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I N D C INTERNATIONAL NUCLEAR DATA COMMITTEE

Summary Report of the Consultants' Meeting on

Assessment of Nuclear Data Needs for Thorium and other Advanced Cycles

IAEA Headquarters

Vienna, Austria

26 - 28 April 1999

Prepared by
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August 1999

IAEA NUCLEAR DATA SECTION, WAGRAMER STRASSE 5, A-1400 VIENNA

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Abstract

The report summarizes the results of discussions at the Consultants' Meeting on Assessment of Nuclear Data Needs for Thorium and other Advanced Cycles. The requirements to the nuclear data for power systems with Th-U fuel cycles are reviewed and updated. The meeting participants recommended to the IAEA Nuclear Data Section to organize the Co-ordinated Research Project "Nuclear Data for Thorium-Uranium Fuel Cycle" to co-ordinate the activity on national programmes for improvement of the data in accordance with the new requirements.

August 1999

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1. SUMMARY OF THE MEETING

Objectives of the meeting

The objectives of the meeting were the following:

- Brief review of the recent developments under national and international projects related with the designs of nuclear power technologies for the future, based on new or advanced fuel cycles and involving new types of nuclear fuel, providing inherent safety of the nuclear systems, solving the problem of radioactive wastes and being resistant to nuclear proliferation.

- Review of status of the nuclear data available now for use in these projects and formulation of new requirements for the quality and uncertainty of evaluated nuclear data.

- Overview of the present and planned world wide activity in the measurements and evaluation of the data for these projects and formulation of the tasks for the new IAEA Co-ordinated Research Project which will not duplicate the current or planned activity in this field.

- Preparation of a list of institutions which could be potential participants and contributors in this CRP.

Participants' presentations and discussions

The Meeting was opened by V.G. Pronyaev, Scientific Secretary, who gave two main reasons for holding this meeting: high activity of new fuel cycle studies in the Member States and demands in nuclear data for current IAEA programmes on benchmark neutronic calculations for advanced fuel cycle systems. After brief self-introduction of the participants (see list of participants in Annex 2), S. Pelloni was elected chairman.

The participants discussed the meeting's goals and adopted Agenda and Schedule (see Annex 1).

The participants considered the advanced fuel cycles proposed for future nuclear power systems.

R. Srivenkatesan presented some results of the Indian Nuclear Power programme based on thorium utilization. Starting from initial build-up of ^{233}U in thorium bundles introduced in Pressurized Heavy Water Reactors and small research thermal reactor with ^{233}U alloy as a fuel, it comes now to a stage of design an Advanced Heavy Water Reactor which is being optimized for large scale thorium utilization.

Perspective of Nuclear Power for near and remote time scale was evaluated by I. Slessarev depending on the solution of the following problems:

- Reduction of Pu-mass including reactors inventories and wastes;
- Simplification of the fuel cycle (including front and back end);
- Simplification of the structure of nuclear power system;
- Expansion of fuel reserves for long-term scale;
- Non-proliferation of weapons grade materials;
- Natural safety potential realization;
- Waste toxicity reduction;
- Reduction of existing weapon grade materials without important wastes.

Possible solutions of these problems which have public, political, economical and technological aspects were considered through the invention of the advanced fuel cycles. Thermal, fast and accelerator driven nuclear power systems with U-Pu, Th-U, and mixed U-Pu-Th fuel cycles have been evaluated. It was shown that some advanced systems may solve the problems enumerated above. Some of them belong to the systems with Th-U fuel cycle.

General requirements to the nuclear data for power systems with advanced fuel cycles were considered and worldwide experimental and evaluation activity to met these requirements was discussed. The meeting participants had admitted that these requirements are well established for systems with U-Pu fuel cycle and work on measurement and evaluation of nuclear data for nuclides of this cycle (transuranium nuclides especially) is currently conducted under a few national and international programmes. The evaluated nuclear data for major isotopes of this cycle are known with an accuracy which is enough for neutronics and engineering calculations.

The situation is just opposite for nuclear data of the nuclides of Th-U fuel cycle. Most evaluated data files for these nuclides in ENDF/B-VI library were originally prepared for the ENDF/B-IV library and had not been revised since beginning of the seventies. Evaluations in the JENDL-3.2 library are based on experimental data and model calculations of the mid-1980s. Since then much progress was achieved in the model description of the neutron cross sections for fissile and fertile nuclei. New experimental data and useful systematics of the cross sections in the high energy region have started appearing. But for exclusion of benchmark calculations there is not enough co-ordinated activity which has relation to the improvement of these data. The participants decided to focus their attention on the nuclear data for Th-U fuel cycle.

V.G. Pronyaev informed the participants about the experimental and evaluated works which are done, or are going, or planned for nuclides of Th-U fuel cycle. They include planned measurements of major cross sections induced by neutrons of ^{232}Th and ^{233}U on the CERN neutron source, programme of measurements in Europe, measurements done in universities of Japan, current evaluation activity in IPPE, Obninsk, Russia and in CNDC, Beijing, China.

A. Ignatyuk presented results of cross sections evaluation for neutrons with energy up to 150 MeV incident on ^{232}Th. Because the content of ^{232}Th in ADS with Th-U fuel is high and few per-cent neutrons of the spallation source have the energy above 20 MeV, it is important to take into account the contribution of these neutrons in the processes in ADS. For this the evaluated data above 20 MeV are needed at least for Th, coolant and main structural materials.

R. Srivenkatesan presented the current requirements to the nuclear data for advanced thermal reactors with Th-U fuel cycle. The problem of handling of irradiated fuel, particularly the radioactivity arising out of the daughter products of ^{232}U is a serious one. The assessment of the ratio of ^{232}U to ^{233}U and the estimation of the concentrations of the isotopes of the Th-U cycle have been done only on a gross level. The content of ^{232}U in ^{233}U as presently estimated for different installations with thermal neutron spectrum is varied from 3 to 100 ppm, which may impose different conditions on fuel handling operations. The main transmutation chains of Th-U fuel cycle nuclides are shown in Fig. 1 (as taken from Ref. [8] in Annex 3).

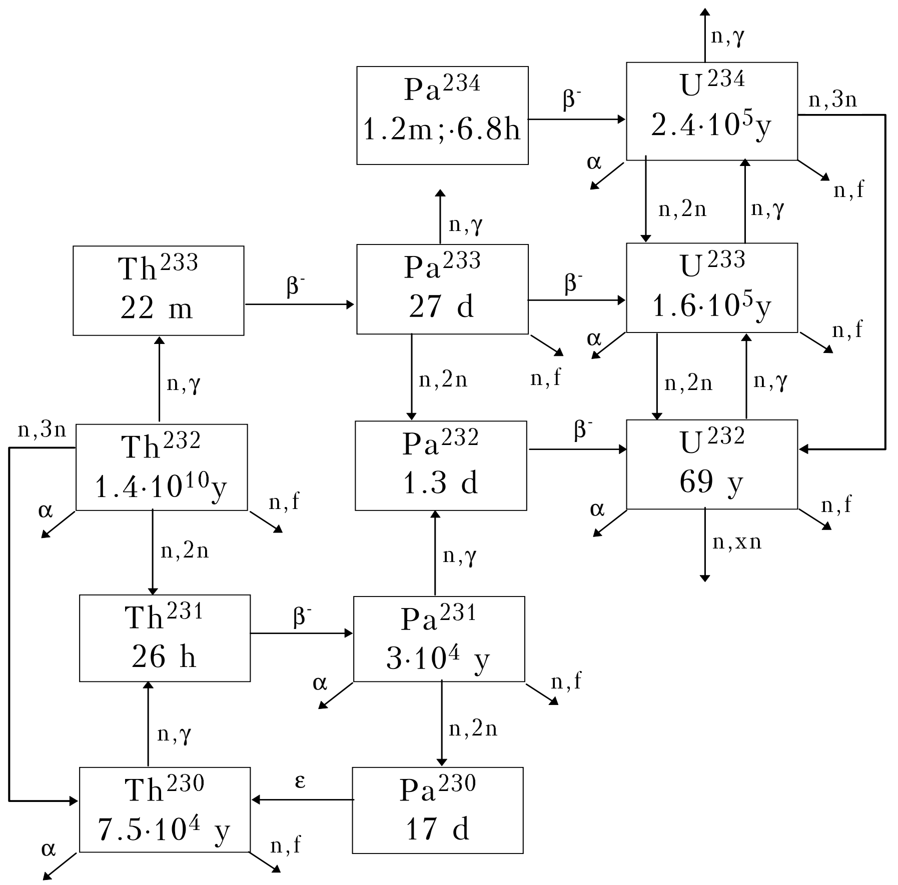

Fig. 1. Scheme of the nuclear transmutations in the Th-U fuel cycle.

For fuel in equilibrium state (with high burn-up) the ^{234}U - ^{235}U - ^{236}U chain should be added. Chains leading to the build-up of ^{232}U includes (n,γ) and (n,2n) reactions with an uncertainty of ^{232}U build-up equally dependent from the uncertainty of (n,γ) and (n,2n) reaction cross sections averaged over the appropriate neutron spectrum.

Requirements for nuclear data for Th-U systems with fast neutron spectra, such as Fast Reactors (FR) and Accelerator Driven Systems (ADS) were evaluated as similar. Although a spallation neutron source has a few percent of neutrons with energy above 20 MeV (upper neutron energy in the standard evaluated data files) the neutronics of the ADS as a whole is determined by the fission processes of nuclei of fissile and fertile materials.

S. Pelloni presented the results of benchmark of fast reactor experiments with thorium, obtained at the Proteus facility in comparison with the results of calculations using data from different evaluated libraries. It was shown that ^{232}Th neutron capture cross section from latest versions of the evaluated libraries probably underestimates the observed capture reaction rate by 5-9%. The importance of the processes of build-up, burn-up and decay of ^{233}Pa for reactivity calculations in ADS with Th-U fuel and approach how to minimize the level of reactivity variation during the reactor campaign were shown.

I. Slessarev reported about results of two benchmark exercises made in framework of the IAEA programme and devoted to the calculations of different integral characteristics and indices in the ADS with Th-U, or transuranium and minor actinide fuel.

The goal of the first benchmark was a verification of reactivity burn-up swing as well as some important reactivity effects for a fast spectrum Th-U ADS with an external, spallation type neutron source at different subcriticality levels. The calculations were done: a) for initial enrichment of the fuel with ^{233}U required to reach k_{eff} = 0.98, 0.96 and 0.94, b) for evolution of the k_{eff} in time, c) for source evolution needed to compensate reactivity during fuel burn-up, d) for neutron source importance and radial distributions of ^{232}Th(n,f)/^{233}U(n,f) spectral index and core power distribution, and e) for void effects and its evolution with burn-up. Different computational schemes and different nuclear constants have been used.

Average dispersion of eleven presented results for ^{233}U initial enrichment (see (a) above) was 1.9% and the difference directly caused by using data from two different evaluated libraries (JEF-2.2 and JENDL-3.2) is 4%. The Pa-reactivity effect (see (b) above) is rather high, - 1.5 - 2% and the maximal reactivity variation (including Pa-effect) in the burn-up region from 0 to 10% was between 1.5 and 3%. The maximal variation in the intensity of the external neutron source required to compensate reactivity in the all burn-up region (see (c) above) was estimated by different participants between 1.4 and 2.5 times. The acceptable agreement of all participant results was obtained for radial distribution of the spectral indexes and core power release (see (d) above). Relatively large dispersion was observed for void effects and its evolution with burn-up (see (e) above). Uncertainty in calculations of many parameters of ADS with Th-U caused by discrepancies in the nuclear data used, appears to be higher than the uncertainty caused by different calculational schemes.

The second calculational benchmark presented by I. Slessarev was aimed at the study of neutronic potential of a modular fast spectrum ADS for radiotoxic waste transmutations. Systems loaded with the discharge of LWR(MOX) transuranium (TRU) equilibrium fuel and with discharge from LWR(MOX+UOX) minor actinide (MA) equilibrium fuel have been considered. The main goal of these studies was the evaluation of maximum rate of waste transmutation, the assessment of minimum TRU and MA mass corresponding to K_{eff}=0.96 and the evaluation of sensitivity of ADS neutron balance to the hardness of the spectrum of the external neutron source. Eight groups participated in this intercomparison.

The results of this benchmark had shown that the critical (near-critical) configurations are predicted with a good accuracy for TRU-fuel and with a much larger error for MA-fuel, both the ^{99}Tc inventory and ^{99}Tc transmutation time are large for given geometry core and blanket, actinide transmutation time is acceptable, uncertainty of neutron leakage from ADS is unexpectedly large. Although the benchmark was not directly aimed at the test of nuclear data, few general conclusions about their quality can be done: (a) data of TRU nuclides contributing in k_{eff} (σ_f, σ_γ cross sections and ν for isotopes of U, Np and Pu) are satisfactory on average, but not for some MA (isotopes of Am and Cm), (b) there is either a drawback in calculational scheme, or in presentation of data, or in data themselves (neutron production cross section and secondary neutron spectra) used by participants, which led to discrepancy in prediction of neutron leakage.

The participants considered the current requirements to the nuclear data of Th-U fuel cycle. Requirement to predict k_{eff} of the systems near their criticality in the limits of 0.5% and build-up of the ^{232}U within uncertainty of 10% was used for estimation of needed accuracy of the data. Because there are no systematical studies of data requirements using the sensitivity calculations, the method of expert evaluation was used to assign uncertainties. Tables 2 and 3 from earlier work (see Ref. [8] in Annex 3) was used as basis for re-assessment of requirements. The tables with requirements prepared by the meeting participants are given in meeting conclusions and recommendations below. ^{232}Th, ^{231,233}Pa, and ^{232,233,234,236}U were included as first priority isotopes. ^{236}U was added in the table because of its build-up in the equilibrium fuel composition. Data for ^{235}U are adequate and there are no new requirements to ^{235}U data related with Th-U fuel cycle.

The required uncertainties of the evaluated cross sections refer to one group, averaged on the spectrum of the system, cross-section value. It could be useful to have a covariance matrix of uncertainty for major cross sections or at least the evaluation of their variances. The half-lives and decay modes determine the build-up of isotopes in the system. The requirements to the accuracy of these data are higher for systems working on equilibrium fuel than for systems with low burn-up campaigns.

The participants discussed the means by which the programme of improvement of nuclear data for nuclides of Th-U fuel cycle can be realized. It was recognized that the IAEA Co-ordinated Research Project (CRP) could be the best mechanism for the participation of all groups that may contribute to the programme. Because the measurements with transactinides are very expensive and this work is partially co-ordinated through some international and national programmes (Neutron Cross Section Measurement Campaign in CERN, GEDEON in EU, Japan programme for Universities accelerator facilities, and possibly in the future through the ISTC project for Russia) the participants recommend limiting the CRP to evaluation activity.

A few groups have been proposed as the potential participants of this CRP, depending from their own priorities in the evaluation work:

– Evaluation group from the Radiation Physics and Chemistry Problems Institute, Minsk-Sosny, Belarus;
– Evaluation Group from the Institute of Atomic Energy, Beijing, China;
– EU Evaluation Group, NEA, France;
– Evaluation Group from BARC, Trombay, India;
– Evaluation group from the Japan Atomic Energy Research Institute (JAERI), Japan;
– Evaluation group from the Institute of Physics and Power Engineering, Obninsk, Russia;
– Nuclear Theory and Applications Group at Los Alamos National Laboratory, USA.

The meeting participants prepared the meeting conclusions and recommendations (see below) with justification for the IAEA CRP with a title: "Nuclear Data for Thorium-Uranium Fuel Cycle" and recommended that the Scientific Secretary submit it for consideration at the 22nd Meeting of the International Nuclear Data Committee.

Meeting conclusions and recommendations

Nuclear power perspective

One solution to the problem of atmosphere pollution by CO_2 (causing the green-house effect) would be a massive increase in the use of nuclear energy. However, before that can happen, some outstanding problems have to be solved such as safety related issues, suitable radioactive waste disposal, and reductions in inventories of weapon-grade plutonium.

Tasks to be solved

In the framework of the current political, social, and environmental requirements, Nuclear Power could contribute in solving some of major issues, such as:

- Reduction of the reactor-grade Pu inventories in storage facilities (processed and unprocessed).

- Reduction of the weapon-grade Pu.

- Proliferation resistant fuel utilization.
- Long lived actinide and fission product waste incineration.
- Improved fuel utilization (high discharge burn-ups).
- Improvement of safety (inherent safety).
- Expansion of fuel reserves for the future.
- Simplification of the fuel cycle to be economically competitive.

Hopes

Innovative fuel cycles such as Th and mixed Th-U offer hope for practical solutions of the above tasks in the near and remote future - especially the first four tasks. Such a fuel cycle can be introduced with different strategies:

- mono stratum (once through/closed cycle);
- double stratum (once through/closed cycle *and* waste transmutation);
- multi-component (once through/closed cycle, waste transmutation *and* reprocessing).

However the development of such a fuel cycle requires considerable efforts in

- technological aspects;
- feasibility;
- accuracy improvements of nuclear data related to the Th cycle.

Current requirement on nuclear data

Data requirements related to three main directions of thorium fuel use in: (i) thermal neutron reactors, (ii) fast neutron reactors and (iii) accelerator-driven subcritical systems, were considered. New concepts of modern power-system designs (the Pu-mass reduction, the long-lived nuclear waste reduction, the nonproliferation of weapon-grade materials, and so on) have required to review some previous estimations of the accuracy of needed nuclear data.

For the thermal reactors the following requirements to the data accuracy (in %) are established:

Data	Th-232	Pa-231	Pa-233	U-232	U-233	U-234	U-236
(n,γ)	1	10	5	10	5	3	-
(n,f)	-	-	-	10	1	-	20
(n,2n)	5	-	-	-	5	-	-
$<\nu_p>$	-	-	-	-	1	-	-
$<\nu_d>$	-	-	-	-	3	-	-
fission product yields*)	-	-	-	-	5	-	-

*) - uncertainty in the neutron consumption by all fission products has to be in these limits.

It seems that the experimental data available now satisfy to these requirements for all capture cross sections and probably for fission cross sections of U-233 and U-236 but all other data are needed in new measurements.

For the fast reactors and accelerator-driven systems the neutron spectra are rather similar and the corresponding data are required with the following accuracy (in %):

Data	Th-232	Pa-231	Pa-233	U-232	U-233	U-234	U-236
(n,γ)	1-2	10	3-10	50	3	5	10
(n,f)	5	20	20	20	1	3	5
(n,n’)	5	-	-	-	10	10	20
(n,2n)	5	50	30	-	5	15	20
(n,3n)	-	-	-	-	-	15	-
total	3	-	-	-	3	5	5
(n,p) and (n,a)	20-30	-	-	-	20-30	20-30	-
$<\nu_p>$	5	-	-	-	1	3	5
$<\nu_d>$	5	-	-	-	3	5-10	50
fission product yields	5	-	-	-	5	10	20-30

Conclusions

The participants came to the following conclusions:

- There is a growing world wide interest for advanced nuclear power technologies of the future involving new types of nuclear fuel, providing inherent safety, being resistant to nuclear proliferation, reduction of weapon grade plutonium and solving the problems of radioactive wastes.

- The Th-U cycle is the most prospective one which meets the above goals.

- There is an activity in the measurements and evaluation of nuclear data for nuclides of the Th-U fuel cycle in different countries which presently is not closely co-ordinated.

- The nuclear data for nuclides of the Th-U fuel cycle have been evaluated in the early seventies and middle of the eighties and do not fulfill the current accuracy requirements. While the experimental and evaluation activities of nuclear data of the U-Pu cycle have been investigated and re-evaluated in recent years, similar co-ordinated efforts need to be undertaken for the Th-U cycle as well.

Recommendations

The participants recommend to the IAEA the following:

1. The Nuclear Energy Department of the IAEA has some programmes which are aimed at the investigation of parameters of systems based on Th-U cycle with participation of many countries. It was shown that a large part of uncertainties in the prediction of such parameters is related to uncertainty in nuclear data. We encourage this activity and propose to estimate in more details what variances of the nuclear data are responsible for the discrepancies observed. We would appreciate it if some simplified benchmark exercise for further tests of nuclear data could be initiated.

2. We recommend that the Nuclear Data Section should, as soon as possible, organize the **Co-ordinated Research Project "Nuclear Data for Thorium-Uranium Fuel Cycle"** to co-ordinate the activity of national programmes to the essential improvement of the data in accordance with the accuracies as requested above (see Tables).

2. ANNEXES

Annex 1: Agenda and time schedule

Monday, 26 April 1999

09:30 a.m. **1. Introductory Items**
- Opening statements;
- Election of meeting chairman;
- Review of meeting goals;
- Adoption of the agenda.

10:00 a.m. **2. Review of the advanced fuel cycles**
- CANDU reactors with new fuel cycles;
- Thermal reactors with ^{233}U-Th fuel;
- HTGR with Th-U cycle;
- Seed-blanket thermal (RTR) reactors with thorium;
- Fast reactors with mixed cycle and breeding of ^{233}U and ^{239}Pu;
- Accelerator driven systems with Th-U fuel cycle;
- BREST - the next generation of fast reactors with a closed fuel cycle;
- Other cycles.

11:30 a.m. **3. Review of the general requirements to the data and existing world wide activities to satisfy these requirements**
- Review of the data needed for different fuel cycles;
- World wide current and planned experimental activity;
- General review of the current world-wide data evaluation efforts;
- Selection of the items which may form the IAEA Co-ordinated Research Project (CRP) on Improvement of Nuclear Data for Advanced Fuel Cycles.

01:00 p.m. Lunch

02:00 - 06:00 p.m. **4. Review of the results of the benchmark calculations and experiments for systems with advanced fuel cycles**
- Intercomparison of evaluated data from different evaluated nuclear data libraries for nuclides important for advanced fuel cycles;
- Discrepancies in prediction of the integral characteristics due to use of different evaluated data sets;
- Results of benchmark experiments for the nuclides of the advanced fuel cycles.

Tuesday, 27 April 1999

09:00 a.m.	**5.**	**Formulation of the requirements to the nuclear data of the advanced fuel cycles** Preparation of the first priority nuclides list; Requirements to the partial cross sections and their uncertainties; Requirements to the decay data and their uncertainties.
01:00 p.m.		Lunch
02:00 - 06:00 p.m.	**6.**	**Preparation of the proposal for CRP on nuclear data for advanced fuel cycles** Formulation of the CRP title; Proposals to the list of the potential participants of the CRP and their possible contribution; Preparation of the detailed tasks which will be solved through CRP and its time schedule.

Wednesday, 28 April 1999

09:00 a.m. - 06:00 p.m.	**7.**	**Preparation of the Meeting Summary Report and Working paper with CRP proposal for consideration at the INDC Meeting (11 - 14 May 1999).**

Annex 2: List of participants

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Annex 3: List of papers distributed during the meeting

1. A.V. Zvonarev et al., “The Research of Thorium Samples Irradiated in the Fast Neutron Reactor Radial Blanket and in Graphite Type Reactor Thermal Spectrum”, paper presented at the 1998 Russian-Indian Seminar on Thorium Fuel, Obninsk, November 1998.

2. V.I. Golubev, A.V. Zvonarev, G.N. Manturov, Yu.S. Chomiakov, A.M. Tsiboula, “Integral Experiments on Fast Critical Assemblies and Reactors for Substantiation of U-Th Cycle”, paper presented at the 1998 Russian-Indian Seminar on Thorium Fuel, Obninsk, November 1998.

3. S. Ganeshan and P.K. Maclaughlin, “Status of Thorium Cycle Nuclear Data Evaluations: Comparison of Cross Section Line Shapes of JENDL-3 and ENDF/B-VI Files for ^{230}Th, ^{232}Th, ^{231}Pa, ^{233}Pa, ^{232}U, ^{233}U and ^{234}U”, Report INDC(NDS)-256, IAEA, Vienna, Austria, 1992.

4. M.F. Troyanov et al., “Some Investigations and Developments of the Thorium Fuel Cycle”, Atomic Energy, Vol. 84, No. 4, p. 225 - 229.

5. V. Arkhipov , V. Onoufriev, “IAEA Activities Related to the Th-U Fuel Cycle”, paper presented at the International Seminar in Sarov, Russia, 22-25 June 1998.

6. E. Adamov, V. Orlov, A. Filin et al., “The Next Generation of Fast Reactors”, Nucl. Eng. and Design, 173 (1997) 143.

7. H.J. Rütten (Compiled), “Results of the Benchmark No. 1: ‘Calculation of the Isotopic Composition, Cross-sections, and Fluxes for a Typical PWR-cell with (Pu-Th)O_2-fuel, as a Function of Fuel burn-up’”, Report on CRP on the Potential of Th-based Fuel Cycle to Constrain Pu and to Reduce Long-term Waste Toxicities, 1996, unpublished.

8. B.D. Kuzminov, V.N. Manokhin, “Status of Nuclear Data for the Thorium Fuel Cycle”, Report INDC(CCP)-416 (1998) 1.

9. I. Slessarev, A. Tchistiakov, “IAEA-ADS Benchmark (Stage 1). Results and Analysis”, presented on TCM on Feasibility and Motivation for Hybrid Concepts for Nuclear Energy Generation and Transmutation, Madrid, Spain, 17-19 September 1997.

10. I. Slessarev “IAEA Benchmark 2.1. Study of a Neutronic Potential of a Modular Fast Spectrum ADS for Radiotoxic Waste Transmutation”, Draft on 30 November 1998, presented in the RCM of the IAEA Co-ordinated Research Project on “Use of Th-based Fuel Cycle in Accelerator Driven Systems (ADS) to Incinerate Pu and to Reduce Long-term Waste Toxicities”, NRG, Petten, The Netherlands, 2-4 December 1998.

11. V. Maslov, Y. Kikuchi, “Statistical Model Calculations of the ^{232}U Fission Cross Section”, Nucl. Sci. Eng., 124 (1996) 492.

12. M. Lang, O. Gremm, “Perspectives of the Thorium Fuel Cycle”, Nucl. Eng. and Design, 180 (1998) 133.

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