EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

REACTOR DOSIMETRY: ACCURATE DETERMINATION AND BENCHMARKING OF RADIATON FIELD PARAMETER, RELEVANT FOR PRESSURE VESSEL MONITORING (REDOS)

CONTRACT N° FIKS-CT-2001-00120

'REDOS' Final Report
(short version, December 2004)

REDOS-P(06)-Issue 1

Dissemination level :

NON CO: Non Confidential. Publishable Final Report

Table of Contents

Reactor Dosimetry: Accurate Determination and Benchmarking of Radiation Field Parameters, relevant for Pressure Vessel Monitoring (REDOS)

A. Ballesteros[1], B. Böhmer[2], B. Ošmera [3], A. Keresztúri[4],
K. Ilieva[5], B. Acosta [6], V. Smutný [7], E. Polke[8], S. Zaritsky[9], P. Ortego[10]

Shared Cost Action / FIKS-CT-2001-00120

1) Tecnatom, Madrid, Spain
2) FZ Rossendorf, Dresden, Germany
3) Nuclear Research Institute, Řež, Czech Republic
4) AEKI, Budapest, Hungary
5) INRNE, Sofia, Bulgaria
6) JRC-IE, Petten, The Netherlands
7) Škoda, Plzen, Czech Republic
8) Framatome ANP GmbH, Erlangen, Germany
9) Kurchatov Institute, Moscow, Russia
10) SEA, Madrid, Spain

SUMMARY

The REDOS project aims to improve reactor dosimetry for radiation embrittlement monitoring of the reactor pressure vessel (RPV) steels. Benchmarking, as well as combined experimental and computational techniques, have been used. Specific objectives were the improvement of the neutron-gamma calculation methodologies through the LR-0 engineering benchmarks for WWER-1000 and WWER-440 reactor types, and the accurate determination of radiation field parameters in the vicinity and over the thickness of the RPV.

The REDOS project started in November 2001 and had a duration of three years. This project was executed under the multi-partners research contract REDOS, cofinanced by the European Commission under the Euratom Specific Nuclear Fission Safety Programme 1998-2002.

A review of the available experimental reactor dosimetry data of Kozloduy Units 1, 4, 5 was performed, and attenuation coefficients through the vessel wall were calculated. Existing data for the WWER-440 and WWER-1000 Mock-ups were reviewed and the preparatory work for subsequent measurement and experimental data analysis was carried out. Measurements of the space-energy distribution of the mixed neutron-gamma field in the WWER-1000 model over the RPV simulator were performed. The most important improvements in the experimental techniques used were the multiparameter spectrometer and a new low noise precise monitoring system in the LR-0 reactor, developed for this type of measurements.

For the WWER-1000 Mock-up and two WWER-440 Mock-ups, and for all positions where measurements were carried out, neutron-gamma transport calculations were performed independently by the project partners using deterministic and/or stochastic codes and associated nuclear data libraries, mostly based on ENDF/B-VI. The calculated neutron and gamma flux integrals, DPA-rates and spectra were compared with each other and with experimental values. More than eight different calculational schemes were used, covering the most important methods used for pressure vessel dosimetry and shielding.

Results of RPV attenuation calculations for WWER-440s and WWER-1000s were obtained. A comparison between Western and Eastern attenuation results was carried out The neutron/fluence (E>0.5 MeV) wall attenuation for WWER-440 and WWER-1000 RPVs is slower than the dpa attenuation. This means that fluence above 0.5 MeV is more conservative approach than the use of dpa. The application/extrapolation of the WWER mock-ups results to power reactors was considered. The attenuation through the RPV of the neutron flux/fluence with energy above 0.5 MeV was determined. The relative difference value does not exceed 10% for WWER-440. The relative difference value does not exceed 10% for WWER-1000 too, except at the position behind the RPV wall.

A. INTRODUCTION

The neutron exposure of the reactor pressure vessel and reactor internals is one of the key factors that should be quantified reliably when assessing the lifetime of these components. Irradiation embrittlement is the most important damaging mechanism in the RPV life evaluation. Despite improvements in the calculation of neutron field parameters with the corrected cross section values, remarkable discrepancies exist between calculated and measured values, especially in interfaces iron-water and in ex-vessel positions. To solve these difficulties and discrepancies the experimental and computational techniques should be combined.

The current procedure for predicting the degree of the reactor pressure vessel material degradation takes into account neutron irradiation only. Recent results of material research have shown that gamma irradiation may substantially contribute to radiation embrittlement, and therefore combined neutron-gamma calculations are needed.

Since the diameter of WWER type RPVs was limited by the requirement for its railway transport to the NPP, the neutron exposure is relatively high, and the reliability of reactor dosimetry plays a very important role in WWER plant life management.

B. WORK PROGRAMME

The project started up with a review of existing data, namely with the WWER-440 and WWER-1000 engineering benchmark experimental data, and NPP data relevant for attenuation coefficients through the pressure vessel wall. The experimental activity (WP-2) was focussed on gamma-ray spectra measurement and extended neutron spectra measurements in a mock-up in the LR-0 reactor (figure 1), to create a 3D (three dimensional) benchmark in the vicinity of a RPV simulator (WWER-1000 engineering benchmark). Neutron and gamma transport calculations were planned for the WP3. The analysis of the benchmark data obtained with experimental and calculational methods was carried out jointly by the project partners. The results of WP-4 provided accurate information on the neutron-gamma exposure parameters through the thickness of the RPV, where important changes in neutron-gamma spectrum are expected.

In summary, the project was divided in four work-packages. Namely,

Work-package 1: Review of available experimental data.
Work-package 2: Experimental programme in the WWER-1000 Mock-up.
Work-package 3: Analytical area. Neutron and gamma transport calculations.
Analysis of the calculated and measured data.
Work-package 4: Determination of radiation field parameters in the vicinity of and over the thickness of the RPV. Study of the applicability of the mock-up results to power reactors.

C. MAIN ACHIEVEMENTS

REDOS Work-package 1 (references [1] to [5]):

WP1 constitute the basis to develop the subsequent work packages. The results of the WWER-440 Mock-up No. 1 and No. 2 experiments in the LR-0 Reactor were collected. The mock-ups were assembled in the LR-0 experimental reactor. The differential neutron energy spectra were measured in a previous project at the crucial positions of the WWER-440 simulator. The measured spectra are presented in the SAILOR group format together with the uncertainties. In order to facilitate the comparison of the calculated and measured data in mock-ups and in power reactors, the integral fluxes and space-energy indices (ratios of different integral fluxes in the measuring points) were also evaluated. The core power pin-by-pin distributions were calculated with Moby Dick code (Czech WWER-440 standard code) supported by WIMS-D4 code for input cross-section data.

A review of the existing data for the WWER-1000 Mock-up (neutron spectra, distribution measurements, etc.) for WP3, and the performance of the preparatory work for subsequent measurements and experimental data analysis (WP2) was carried out. The WWER-1000 pressure vessel simulator consists of four 5 cm thick steel layers, which can be successively moved in radial direction in order to form an additional air gap layer of 65 mm width for the spectrometric measurements over the pressure vessel thickness.

Collecting of the NPP experimental data was performed for later use in WP4, specially 54Mn activity measurement from scraps taken out from the inner wall and activity of the ex-vessel detectors (iron, copper, niobium) placed in the air cavity behind the vessel of unit 1 (WWER-440/230) of Kozloduy NPP. Geometry description and material specification have been reported for Unit 1 (WWER-440), Unit 4 (WWER-440) and Unit 5 (WWER 1000) of Kozloduy NPP. Measured specific activities, reaction rates and effective activation cross-sections of the ex-vessel detectors, irradiated in the vicinity of the reactor vessel, have been reported for 18th cycle of Unit 1, 13th and 14th cycles of Unit 4 and 5th and 6th cycles of Unit 5. The ASYNT method, based on the three-dimensional adjoint solution of neutron transport equation, was applied for calculational determination of detector activity, reaction rate, and effective activation cross-section. Comparison of measured and calculated results for cycles 15-18 of Unit 1, cycle 13-14 of Unit 4 and cycle 4-5 or Unit 5 was performed.

REDOS Work-package 2 (reference [6]):

The WWER-1000 model was assembled in the LR-0 experimental reactor in the Nuclear Research Institute Rez, and put into operation in order to measure the gamma ray and neutron spectra to complete the existing neutron data. The photon and neutron spectra were measured simultaneously with a stilbene scintillator and the multiparameter technique. The thermal neutron flux was measured in several points with the 3He miniature chamber. All results were evaluated as absolute values per pulse of the fixed monitor of the LR-0 reactor power. The monitor, that is located outside the LR-0 core, relates to the core power via absolute thermal flux measurements with gold foils in the central channel in the central plane of the core.

The spectra was measured before the RPV, at the 1/4, 1/2, 3/4 positions of its thickness and behind the RPV simulator in the energy range ~ 0.5 - ~ 10 MeV. The measured data consist of integral data – ratios of integral photon and neutron fluxes in the measured points and differential neutron and photon spectra in the measured fine structure and in the BUGLE energy group format.

The azimuthal distribution of the neutron flux above 1 MeV in the point 3 (before the RPV simulator) is given in the Table 1, and the azimuthal mapping setup is showed in the Figure 2. The azimuthal distribution of the integral neutron flux above 1 MeV in the point 3 is measurable, nevertheless the standard deviations are relatively high (8-12%). The ratio of the photon flux above 1 MeV and the fast neutron flux is presented in the Table 2. The photon spectrum at the one quarter position of the RPV simulator is shown in the Figure 3.

REDOS Work-Package 3 (reference [7]):

The peculiarities of this project distinguishing it from similar benchmark intercomparisons are the comparison of not only integral values but also of neutron and gamma spectra, as well as of thermal neutrons connected with a realistic modelling of the WWER-reactor RPV environment.

The following three Mock-ups were considered:

1. WWER-1000 Mock-up: WWER-1000 with a simple core loading.
2. WWER-440 Mock-up No 1: WWER-440 with “standard” core loading, with the core simulating the “steady – state” power distribution (after several fuel cycles), and with maximum leakage neutron flux density along the Mock-up symmetry axis.
3. WWER-440 Mock-up No 2: WWER-440 with dummy steel assemblies at the core boundary, with minimum leakage neutron flux density along the Mock-up symmetry axis.

For the WWER-1000 Mock-up and the two WWER-440 Mock-ups and for all positions, where measurements had been performed, neutron-gamma transport calculations were performed independently by the participants using deterministic and/or stochastic codes and associated nuclear data libraries, mostly based on ENDF/B-VI. The calculated neutron and gamma flux integrals, DPA-rates and spectra were compared with each other and with experimental values. Seven institutions from 5 countries (Bulgaria, Czech Republic, Germany, Hungary and Spain) delivered calculation results for the WWER-1000 Mock-up, six institutions from 4 countries performed calculations for one or both WWER-440 Mock-ups.

More than eight different calculational schemes were used, covering the most important methods used for pressure vessel dosimetry and shielding. The codes used were the stochastic codes MCNP and TRAMO and the deterministic codes ANISN/DORT and TORT. They were associated with different data libraries and data preparation schemes. The BUGLE 47n/20g group structure was used for comparisons of calculated spectra as well as for comparison with experimental spectra. Figures 4 and 5 are examples of comparison of results obtained by different benchmark participants. Some of them compared also calculation results with those obtained from the experiments in a finer group structure.

The comparison of the different calculation results showed considerable discrepancies for the calculation of absolute flux spectra normalized to one source neutron per second in the core for thermal neutrons and photons. The attenuation coefficients and spectra related to the spectrum in a special point had slightly lower discrepancies. The measured spectra and attenuation coefficients agree mostly with the calculated values within the limits of experimental and calculational errors. Considerable discrepancies are found for the gamma to neutron relation at the outer surface of the barrel (point 2). The neutron attenuation through the RPV tends to be calculated somewhat too small.

The uncertainties of the calculations were evaluated on the basis of the dispersion of the participants results, of the discrepancies between calculated and measured results and of the scattering of results obtained with different data libraries and data treatment procedures.

REDOS Work-Package 4 (references [8] and [9]):

The values of the relative integral neutron flux/fluence for E>0.5 MeV, 1 MeV, displacements per atom dpa, and effective fluence at different places through the vessel wall of

WWER-440/230 type of reactors, for standard and dummy cassettes loadings, as well as for WWER-1000 type of reactor were calculated. The values of the approximation exp(-0.24x) according to the formula given in the American Regulatory Guide 1.99 revision 2 was also determined.

As it is seen from the results the flux/fluence (E>0.5 MeV) attenuation through the WWER-440 and WWER-1000 RPV is slower than the dpa attenuation. This means that the fluence with energy above 0.5 MeV is more conservative approach than the use of dpa. Figure 6, developed for WWER-1000 Units, shows a similar attenuation behaviour to Western PWRs. That means, the dpa and effective neutron fluence approaches show a lower attenuation than the neutron fluence greater than 1 MeV. The American standard ASTM-E900-02, which uses the DPA concept for the RPV wall attenuation, cannot be applied to the Russian formula for evaluation of the reference temperature shift ΔTK.

The conformity between the WWER Mock-ups and WWERs Nuclear Power Plant results was considered. The calculated RPV attenuation values for the neutron flux with energy above 0.5 MeV were compared. The WWER Mock-ups results are compared with those from Kozloduy NPP (WWERs Unit 3, Unit 4 and Unit 5).

It has been stated that the conformity is within 10% for the WWER-440 Mock-up 1 (standard core loading) and the Mock-up 2 (core loading with dummy cassettes).The conformity for WWER-1000 is within 10% for the positions inside the RPV thickness and more than 10% for the position behind the RPV. The higher inconsistency for the position behind the RPV could be explained by the difference in the geometry and material composition of the Mock-up and NPP biological shielding.

For the conformity evaluation the attenuation factor (AF), equal to the ratio of the calculated flux/fluence (with energy above 0.5 MeV) value at the considered position to its value at the position close to the RPV inner wall, was used. The comparison was carried out using the AF values at the level of the seam weld No.4 for WWER-440 and seam weld No. 3 for WWER-1000. The AF relative difference between the results of the LR0 WWER-1000 Mock-up and the corresponding NPP WWER-1000 is presented in the Table 3.

D. DISSEMINATION AND EXPLOTATION OF THE RESULTS

Some of the results achieved in REDOS project were presented at the 11th International Symposium on Reactor Dosimetry, references [10] to [14]. A web page describing the REDOS Project is located at the JRC-IE site on http://ie.jrc.cec.eu.int/ames/relproj/redos.htm. JRC-IE takes care of its maintenance and upgrading. Project partners agreed to publish the project results as an AMES report (EUR report) in the year 2005.

The project results are of high interest for the validation of the methodologies being used by the project partners in their respective national programmes. The REDOS project is a follow up of the MADAM project co-financed by the European Commission under the Euratom specific Nuclear Fission Safety Programme 1994-1998.

E. CONCLUSIONS

Measurements of the space-energy distribution of the mixed neutron-gamma field in the WWER-1000 model over the RPV simulator were performed. The most important improvements in the experimental techniques used were the multiparameter spectrometer and a new low noise precise monitoring system in the LR-0 reactor, developed for this type of measurements.

Final results of the REDOS project is a reduction of the uncertainty in the neutron-gamma field determination in comparison with the current standard, and a complete description of the key field parameters in the vicinity and over the thickness of the RPV wall. The national RPV surveillance programmes will take benefit of these results.

Facing future research, it is recommended to perform neutron and gamma spectra measurements using advanced methods, such as optic fibres and small detectors. Measurements are of special interest in the interface between water and iron where dosimetry measurements and calculations disagree.

References

[1] Report REDOS / R(01) / February 2002 / Issue 1, WWER-1000 Mock-up Experiments in the LR-0 Reactor. Mock-up Description and Experimental Data.

[2] Report REDOS / R(02) / November 2004 / Issue 1, NPP Experimental Data.

[3] Report REDOS / R(03) / December 2002 / Issue 0, WWER-440 Mock-up Experiments in the LR-0 Reactor. Experimental Data.

[4] Report REDOS / R(04) / October 2004 / Issue 1, WWER-440 Mock-up Experiments in the LR-0 Reactor. Mock-up Nº 1 Description.

[5] Report REDOS / R(05) / December 2002 / Issue 0, WWER-440 Mock-up Experiments in the LR-0 Reactor. Mock-up Nº 2 Description.

[6] Report REDOS / R(06) / March 2004 / Issue 1, The Results of Photon Spectra Measurements over the RPV Simulator in WWER-1000 Model (Engineering Benchmark) in the LR-0 Experimental Reactor.

[7] Report REDOS / R(07) / October 2004 / Issue 1, Deep Penetration Benchmarking, Conclusions and Recommendations.

[8] Report REDOS / R(08) / October 2004 / Issue 0, Attenuation through the RPV Wall.

[9] Report REDOS / R(09) / October 2004 / Issue 0, Conformity between LR0-WWER Mock-ups and WWER Nuclear Power Plants Results for RPV Attenuation.

[10] B. Ošmera, S. Zaritsky, "Review of Experimental Data for WWER Reactor Pressure Vessel Dosimetry Benchmarking". Proceedings of the 11th International Symposium on Reactor Dosimetry. Brussels. August 2002.

[11] B. Ošmera, J. Kyncl, M. Mařík, F. Cvachovec, V. Smutný, M. Králík, "Gamma Ray Exposure of WWER-1000 Reactor Pressure Vessel. The Gamma Ray Spectra Measurement in Engineering Benchmark". Proceedings of the 11th International Symposium on Reactor Dosimetry. Brussels. August 2002.

[12] Z. Bures, J. Cvachovec. F. Cvachovec, P. Celeda, B. Ošmera, "Multiparameter Multichannel Analyser System for Characterisation of Mixed Neutron Gamma Field in the Experimental Reactor LR-0". Proceedings of the 11th International Symposium on Reactor Dosimetry. Brussels. August 2002.

[13] S. Belousov, K. Ilieva, D. Kirilova, "Sensitivity Analysis and Neutron Fluence Adjustment for WWER-1000 RPV". Proceedings of the 11th International Symposium on Reactor Dosimetry. Brussels. August 2002.

[14] K. Ilieva, S. Belousov, T. Apostolov, D. Kirilova, B. Petrov, "Evaluation of the Impact of Radial Gradient of Neutron Source in WWER neutron Fluence Calculation". Proceedings of the 11th International Symposium on Reactor Dosimetry. Brussels. August 2002.

Table 1: Relative Azimuthal Distribution of Neutron Flux above 1 MeV in Point 3

Point of Measurement	Neutron Flux with Standard Deviation	Angle [°]
3/0	1 ± 0.08	0
3/2	1.043 ± 0.08	2.5
3/4	1.062 ± 0.13	5.0
3/6	1.087 ± 0.09	7.5
3/8	1.191 ± 0.10	10.0
3/10	1.116 ± 0.09	12.5
3/11	1.097 ± 0.09	13.85

Table 2: Ratio of Photon Integral Flux above 1 MeV
to the Neutron Flux above 1 MeV in the Point 2 – 7

Point	ϕ (γ >1 MeV) / ϕ (n >1 MeV)	Standard deviation
2	5.2	0.21
3	30.40	1.90
4	13.47	0.38
5	7.73	0.14
6	4.79	0.20
7	3.74	0.14

Table 3: RPV AF values relation (WWER-1000 one-dimensional model)

Position	Distance from the inner RPV surface	AF(LR0BS)	AF(WWERBS)	Relative difference, %
0T	0.55	1.000	1.000	0.0
1/4T	5.75	0.733	0.731	+0.3
2/4T	10.25	0.496	0.492	+0.9
3/4T	15.25	0.301	0.293	+2.9
Behind RPV	23.0	0.167	0.150	+11.2

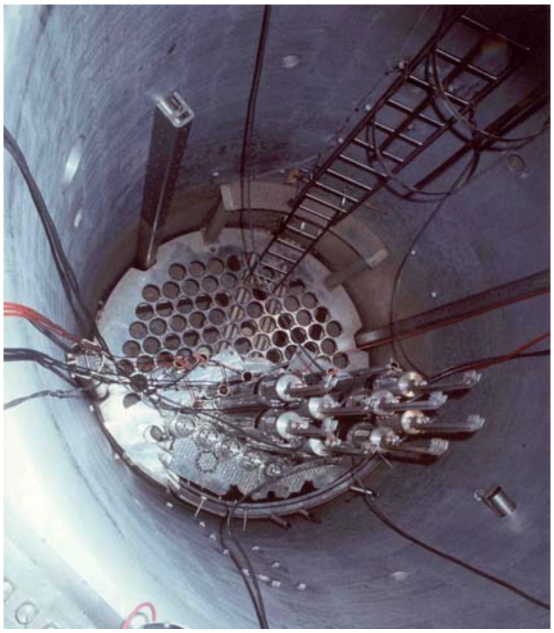

Figure 1: LR-0 reactor

Figure 2: Azimuthal mapping setup

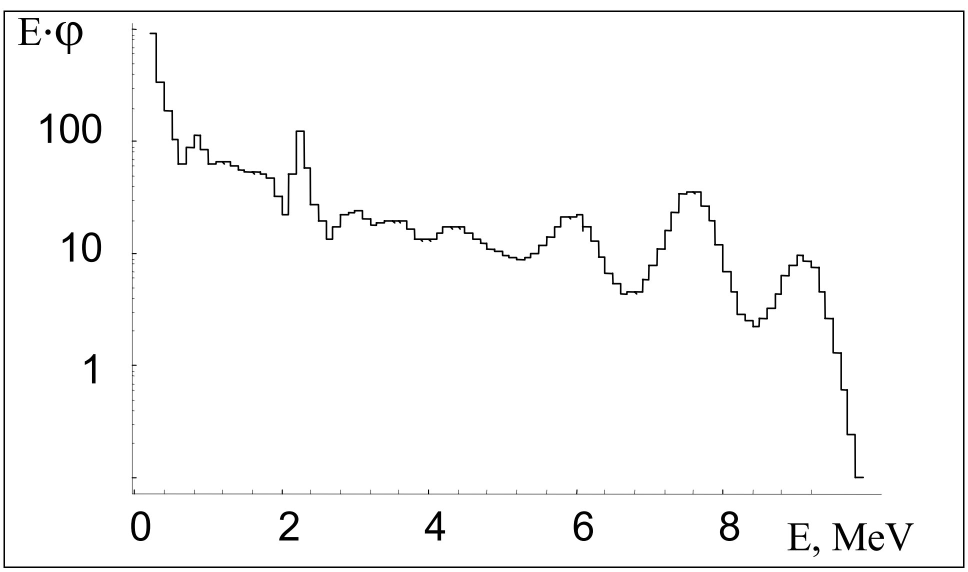

Figure 3: Photon spectrum measured at the one quarter position of the RPV simulator

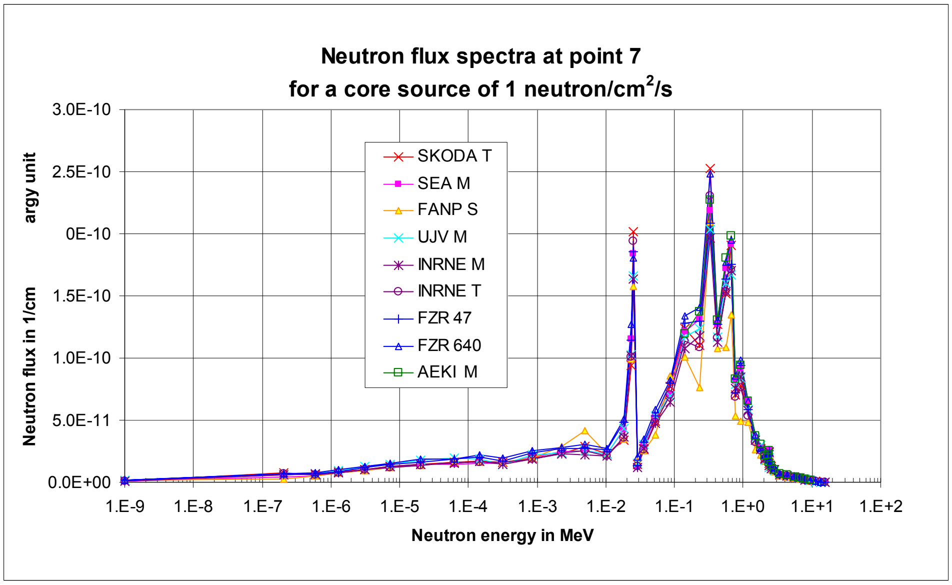

Figure 4: Neutron flux spectra calculated by the participants in point 7 for the WWER-1000 Mock-up

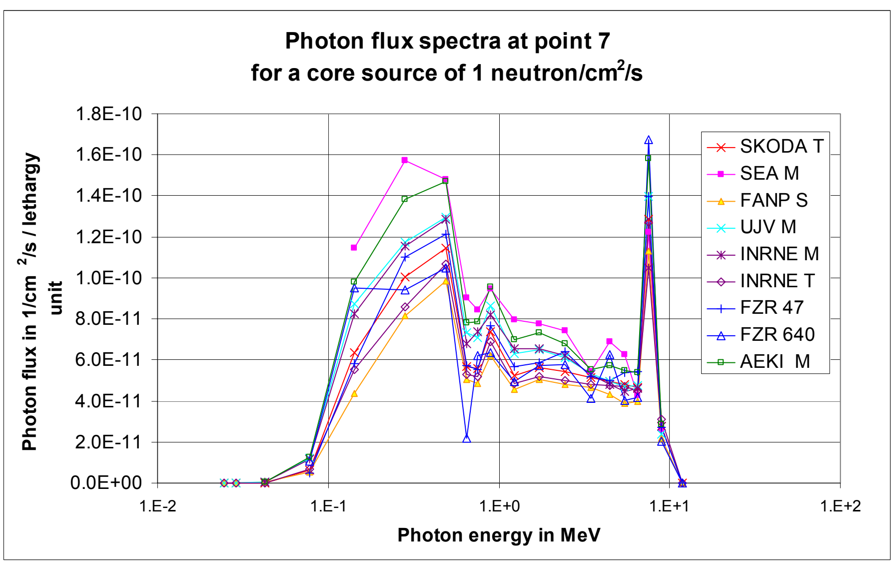

Figure 5: Photon flux spectra calculated by the participants in point 7 for the WWER-1000 Mock-up

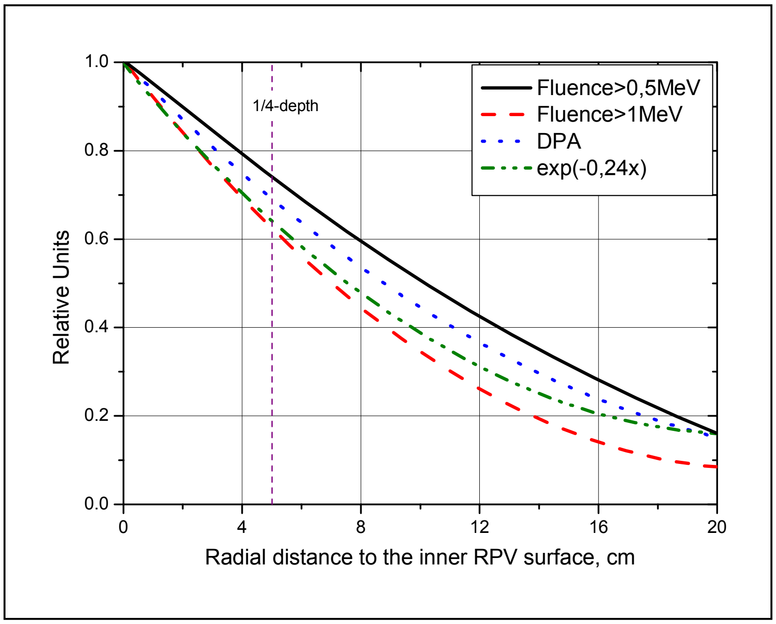

Figure 6: RPV wall attenuation in WWER-1000 RPV