrounded on all sides by a 6 cm thick layer of pure technical paraffin $(CH_2)_n$ which was molten into two half-shells to surround the lead core. The total proton fluence in each experiment was determined using the monitor reaction ^{27}Al(p,3pn)^{24}Na in an aluminium foil of 31 µm thickness (Westmeier et al., 2005). Five ^{139}La samples in the form of $LaCl_3*7H_2O$ are placed on top of the surface of the paraffin moderator, and a ring of 6 samples around the paraffin shell at the position of the second top sample. The ring of samples served for control/correction of the azimuthal neutron anisotropy. The first sample sits exactly over the front of the lead target where the beam impinges onto it, and distances between samples are 50 mm. Reaction rates were measured as B-values defined as B(^{140}La) = Number of atoms of ^{140}La produced in 1 g of ^{139}La sample material per 1 primary proton. In each experiment radioactive samples of ^{129}I and ^{237}Np were irradiated on the surface of the paraffin moderator shell and neutron capture reaction rates were measured.

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