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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

THE RUSSIAN
NUCLEAR DATA RESEARCH PROGRAMME

Atomic Energy Ministry of the Russian Federation

Nuclear Data Committee
State Scientific Centre
Institute of Physics and Power Engineering

Obninsk
1995

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Abstract

The report contains the Russian programme of nuclear data research, approved by the Russian Nuclear Data Committee on 16 December 1994. It gives surveys on nuclear data needs, on the structure of nuclear data activities, on experimental facilities for nuclear data measurements at five Russian institutes, on theoretical model work, nuclear data evaluation, and nuclear data testing. It describes four Russian nuclear data centers and their relations to the International Nuclear Data Centres Network, and their holdings of nuclear data libraries of Russian and international origin. A summary of nuclear data applications in energy and non-energy fields is given. An appendix contains a detailed nuclear data research programme for the years 1995 - 2005.

Translated by the IAEA from a Russian report (without report identification) entitled "Programma Perspektivnykh Issledovanij po Jadernym Dannym", Obninsk 1995.

Contents

The present programme has been prepared, on the instructions of the Ministry of the Russian Federation for Atomic Energy (MAE), by a working group of the Nuclear Data Committee (NDC) consisting of:

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The programme was considered and approved by the Nuclear Data Committee at its meeting held on 16 December 1994.

INTRODUCTION

Nowadays nuclear transformations have a broad range of applications in a number of sectors of the economy and in science.

They include:

- Nuclear power engineering (fission reactors, fusion reactors and radioisotope sources);

- Transmutation of nuclides (radioisotope production for medical and other applications and burning of long-lived radionuclides);

- Industrial nuclear instruments (activation analysis, nuclear microanalysis, monitoring of fissionable materials);

- Scientific research (fundamental nuclear physics, nuclear astrophysics, radiobiology, agricultural radiology, ecology, etc.).

Design calculations and predictions of the operating process of nuclear facilities for various purposes are based on fundamental constants which characterize the properties of nuclear reactions, the structure of nuclei and radioactive decay properties. The radiation and nuclear safety, and the ecological acceptability of nuclear facilities depend on the completeness and quality of the nuclear data used in calculations for these facilities.

Nuclear data are an integral part of nuclear technology fundamentals. Considering the vast economic scope of the industries which use nuclear data and the major role played by nuclear data in the various steps of development of these industries, we can conclude that financial resources expended on nuclear data activities represent an exceptionally effective form of national investment.

Updating, enlargement of the volume and improvement of nuclear data raise the cost-effectiveness of the operating nuclear facilities by reducing design margins without detriment to the necessary level of safety, providing the current designs with reliable nuclear data and decrease the time lag in providing data for the nuclear technology of the future.

Nuclear technologies involve processes based on the most diverse nuclear transformations for more than 500 stable and radioactive nuclides with incident particle energies ranging from hundredths of an eV to several GeV.

The national resources earmarked for nuclear data activities in Russia are not sufficient to obtain high-quality data to describe the entire spectrum of nuclear interactions in the above energy region. The same is also true in other countries.

As a result, there has been a natural gravitation towards international co-operation in nuclear data activities. International collaboration takes place both under the aegis of the IAEA and in the form of bilateral agreements. International exchange of experimental and evaluated nuclear data, participation in international nuclear data projects, joint experimental and theoretical work all considerably increase the volume of accessible information on nuclear data for each collaborating country, create the conditions for objective evaluation of the nuclear data quality and provide the means of utilization of data which cannot be obtained in national laboratories for lack of the appropriate experimental capability.

International nuclear data activities are stimulated by the similarity of national needs and problems in the field of nuclear data. Any difference stems mainly from priorities associated with the specific requirements of national programmes in the field of nuclear technologies.

The generation of nuclear data is a complex scientific process demanding highly-qualified manpower and precision instruments.

The time is now ripe for developing a co-ordinated, scientifically justified programme of work on nuclear data to resolve current or short-term problems and to provide future advanced technologies with nuclear data. A joint programme will help to keep costs to a minimum, identify priority tasks, provide access to a world bank of nuclear data and preserve a minimum of scientific potential and the experience and knowledge gained over decades in the field of nuclear data. Programmes of this type have recently been prepared in the USA and, independently, in Western Europe, and aspects of these programmes which are of relevance to Russia have been used in preparing our national programme.

The creation of a nuclear database as part of a single State programme will help to control the quality of the nuclear data provided to the various users and to ensure that the systems of constants used in technical designs conform to international standards.

The following sections make a survey of the status of investigations in the area of nuclear data in Russia, highlighting its place in the world community and identifying the range of strategical problems in this area whose solution is essential for further development of nuclear technology.

I. STRUCTURE OF NUCLEAR DATA ACTIVITIES

There are several types of nuclear data:

- Differential experimental nuclear data characterizing nuclear interactions for basic research;

- Reference or standard nuclear data, which are measured with particular care and precision;

- Theoretical data, based on model calculations;

- Integral nuclear data characterizing the overall effect of several types of nuclear interaction in different media, or differential characteristics averaged over a wide energy spectrum;

- Evaluated nuclear data obtained on the basis of both experimental data and theoretical models of nuclear reactions;

- Problem-oriented data.

The main purpose of nuclear data activities is to create a universal library of evaluated nuclear data which can be used as basic data to meet the specific requirements of various nuclear technologies.

Figure 1 shows the organizational chart of nuclear data activities, as evolved over several decades. This pattern will evidently remain valid also for the foreseeable future, since elimination of any of the boxes would upset the activity as a whole or lead to a considerable decline in nuclear data quality.

Nuclear data users set specific requirements regarding the accuracy of the calculation of parameters or functionals characterizing the properties of a planned nuclear facility. On the basis of these specific requirements specialists prepare a list of nuclear data requirements with permissible uncertainties. An uncertainty is considered to be acceptable if it is less than the unavoidable component of uncertainty due to the manufacturing process or if it leads to an error which can easily be compensated for by the standard control elements. In the first stage of design, when the feasibility of the facility is studied, the accuracy of the nuclear data is not essential. At later stages of design, however, when conceptual problems are being tackled and safety and economic aspects gain importance, much more accurate data are required.

If the specified requirements cannot be met by the experimental and evaluated nuclear data available in banks, a programme of investigations is prepared. The volume of such investigations is determined by the available funds.

Differential nuclear data are measured either to validate nuclear models or to normalize calculated results with regard to precision experimental data, or for special applied purposes. The results of differential nuclear data measurements are a primary source for generating evaluated data.

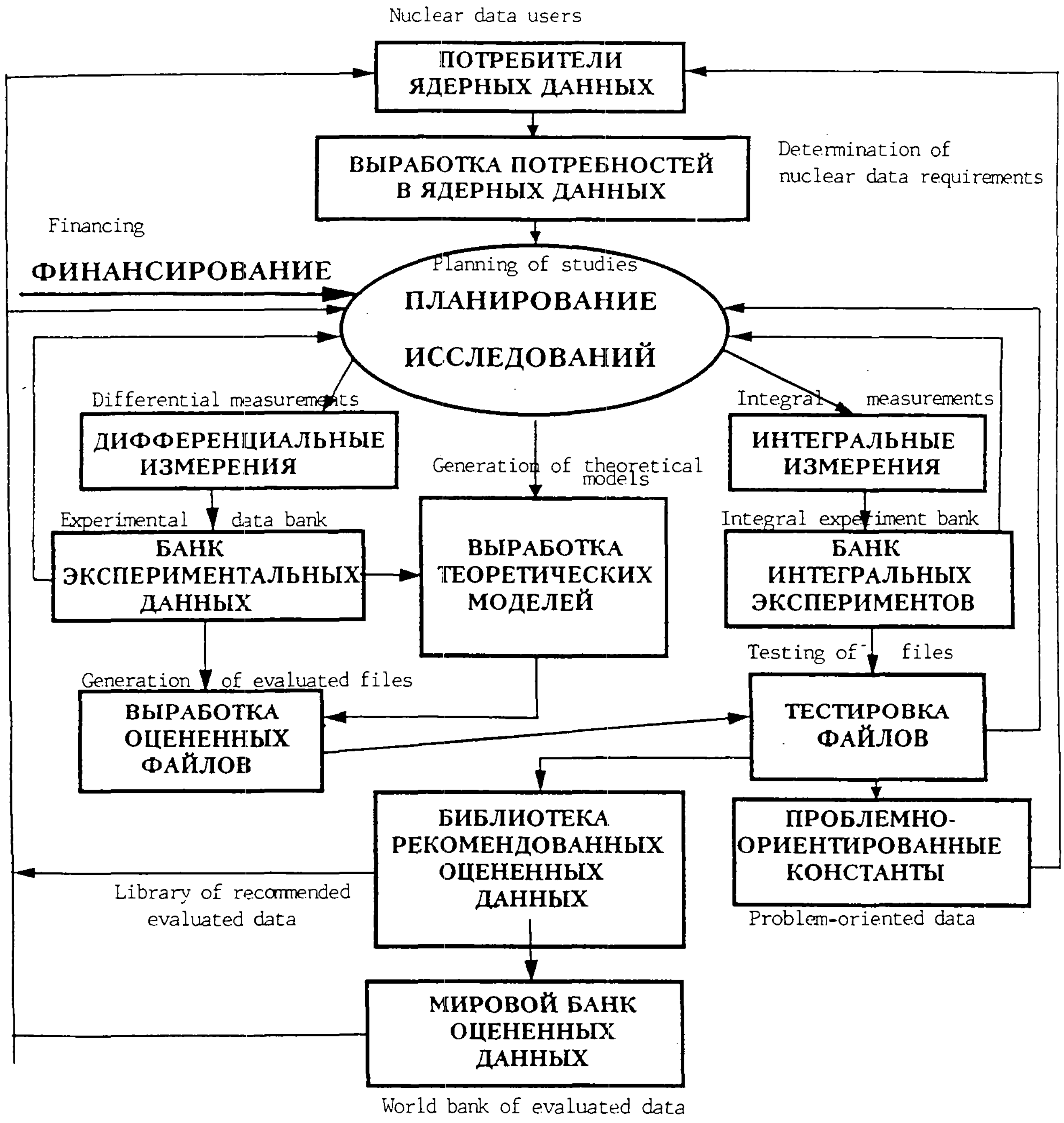
Theoretical modelling of nuclear interactions currently plays an important role in meeting nuclear data requirements, since on financial grounds or in view of the time needed it is not possible to resolve a nuclear data problem covering more than 500 stable and radioactive nuclides and energies of up to several GeV only by means of measurements. Model calculations give an actual representation of the shape of curves, but absolute values of the calculated reaction cross-sections are still unsatisfactory although in narrow regions errors do not exceed 50%. The results of calculation need to be normalized with respect to reference experimental data in order to improve their accuracy.

Thus, theoretical and experimental results successfully supplement each other: theory enables us to work out the shape of continuous curves, experiment considerably increases the accuracy of the absolute values of data and provides a number of parameters which can be incorporated in theoretical models, for example, fission barrier characteristics, level density, optical model parameters and so on. Further progress in the theory of the nucleus and appropriate computer programs will undoubtedly enhance the role of theory in the nuclear data generation process.

A vast quantity of detailed experimental and theoretical data has been accumulated to date, but the results obtained by the different authors do not always agree. Experimental and theoretical information should pass through an evaluation stage before being used in nuclear technology. At this stage, specialists are collecting all the accessible information for an isotope or an element, making a critical analysis of the experimental and theoretical data and obtaining the best values, which are being included in the evaluated data file. The evaluated data are being recorded in a standardized international computer format.

The generated file undergoes format and physical checking and is sent to the national evaluated nuclear data library.

Fig. 1


Nuclear data users
ПОТРЕБИТЕЛИ ЯДЕРНЫХ ДАННЫХ
ВЫРАБОТКА ПОТРЕБНОСТЕЙ В ЯДЕРНЫХ ДАННЫХ
Determination of nuclear data requirements
Financing
ФИНАНСИРОВАНИЕ
Planning of studies
ПЛАНИРОВАНИЕ ИССЛЕДОВАНИЙ
Differential measurements
ДИФФЕРЕНЦИАЛЬНЫЕ ИЗМЕРЕНИЯ
Generation of theoretical models
Integral measurements
ИНТЕГРАЛЬНЫЕ ИЗМЕРЕНИЯ
Experimental data bank
БАНК ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ
ВЫРАБОТКА ТЕОРЕТИЧЕСКИХ МОДЕЛЕЙ
Integral experiment bank
БАНК ИНТЕГРАЛЬНЫХ ЭКСПЕРИМЕНТОВ
Testing of files
Generation of evaluated files
ВЫРАБОТКА ОЦЕНЕННЫХ ФАЙЛОВ
ТЕСТИРОВКА ФАЙЛОВ
БИБЛИОТЕКА РЕКОМЕНДОВАННЫХ ОЦЕНЕННЫХ ДАННЫХ
ПРОБЛЕМНО-ОРИЕНТИРОВАННЫЕ КОНСТАНТЫ
Library of recommended evaluated data
Problem-oriented data
МИРОВОЙ БАНК ОЦЕНЕННЫХ ДАННЫХ
World bank of evaluated data

The integral measurement results are used to test evaluated data and to validate calculation methods. They can be used, for example, to determine with what degree of reliability the evaluated differential data are capable of describing the most important parameters of reactors which characterize their nuclear and radiation safety, the required fuel enrichment, the efficiency of absorber materials, the distribution of heat release, and so on. However, integral measurements are, as a rule, specific to a nuclear facility of a particular type and are used to obtain problem-oriented data. The differential data are used to extrapolate calculations to facilities of different types, to predict the behaviour of facilities in time, for non-power applications, and so on.

Thanks to its participation in international co-operation, the national experimental data bank contains the results of practically all the experimental work carried out in the world (about 8000 studies). The evaluated databank also contains practically all the evaluated nuclear data existing in the world.

One of the important aims is to ensure speedy response to the needs of new nuclear technologies so that lack of nuclear data does not slow down their development. Since nuclear data generation is a rather time-consuming process - more than five years elapse from the time of formulation of a problem to the time of generation of the evaluated data - it is necessary to develop the nuclear databank continuously by improving the quality and increasing the volume of data and extending the energy range. Only then will it be possible to respond speedily to the most unexpected nuclear data requirements of new incipient technologies.

The volume of information stored in evaluated nuclear data libraries is exceedingly large and the structure of these data is highly complex so that engineering calculation programs do not, as a rule, use libraries of evaluated data but the group constants obtained on their basis.

Group constants, which are used to describe the interaction of neutrons with matter, are cross-sections averaged over a fairly broad energy intervals. Since the cross-sections in these intervals sometimes vary by several orders of magnitude, the result of averaging depends on a number of factors (the concentration of nuclides in the medium, the temperature). This dependence is taken into account by means of special self-shielding factors, which are also regarded as group constants. Spectra and angular distributions of scattered neutrons are described by additional group constants.

During the preparation of group constants the fullest possible account is taken of the characteristics of the system being calculated, in particular, the heterogeneous structure of the reactor cores, fuel burnup and so on. Thus, programs for preparing group constants for calculation are closely linked with reactor neutron physics calculation programs.

In Russia the most widely used and only professionally supported group constant system is the BNAB constant system, the latest version of which, BNAB-93, together with the program package for preparing these constants for calculation, CONSYST-2, is currently at the stage of testing and trial use. The adoption of this system as the State system of standard reference data is under consideration. The nuclear data development programme should therefore include improvement of the CONSYST system with BNAB constants based on the BROND evaluated data file library.

In the activities on supplying users with nuclear data an important part is played by the nuclear data centres. They gather and compile numerical and bibliographical data, provide a computerized databank service, participate in the development of evaluated databases, co-ordinate work on nuclear data evaluation, supply users with information in accordance with their requests, and so on.

II. EXPERIMENTAL FACILITIES FOR NUCLEAR DATA STUDIES

Measurements of differential nuclear data constitute the most expensive and time-consuming part of nuclear data activities.

These measurements are carried out with the use of powerful neutron sources based on reactors and accelerators of different types, charged particle accelerators in the energy range from tens of MeV to several GeV, complex equipment for recording and spectrometry of the nuclear reaction and radiation products, and computerized systems for collection and treatment of experimental data.

Below is a list of the national facilities used for investigations in the area of nuclear data and the topics of such investigation.

Institute, facilities	Topic
1. Institute of Physics and Power Engineering	
KG-0,3 accelerator (14 MeV neutron generator)	Integral experiments on spherical samples, photon production cross-sections, double differential cross-sections for the $(n,n'\gamma)$ reaction.

KG-2,5 cascade generator (maximum current 500 μA, maximum potential 2.2 MV).	Fission cross-sections for transuranic nuclides, delayed neutron yields, fission neutron spectra, activation cross-sections, physics of nuclear fission, (n,α) reaction.
EG-1 Van de Graaff accelerator (maximum potential 4.6 MV, current in the continuous mode 30 μA and in the nanosecond pulsed mode 6 μA).	Fission cross-sections for transuranic nuclei, neutron radiative capture cross-sections, inelastically scattered neutron cross-sections and spectra, physics of nuclear fission.
EGP-10M tandem accelerator (maximum potential 4.5 MV, pulsed mode: pulse height 1 ns, frequency 1 and 5 MHz, average current 2 μA).	Fission cross-sections for transactinides, fission neutron spectra, double differential cross-sections for neutron emission in the (p,n) and (d,n) reactions; the (n,α) reaction cross-sections and mechanism; optical potential near the Coulomb barrier.
BR-10 fast neutron reactor with thermal column.	Reference reactions with thermal neutrons.

The set of accelerators at the Institute of Physics and Power Engineering can be used for the study of monoenergetic neutrons in the region up to 25 MeV.

2. All-Russian Scientific Research Institute for Experimental Physics

EGP-10 tandem accelerator (maximum potential 6.5 MV).	Physics of nuclear fission in reactions (d, pf), (t,pf), etc. Fusion reactions for light nuclei.
LU-50 linear electron accelerator (electron energy 55 MeV, white spectrum neutron source in the 0.5-14 MeV range, pulse height 10 ns, frequency 2400 Hz, average yield 2 x 10^{-13} fast neutrons per second)	Average number of prompt neutrons, fission cross-sections, total neutron cross-sections, gamma production cross-sections.

3. Radium Institute

14 MeV neutron generator	Fission neutron spectra, cross-sections of nuclear activation, tritium yield during fission, photon spectra and yields during interaction of neutrons with heavy and fissile nuclei
Van de Graaff accelerator (maximum potential 3.5 MV)	Radiative capture cross-sections, low-level excitation cross-sections during neutron inelastic scattering, absolute fission cross-sections, tritium yield during fission, fission neutron spectra.
Proton synchrotron (maximum energy 200 MeV)	Proton-induced fission cross-sections for actinides, cross-section for the (p,xn) reaction , photon yields during the interaction of protons with nuclei.

4. Neutron Physics Laboratory, Joint Institute for Nuclear Research	
IBR-30 pulsed fast reactor. White-spectrum neutron source.	Transmission through fissile material samples, self-shielding, Doppler effect, physics of nuclear fission, fission cross-sections for actinides, fission photon yield.
5. Scientific Research Institute for Nuclear Physics, Moscow State University	
Split microtron - continuous electron accelerator (maximum design energy 175 MeV, current 100 μA).	Cross-sections of reactions with the emission of various particles ((γ,n), (γ,p), (γ,d), (γ,t), (γ,γ'), etc.), reaction yields, product particle spectra, yields of radioactive product nuclei.
Microtron - elementary particle accelerator (p,d,t,α) (maximum proton energy 7 MeV)	Cross-sections, yields, energy spectra, angular distributions, angular correlations.

A weak point as regards the national experimental facilities for nuclear data investigations is the lack of high-resolution equipment to study the resonance structure of cross-sections.

Various institutes in Russia have a number of facilities, which, in addition to their basic functions, can be used for nuclear data work. These are:

- The proton accelerators of the Radium Institute, the St. Petersburg Institute of Nuclear Physics, the Institute of High-Energy Physics, the Joint Institute for Nuclear Research, the Institute of Theoretical and Experimental Physics and the Institute of Nuclear Research of the Russian Academy of Sciences can be used to measure nuclear data in the intermediate- and high-energy regions;

- The GNEIS facility (St. Petersburg Institute of Nuclear Physics), the FAKEL accelerator (Kurchatov Institute) and the IBR-30 pulsed reactor (Joint Institute for Nuclear Research) can be used to study the resonance cross-sections of nuclei.

Considering that it is extremely expensive to maintain in working order and to run the operating accelerators and that construction of new large facilities is not a feasible proposition, it is necessary:

- To develop a minimum programme of experimental studies for the purpose of testing theoretical models and making precision measurements of the most important constants which cannot be performed by other means;

- To prepare a list of the minimum key operating facilities necessary to resolve current and future problems in the field of nuclear data and to allocate special funds for their operation;

- To organize the co-operation of groups of experimenters within Russia with a view to the joint use of the operating facilities and experimental equipment;

- To establish pools of separated stable and radioactive isotopes for collective use;

- To strengthen the existing co-operation in the area of experimental studies with laboratories abroad and to prepare proposals for expanding such co-operation.

III. DEVELOPMENT OF THEORETICAL MODELS

It is impossible to meet nuclear data requirements by means of measurements alone. Therefore, one of the main tasks of physicists is to develop model representations of the processes of neutron-nucleus interactions which can ensure the required reliability of the results of calculations.

In order to study the mechanism of nuclear reactions occurring in nuclear facilities for different purposes, the Institute of Physics and Power Engineering developed a comprehensive programme for the study of the equilibrium and non-equilibrium processes, covering the reactions (n,n'), (p,n), (α,n) and (n,2n) for an extensive range of nuclei and energy. As a result of these studies, it has been possible to determine the contribution of the direct processes to neutron spectra and the excitation functions of collective levels of nuclei at incident neutron energies of up to 14 MeV. Efficient theoretical methods have been devised to describe the direct transitions and, for higher neutron energies, a generalized exciton model based on the concept of a leading particle has been developed.

In the statistical theory, the nuclear level density plays a decisive role at sufficiently high excitation energies. The studies referred to above have, to a noticeable degree, filled a gap in the experimental data on the energy dependence of level density. For the purpose of level density analysis, consistent methods of describing the shell, superfluid and collective effects have been developed, together with phenomenological systematics of the energy changes of level density suitable for practical application. The level density studies carried out at the Institute of Physics and Power Engineering have won international recognition, and the proposed level density systematics are used extensively in many of the latest evaluations of nuclear reaction cross-sections.

Russian scientists have made a notable contribution to the development of the physics of fission. Extensive information has been obtained on the shape of the fission barrier for heavy nuclei, the quasi-stationary states in the second well of the potential barrier, the spectrum of the transitional states of nuclei, the statistical characteristics of such states at high excitation levels, the dynamic characteristics of the fission process, the mass and kinetic energy distribution of fission fragments, the process of neutron emission by excited fragments, and so on. The final result of this series of studies was the systematics of the various fission process characteristics which are important from the standpoint of practical applications. By their wide coverage of the problem and interpretation of the laws found, Russian studies of the nuclear fission process are a pace-setter in world achievements in this branch of science.

The results of the experimental and theoretical studies of the physics of the neutron-nucleus interaction processes have not only considerably enriched and widened our understanding about the properties of nuclei and the mechanisms of nuclear reactions, but have also served as a basis for the development of systematics and evaluations of nuclear data which cannot be measured directly.

In recent years, a good deal of attention has been paid to nuclear data for intermediate and high energies of incident particles. The intermediate range usually covers incident particle energies from ~ 20 MeV to the π-meson generation threshold (~ 150 MeV) and the high range covers up to the nucleon generation threshold ($\sim$ 1500 MeV). This division reflects the specific characteristics of the nuclear reaction mechanisms at the corresponding energies. For intermediate energies, there is a predominance of multi-stage direct processes leading to the excitation of different collective degrees of freedom of the nuclei and subsequent dissipation of collective motion in relation to possible quasi-particle excitations. At higher energies intranuclear nucleon-nucleon collisions predominate, with substantially weakened collective effects.

Despite the marked success of the modern theory of multi-stage direct and pre-equilibrium reactions, a rigorous theoretical description has not yet been found for many characteristics of reactions at intermediate and high energies. Hence there is continued interest in experimental studies of the cross-sections for the various nuclear reactions in the corresponding energy ranges and in the development of more rigorous theoretical models for their analysis.

Promising areas of study are further development of statistical methods proposed earlier to describe the highly excited states of nuclei, methods of taking account of the influence of nuclear viscosity on the competition of the fission and multiple nucleon emission processes, microscopic methods of describing cluster formation, methods of consideration of multi-stage direct and compound nuclear processes on the basis of microscopic analysis of the effective nucleon-nucleon interactions and the corresponding transition densities of quasi-particle excitations.

Since experimental capabilities are limited and, in many cases, it is basically impossible to obtain experimental data, particularly on fission product nuclei, we must further develop the methods of calculating the most important reaction cross-sections for these nuclei.

IV. NUCLEAR DATA EVALUATION

The evaluation process consists of obtaining, on the basis of the available experimental data and theoretical model representations, a continuous curve describing a particular characteristic of the neutron-nucleus interaction in the reactor energy range (0-20 MeV) and determining the error in this description. The evaluations are used to generate files - consistent sets of all the characteristics of neutron interactions with this nucleus.

The Institute of Physics and Power Engineering has carried out a considerable amount of studies to develop and implement evaluation methods for fissile nuclei, the nuclei of structural and other materials used in fission technology, and fission products.

The relations of the optical-statistical model of nuclear reactions are used extensively in nuclear data evaluation work. The generalized optical model can be used, on the basis of limited experimental data on angular distributions of elastically scattered neutrons, to determine with sufficient reliability the changes in neutron angular distributions and the total neutron cross-sections in wide incident neutron energy ranges. The optical model is also used to calculate the neutron transmission coefficients needed for calculating the neutron inelastic scattering and radiative capture cross-sections, and the fission cross-sections for heavy nuclei. At present the Nuclear Data Centre of the Institute of Physics and Power Engineering has developed several standard program packages for optical-statistical calculation which have been tested at international level.

In the case of the main fissile nuclei, the individual neutron resonance parameters have been fully analysed, and the neutron and radiation strength functions have been found, and a consistent optical-statistical description has been obtained for the total neutron cross-sections, the elastic and inelastic scattering cross-sections, the fission cross-sections, the neutron spectra and the excitation functions for the (n,2n) reactions.

In generating the files for structural materials, thanks to the new approaches that have been developed, account could be taken of the contributions of direct and pre-equilibrium reaction mechanisms over the whole neutron energy range and a correct evaluation could be made of the excitation functions of low-lying levels and the neutron spectra of separated isotopes, for which in the majority of cases there are no direct experimental data.

New neutron cross-section evaluations were performed for the most important fission products which make a dominant contribution to core poisoning and to the residual activity of the spent fuel. Comparisons with evaluated data from abroad have demonstrated the confidence level and reliability of the Russian recommended nuclear data.

One of the urgent problems awaiting solution in the area of nuclear data evaluation is the determination of the uncertainties and correlations of the recommended data. In recent years the Institute of Physics and Power Engineering has devoted much attention to developing efficient algorithms to solve this problem and has made considerable progress in determining the co-variance matrices of errors for the file of standard and dosimetric reactions. However, much work still has to be done to extend similar methods to the full neutron data files.

Another problem which has acquired urgency lately is creation of libraries of evaluated cross-sections for the dominant nuclear reactions for intermediate neutron and proton energies. Such data are very important in the area of medical radiotherapy, protection of spacecraft against radiation and development of methods for burning radioactive waste in accelerators. The volume of data required is so huge that a full solution to the problem can only be found through international co-operation by pooling the efforts of all nuclear centres. The need for such co-operation was underlined in the recommendations of the Working Party on International Evaluation Co-operation (Oak Ridge, 4-6 May 1994).

V. RUSSIAN EVALUATED NEUTRON DATA LIBRARY

Work began on the establishment of a national computerized evaluated neutron data library at the Institute of Physics and Power Engineering in the early 70s, and the first version of the Recommended Evaluated Neutron Data Library (BROND-1) was developed in 1985. It included about 70 complete files for the most important fuel, structural and other materials used in reactor technology.

During the development of the revised version, BROND-2, attention was focused on nuclear data requirements for advanced nuclear reactors. The new version of the library containing 121 files was produced in 1990 for the main reactor materials. The library contains evaluations carried out at the Institute of Physics and Power Engineering and at Minsk. In the case of materials whose cross-sections are used as standards, files recommended by the IAEA were taken. The library contains full sets of neutron data (cross-sections of all reactions, angular and energy distributions of secondary neutrons) for the 10 eV - 20 MeV incident neutron energy range. All the files were checked for the physical consistency of the cross-sections and conformity with the ENDF/B international format, and after routine corrections had been made the BROND-2 library was disseminated to Russian nuclear data users and sent to the IAEA for international exchange. The updated content of the library is given in Table 1.

It should be noted that, in addition to the BROND library files, a large number (more than 50) of revised and supplemented files from foreign libraries are also used for reactor calculations. These additional files are included in the FOND-2 library, the content of which is given in Table 2. The BROND + FOND files served as the basis for the latest version of the BNAB-90 group constant system, which is used directly in practical calculations for national nuclear reactors.

In recent years a revised library of evaluated thermal reactor data, KORT (93), and a library of neutron resonance parameters, LIPAR (94), have been prepared at the Kurchatov Institute. The latter includes full sets of resolved resonance parameters for the 96 most important isotopes. Together with the BNAB-90 group constants, the KORT + LIPAR libraries meet the basic calculation needs for national thermal reactors, including precision calculations associated with reactor safety analysis and the development of new advanced reactors.

The Atomic and Nuclear Data Centre contributes to the development of the ENSDF international library for nuclear structure, which is widely used in Russia.

In addition to the general-purpose file of the BROND-2 library, the Nuclear Data Centre is working on the development of specialized nuclear data libraries. In 1990 work began on a library of evaluated photoneutron data (BOFOD). It includes neutron formation cross-sections, neutron spectra and photofission cross-sections for transuranics. The first version of the library includes 26 files of the most important reactor materials and shielding materials: ^{9}Be, ^{23}Na, ^{52}Cr, ^{55}Mn, ^{00}Zr, $^{92,94,96,98,100}Mo$, $^{182,184,186}W$, ^{00}Pb, ^{209}Bi, ^{232}Th, $^{233,234,235,236,238}U$, ^{237}Np, $^{239,241}Pu$ and $^{241,243}Am$. In 1993 evaluations were also made of the photoneutron cross-sections of a number of the most important fission products: ^{90}Sr, $^{93,94}Zr$, ^{99}Tc, $^{121,126}Sn$, ^{107}Pd, ^{108}Ag, $^{135,137}Cs$, ^{129}I, ^{166}Ho, $^{147,148,151}Sm$, ^{158}Tb.

In 1994 the Nuclear Data Centre prepared the Russian dosimetric file for neutron reactions, RDF-94, used as standard neutron cross-sections. The content of the file is given in Table 3. The file includes the errors and the error covariant matrices for all the reactions. The use of a single dosimetric file in neutron spectrum measurements for different nuclear power plants is very important from the point of view of standardization of the relevant measurements and analysis of radiation damage in reactor structural materials.

In 1993 the Obninsk Institute of Nuclear Power Engineering and the Institute of Physics and Power Engineering collaborated in preparing a new version of the activation cross-section library ADL-3. It contains more than 33 000 neutron reactions for stable and radioactive isotopes and also for nuclei in isomeric states. The cross-sections were obtained on the basis of analysis of the entire set of available experimental data and calculations using the latest theoretical models. It is the most complete library of activation cross-sections intended for calculations of the activation of materials in strong neutron fields, particularly materials for planned fusion reactors and high-flux accelerator blankets.

The Nuclear Data Centre is currently also preparing a nuclear data library for intermediate- and high-energy neutrons and protons. The first version of the library (MENDL-2) includes intermediate-energy (up to 100 MeV) neutron activation cross-sections for 500 stable and long-lived radioactive nuclei obtained from statistical calculations. This library is important for analysis of the activation of the targets and structural materials for various designs involving the use of high-energy accelerators.

In recent years the Nuclear Data Centre and the Moscow Institute of Physics and Engineering have started collaborating in the creation of a library of fission product yields (ASIYaD), which includes the evaluated mass-charge distributions of fission products for the most important fissile isotopes.

Table 1 List of files included in BROND-2.2

Isotopes	Eval./rev.	Authors
H-2,3	1988	Nikolaev M.N.
He-3,4	1988	Nikolaev M.N.
He-4	1976	Nikolaev M.N. et al.
Li-6	1989	Nikolaev M.N.
Li-7	1984	Bondarenko I.M.
N-14,15	1988/1993	Blokhin A.I. et al.
O-16	1977	Nikolaev M.N. et al.
F-19	1990	Blokhin A.I. et al.
Na-23	1978	Nikolaev M.N. et al.
Si-000	1985/1993	Hermsdorf D., Blokhin A.I. et al.
P-31	1989	Koscheev V.N.
Cl-000	1990	Nikolaev M.N. et al.
Cr-000	1984/1988	Pronyaev V.G. et al.
Cr-50,52, 53,54	1987	Blokhin A.I. et al.
Fe-000	1985/1994	Pronyaev V.G. et al.
Fe-54,56, 57,58	1985	Pronyaev V.G. et al.
Ni-000	1984	Blokhin A.I., Ignatyuk A.V. et al.
Ni-58,60,61, 62,64	1985	Blokhin A.I., Ignatyuk A.V. et al.
Cu-000	1981	Nikolaev M.N. et al.
Zn-000	1989	Nikolaev M.N., Zabrodskaya S.V.
Sr-90	1990	Grudzevich O.T., Zelenetsky A.V.
Zr-000	1983	Grudzevich O.T., Zelenetsky A.V.
Zr-90,91,92, 94,96	1988/1993	Grudzevich O.T. et al./Blokhin A.I.
Zr-93,95	1989	Grudzevich O.T., Zelenetsky A.V.
Nb-93	1988/1993	V.G.Pronyaev et al.
Nb-95	1990	Grudzevich O.T., Zelenetsky A.V.
Tc-99	1984	Ignatyuk A.V., Kravchenko I.V.
Ru-101,102, 104,106	1984	Ignatyuk A.V., Kravchenko I.V.
Rh-103	1985	Ignatyuk A.V., Kravchenko I.V.
Pd-105,107	1985	Ignatyuk A.V., Kravchenko I.V.
Pd-106,108	1987	Belanova T.S., Ignatyuk A.V.
Ag-109	1985	Ignatyuk A.V., Kravchenko I.V.
Sn-000	1990/1993	V.G.Pronyaev et al.
I-129	1985	Ignatyuk A.V., Kravchenko I.V.
Xe-131	1985	Ignatyuk A.V., Kravchenko I.V.
Cs-133,135	1985/1991	Ignatyuk A.V., Kravchenko I.V.
Ce-140,142, 144	1990	Ignatyuk A.V., Ulaeva M.V.
Nd-143,145	1985	Ignatyuk A.V., Kravchenko I.V.
Pm-147	1985	Ignatyuk A.V., Kravchenko I.V.
Sm-000, 144,154	1989	Belanova T.S. et al.
Sm-147,149, 151	1985	Ignatyuk A.V., Kravchenko I.V.
Sm-148,150, 152	1987	Zakharova S.M., Ignatyuk A.V.
Eu-153	1985	Ignatyuk A.V., Kravchenko I.V.
Gd-000,152, 154,155,156, 157,158,160	1989	Blokhin A.I.
Er-162,164, 166,167, 168,170	1976	Zakharova S.M. et al
Ta-181	1988	Manturov G.N., Korchagina G.A.
W-182,183, 184,186	1983	Abagyan L.P., Manturov G.N.
Re-000	1988	Nikolaev M.N. et al.
Os-000	1990	Nikolaev M.N.
Ir-000	1990	Nikolaev M.N., Zabrodskaya S.V.
Pb-000	1984/1994	Hermsdorf D.,Blokhin A.I.
Pb-204,206, 207,208	1990/1993	Blokhin A.I. et al.
Bi-209	1990/1993	Blokhin A.I. et al.
Th-232	1983	Nikolaev M.N. et al.
Pa-231,233	1994	Blokhin A.I. et al.
U-233	1990	Sukhovitsky E., Klepatsky A.
U-235,236	1986	Konshin V.A. et al.
U-238	1980	Nikolaev M.N. et al.
Pu-238	1987	Sukhovitsky E., Klepatsky A.
Pu-239,240, 241,242	1980	Konshin V.A. et al.
Am-241,242, 242m,243	1990/1994	Blokhin A.I., Maslov V.M.
Cm-242,244	1987	Sukhovitsky E., Klepatsky A.

Table 2 Additional files included in FOND

Elem	Eval/Rev	Origin	Comments
*H	1989/1993	ENDF/B-6	Capture data were modified.
Be	1983/1993	-"-	Thermal capture was corrected.
B	1989	-"-	B-10,11 files were used.
*N	1983-1990	-"-	N-14,15 files were used.
*O	1990	-"-	
*F	1990	-"-	
Mg	1987	JENDL-3	
Al	1988	JENDL-3	
*Si	1989	JENDL-3	
*S	1979/1993	ENDF/B-6	INT law for MT=103 was corrected.
*Cl	1979/1993	ENDF/B-6	INT law for MT=103-107 was corrected.
Ar	1979	JEF-1	
K	1987	JENDL-3	
Ca	1987/1993	JENDL-3	Γ_{compet} were added for res.
Sc	1988	JENDL-3	
Ti	1988/1993	JENDL-3	Threshold for 1-st inelastic level was corrected.
V	1982	ENDL-83	
Mn	1988	ENDF/B-6	
Co	1989	ENDF/B-6	
*Ni	1989/1993	ENDF/B-6	Ni-58,60,61,62,64 files were used and missed p-res. were added.
*Cu	1987	JENDL-3	
Ga	1982	ENDL-83	
Ge	1974	ENDF/B-6	Ge-70,73,74,76 files were used, res. param. for Ge-70 were modifyed.
As	1982	ENDL-83	
Se	1974/1993	ENDF/B-6	Data in resonance and fast regions were revised.
Br	1974/1992	ENDF/B-6	Br-79 and Br-81 files were used and (n,2n) reactions were added.
Kr	1974-1984	ENDF/B-6	Kr-78,80,82,83,84,86 files were used.
Rb	1984	JEF-1	Rb-85,87 files were used.
Sr	1984/1992	ENDF/B-6	Sr-84,86,87,88 were used, (n,2n) reactions were added.
*Zr	1977	JENDL-3	
Mo	1989	JENDL-3	Mo-nat,95,97,98,100 files were used.
Ru	1990	ENDF/B-6	Ru-96,98,99,100 files were used, others - from BROND-2.
Pd	1980-1991	ENDF/B-6	Pd-102,104 files were used, others - from BROND-2.
Ag	1977	JENDL-3	Ag-107 was used, Ag-109 - from BROND-2.
Cd	1975/1991	ENDF/B-6	Cd-nat and Cd-113 files were used. Energy spectra (n,2n) reaction were corrected.

Elem	Eval/Rev	Origin	Comments
In	1974-1979	ENDF/B-6	In-113,115 files were used.
Sb	1974-1979	ENDF/B-6	Sb-121,123,125 files were used.
Te	1974-1980	ENDF/B-6	Te-120,122,123,124,125,126, 128,130 files were used.
I	1980	ENDF/B-6	
Xe	1978	ENDF/B-6	Xe-124,126,128,129,130, 132,134,136 files were used.
Cs	1974-1978	ENDF/B-6	Cs-134,137 files were used.
Ba	1978	ENDF/B-6	Ba-134,135,136,137,138 files were used. Ba-130,132 were considered as Ba-134.
La	1977	JENDL-3	
Pr	1984/1991	ENDF/B-6	
Nd	1974/1980	ENDF/B-5	Nd-142,144,146,148,150 files were used. Nd-143,145 - from BROND-2.
Eu	1986	ENDF/B-6	Eu-151 was used, Eu-153 - from BROND-2.
Tb	1980	ENDF/B-6	
Dy	1974-1980	ENDF/B-6	Dy-160,161,162,163,164 files were used with res. param. modifyed. Dy-156,158 consider as Dy-160.
Ho	1974/1980	ENDF/B-6	
Lu	1967/1980	ENDF/B-6	Lu-175 and Lu-176 files were used
Hf	1989	JENDL-3	Hf-nat,174,176,177,178,179 and Hf-180 files were used.
*Ta	1989	JENDL-3	
Pt	1982/1991	ENDL-83	Some errors were found and removed.
*Pb	1989	JENDL-3	Selection is based on integral experiments.
Th	1981	JENDL-3	Th-228,229 files were used.
	1982/1993	ENDF/B-6	Th-230 was used. Thermal cross sections were corrected.
*Pa	1977-1978	ENDF/B-6	Pa-231,233 were files used.
*U	1978-1989	ENDF/B-6	U-232,234,235 files were used.
Np	1978/1990	ENDF/B-5	Np-237 was used and (n,2n) cross sections were modified.
	1989	JENDL-3	Np-239 file was used.
*Pu	1987/1993	JENDL-3	Pu-239 was used; LIPAR-5 library was used below 100 ev.
Pu	1976-1978	ENDF/B-6	Pu-243 and Pu-244 files were used
Cm	1976-1978	ENDF/B-6	Cm-243,245,246,247,248 files were used.
	1987	JENDL-3	Cm-249,250 files were used.
Bk	1986	ENDF/B-6	Bk-249 file was used.
Cf	1975-1986	ENDF/B-6	Cf-249,250,251,252,253 files were used.
Es	1975	ENDF/B-6	Es-253 file was used.

Table 3 List of reactions included in RDF-94

7-Li(n,t)*	52-Cr(n,2n)	93-Nb(n,n')m
10-B(n,α)	55-Mn(n,2n)	93-Nb(n,2n)m
19-F(n,2n)	55-Mn(n,γ)	115-In(n,2n)
23-Na(n,γ)	54-Fe(n,2n)	127-I(n,2n)
24-Mg(n,p)	54-Fe(n,p)	139-La(n,γ)
27-Al(n,p)	56-Fe(n,p)	141-Pr(n,2n)
27-Al(n,α)	59-Co(n,2n)	181-Ta(n,γ)
45-Sc(n,2n)	58-Ni(n,2n)	197-Au(n,2n)
45-Sc(n,2n)m	58-Ni(n,p)	197-Au(n,γ)*
45-Sc(n,2n)g	60-Ni(n,p)	232-Th(n,γ)*
46-Ti(n,p)	63-Cu(n,2n)	232-Th(n,f)*
46-Ti(n,2n)	63-Cu(n,γ)	235-U(n,f)*
47-Ti(n,x)	65-Cu(n,2n)	238-U(n,γ)*
48-Ti(n,x)	89-Y(n,2n)	238-U(n,f)*
48-Ti(n,p)	90-Zr(n,2n)	237-Np(n,f)*
51-V(n,α)		

* Reactions selected from IRDF-90

The national nuclear data libraries are widely used in international exchange and intercomparison of nuclear data. In particular, 10 files from the BROND-2 library are included in the FENDL-1 library, prepared by the IAEA for the international thermonuclear reactor project (ITER). The ADL-3 library is also widely used in the preparation of a consistent international library of activation cross-sections for a broad range of analytical work for advanced nuclear technologies. Intensive exchange of experimental and evaluated nuclear data takes place at the specialized meetings jointly organized by the IAEA Nuclear Data Section and the Nuclear Energy Agency of the OECD. The annual meetings of the Working Party on International Evaluation Co-operation provide the means for continuing work on analysing discrepancies in the most important neutron cross-sections. The results of international meetings serve as the most important basis for correcting and improving national libraries, for bringing points of view closer together and for improving the reliability of data. The intercomparison process involves the exchange of data, evaluation methods and programs for data treatment and cross-section evaluation calculation. Thanks to international exchange and its collaboration in supplying nuclear data for international projects, the Nuclear Data Centre has at its disposal practically all the libraries and necessary calculation programs for cross-sections, including those which are not officially disseminated through the IAEA. A list of the main nuclear data libraries available at the Nuclear Data Centre is given in Annex 1.

VI. TESTING OF NUCLEAR DATA

Almost all the information contained in the results of nuclear physics experiments and obtained by means of in-depth theoretical analysis currently available is concentrated in evaluated nuclear data files. If the level of accuracy of these data (determined by error covariance matrices) is inadequate, it can only be further improved on the basis of new experimental information.

It should be noted that it is extremely expensive to reduce the experimental errors of the results of nuclear physics experiments. There are relatively few values left whose accuracy could (and should) be appreciably improved by additional nuclear physics experiments unless basically new experimental facilities are built.

One other means of improving the accuracy of evaluated data is to make a more careful evaluation of the experimental data so as to take account of virtually all the available nuclear physics information, including the most recent. Re-evaluation work must be planned as part of the programme for the further improvement of nuclear data. However, even this has a small margin for improving the accuracy of the calculated predictions of reactor and shielding characteristics and a radical reduction in the overall level of uncertainty of data should not be expected from this method.

Under these conditions, the role of integral experiments increases. Integral experiments include measurements of average cross-sections for well-known spectra (fission spectra, the slowing-down spectrum and so on) and all experiments at critical assemblies and power reactors, experiments on various shielding material compositions and experiments to measure the spectra of neutrons emitted from samples of the material under study where the source is placed inside.

A large number of macroexperiments carried out earlier can be used to improve the accuracy of nuclear data, if the information on the relevant experimental conditions scattered in reports and journals is collected and analysed with the help of the latest calculation methods and data. Numerous critical experiments carried out in the area of defence, experiments on the critical start-up conditions of power reactors and the large number of experiments performed for 40 years on critical assemblies are also useful.

Among the large number of integral experiments, one can distinguish a class of experiments with the simplest geometry where the samples under study are in the form of spheres with a point neutron source in the centre. The majority of experiments were carried out for two types of neutron source: the spontaneously fissioning isotope ^{252}Cf and the T(d,n) reaction producing neutrons in the region of 14 MeV. Such measurements usually involve the energy and angular spectra of leakage neutrons from the sphere surface and the spectra of gamma radiation resulting from the interaction of the source neutrons with the sphere material. Thanks to their "simplicity" and one-dimensional geometry, such experiments are mainly used to verify and test microscopic evaluated nuclear data files. In many countries great importance is attached to such experiments, since they are used as the basis for primary work on the testing of new national nuclear-neutron data libraries. In Russia, considerable attention has traditionally been paid to these experiments at scientific centres such as the Institute of Physics and Power Engineering, the Kurchatov Institute and the Institute of Technical Physics at Chelyabinsk-70. Studies have mainly been carried out for materials that are of interest as structural components of nuclear power facilities, shielding materials and fuel materials. However, there is still a need to conduct such experiments on many materials (for example for P, S, K, V, Sn, Ba, Ta, etc.).

Transmission experiments are performed in order to test evaluated data on resolved and unresolved resonance parameters, on the total neutron interaction cross-section, on the neutron absorption cross-section and on the corresponding resonance self-shielding factors. The Institute of Physics and Power Engineering and the Kurchatov Institute have carried out studies on structural and shielding materials of interest for the usual designs of facilities. At present integral measurements of this type are actively and successfully used both for testing microscopic evaluated neutron data files and for smoothing of group constant systems.

In order to systematize and standardize nuclear data testing, the Institute of Physics and Power Engineering has begun work on the establishment of specialized libraries, in which the experimental data on integral measurements would be presented in computerized format. However, at present no unified approach and format for the compilation of this type of data has been devised. Work in this area must be continued with the use of international experience in the establishment of such libraries. It is difficult to overestimate the importance of collecting and analysing all the accumulated data on integral experiments and preserving them for practical use in the future. In other countries this work has already been organized and the results obtained in Russia at critical assemblies and in spherical experiments have been included in a compilation of evaluated macroexperiments.

There are long-term international nuclear data testing programmes supported by the IAEA and programmes developed under the aegis, for example, of the European Union. Participation in these programmes is generally voluntary and has to be supported and financed from national sources. This factor presents a major obstacle to active Russian participation in this type of programme. The situation is somewhat better in the case of bilateral co-operation with no foreign exchange component. Examples of such co-operation are the direct contacts of the Institute of Physics and Power Engineering with the Atomic Energy Institute of China and with the Institute of Neutron Physics and Reactor Engineering at Karlsruhe, Germany.

VII. NUCLEAR DATA CENTRES

International Nuclear Data Centres Network

The network of nuclear data centres and international co-operation between such centres was organized in 1964 under the auspices of the International Atomic Energy Agency (IAEA) to co-ordinate the collection and dissemination of nuclear data at international level.

It is only through international co-operation among interested groups of scientists from different organizations and different countries that duplication of efforts can be avoided and the fullest use made of the specialized expertise of each of the co-operating countries.

The network of centres co-ordinates its activities by means of a system of regular meetings, organized by the IAEA's Nuclear Data Section through direct links between the centres.

The rules and procedures for data compilation and exchange and agreement on the division of responsibilities between centres with respect to nuclear data work and the provision of service to users are determined at meetings of nuclear data centre representatives.

The information collected or obtained at any collaborating centre is fully available to other centres party to the collaboration agreement. In turn, each centre transmits this information to its users free of charge.

The centres' main task is to provide nuclear data and the relevant documentation to users. For this purpose, the centres carry out the following activities:

- Compilation of bibliographical information and experimental data;
- Collection of evaluated nuclear data;
- Exchange of all types of data;
- Assistance in the development of specialized evaluated data libraries;
- Development of formats for the computerized data exchange;
- Development of compatible software for data work and dissemination;
- Development of compatible software for nuclear data users;
- Listing of existing and future nuclear data users in order to meet user demands.

The following centres currently form the nucleus of the world network of centres:

- The National Nuclear Data Center at Brookhaven National Laboratory (USA);
- The Data Bank of the OECD/Nuclear Energy Agency (Paris, France);

- Nuclear Data Section of the IAEA (Vienna, Austria);

- The Nuclear Data Centre of the Institute of Physics and Power Engineering (Obninsk, Russia);

- Nuclear Structure and Reaction Data Centre (Moscow, Russia).

These centres co-ordinate the provision of all nuclear data to users and ensure the full compilation of bibliographical and experimental neutron data on a world scale.

A number of regional, national and specialized centres and groups supplement to a substantial extent the work of these centres by participating in the collection and dissemination of data for specialized applications or data of a specialized type. In Russia, these include the Centre for Data on Photonuclear Experiments at Moscow State University, the Centre for Radionuclide Data at the Khlopin Radium Institute (St. Petersburg) and the Nuclear Data Centre of the St. Petersburg Institute of Nuclear Physics (Gatchina).

Nuclear Data Centre

The Nuclear Data Centre of the Institute of Physics and Power Engineering, Obninsk, was established in 1963 and right from the start has been part of the international network of nuclear reaction data centres under the auspices of the IAEA. It performs all the scientific and technical activities involved in the establishment and maintenance of a neutron data bank, the international exchange of data and the provision of data to organizations belonging to this area.

The Nuclear Data Centre carries out the following activities:

- Compilation of information on measurements, calculations and evaluation of microscopic neutron data in Russia for the world catalogue of neutron data, CINDA;

- Compilation of numerical experimental neutron data measured in Russia for the world library, EXFOR;

- Determination of the nuclear data requirements for all applications;

- Co-ordination of the neutron data evaluation activities for national libraries of data for general and specialized applications;

- Organization of nuclear data evaluation for national and international data libraries;

- Development and use of application software for generation, checking, correction, search and retrieval, conversion and graphical representation of data;

- Provision of data to institutes and organizations in Russia;

- Publication of the serial "Problems of Atomic Science and Technology, Series: Nuclear Constants" (in Russian).

The Nuclear Data Centre has the latest computer programs for calculating nuclear data on the basis of theoretical models of nuclear reactions, for preparing group constants and testing data, and for calculating the activation and radiation damage of the materials of nuclear facilities. At present, the Centre has a modern ALPHA-3600 computer with 10 terminals. The existing hardware and software is suitable for organizing a local area network and, if there is a good link with the national and international systems, can enable organizations in the sector to have direct access to the Centre's data and the Centre to have direct access to the data of centres abroad.

Since it was established, the Nuclear Data Centre has:

- Set up a nuclear data bank containing all the world information on experimental neutron data and practically all the international and national nuclear data libraries and bases;

- Supplied numerical data from 1200 national or regional studies on neutron physics for inclusion in EXFOR and information on data from 2500 national studies for CINDA;

- Evaluated more than 60 complete data files and set up a national library of recommended evaluated neutron data (BROND) containing 121 data files;

- Established the Russian Dosimetric File (RDF-94) containing 52 reactions used in reactor dosimetry in metrology and as standards for measurements;

- Answered more than 4000 nuclear data inquiries from 50 organizations belonging to this and other areas;

- Published two neutron data handbooks;

- Prepared for publication more than 60 issues of the "Problems of Nuclear Science and Technology, Series: Nuclear Constants" and the proceedings of four neutron physics conferences.

The activities of the Nuclear Data Centre have made it possible to set up the BNAB, KORT and other group constant systems, and have enabled Soviet scientists to obtain a large number of the latest foreign programs for nuclear data calculation and processing. The data bank is constantly updated with new national and foreign data. It is doing continuous work on sorting, checking, correcting, updating and expanding, searching, retrieving and converting information for data users and on the generation of exchange data exchanges.

Nuclear Structure and Reaction Data Centre

This (Kurchatov Institute, Moscow) Centre was set up in 1973 and joined the international network of nuclear reaction data centres. Its functions are:

- To compile numerical and descriptive information and to co-ordinate the efforts of all groups working on the compilation of data on charged particle-induced reactions;

- To co-ordinate the compilation and evaluation of data for a number of chains of atomic masses for the international library of evaluated data on the structure of the atomic nucleus (ENSDF);

- To determine non-neutron data requirements;

- To develop software for libraries and databases;

- To provide enterprises in this area and other organizations with data on the structure of the nucleus and charged-particle reactions, etc.

Centre for Data on Photonuclear Experiments

This Centre (Scientific Research Institute for Nuclear Physics, Moscow State University) was set up in 1978 and joined the international nuclear data centre system in 1982. Its functions are:

- To compile numerical and descriptive information on photon-induced reactions;

- To set up a world bibliography on photonuclear reactions;

- To provide photonuclear data to institutes and organizations in Russia.

Since it was established, the Centre has:

- Set up a bibliographical photonuclear database containing practically all the international information on experimental photonuclear data;

- Supplied numerical data from 500 published works with experimental photonuclear data for EXFOR;

- Answered inquiries on photonuclear data;
- Regularly published information bulletins, indexes and reviews.

Radionuclide Data Centre

This Centre (Radium Institute, St. Petersburg) was set up in 1992. Its main activities are:

- To establish a computerized data bank on the decay characteristics of radionuclides and parameters of standard radionuclide sources;

- To evaluate and obtain recommended data in order to provide enterprises in the area with data on the properties of radionuclides used in practice and parameters of the radionuclide sources employed.

It has developed a computerized evaluation system for the nuclear physics characteristics of radionuclides.

VIII. THE HUMAN FACTOR

There is an urgent need for a programme to improve data for nuclear technologies. The reason for this urgency is that the average age of the persons working in the field of experimental nuclear physics is over 50 years, and the average age of those working in the field of experimental reactor physics is over 55. The situation abroad is even more critical. Thus, the opportunities for performing the necessary additional experiments are dwindling rapidly. In particular, it should be stressed that there is a danger of losing the experience and knowledge acquired over the past decades in the field of nuclear data and also of losing the wealth of information gained at critical assemblies and reactors, which is stored haphazardly and is only accessible to the surviving participants in the work in the 60s and 70s.

At the present time the scientific community in all countries is concerned about the problem of collecting and systematizing the scientific heritage in the nuclear data field in order to pass it on to future generations. The IAEA and individual countries are taking the appropriate organizational steps. It is clear, however, that in Russia the success of this activity will depend both on the availability of material resources for the national programme and on governmental support for extensive international co-operation in the area of nuclear data.

IX. CURRENT NUCLEAR DATA REQUIREMENTS

The development of nuclear technologies is proceeding along two paths - improvement of traditional approaches and coverage of an ever increasing number of other spheres of activity. This development inevitably gives rise to new nuclear data requirements. As a result, the nuclear data generated by scientists in previous years are constantly being supplemented quantitatively and improved qualitatively and the extent to which they fail to meet current users' needs depends not only on the constantly changing situation with regard to nuclear data applications but also on the experimental and theoretical level achieved in nuclear physics and on material investment in nuclear data activities.

The new requirements for nuclear data which have arisen recently are associated with the sharp increase in rigorousness of the requirements imposed on the analysis of severe reactivity accidents, the search for the safest methods of recovering weapons plutonium and plutonium from power plants, development of nuclear power plant technology with a closed fuel cycle, including resolution of the problem of transmutation of actinides formed in this cycle. Specific data requirements also stem from the development of fusion facilities, the progress of nuclear medicine and so on.

The permissible uncertainties of the required data are of great significance, since they - to a considerable degree - determine the scale of expensive margins built into designs.

Nuclear data should be universal so that their applicability is not limited by either the spectral or other characteristics of planned nuclear facilities. This is particularly important in the case of reactivity accidents where neutron spectra in a multiplying system can change radically from thermal to fast spectra.

Nuclear data should be comprehensive to allow calculation of neutron fields and their functionals, gamma fields and their functionals, induced radioactivity and its developments in time, reactor kinetics, and so on. When considering electronuclear facilities calculations are needed for reactions in an energy range of up to several GeV.

The volume of nuclear data required and their permissible uncertainties can vary substantially, depending on their field of application. Therefore, the nuclear data requirements for different fields of activity are given separately below.

1. ECONOMIC AND SAFE ENERGY PRODUCTION AT OPERATING NUCLEAR POWER PLANTS

Safety, environmental acceptability and economic feasibility are the fundamental considerations in the modern concept of nuclear power production. Operating nuclear power plants are much more competitive and profitable if they fully satisfy these principles. However, the design parameters of many nuclear power plants have margins, the magnitude of which was determined by the accuracy of the basic integral experiments and the uncertainty of the data used, this accuracy and uncertainty being those obtained in the reactor's design phase. Using the latest improved data for calculations, we can reduce the cost and increase the stability of operating nuclear power plants, while maintaining the required level of safety. In particular, attention should be paid to the following aspects.

Revision of calculations for the required fuel enrichment and the quantity of burnable absorbers to be inserted would enable us to optimize the energy production cycle from fuelling to refuelling without the need for margins.

Determination of the maximum local heat release with a lower uncertainty would help increase the reactor's total heat productions.

Greater accuracy in calculating the neutron fluence, the number of atomic displacements and the intensity of gas release in the reactor vessel would provide a means of justified extension of the service life of a reactor.

Revision of the calculated prediction for the ability of burnable additives to ensure reactor shutdown at any instant taking into account fuel burnup, the accumulation of fission products and minor actinides may extend the service life of the core and increase the total energy production during the reactor's operating lifetime.

Review of the kinetic parameters (delayed neutron yields, temperature and power coefficients and neutron lifetime) would enable more reliable assessment of the safety level of a reactor.

Reduction of the error of calculation of the radiation burden on reactor equipment and personnel is an important factor in assessing how these parameters satisfy accepted standards and in reducing shielding margins.

Organization of the safe storage of irradiated fuel requires sound knowledge of the afterheat release due to fission product and actinide decay and the ability to predict with a high level of confidence the criticality of the fuel in various geometrical configurations.

In order to determine the above characteristics of power reactors with a higher accuracy, we need neutron and photon interaction cross-sections, decay schemes and half-lives for a wide range of materials and radionuclides. Fuel elements contain the nuclei of isotopes of uranium, plutonium and heavier actinides and also the nuclei of fission products. Structural materials, coolant, burnable absorbers and control elements contain the nuclei of zirconium, iron, hydrogen, oxygen, sodium, hafnium, boron, gadolinium, erbium, silver and indium.

While many neutron interaction cross-sections and decay data are now known with satisfactory accuracy, the quality of nuclear data in a number of cases is still inadequate.

Evaluations of the residual energy release due to decay of uranium-235 and/or plutonium-239 fission products made by different persons differ by as much as 10% in some time intervals. This uncertainty has to be compensated for by expensive margins in emergency cooling systems, and by extension of the spent fuel decay and storage times. There is a sharp increase in the uncertainty for fuel with a complex composition (recycled plutonium burnup, actinide transmutation).

It is necessary to carry out new measurements of yields and decay data for fission products whose contributions are the most pronounced in time intervals where discrepancies are observed, and to verify the influence of the changing reactor neutron spectrum on fission product yields as well as various auxiliary contributions: delayed neutron fissions, minor actinide decay, transmutation of fission products and activation of structural materials. For a fuel lifetime corresponding to an energy production of up to 50 GW/t, about 50 isotopes need to be checked in this way.

The existing uncertainties in the fission and capture cross-sections for actinides mean that even when using non-recycled but high-burnup uranium or plutonium fuel 10-15% margins have to be allowed for in the permissible quantity of fuel shipped in one container. In the case of recycled fuel, or fuel containing transmutable actinides, the margins are markedly higher. The accuracy of fission and neutron radiative capture cross-sections for minor actinides should be substantially improved and the error of neutron capture cross-sections for fission products reduced to 10%.

Data on cross-sections for the main structural materials above 1 MeV are still unsatisfactory (there is an uncertainty of up to 20% in the scattering cross-section for iron). Cross-sections in the 1-5 MeV region are important not only from the point of view of radiation damage to structural materials but also because of the effect on reactivity. It is necessary to carry out new measurements with a target error of 5% for iron and 10% for chromium and nickel.

There are persistent discrepancies between the calculated and measured temperature coefficient of the moderator. New measurements of the capture cross-sections for uranium-238 and of the value of η for uranium-235 have confirmed the low accuracy of the old nuclear data. Further measurements are needed with high resolution of the shape of uranium-238 resonance in UO_2 at different temperatures.

New measurements of the neutron inelastic scattering cross-sections and spectra for uranium-238 and the delayed neutron yields and spectra for uranium-238 should be performed in order to resolve the existing discrepancies in nuclear data.

2. ADVANCED NUCLEAR REACTORS

(a) Reactors with inherent safety

The main objective of the development of new and the upgrading of operating reactors is to ensure their inherent nuclear safety. Instead of relying on engineering methods to guarantee safe operation, emphasis is placed on the natural properties of nuclei and materials. This imposes especially high requirements on a very wide range of nuclear data.

One of the most important factors determining the inherent safety of reactors is a sufficiently high negative Doppler temperature coefficient of reactivity in reactors with uranium-238. In reactors which use "surplus" thorium neutrons as an absorber, this effect has the same sign and is not smaller in magnitude, although the uncertainty in the calculated evaluation increases from 10% to 20-25%. In transmutation reactors (as in the blankets of accelerator breeders for transmutation) the neutrons that are in excess for the chain reaction are absorbed in the burnable actinides, where the accuracy of evaluation of the Doppler effect can be much lower. The uncertainty in individual cases may be as high as 100% (i.e. the Doppler temperature effect may even be positive). It is obvious that there is a pressing need to improve the accuracy of the theoretical prediction of the Doppler effect.

(b) Increased fuel burnup

Increased fuel burnup is one of the characteristics of the new generation of reactors. More accurate knowledge of nuclear data for minor actinides and fission product nuclei is needed in order to avoid providing for too much built-in reactivity in the design. In particular, inelastic scattering cross-sections and more accurate data on the neutron radiative capture cross-sections for these nuclides are becoming important.

Table 4 shows the generalized required accuracies for nuclear data in the light of the development of reactor technology.

Table 4.
Required accuracy of nuclear data (%)

Reaction \ Materials	Fuel materials	Source materials	Minor actinides	Structural materials	Fission products
Fission cross-section	1	1	5	-	-
Number of secondary fission neutrons	0.5	1	3	-	-
Neutron radiative capture cross-section	3	2	5	5	5
Neutron inelastic scattering cross-section	5-10	5	10	5	5
Cross-section for the (n,2n) reaction	5	5	10	10	10
Total cross-section	2	3	5	5	5
Hydrogen, tritium and helium formation cross-section	15	15	20	15	15

(c) Use of plutonium from nuclear power plants and weapons plutonium

As a result of the accumulation of plutonium for weapons and plutonium produced in nuclear power plants and mobile nuclear facilities there is a pressing need to resolve the problem of its use. In this connection, projects on the use of plutonium in thermal reactors with closely spaced lattices are under consideration. This calls for a careful study of the problem of resonances in the cross-sections for plutonium-239 and its heavier isotopes, since there are noticeable discrepancies in the evaluated capture and fission cross-sections in the resonance energy region. In thermal and fast reactors only a small proportion of all fissions occurs in this region and the above uncertainty has little effect on the results. In the intermediate spectra, occurring in thermal reactors with a closely spaced lattices, which it is proposed to use for the burning of plutonium, these uncertainties are substantial and they need to be resolved.

The quantity of uranium-238 in reactors must be minimized in order to reduce the further accumulation of plutonium. The replacement of depleted uranium in fast reactor blankets by structural materials (for example, steel) will sharply raise the accuracy requirements for the nuclear data on iron, chromium and nickel, which are constituents of steel.

Another alternative for the burning of plutonium-239 is offered by the fast breeder designs where uranium-238 is replaced by thorium-232. In this case, plutonium-239 is burnt and uranium-233 is produced, the latter being an efficient fuel for thermal and fast reactors. Until recently, nuclear data for the thorium cycle were not a pressing problem, therefore only a part of nuclear data needed to resolve this problem is available and even they need to be improved. The aim is to generate nuclear data files for use in the calculations for the thorium cycle. The accuracy requirements for the cross-sections are less stringent than in Table 4, since at this stage it is only necessary to study the feasibility and not the technical implementation of the project.

Nuclei to be studied: thorium-232, protactinium-231, 232, 233, uranium-232,233,234.
Accuracy for fission cross-sections: 3-5%.
Accuracy for radiative capture cross-sections: 3-5%.
Accuracy for the neutron inelastic scattering cross-section: 20%.
Neutron energies: thermal, resonance and up to 20 MeV.

(d) Other technological innovations

It is necessary to make a careful study of the nuclear data requirements in connection with the consideration of new fuel compositions (mixed fuel, fuel containing transmutable actinides, uranium-thorium cycle fuel and so on) and new coolants (lead, molten salts and so on).

In particular, the discrepancies in the total cross-section data for lead in the region of hundreds of keV contribute substantially to the uncertainty in the calculated critical characteristics of lead breeders and have no less of an effect on the critical safety parameters of the lead-cooled target of accelerator-driven transmutation facilities.

3. TRANSMUTATION OF RADIOACTIVE WASTE

Whether the justification for choosing a concept for the transmutation of long-lived radioactive waste is reliable and whether the choice is sound depend to a large extent on the completeness and accuracy of the nuclear data used in the theoretical modelling of transmutation processes at nuclear facilities.

At least two main options for transmutation are being considered: burner reactors and accelerators with a proton energy of about 1.5 GeV coupled with a subcritical reactor as a target or blanket.

(a) Burner reactors

The criticality safety of actinide transmutation facilities depends to a great extent on the effective delayed neutron fraction. The problem here is not just the fact that the delayed neutron fractions and energy spectra for minor actinides are not known with sufficient accuracy, but also the fact that the importance of delayed neutrons in systems with fuel with a fission threshold depends very strongly on the inelastic scattering cross-sections of transmutable actinides, for which only calculated estimates are available. For this reason, the accuracy of nuclear data needs to be increased considerably in the reactor energy range for minor actinides, whose content in the fuel may be as much as several tens of percent (delayed neutron yields, fission fragment yields for neptunium-237, americium-242, 243 and plutonium-238, inelastic neutron scattering cross-sections and spectra for neptunium-237, plutonium-238 and americium isotopes, fission and neutron radiative capture cross-sections for curium isotopes).

Table 5 shows one-group evaluations of the uncertainties in the cross-sections for fissile nuclides and the accuracies required in the fast neutron region.

Table 5

	$\Delta^{\sigma}_{n,\gamma}$, %		Δ^{σ}_{f}, %		Δ^{σ}_{in}, %	
	Achieved	Required	Achieved	Required	Achieved	Required
Np-237	15	5	7	5	30	10
U-238	5	3	3	3	10	10
Pu-238	25	10	10	5	40	20
Pu-239	6	4	3	3	20	15
Pu-240	10	5	5	3	20	15
Pu-241	15	5	5	3	20	25
Am-242m	30	10	15	5	40	20
Am-243	30	10	10	5	30	20
Cm-242	50	10	15	5	30	30
Cm-243	50	10	15	5	30	30
Cm-244	50	10	10	5	30	30

Fission and neutron radiative capture cross-sections are also necessary for the short-lived nuclei of uranium-237, 239, neptunium-238, 239, plutonium-243 and americium-242, 244 in the thermal region.

There are marked discrepancies in the shape of the evaluated fission neutron spectra. The shortage of neutrons capable of splitting uranium-238 can be compensated, and is in fact compensated, during power reactor calculations by increasing the cross-section for uranium-238. However, in reactors containing other actinides with a high fission threshold (plutonium-240 and neptunium-237) such compensation will not be possible. Consequently, the fission spectra need to be refined.

Data on the neutron radiative capture cross-sections for actinides present a major problem. It is extremely difficult to measure these cross-sections. Since heavier actinides are formed by successive neutron captures, the existing correlation of the uncertainties in nuclear data on capture cross-sections leads to a corresponding increase in the uncertainty of the results of modelling heavy actinide accumulation.

In this connection, one of the important aims is to improve the theoretical models for calculating radiative capture cross-sections.

(b) Accelerator coupled with a subcritical reactor as a target or blanket

The entire set of nuclear data mentioned above is also necessary to study this option, since the transmutation process takes place in a high neutron flux in the subcritical reactor with a spectrum close to the neutron spectrum in the burner reactor or in a thermal neutron flux.

In addition, a vast amount of nuclear data is needed in the 20 MeV-1.5 GeV region. The list of data required includes double differential cross-sections for neutron production in the target materials, neutron and gamma emission cross-sections, activation cross-sections, cross-sections for calculating heat production, radiation damage and gas generation in structural materials and shielding and so on.

The following materials can be considered as possible components for the system:

1. Actinides: ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, $^{242}Am^{m}$, ^{243}Cm, ^{242}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm;

2. Target: Ta, W, Pb, Bi;

3. Materials for the structural components, shielding, coolant etc.: H, C, N, O, Na, Mg, Al, Ar, K, Ca, Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr.

The experimental data available in the 20 MeV-1.5 GeV region have not been systematized and are fragmentary. They require careful analysis and conversion to computerized format (EXFOR).

The theoretical models and systematics developed to describe nuclear processes in the above region do not guarantee the required accuracy of the calculation results and need further improvement.

It would be advisable to support the system that is being developed abroad for the production of the most important nuclear data for accelerator-driven transmutation and to participate in it.

It consists of the following:

1. The establishment of a nuclear data library (neutron and proton data) for the most important nuclei in the 20-100 MeV region;

2. The establishment of a library of reference (standard) data files up to an energy of 1.5 GeV. These data can be used as reference data for measurements and also for testing and comparing different theoretical models and computer programs;

3. The establishment of a library of activation cross-sections up to 100 MeV for neutrons and protons.

4. FUSION FACILITIES

An extensive nuclear data base is required for the design of such fusion facilities as, for example, ITER in order to calculate the rate of fusion reactions in plasma; to predict neutron and photon propagation in the materials of the facility's assemblies, to calculate the rate of tritium formation in blankets; to calculate nuclear heating, induced radioactivity and decay heat; to predict the rate of gas formation and the number of atomic displacements as indicators of radiation damage to materials.

The most likely materials to be used in the construction of ITER are:

- Structural materials: Fe, Cr, Mn, Ni, Ti, Al, V;

- Blanket for tritium breeding and cooling: ^{6}Li, ^{7}Li, Pb, H, O, Ga, Na, K;

- Neutron multipliers: Be, Pb;

- Magnets and their shielding: Fe, Cr, Ni, Cu, Nb, Sn, Ti, Al, V, W, ^{10}B, ^{11}B, C, H, O, Na, K, Li, Ga;

- The plasma-faced first wall: Mo, Nb, W, Cu, Fe, Cr, Ni, Ti, Al, V;

- Biological shield: B, C, O, Si, Ca, Ba.

For all these elements (approximately 30) and all their stable isotopes data are needed on all the neutron reaction cross-sections in the energy range from a few eV to 20 MeV.

Many data in the 0-10 MeV region, obtained for fission reactors can also be used for the calculation of fusion facilities. However, the 7-20 MeV region is specific to fusion reactors and here one needs a great deal more accurate and detailed nuclear data than have been obtained to meet the requirements of fission reactors.

In the case of fusion reactors, such reactions as (n,n′), (n,2n), (n,3n), (n,p), (n,np), (n,α), (n,nα) and the energy and angular distributions of secondary particles generated in these reactions assume particular importance.

Covariance matrices are needed for the main elements of the most important materials and assemblies in order to study the sensitivity of the calculated characteristics of fusion reactors to uncertainties in the neutron cross-section values.

Table 6 gives the permissible uncertainties (%) of nuclear data for various types of neutron interaction and different assemblies in a fusion facility.

Table 6

Neutron cross-section	Tritium breeding blanket	Neutron multipliers	Magnet	First wall	Shielding
σ_{tot} < 10 MeV > 10 MeV	 3 3	 3 3	 3 3	 3 3	 3
Neutron emission (Θ,E')	10	10	20	-	5
Neutron multiplication (n,2n), (n,3n)	-	3	-	-	-
(n,n) (Θ)	10	10	20	-	3

The nuclear data situation in the region close to 14 MeV is on the whole satisfactory but in the 7-14 MeV range efforts need to be made to obtain nuclear data for double-differential neutron emission cross-sections and for photon formation.

A 3% accuracy for the $^{6}Li(n,n'\alpha)T$ reaction cross-section has not been attained.

Data for (n,xp) and (n,xα) reactions are incomplete and are not sufficiently reliable. Further experimental and theoretical work is needed to investigate these reactions.

The accuracy attained for dosimetric reaction cross-sections is not the same for the various reactions and varies from 2 to 30%. Uncertainties near the reaction threshold and in the region above 17 MeV considerably exceed those in the region between these boundaries. The problem of covariance matrices has not been finally resolved.

The status of data on activation reaction cross-sections is still unsatisfactory. There are large gaps and discrepancies in all types of experimental activation cross-sections. Most of the available calculated data for these cross-sections have been obtained with the use of calculation models which do not guarantee the necessary quality. Some data on nuclide half-lives are unreliable.

Existing data files for charged-particle-induced fusion reactions - DATLIB (Austria), ECPL (USA) and ECPNDL (Russia) - contain all the nuclear fusion reactions related to the (d,t) cycle.

The uncertainties in the reaction cross-sections are as follows: D(d,n) - 3%, D(d,p) - 3%, T(t,n) - 8%, T(d,n) - 2%, 3He(d,p) - 8%, and are perfectly adequate for fusion reactors.

5. NUCLEAR MEDICINE

The use of nuclear science and technology in medicine has become very extensive and new prospects are increasingly being opened up for the diagnosis and treatment of tumours, heart diseases, brain function disorders and other diseases, as well as for the study of biochemical and physiological processes.

The basic tools of nuclear medicine are radionuclides and various particle beams.

Appropriate nuclear data are generally available for the production of medical radioisotopes using existing accelerators and reactors. However, in order to optimize the radioisotope production systems so as to minimize the radioactivity due to impurities we need to have more accurate and systematized knowledge of the nuclear interaction processes, particularly where thick targets are used. High impurity radioactivity reduces the permissible quantity of the useful radionuclide for the patient.

More accurate information is needed on the decay schemes of ^{90}Y, $^{186,187}Re$ and ^{153}Sm, which are intended for use in internal radiotherapy, in order to calculate with permissible errors the radiation dose to the patient.

The use of accelerators with particle energies of several hundred MeV for the production of medical radioisotopes in breakup and other reactions requires data on the cross-sections for the formation of these isotopes.

In many cases, fast reactors have advantages for the production of some isotopes for internal therapy. Data on the cross-sections in the region of epithermal and fast neutrons for many nuclei of interest are either lacking or have a large uncertainty. It is also necessary to have cross-sections for the evaluation of impurity formation in this region.

Photon and positron emission tomography is an efficient method for the diagnosis of diseases and for the study of biochemical, physiological and pharmacological functions at the molecular level. Physiological and medical preparations labelled with short-lived photon- and positron-emitting radionuclides are employed in this method. Radionuclides with a dominating 70-250 keV gamma line such as $^{99}Tc^{m}$, ^{123}I and ^{201}Tl are used in photon diagnostics and nuclides such as ^{11}C, ^{13}N, ^{15}O and ^{18}F in positron diagnostics. The above-mentioned short-lived positron emitters are produced in cyclotrons with a particle energy of 10-30 MeV. Data on the cross-sections for the formation of these isotopes are available, but many of them do not agree with each other.

There are about 100 promising candidates for positron emitters. The formation cross-sections and decay schemes for these new nuclides are needed. Some of them occur as impurities during the production of the above-mentioned positron emitters (^{11}C, ^{13}N, ^{15}O and ^{18}F) and create a problem in positron tomography dosimetry.

At present, the possibility of producing short-lived isotopes for positron tomography using small accelerators with a 2-4 MeV beam of protons, deuteron or helium-3 is being considered. Such accelerators could be affordable for most clinics. In this energy range, the cross-section data are either poorly covered or lacking.

A geometrically shaped beam of accelerated particles or neutrons is used in external beam radiotherapy. Nuclear data in the 20-70 MeV region have to be measured and evaluated for the most important materials (H, Be, C, N, O, Ca, Fe, Ni, Cu, Zr, W and Pb) in order to optimize the collimators and shielding.

There is a need for a better description of nuclear interactions at high energies, particularly for breakup reactions in tissues and their effect on the dose to the patient. For heavier ions, no data exist on the fragmentation process.

One promising area is the use of radionuclide beams with a fixed E/m for selective radiotherapy. The main advantage of such beams is that the Bragg peak region is a sensitive function of E/m and therefore it is possible to create beams which can be localized precisely in the therapy region. There are no cross-sections for the formation of such nuclides during bombarding of the target with the primary beam and work should be done in this area.

For the purpose of predicting the effect of neutron beams, it is necessary to improve existing data on the interaction of neutrons with tissue at energies below 20 MeV. In the 20-70 MeV region there are no such data. Data on the kerma factor for C, O and other nuclei in this energy region are needed.

For neutron capture therapy, which involves preliminary loading of the tissue with nuclides having a large cross-section for charged-particle formation reactions, detailed information is required on energy release at the end of the track.

It would be very useful for practical purposes to publish a manual on medical radioisotopes giving the yields of each type of radiation, the path lengths and the differential energy losses in the tissue.

6. DECOMMISSIONING OF FISSION REACTORS

In the near future, a large number of reactors currently in operation will reach the end of their lifetime and will have to be decommissioned; after an appropriate cooling period, they can be dismantled.

Knowledge of the activation of materials used for structures (vessel and vessel internals) and concrete reactor shielding is of crucial importance in determining the dose burdens during the decommissioning process, the cooling time before decommissioning and the volume of material subject to containment and disposal. Since several tens of thousands of cubic metres of concrete and thousands of tonnes of metal are involved, the problem is particularly important from both the technical and the economic point of view if the activation level of all these materials is such that they have to be disposed of in bulk.

This problem should also be taken into account in designing new nuclear facilities by selecting materials which have small activation cross-sections or in which short-lived radionuclides are formed.

It should be noted that a large contribution to the induced radioactivity is made by the alloying additives and impurities, whose content cannot be always checked with sufficient accuracy. The principal contributors to long-lived activation of the WWER reactor vessel steel and the concrete shielding with serpentinite filler used in Russian reactors are:

- In steels: ^{55}Fe (2.68 years), ^{54}Mn (312 days), ^{60}Co (5.27 years), ^{59}Ni (7.5 $\times$ 10^5 years), ^{63}Ni (100 years), ^{108}Ag^m (418 years) and ^{110}Ag^m (249 days);

- In concrete: ^{41}Ca (1.03 10^5 years), ^{45}Ca (154 days), ^{55}Fe (2.68 years), ^{54}Mn (312 days), ^{60}Co (5.27 years), ^{108}Ag^m (418 years), ^{134}Cs (2.06 days), ^{151}Sm (90.0 years), ^{152}Eu (13.2 years) and ^{154}Eu (8.8 years).

These radionuclides are formed mainly in neutron capture reactions, the cross-sections of which for thermal and epithermal neutrons are fairly well known. However, in the case of the formation of radionuclides in isomeric states (the isomers of Eu and Ag), the isomeric ratios have not been determined reliably even at 14.8 MeV and there are no experimental measurements of the energy dependence of the isomeric formation cross-section. Therefore experimental measurements are needed for the excitation functions of the above-mentioned isomers in capture reactions. It is also necessary to improve the accuracy of the neutron capture cross-sections for Ca isotopes and rare-earth elements such as Eu, Re, Hf and Ir, which enter into the composition of fast reactor structural materials in the form of alloying additives and impurities.

7. REFERENCE CROSS-SECTIONS AND VALUES

Russia has adopted the system of reference or standard values recommended by the IAEA (INDC(SEC)-101). This system needs to be further developed, refined and supplemented.

In the 0-20 MeV energy range, an accuracy of 1% is required for standards, whereas the accuracy attained is 2-3%. In the region above 20 MeV the standards used for the time being are the neutron scattering cross-section for hydrogen and the fission cross-section for uranium-235. It is necessary to develop theoretical models for these reactions and to seek other reactions to serve as standards at higher neutron and proton energies.

The following reactions could be considered as candidates for additional standards in the region above 20 MeV:

Scattering standard: C(n,n), ^{4}He(n,n);

Standards for capture and inelastic scattering reactions: ^{12}C(n,n'γ), ^{56}Fe(n,n'γ), ^{208}Pb(n,n'γ), ^{7}Li(n,n'γ), ^{27}Al(n,γ), ^{54}(Fe(n,2nγ);

Standards for charged-particle formation reactions: ^{12}C(n,p), ^{3}(He(n,p), ^{3}He(n,d), ^{46}Ti(n,p), ^{51}V(n,xα);

Standards for fission and fragmentation reactions: ^{232}Th(n,f), ^{235}U(n,f), ^{238}U(n,f), ^{2,9}Bi(n,f), ^{208}Pb(n,f), Cd(n,xf).

8. NUCLEAR DATA FOR NUCLEAR MICROANALYSIS OF MATERIALS

For nuclear, atomic and molecular microanalysis, it is necessary to measure the nuclear cross-sections for the interaction of thermal and fast neutrons, and also protons, deuterons and alpha particles in the energy range of 0.5-2.5 MeV with gas-forming, structural and other materials used in reactor technology. Moreover, it is also necessary to measure and evaluate the cross-sections and yields of characteristic X-rays for intermediate-mass and heavy nuclei, and to measure the secondary ion yields during bombardment by hydrogen, helium, argon and other atoms.

The data under study are used for rapid nuclear physics microanalysis of structural materials in the nuclear power industry and for other purposes.

- Validation of the manufacturing processes and treatment of structural materials.
- Study of problems of corrosion of steels in liquid-metal coolant media.
- Study of individual problems of the radiation resistance of materials.
- Study of the quality and the impurity composition of monocrystalline materials.
- Study of the single- and multi-layer surface coatings used in microelectronics (distributions in depth, the presence of impurities, interdiffusion, etc.).

It is desirable that a manual on nuclear data for nuclear microanalysis should be published.

9. NON-PROLIFERATION SAFEGUARDS FOR FISSILE MATERIALS

The technique used for non-destructive testing of the quantity and type of nuclear materials contained in any device is based on the recording of spontaneous or induced emissions.

Obtaining the necessary information from the results of these test measurements requires different kinds of highly accurate nuclear data.

The most frequently used signature for fissile materials is fission neutrons. Accordingly, there is a need for data on prompt neutron multiplicity distribution in the induced fission of nuclei such as $^{239,\,240,\,241}Pu$ and $^{235,\,238}U$ as a function of the excitation energy of the fissile nuclei, and in the spontaneous fission of $^{238,\,240,\,242}Pu$ and ^{238}U.

The demand for data on half-lives and yields of delayed neutrons for $^{234,\,236}U$ and ^{237}Np has still not been met.

It is necessary to improve the accuracy of data on the (α, n) reaction cross-sections and on the spectra of neutrons formed by the action of natural α-activity of fissile materials.

In many cases, for the purpose of fissile material monitoring, use can be made of the existing nuclear data or the theoretical models for calculation of the various characteristics of the nuclear fission process.

There is an obvious need to conduct further studies on the nuclear fission process, since the more details we know about the individual characteristics of the emissions associated with the fission of various nuclides, the greater will be the scope for identifying those nuclides.

10. SPACE APPLICATIONS

Space exploration programmes, in particular the planned flights to Mars, will involve prolonged exposure of electronic equipment and man to cosmic radiation. The most probable power plant in the space ship will be a nuclear reactor - an additional source of radiation.

Reducing the dose burden on cosmonauts through radiation shielding involves considerable expenditure, since each ton of load taken into space is too expensive. The data used in the calculations must therefore ensure minimal margins in the shielding. Furthermore, the effect of radiation on instruments and computers needs to be evaluated. The uncertainty in calculation results attributable to nuclear data should not exceed 15%.

CONCLUSIONS AND RECOMMENDATIONS

1. It will be very expensive to satisfy in full the nuclear data requirements listed above. The prevailing economic situation makes it necessary to concentrate on a national nuclear data programme for the solution of the most important problems to ensure a high degree of reliability in the nuclear safety, ecological acceptability and low cost of the operating, advanced or planned nuclear facilities and the different fuel cycles. This applies, first of all, to the nuclear data for inherently safe reactors, for reactors with high burnup, for the problem of using plutonium from power reactors and weapons plutonium, and for the development of various options for transmutation of radioactive waste. Participation in the international nuclear data projects under the IAEA and OECD programmes and under bilateral agreements will widen the range of problems to be resolved in the nuclear data field.

2. The scope of measurements of differential nuclear data in the region below 20 MeV should be restricted to testing nuclear models used for the evaluation of nuclear data, to

obtaining reference (standard) cross-sections and to measuring the most important values the required accuracy for which cannot be attained by another method.

3. At the institutes under the Ministry of the Russian Federation for Atomic Energy the following minimum facilities are available for neutron studies:

Institute of Physics and Power Engineering (IPPE)

The group of the KG-2.5, EhG-1 and EhGP-10M accelerators produce monoenergetic neutron fluxes in the range from 30 keV to 25 MeV. It is advisable to complete the construction of the injector for the new EhGP-15 accelerator and then to mothball the EhGP-10M accelerator;

All-Russian Scientific Research Institute for Experimental Physics (VNIIEhF)

A pulsed white-spectrum neutron source in the range from 0.5 to 14 MeV, based on the LUEh-50 electron accelerator;

Neutron Physics Laboratory, Joint Institute for Nuclear Research (JINR)

An IBR-30 pulsed neutron source in the resonance energy region;

Khlopin Radium Institute

An NG-400 neutron generator for 14 MeV;

Scientific Research Institute for Atomic Reactors (NIIAR)

A mechanical selector in the BOR-60 reactor beam for the study of the resonance structure of cross-sections for radioactive nuclei.

Financial provision should be made for maintaining these facilities and for the travel expenses involved in carrying out joint activities.

For work in the region of intermediate and high energies it is advisable to hire for a minimal period the high energy accelerators of the Joint Institute for Nuclear Research, the Institute of Theoretical and Experimental Physics, the St. Petersburg Nuclear Physics Institute and the Institute for Nuclear Research (Russian Academy of Sciences) or to organize joint activities with these institutes.

It should also be taken into account that detector systems, measuring equipment, targets and samples need to be replaced periodically.

Pools of separated stable and radioactive isotopes should be established, and the financial resources found for their use in nuclear data measurements.

4. One of the main tasks of physicists continues to be the development of model representations of the processes of interaction of neutrons and protons with nuclei. Further studies should be focused on further developing the statistical methods describing the highly-excited states of nuclei, methods of taking into account the influence of nuclear viscosity on the competition between the processes of fission and multiple nucleon emission, microscopic methods of considering particle cluster formation at intermediate energies, method of considering multistage direct and compound nuclear processes on the basis of microscopic consideration of effective nucleon-nucleon interactions and the respective transition densities of quasi-particle excitations.

Many features of reactions at intermediate and high energies have not yet been subjected to rigorous theoretical description. Thus, there is continuing interest in the experimental studies of the cross-sections of the various nuclear reactions in the respective energy ranges, and in the development of more rigorous theoretical models for their analysis.

Considering that there is limited scope for obtaining experimental data for the nuclei of fission products and minor actinides, the methods used for evaluating the most important reaction cross-sections for those nuclei should be developed further.

5. An urgent problem for nuclear data evaluation is to determine the uncertainties and correlations of recommended data. It is necessary to develop methods of determining covariance matrices or simpler methods of expressing the uncertainties for complete neutron data files.

6. In the region of intermediate and high energies it is advisable to adopt the structure of the international programme - the establishment of a library of nuclear data in the 100-150 MeV region, measurements of reference cross-sections in the region up to 1.5 GeV for testing nuclear reaction models and for use as standards and the establishment of a library of activation cross-sections in the 20-100 MeV region - and to join in international co-operation in its implementation.

7. Russia, as a State with a mighty nuclear technology, cannot do without a national library of evaluated nuclear data. Its BROND library should be developed through the

creation of new files and the improvement of existing files to take account of new experimental and theoretical information. There is an urgent need to revise the files for ^{232}Th, ^{235,236,238}U and plutonium isotopes, to incorporate inelastic scattering cross-section into the fission product files, to establish a file for ^{237}Np, and to include gamma-ray production cross-sections in the files. The practice of setting up specialized nuclear data libraries should continue.

Russia's participation in the preparation of ENSDF and the international database on nuclide decay properties should be ensured.

Russia should continue to participate in the international exchange of nuclear data so as to have access to the world bank of nuclear data.

8. It is necessary to organize collection and analysis of all the accumulated information on integral experiments, to develop a unified approach and format for data compilation, and to establish a library of evaluated integral experiments for nuclear data testing. The cycle of measurements for leakage neutron spectra in spherical experiments for the most important materials has not yet been completed. A number of the most important specialized libraries are based only on theoretical calculations and need to be tested (ADL-3, MENDL-2). It is important to make maximum use of other countries' experience in testing the evaluated data.

9. The CONSYST program package for preparation of data for calculation should be further improved with the BNAB constants based on the national BROND library of evaluated data files.

10. It has become necessary to establish an on-line network that would give Russian institutions direct access to the databanks of nuclear data centres in the country, and to link these centres with others abroad.

11. It is advisable to standardize the programs for treating the results of measurements of radiation used in the various areas of nuclear technology, and regularly update the systems of data used in these programs.

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APPENDIX 1

NUCLEAR DATA LIBRARIES AVAILABLE AT THE NUCLEAR DATA CENTRE

1. CINDA INTERNATIONAL CATALOGUE OF BIBLIOGRAPHICAL NEUTRON DATA

It contains all the bibliographical information available worldwide on neutron data from experimental and theoretical work and evaluation work. It is also a catalogue of the EXFOR experimental data library. It has a set of programs for generation, search and retrieval of information on any parameter.

2. EXFOR WORLD LIBRARY OF EXPERIMENTAL NEUTRON DATA

It contains experimental data from 7700 papers on neutron physics (45 000 data sets, 3.2 million lines of data). It has a set of programs for verification, search and retrieval, format conversion and graphical representation of data.

3. BROND2.2 EVALUATED NEUTRON DATA LIBRARY (RUSSIA)

It contains 121 complete files for fissile, structural and other materials used in reactor technology and fission products in the ENDF/B-VI format, supplemented by a set of utility programs for the ENDF/B-VI format.

4. ENDF/B-VI LIBRARY OF EVALUATED NEUTRON DATA (USA)

It contains 250 files for stable isotopes and actinides and 70 files for fission products. There are additional specialized libraries:

- Data on thermal neutron scattering laws;
- Data on radioactive decay;
- Data on fission product yields;
- Data on interactions with photons;
- Data on the interaction of high-energy neutrons and protons with ^{12}C, ^{56}Fe, ^{208}Pb and ^{209}Bi.

There is an extensive utility program package for the ENDF/B format and an NJOY program package for preparing group constants and calculating reactor functionals.

5. JENDL-3 LIBRARY OF EVALUATED NUCLEAR DATA (JAPAN)

It contains complete data files for 324 nuclides (including 172 files for fission products) in the ENDF/B format.

6. CENDL-2 LIBRARY OF EVALUATED NUCLEAR DATA (CHINA)

It contains 53 complete nuclear data files.

7. JEF-2 LIBRARY OF EVALUATED NUCLEAR DATA (WESTERN EUROPE)

It contains evaluated data for 303 elements and isotopes and 4 specialized libraries:

- Data on thermal neutron scattering laws;
- Data on radioactive decay;
- Data on fission product yields;
- Data on interaction with photons.

8. EAF-2 EUROPEAN LIBRARY OF ACTIVATION DATA

This library contains neutron cross-sections for 11 000 reactions for 667 nuclides.

9. ADL-3 ACTIVATION DATA LIBRARY (RUSSIA)

It contains more than 30 000 excitation functions for neutron reactions with stable and radioactive nuclei, including isomeric states.

10. IRDF-90 INTERNATIONAL DOSIMETRIC FILE

It contains data on 44 reactions used in reactor dosimetry and as standards for neutron measurements.

11. RDF-94 RUSSIAN DOSIMETRIC FILE

It contains 40 reactions used in reactor dosimetry and as standards for neutron measurements.

12. BOFOD PHOTONEUTRON DATA LIBRARY (RUSSIA)

It contains cross-sections for the interaction of photons with nuclei for 27 materials from ^{9}Be to ^{243}Am.

13. ASIYaD LIBRARY OF FISSION PRODUCT YIELDS (RUSSIA)

It contains data on fission product yields for 21 fissile nuclei from U to Cm.

14. ENSDF INTERNATIONAL LIBRARY OF DATA ON THE STRUCTURE OF THE ATOMIC NUCLEUS

It contains all the available experimental data on nuclear level schemes, half-lives and spectroscopic characteristics of nuclear transitions.

APPENDIX 2

PROGRAMME OF NUCLEAR DATA STUDIES FOR 1995-2005

	Activity	Institution*	Period	Expenditure (in 10^6 roubles)	Expected results
1	2	3	4	5	6
1	**Nuclear data measurements**		1995-2005		
1.1	Measurements of nuclear data characterizing the interaction of neutrons and protons with the most important actinides	IPPE, VNIIEhF Radium Institute, Neutr. Phys. Lab of JINR, NIIAR, Kurchatov Institute	1995-2005		Fission cross-sections, fission neutron spectra, delayed neutron yields, inelastic scattering cross-sections, capture cross-sections, prompt fission gamma yields for minor actinides and refinement of a number of data for the main fuel nuclei

*

IPPE	Institute of Physics and Power Engineering
ITEhF	Institute of Theoretical and Experimental Physics
MIFI	Moscow Institute of Physics and Engineering
NIIAR	Scientific Research Institute for Atomic Reactors
NIIYaF of MGU	Scientific Research Institute for Nuclear Physics, Moscow State University
OIATEh	Obninsk Institute for Nuclear Power Engineering
JINR	Joint Institute for Nuclear Research
TsNIIAI	Central Scientific Research Institute for Information and Techno-economic Studies in the Field of Atomic Science and Technology
VNIIEhF	All-Russian Scientific Research Institute for Experimental Physics
VNIITF	All-Russian Scientific Research Institute for Theoretical Physics

1	2	3	4	5	6
1.2	Measurements of nuclear data for fission products, structural materials and coolants	IPPE, Radium Institute, VNIIEhF, ITEhF, NIIAR, Kurchatov Institute	1995-2005		Inelastic scattering and capture cross-sections for fission product nuclei, formation cross-sections and gamma-ray spectra and neutron resonance parameters
1.3	Precision measurements of the characteristics of nuclear reactions for development of standards and reference cross-sections	Radium Institute	1995-2005		Reference cross-sections in the intermediate and high energy region
1.4	Experimental studies on radioactive decay of nuclei and their structure	Radium Institute, Kurchatov Institute	1995-2005		Decay schemes; half-lives; gamma, beta and alpha yields and spectra
1.5	Production and calibration of targets and samples of stable and radioactive nuclei, organization of stable isotope pool	Radium Institute, NIIAR, VNIIEhF, IPPE	1995-2005		Targets of individual radioactive and stable isotopes for the measurement of nuclear data and study of nuclear reaction mechanisms
1.6	Procurement of resources for the operation of facilities for experimental studies, establishment of special operating conditions for accelerators and detection systems for nuclear data measurement	IPPE, VNIIEhF, Radium Institute, NIIAR, Neutr. Phys. Lab of JINR	1995-2005		Sources of monoenergetic neutrons and white-spectrum neutrons in the 0-25 MeV region
2	**Development of theoretical models for nuclear data evaluation**		1995-2005		

1	2	3	4	5	6
2.1	Development and improvement of theoretical models and systematics of the nuclear fission process	IPPE, Radium Institute, MIFI, Neutr. Phys. Lab. of JINR, Kurchatov Institute	1995-2005		Models of nuclear fission and systematics of fission cross-sections, spectra and average number of prompt fission neutrons, delayed neutron spectra and yields, kinetic energies and fission product yields
2.2	Improvement of existing and development of new theoretical models for nuclear reactions with emission of nucleons and light clusters	IPPE, OIATEh, Neutr. Phys. Lab. of JINR, Kurchatov Institute	1995-2000		Development of theoretical models for the calculation of nuclear data, including microscopic methods for the study of particle cluster formation; multi-stage direct and compound nuclear processes of effective nucleon-nucleon interactions and the corresponding transition densities of quasi-particle excitations
2.3	Development of a theoretical description of nuclear reactions and of calculation programs for the intermediate- and high-energy region	IPPE, OIATEh, Radium Institute	1995-2005		Methods for describing nuclear reactions with neutrons and charged particles in a wide energy region
3	**Testing of nuclear data**		1995-2005		
3.1	Creation of a library of evaluated integral experiments	IPPE	1995-2005		Set of evaluated integral experiments covering critical experiments in critical assemblies and materials relating to startup work at reactors
3.2	Testing of files on basic structural materials using the results of experiments performed in spherical geometry	IPPE	1995-1998		Comparison of measurement results for leakage neutron spectra with calculations using existing files, and determination of the causes of divergences
3.3	Study of resonance self-shielding and the Doppler effect in transmission experiments	IPPE, Neutr. Phys. Lab. of the JINR	1995-2000		Resonance self-shielding coefficients, Doppler effect for fissile nuclei

1	2	3	4	5	6
3.4	Testing of files in the BROND national library. Comparison with files in foreign libraries	IPPE	1995-2005		Results of comparison of national files with foreign files, determination of causes of divergences and elimination of those causes
3.5	Certification of nuclear data	IPPE, TsNIIAI, Radium Institute	1995-2005		Certification of nuclear data as standard or recommended data
4	**Development of national nuclear data bank**		1995-2005		
4.1	Updating and expansion of the BROND national library	IPPE	1995-2005		New version BROND-3 with revised and expanded files of most important materials and corresponding error matrices
4.2	Creation of specialized nuclear data libraries	IPPE, Radium Institute, OIATEh, MIFI, NIIYaF of MGU, Kurchatov Institute, ITEhF	1995-2005		Libraries for reactor- and accelerator-driven transmutation, calculation of radiation damage and activation of materials, etc.
4.3	Development of techniques for determining the uncertainties of evaluated nuclear data	IPPE, Kurchatov Institute	1995-1998		Inclusion of covariance matrices of uncertainties in the files of BROND and specialized libraries
5	**Operation of nuclear centres**				
5.1	Technical support for the Nuclear Data Centre and the Centre for Atomic and Nuclear Data	IPPE, Kurchatov Institute	1995-2005		Software and hardware for work with a computerized nuclear data bank
5.2	Fulfilment of the international obligations of the Nuclear Data Centre and the Centre for Atomic and Nuclear Data	Nuclear Data Centre, Centre for Atomic and Nuclear Data	1995-2005		Participation in the setting up of an international data bank and maintenance of data exchange among the network of the centres

1	2	3	4	5	6
5.3	Creation of a unified network for direct data exchange within the sector and with foreign centres	IPPE, Kurchatov Institute, TsNIIAI	1995-2005		On-line access for institutions in the sector to national and international databases
5.4	Maintenance of operation of the Centre for Radionuclide Sources and the Data Centre for Photonuclear Experiments	Radium Institute, NIIYaF of MGU	1995-2005		Evaluated data on the decay properties of radionuclides. Library of evaluated photonuclear data
5.5	Publishing activities	IPPE, Radium Institute, TsNIIAI	1995-2005		Publishing of "Problems of Nuclear Science and Technology, Series: Nuclear Constants", cross-section atlases and handbooks
6	**International co-operation**		1995-2005		
6.1	International co-operation under IAEA auspices	IPPE, Radium Institute, Kurchatov Institute, OIATEh, NIIYaF of MGU, VNIIEhF, VNIITF, TsNIIAI	1995-2005		Participation in specialized conferences, development of international data libraries, maintenance of the quality of national libraries at the same level as world standards.
6.2	Participation in international evaluation co-operatiion under OECD auspices	IPPE, Radium Institute	1995-2005		Co-ordinated evaluation of files from regional and national libraries in order to improve quality.
6.3	Bilateral co-operation	IPPE, Radium Institute, Neutr. Phys. Lab. of JINR, ITEhF, VNIIEhF, VNIITF, Kurchatov Institute	1995-2005		Mutual use of methodologies and experimental facilities for precision measurements of nuclear data and validation of theoretical models.

1	2	3	4	5	6
6.4	International conferences and meetings	IPPE, Radium Institute, OIATEh MIFI, NIIYaF of MGU, VNIIEhF, VNIITF, Kurchatov Institute	1995-2005		Acquisition of latest information in the nuclear data field, dissemination of national work, contacts with foreign scientists.

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