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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

REQUIREMENTS VERSUS PRESENT STATUS OF EVALUATED NEUTRON NUCLEAR DATA FOR FAST REACTOR DESIGN*

by

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International Atomic Energy Agency

* Invited lecture presented at the International Summer School on Nuclear Data for Reactors and Reactor Physics, Predeal/Romania, 30 April - 9 September 1972

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Contents

A. International cooperation in the field of neutron nuclear data: General background

In response to the increasing neutron nuclear data demands of the nuclear technical and scientific community a world-wide organizational effort has developed in the last ten to fifteen years in the detailed assessment of the data requirements and in the measurement, compilation and evaluation of this required data. It is the purpose of this chapter to describe the objects and achievements of this international effort. A more extensive description may be found in references [1,2].

At the beginning of the nuclear reactor development in the fifties the interest was centered on thermal neutron reactors and rather crude calculational methods; at that time only the rather limited amount of neutron nuclear data information in the range of thermal and low neutron resonance energies was essentially needed. Since the second half of the fifties and the beginning of the sixties the situation has changed completely. Neutron nuclear data compilation and evaluation rapidly evolved into a large international effort going on amongst various laboratories and centres. This was essentially due to the fact that interest became more and more focussed on the development of fast reactors, and thus on the much larger neutron energy range between meV and MeV energies. Simultaneously the rapid computer development allowed and forced steadily increasing refinements of the reactor theory methods; these went parallel with and were also provoked by the increasing refinements of the measurement techniques of experimental reactor physics. These refinements in reactor theory and experiment opened the possibility of much more detailed and reliable predictions of reactor physical properties with almost the only condition that the neutron nuclear data involved be known to sufficient completeness, detail and reliability over the whole energy range of reactor neutrons. Since then it became indispensable that measurement, compilation and evaluation of neutron nuclear data for a given element or isotope should cover the whole neutron energy range from almost 0 to at least 15 MeV, and all possible neutron reactions occurring in that range. Moreover it was increasingly recognized that the data must be available on punched cards or magnetic tape so that the computer can be used to prepare derived quantities (such as multigroup constants) needed for reactor calculations.

The increasing amount of neutron nuclear data concerned required enhanced coordination between reactor designers who put forward the data requirements including their priority and accuracy with due justification and nuclear scientists who were to fulfill these requirements by measurement, compilation and evaluation and enhanced coordination between nuclear data measurers, compilers and evaluators themselves. This coordination was essentially accomplished by

1. national, regional and international nuclear data committees, and
2. an international network of neutron data compilation centers.

At present, the countries with major nuclear data programmes such as the U.S.A., U.S.S.R., U.K., Japan, India and others have their own national nuclear data committees which coordinate the nuclear data efforts on the national level. Before the end of the sixties the only international nuclear data committee was the EANDC (European American Nuclear Data Committee). Under the sponsorship of the European Nuclear Energy Agency (ENEA) of the OECD this Committee was founded in 1960 with participation from all OECD countries. Regional subcommittees of EANDC developed in the area of EURATOM countries and of small European countries not belonging to EURATOM. The regional subcommittees and the national nuclear data committees in OECD countries work closely together with EANDC.

In the past EANDC met at intervals of about nine months, recently about annually. Its prime responsibilities are the promotion and coordination of nuclear data research within the OECD area. One of the most important tasks of EANDC is the critical assessment of the nuclear data requirements and the review of experimental progress towards meeting these requirements in OECD Member States. Within this context EANDC discusses and stimulates the development of measurement techniques and the establishment of new experimental groups and facilities. It advises on the allocation of enriched isotopes and other special samples needed for the requested nuclear data measurements. It encourages the coordination and distribution of the required experimental work along various research lines and according to the experimental capabilities and experiences of the various laboratories.

In accordance with its statutory objectives, i.e. " to foster the exchange of scientific and technical information on peaceful uses of atomic energy " the International Atomic Energy Agency (IAEA) already in the early sixties has taken an active interest in international coordination of the nuclear data field. In the formulation of its nuclear data programme the IAEA has been aided by the International Nuclear Data Scientific Working Group (INDSWG) which in 1969 was consolidated as a continuing advisory body with the name International Nuclear Data Committee (INDC). INDC is composed of members from countries with major nuclear data programmes with due consideration given to a balanced geographical representation. INDC meets annually. It has objectives very similar to EANDC on a fully international scale. Its prime responsibility is to promote international cooperation in all phases of nuclear data activity and to advise the Director General of the IAEA in this field.

The nuclear data programme of the IAEA is implemented by its Nuclear Data Section (NDS) which was formed in 1964 and, which also acts as secretariat to the INDC. Its objective is to promote the world-wide compilation and exchange of nuclear data information, to assess the requirements for nuclear data and to promote national and regional nuclear data programmes to fulfill these needs. To fulfill these objectives, with the primary emphasis being still on neutron nuclear data for reactors, it cooperates closely with three other neutron data centers:

- the National Neutron Cross Section Center (NNCSC) at the Brookhaven National Laboratory in the USA;

- the Centr po Jadernym Dannym (CJD = Nuclear Data Centre) at the Institute of Physics and Energetics, Obninsk, in the USSR; and

- the Neutron Data Compilation Centre (NDCC) of the European Nuclear Energy Agency (ENEA) at Saclay in France.

NNCSC was founded in 1967, within the framework of the programme of the US Atomic Energy Commission. It grew out of the famous much older Brookhaven Sigma Center and comprizes in one large unit the formerly dispersed compilation, evaluation and programming efforts. A particularly important task of NNCSC is the coordination of the US neutron data evaluation effort and the establishment of an evaluated neutron data file (ENDF) for the U.S.A.

NDCC was set up in 1964 as part of ENEA when it became apparent that the Brookhaven Sigma Center could not keep pace with the increasing neutron data production both in Western Europe and in Northamerica (U.S.A. and Canada). In 1965 a cooperative arrangement was made between the ENEA and the U.S. Atomic Energy Commission for the exchange of neutron data information between NNCSC and NDCC.

CJD was also founded in 1964. It serves similar purposes for the U.S.S.R. as NNCSC for Northamerica and communicates through IAEA/NDS with the Western centres.

Each of these four neutron data centres services one part of the world, i.e. it compiles all neutron data and fulfills neutron data requests from this area. The service areas are

- for NNCSC: the USA and Canada,

- for CJD: the USSR,

- for NDCC: all Member States of the Organization for Economic Cooperation and Development (OECD) in Western Europe and Japan,

- for NDS: all other countries in Eastern Europe, Asia, Australia and New Zealand, Africa, Central and South America.

Representatives from the four centres meet annually to discuss policies and technical detail of their cooperation.

B. International cooperation in the field of neutron nuclear data: Implementation

Through the efforts of the international nuclear data committees such as INDC and EANDC and through the network of the four neutron data centres a kind of "closed loop" operation between neutron data users and producers has been developed on an international scale. This is illustrated by figure 1. The individual features of this operation are described in more detail below.

B1. RENDA

We restrict ourselves to nuclear reactor design and nuclear data requirements for this purpose. In order to illustrate how large the nuclear (mostly neutron) data scope is which enters into reactor design studies it may be useful to start with a list of nuclear data types required for this purpose [2]:

a) microscopic cross sections for all neutron induced reactions between 0 and at least 15 MeV (for example, (n,f), (n,γ), (n,n), (n,n'), (n,p), (n,α), (n,2n) and other threebody break-up reactions), together with quantities involving cross section ratios such as $\alpha = \sigma_{n\gamma} / \sigma_{nf}$ and $\eta = \bar{\nu}/(1+\alpha)$;

b) angular distributions for elastically scattered neutrons and elastic scattering polarization data and Legendre polynomial coefficients of scattering angular distributions;

c) angular and energy distributions for inelastically scattered neutrons;

d) differential angular and energy dependent excitation data for outgoing neutrons, protons, α-particles, gamma-rays, etc., outgoing combination of these particles;

e) number, energy spectra and angular distributions of prompt and delayed fission neutrons and the half-lives of delayed neutron precursors;

f) resolved and statistical resonance parameters, statistical distributions of resonance partial half widths and level spacings;

g) nuclear temperatures and single particle level densities derived, e.g., from neutron inelastic scattering to the "continuum" range of residual nuclear energy levels and similar physically significant parameters derived by experimenters from their measurements;

h) fission product yields and cross sections;

i) "clean" integral data having immediate application in experimental neutron physics and in evaluation. The principal types are average cross sections measured in well-defined neutron spectra, such as thermal reactor and neutron fission spectra, together with so-called infinite dilution resonance integrals for neutron absorption and fission processes.

All of these data are required for a large number of reactor materials and isotopes the weight of the individual data being essentially determined by their influence on the neutron economy and the basic design characteristics such as critical mass, K_{eff}, breeding ratio, safety coefficients and others.

A powerful means of getting these nuclear data requirements known to experimental nuclear physicists are request lists compiled by reactor designers and made available to these physicists. Those request lists for neutron data measurements have for a long time been compiled, issued and critically reviewed by EANDC with restriction to requestors in OECD countries on the basis of national and regional request lists. The EANDC request lists fulfilled an important function in the promotion of neutron data measurement programmes and led to an increasingly detailed and accurate knowledge of reactor neutron data. The latest EANDC lists (see e.g. [3]) have been prepared by the EANDC Secretariat from a computer file of the requests which allows for rapid updating, country and other retrievals and, which is called RENDA (= REquests for Neutron DAta Measurements).

Recently NDS compiled a similar list of neutron requests from the Soviet Union and from other countries outside the OECD area. Following recommendations by INDC and EANDC these requests were combined with updated requests from the EANDC area at ENEA/NDCC. The result of this cooperative effort of ENEA * and IAEA is a first world-wide request list for neutron data measurements for reactors called RENDA 72 which is published by IAEA on behalf of ENEA/NDCC and IAEA/NDS in the fall of 1972 [4].

Simultaneously the responsibilities for future production and review of RENDA have been passed from EANDC and ENEA to INDC and IAEA. NDS will take over from NDCC the operation of the RENDA computer system. It is expected that a four neutron data centres operation can be implemented in which the centres send revised and new requests arising from countries in their area to NDS for an annual revised publication of the RENDA list. The RENDA system to be operated by NDS will be open-ended so as to allow inclusion in the file of other application areas than reactors and of non-neutron nuclear data.

Figure 7 contains a sample page of RENDA 72 for illustration of the structure of a RENDA request. An individual request specifies the neutron quantity to be measured for a given element or isotope and neutron energy range. It furthermore specifies the desirable experimental accuracy and the priority in accord with the needs of the requesting nuclear reactor programme. Requestors are usually indicated by their name and laboratory. Usually a brief outline of purpose and justification of a request is given in the comments column together with a short description of the status of the requested data including

* ENEA has recently been renamed NEA = Nuclear Energy Agency

non-availability.

In the following I would like to demonstrate the truly international character of this list, the necessity for international cooperation in the fulfilment of RENDA requests, and to outline fields of neutron data measurements in which developing countries could make valuable contributions to the international neutron data effort. This will be done by grouping the requests according to application and/or data type and required experimental technique.

I. In many different countries similar types of reactors are being developed and/or installed such as light, heavy water and high temperature thermal reactors, converters and fast breeder reactors. Therefore the neutron data needs as expressed in RENDA requests are very similar to many countries, the same neutron data being involved in the reactor design. This is reflected by the multiplicity of requests for important (priority 1 and 2) neutron data and for standard cross sections in RENDA. The following examples are taken out of RENDA 72 [4]:

a. thermal reactors:

η (U-235): 4 requests; prior.1; acc. 0.1-0.5%; France, UK, USA;

σ_γ (U-238): 4 requests; 2 prior. 1, 2 prior. 2; acc. 0.5-3%: Canada, France, Pakistan, UK;

σ_f (Pu-239): 6 requests; 5 prior. 1, 1 prior. 2; acc. 0.3-1%; Canada, France, USA;

η (Pu-239): 5 requests; 3 prior. 1, 2 prior. 2; acc. 0.5-1%; Canada, France, IAEA, UK, USA

b. fast reactors:

σ_f (Pu-239): 16 requests; 13 prior. 1, 3 prior. 2; acc. 1-5% (1 requ. 10%); France, IAEA, Japan, India, Pakistan, UK, USA, USSR;

α or σ_γ (Pu-239): 15 requests; 8 prior. 1, 6 prior. 2, 1 prior. 3; acc. 3-10%; Australia, France, FRG, India, Japan, Sweden, South Africa, Pakistan, UK, USA, USSR;

σ_γ (U-238): 9 requests; 7 prior. 1, 2 prior. 2; acc. 1-10% (mostly around 3%); France, Japan, Pakistan, Sweden, FRG, UK, USA, USSR.

c. standard cross sections:

σ_p (He-3): 1 keV - 15 MeV; 7 requests; 2 prior. 1, 5 prior. 2; acc. 1-10% (av. 4%); France, India, UK, USSR;

σ_α (Li-6): thermal - 18 MeV; 13 requests; 9 prior. 1, 3 prior. 2, 1 prior. 3; acc. 1-10% (av. 4%); Belgium, France, FRG, India, UK, USA;

σ_α (B-10): thermal - 18 MeV; 10 requests; 8 prior. 1, 2 prior. 2; acc. 1-10% (av. 4%); Belgium, UK, USA;

σ_γ (Au-197): thermal - 7 MeV; 8 requests; 5 prior. 1, 3 prior. 2; acc. 1-10% (av. 5%, Jap. therm. requ. 0.1%); Belgium, EURATOM, France, Japan, USA;

σ_f (U-235): thermal - 15 MeV; 18 requests; 13 prior.1, 5 prior. 2; acc. 1-5% (av. 2.5%) for 16 fast energies requests, acc. 0.3 and 1% for 2 thermal requests; France, FRG, Japan, India, Pakistan, Sweden, South Africa, UK, USA, USSR;

$\bar{\nu}$ (Cf-252): spontaneous fission; 8 requests; 5 prior. 1, 3 prior. 2; acc. 0.1 - 0.5% (av. 0.4%); Canada, France, FRG, Australia, IAEA, USA, USSR.

Comments:

(i) All above requests are high priority high accuracy requests for precision measurements; they stem from developed and developing countries;

(ii) fulfillment of these requests requires use or development of sophisticated methods and facilities and long-term experimental experience generally only available in developed countries;

(iii) not every-one even of the developed countries with only very few exceptions will have the experimental and/or financial capability to fulfill its own requirements.

Conclusions:

(i) The fulfillment of the above requests quoted under a-c and similar groups of urgent requests requires cooperation particularly between developed countries;

(ii) the fulfillment of these requests by developed countries will be of cost saving benefit to developing countries.

Note:

IAEA enters several times as requestor under a, b and c. These are the only requests not connected to national reactor development programmes. IAEA/NDS takes interest in developing internationally acceptable standard values particularly for standard reference cross sections and data. It requests those data where previous evaluations and measurements have still not met accuracy requirements for reactor projects in many of its member states.

II. RENDA contains many requests with priorities 2 and 3, which concern future applications or applications to individual aspects of nuclear energy programmes (priority 2) or nuclear data of more general interest or required to fill out the body of information needed for nuclear technology (priority 3).

These requests are generally moderate-accuracy requests and thus do not necessarily require sophisticated techniques and highly experienced manpower for their fulfilment.

Here developing countries could make a valuable contribution which will be of benefit to both developing and developed countries. The benefit to the developing countries will be threefold:

a. the measurement results can be used directly in their own nuclear energy programmes (special case: if capability available, developing countries could participate in fulfilling their own requirements, if these are of basic interest to their national programmes. Example: nuclear data requirements for Thorium breeder developments of monazite rich countries like India or Brazil);

b. RENDA requests provide a basis for applied scientific programmes also to smaller countries which do not have an own nuclear energy development programme, but which can thus participate in an overall international effort with benefits such as participation in international conferences, acceptance in the international scientific community, enhancement of technical self-confidence and independence;

c. neutron data experiments serve education and training purposes, not only in nuclear physics itself, but also in other fields like electronics, vacuum technology, material properties, machine techniques, etc., which are needed for these experiments, but whose knowledge is also useful in other branches of science and technology; they would thus help to broaden the scientific/technical knowledge, experience, capability and technical infrastructure of developing countries.

Examples

1. Requests for measurements of (np), (nα), (n2n) and similar cross sections around 14 MeV amenable to $T(d,n)He^4$ neutron sources (in many cases no data available)

(Neutron energies from T(d,n) reaction lie between 12.8 MeV (backward scattering) and 15.8 MeV (forward scattering))

Altogether more than 110 requests for various purposes with accuracies between 10 and 20% and mostly priorities 2 and 3 where 14-16 MeV is mostly the upper limit of the required energy range (requests with greater accuracy requirements are omitted):

a. Neutron absorption in fast reactors (e.g. He-build-up)

24 requests for (np) and (nα)
11 for (np): V, Cr-52, Mn, Fe, Co, Ni, Zr, Nb and Mo;
13 for (nα): Ti, V, Cr, Mn, Fe, Co, Ni, Ni-58,60, Zr, Nb and Mo.

Requesting countries: France, FRG and Sweden.

Note that mostly data for elements, not separated isotopes are requested; this eases the sample supply problem.

b. Specific reactor purposes such as neutron economy and multiplication, transmutation rates, radioactive afterheat, radiation damage, etc.

32 requests all from Belgium/Mol and EURATOM/Geel;

10 for (np): N-14, F-19, Ti, V, Cr, Fe, Ni, Nb, Mo, W;

12 for (nα): Be-10 ($1.9 \cdot 10^6$y), N-14, O-16, F-19, Ti, V, Cr, Fe, Ni, Nb, Mo, W;

10 for (n2n): Li-7, F-19, Ti, V, Cr, Fe, Ni, Nb, Mo, W.

c. Activation detection and analysis and 14 MeV systematics

34 requests:

15 for (np): O-16, Ar-40, K-41, Ti-46,47, Fe-54, Co-59, Ni-60, Mo-95, Sm-152, Gd-158, Er-166,168, Tm-169, Yb-174;

1 for (nnp): Ni-58;

3 for (nα): Fe-54, As-75, Tm-169;

15 for (n2n): N-14, F-19, Co-59, Ni-58, Zn-64, Ga-69, As-75, Y-89, Sm-144, Lu-175, W-182,186, Au-197, Tl-203,205.

Requesting countries: France, Hungary, Japan.

d. Threshold detectors and neutron flux/fluence measurements

13 requests:

9 for (np): He-3, P-31, S-32, Sc-45, Ti-46,47, Fe-54, Mo-92,95;

4 for (nα): Li-6, B-10, Sc-45, Mo-92.

Requesting countries: France, FRG, Switzerland, USA; and EURATOM/Geel.

2. Requests for fission product capture cross sections

Altogether more than 80 requests in RENDA 72 from 10 countries: Canada, Denmark, France, FRG, Hungary, Belgium, Japan, Sweden, UK and USA;

40% for stable nuclides; 60% for radioactive nuclides (out of these 15% with $\tau_{\frac{1}{2}} \geq 10^5$y; 85% with $\tau_{\frac{1}{2}} < 10^5$y);

The high number of requests and the large spread of requesting countries illustrate e.g. the importance of the problem of fission product poisoning in reactors and of reliable estimates of time dependent fission product reactivity equivalent and plea for international cooperation.

Between 40 and 50% of these requests are amenable to measurements in thermal research reactors in developing countries (several of these requests go higher in energy than amenable to thermal reactors). The requests are listed in the table below.

80% of these requests concern stable nuclides, 10% radioactive nuclides with $\tau_{\frac{1}{2}} \gtrsim 10^5$y;

energy range: 10^{-3} eV - 1 KeV and higher;

accuracy: 5-25%; av. 10% (23% - 5% acc.; 60% - 10% acc.; 14% - 20% acc.; 3% - 25% acc.);

priority: 30% prior. 1; 70% prior. 2

requesting countries: Belgium, Denmark, Canada, Japan, Sweden, UK and USA.

Target nucleus	$\tau_{\frac{1}{2}}$ (y)	Energy	Accuracy	Priority	Requesting country
Tc-99	$2.1.10^5$	10^{-3} - 10 eV	5	1	Japan
"	"	10 eV - 50 keV	20	1	Japan
"	"	>10 eV	10	2	Sweden
Ru-100	stable	10^{-3} - 10 eV	10	2	Japan
"	"	10 eV - 50 keV	25	2	Japan
Ru-101	"	>1 eV	10	2	Sweden
Ru-102	"	>1 eV	10	2	Sweden
Rh-103	"	10^{-3} eV - 1 KeV	5		Denmark
"	"	10^{-3} eV - 1 eV	10	2	USA
Pd-105	"	>1 eV	10	2	Sweden
Pd-107	$7 . 10^6$	10^{-3} eV - 10 KeV	10	2	USA
"	"	>1 eV	10	2	Sweden
Ag-109	stable	10^{-3} - 1 eV	10	2	USA
Sn-126	10^5	thermal	120b	2	Canada
Sb-121	stable	0 - 1 KeV	20	2	Belgium
Xe-131	"	thermal	10	2	UK
"	"	RI^{∞}_{γ} (0.55 eV)	10	2	UK
"	"	>10 eV	10	2	Sweden
Cs-133	"	0 - 1 KeV	20	2	Sweden
Cs-135	$2 . 10^6$ y	>1 eV	10	2	Sweden
La-139	stable	1 eV - 10 KeV	10	2	Sweden
Pr-141	"	1 eV - 150 KeV	10	2	Sweden
Nd-143	"	10^{-3} eV - 1 KeV	10	1	USA
"	"	1 eV - 50 KeV	20	1	Japan
Nd-145	"	10^{-3} eV - 1 KeV	10	1	USA
Nd-146	"	thermal - 10 KeV	5	2	USA
Sm-147	stable	10^{-3} eV - 1 KeV	10	2	USA
"	"	RI^{∞}_{γ} (1 eV)	10	2	USA
Sm-149	"	10^{-3} eV - 1 KeV	5		Denmark
"	"	> 1 eV	10	2	Sweden
Sm-150	stable	10^{-3} - 10 eV	5	1	Japan
"	"	10^{-3} eV - 1 KeV	5	1	USA
"	"	RI^{∞}_{γ} (>1 eV)	< 5	1	USA
"	"	10 eV - 50 KeV	20	1	Japan
Sm-152	"	10^{-3} - 10 eV	5	1	Japan
"	"	10^{-3} eV - 1 KeV	10	2	USA

3. Shielding requests (mostly for reactor shielding)

a. inelastic scattering - secondary neutrons

Requested quantities: $\sigma_{n'}(E)$; $\sigma_{n'}(E,E')$; $\sigma_{n'}(E,E'\Theta)$;
10 requests; threshold - 16 MeV; 1 prior. 1, 2 prior. 2, 7 prior. 3;
C-12, Na-23, Al-27, Ca, Cr, Fe, Nb-93, Ba and W;
acc. 5-20%, av. 10%;
Euratom, Belgium, France, South Africa, UK.

b. inelastic scattering - secondary γ-rays

Requested quantity: $\sigma_{n'}\ (E,E_\gamma,\Theta)$;
7 requests from EURATOM and Belgium;
threshold -15 MeV; all priority 3 and acc. 15%;
Be-9, Ti, V, Fe, Ni, Nb-93 and Mo.

c. neutron emission cross sections

Def. $\sigma_M = \sigma_{n'} + 2\ \sigma_{2n} + 3\ \sigma_{3n} + \sigma_{np} + \quad .....$
Requested quantities: $\sigma_M(E)$; $\sigma_M\ (E,E')$; $\sigma_M\ (E,E',\Theta)$;
15 requests; 0.5 - 16 MeV; 2 prior. 1, 12 prior. 2, 1 prior. 3;
O, Al-27, Si, Cr, Fe, Ni, W and Pb;
acc. 5-15%, av. 10%;
France, Sweden, USA (5 US requests for W, probably to be fulfilled by the USA)

d. γ-ray production cross sections (however, big USA programme!)

Requested quantities: $\sigma_G\ (E)$; $\sigma_G\ (E,E_\gamma)$; $\sigma_G(E,E_\gamma,\Theta)$;
20 requests; 0.001 eV - 16 MeV; 3 prior. 1, 17 prior. 2;
O, Al-27, Si, Ca, Cr, Fe, Ni, W, Pb, Th-232 and U-238;
acc. 10-20%, av. 15%;
France, South Africa, USA.

III. There is a need for double/multiple check of neutron nuclear data measurements by independent other experiments or techniques and/or evaluations to enhance the confidence level of the data

The experience shows discrepancies in almost all neutron nuclear data measurements for the same nuclide and quantity. The more important the required quantity, the more urgent the need of double or multiple check of individual measurements. In many cases a careful evaluation might suffice to either fulfill a request or (more rarely) to confirm measured data. Also in this case international cooperation is surely called for.

IV. Nuclear data measurements consume appreciable financial and manpower resources. Therefore RENDA requests should be fulfilled in the most economic way. This can be achieved by appropriate international coordination of measurement programmes, e.g. by grouping together requests of the same data type and energy range (inelastic scattering, fast fission, etc.) and allocating measurements of this data to appropriate facilities.

EANDC was very successful in such international coordination. It promoted and stimulated comprehensive programmes on elastic and inelastic neutron scattering at Argonne, fast neutron capture at Karlsruhe, resonance fission at Saclay and BCMN Geel and others; it promoted the installation of new facilities such as the tandem accelerator at Argonne and even the creation of new laboratories such as the BCMN Geel.

The INDC plays here a similar role particularly also with regard to East-West cooperation and to cooperation between developing and developed countries.

V. There are finally arguments of a social and moral nature which quite generally speak for international cooperation, also in the very special field of nuclear data measurements, such as summarized below:

(i) The nuclear data efforts contribute to solving the problem of future energy supply for mankind;

(ii) they contribute to mutual understanding and peace through correspondence and cooperation of laboratories and scientists in different countries, particularly between developing and developed countries;

(iii) they contribute to progress in scientific knowledge of benefit to mankind.

Appendix I contains further statistics on RENDA 72 concerning the international character of this list. In addition to this statistics a need is indicated for the following more thorough statistical analyses of RENDA lists and their background to be performed in the future:

a. Establishment of the relationship between the number of (priority and accuracy weighted) requests of a country, the national effort and funding for fulfilment of these requests, the total national expenditures for nuclear physics and the national social product; the same relationship would be of interest for requests originating from outside the country;

b. Requesting and measuring institutions in the present analysis should be broken down according to laboratory - university - industry - international organization;

c. Comparison of effort and funding spent by individual laboratories on work on RENDA requests;

d. Breakdown of the cooperation between USA - Western Europe - USSR - Small(er) countries in fulfilment of requests (USA requests being measured in Western Europe and vice versa, etc.);

e. Breakdown of requests according to gross purposes such as fast reactors, shielding, activation, transactinides, etc. (with average priorities, etc.); ratio of requests "no work/ work going on" for these fields; overall estimates and breakdown by country. This would allow to establish field importance profiles (national and international) of RENDA requests.

B2. Production

For the measurements of neutron data the following facilities and neutron sources are most common in the following energy ranges:

thermal: choppers, crystal spectrometers and other monochromators in conjunction with thermal research reactors;

resonance: electron linear accelerators, underground nuclear explosions, Van de Graaffs, pulsed fast reactors;

fast: Van de Graaffs, cyclotrons, underground nuclear explosions;

monochromatic neutron sources:

e.g. Sb-Be (γ,n) $\sim$ 30 KeV

$T(d,n)He^3$ $\sim$ 14 MeV

The volume of data production from these devices is rather small for the thermal range (except for thermal scattering law data) and largest for the resonance range with up to several 1000 (E,σ) pairs per individual measurement.

National and international cooperation in the production of requested neutron data is promoted by INDC, EANDC and other regional committees and by national nuclear data committees by means of:

- publication and wide distribution of national annual reports on progress in neutron nuclear data work partly performed upon recommendation of INDC and EANDC;
- discussion of RENDA requests and promotion of measurements, development of techniques, facilities and laboratories;
- discussion of status of important applied and standard reference neutron data and recommendations for further measurements, evaluations, specialist discussions, etc.

IAEA/NDS is supporting nuclear data measurements in developing countries by financial and other means of assistance in the purchase of accelerator targets and samples.

B3. Compilation and Evaluation

In contrast to other physics domains where the terms "compilation" and "evaluation" have about the same meaning, they have acquired quite different meanings in the fields of neutron physics and data. For the sake of conceptual clarity and in order to elucidate the various steps in the process between data production and data use it has first to be explained what is meant by "compilation" and "evaluation" [2].

B3.1. Definition of terms

In the field of neutron data, "compilation" means the gathering of literature references on experiments and of the data contained in these references for neutron reactions with given nuclides in given energy ranges. It involves furthermore the organization and storage of the compiled material in a medium appropriate for retrieval and satisfaction of user requests, i.e. in computer data files. Compilation finally involves extensive extraction and documentation of information (frequently unavailable elsewhere) characteristic for the experimental method and the publication of compendia of experimental data. Compilation is always understood to include the available material as completely as possible.

"Evaluation" comprises the following individual steps:

- critical comparison, selection and averaging of the compiled experimental data,
- inter- and extrapolation of experimental data and use of nuclear theory and systematics in the case of gaps and inconsistencies in the experimental information,
- build-up of a computer library of complete self-consistent and easily interpolable data sets from which, for example, multigroup constants and related quantities can be calculated for direct input to reactor design calculations.

Whereas compilation generally could be conceived as the first step in the process of evaluation, it required, in the case of neutron data, an international coordination of its own because of the increasingly large amount of data measured. Neither were the experimenters in a position to supply the data to each individual requestor nor were the evaluators able to collect the data information individually from every experimenter. As was mentioned above this situation was one of the main reasons for the establishment of the four neutron data centres network. Nowadays neutron data compilation is predominantly done by these centres, whereas evaluation is predominantly taking place in national nuclear research laboratories in connection with nuclear energy projects.

B.3.2. CINDA

For the international coordination of compilation the establishment of a comprehensive and regularly updated international list of bibliographic references to experimental neutron data appears to be the first requirement. Out of various private indexing activities particularly of neutron data evaluators only the computer-based reference index CINDA (= Computer Index of Neutron DAta) which has been developed by Professor H. Goldstein and his collaborators in the USA gained world-wide recognition and has become the primary reference source in the neutron data field. Today there is a co-operation on CINDA between the Division of Technical Information Extension (DTIE) of the United States Atomic Energy Commission (USAEC) at the Oak Ridge National Laboratory in the USA, the neutron data centres CJD, NDCC and NDS and a world-wide net of voluntary readers. By these centres and individuals the international neutron physics literature, consisting of regular publications, laboratory reports, preprints and other information sources, is systematically scanned and abstracted in the form of entries to a CINDA computer file. The content and format of these entries is exactly tailored to the needs of the users of CINDA, i.e. evaluators, reactor designers, nuclear physicists and others. They want to be informed by CINDA in a most compressed and up-to-date form upon nuclide and measured quantity, experimental energy range, reference, history of an experiment, main author and some prominent feature of the data given in a very short comment. In addition the CINDA file contains also references to data evaluations and to theoretical articles and reports of interest in the neutron data field.

The CINDA computer file and programme system were developed and are operated by NDCC and DTIE. The content of the file is published annually with half-yearly supplements and distributed to more than 1500 users throughout the world. The first four international CINDA issues were published by the USAEC/DTIE and by ENEA/NDCC in alternation. The fifth issue, CINDA 71, was the first to be published by IAEA on behalf of CJD, NDCC, NDS and DTIE [5]. Each of these four centres is responsible for compiling the CINDA entries from published literature and other information sources available from its service area, with DTIE covering the same geographical area as NNCSC. CINDA 71 contains about 70,000 entries extracted from more than 240 scientific journals, 180 report series, 110 books and conference proceedings and from private communications.

Figure 4 contains a sample page taken from CINDA 71. In cooperation between DTIE, NDCC and NDS, CINDA is now being developed towards an index to the experimental neutron data files of the four neutron data centres to be discussed in the next section. Until this index is established, each centre is maintaining its own data index. For NDS this is CINDU, which is an index to all experimental and evaluated neutron data held in the NDS data libraries. It is recurrently published by NDS, the most recent edition, CINDU-10, being issued in May 1972 [6]. Figure 5 contains a sample page taken from CINDU-10.

B3.3. EXFOR

While the four neutron data centres had developed, maintained and exchanged their own experimental neutron data files for quite some time, it was only rather recently that they met on a regular basis and implemented a common exchange format for experimental neutron data, which is known under the name EXFOR. Instrumental for the development of EXFOR was the Panel on Neutron Data Compilation which, upon recommendation of INDC, the IAEA convened at Brookhaven National Laboratory in February 1969 and in which experts from 12 IAEA Member States and from ENEA participated [7,8]. Following an agreement which was concluded between CJD, NDCC, NDS and NNCSC in July 1970 the four centres do not only compile and exchange neutron data and associated bibliographic information, but also the most important experimental characteristics. The centres use the same terminology, keywords codes and other conventions, so that the information mentioned above is coded and transmitted in an unequivocally recognizable way. The system is open-ended so that new quantities, definitions, etc., can be added when need arises, and is continuously reviewed between and at the annual meetings of the four centres convened and coordinated by IAEA/NDS. It was of unique importance for the successful implementation of EXFOR that CJD uses English language, codes and conventions and uses IBM tapes and Western tape units for data transmission.

Figure 6 contains an example for an EXFOR entry together with some explanations. A description of the EXFOR system may be found in reference [9].

B3.4. Evaluated data

As a further step the neutron data centres also compile and exchange evaluated neutron data which mostly originate from evaluation work and evaluated neutron data libraries in national nuclear research laboratories. The main data libraries more widely in use at present are the Evaluated Neutron Data File (ENDF/B) of the United States [10], the UK Neutron Data Library (UKNDL) [11] and the German evaluated data library KEDAK [12]. In the USSR a comprehensive system of neutron data averaged over 26 neutron energy groups has been established [13] and a computer library of evaluated energy dependent neutron data for nuclear technology use is under development. Comprehensive fission product neutron data libraries have been established by Italian and Australian evaluators, and a number of smaller, rather specialized data libraries have been produced in various countries.

Whereas nowadays experimental neutron data are freely exchanged throughout the world, the exchange of evaluated neutron data is still rather restricted, although an increasing need to obtain and use those data can be seen in many countries, particularly in developing countries. In response to this need, and, again upon a recommendation of INDC, the IAEA convened a Panel on Neutron Nuclear Data Evaluation in Vienna, in September 1971 [14], in which evaluation experts from 11 IAEA Member States and from ENEA participated. This panel reviewed the methods, the quality and the present status of neutron nuclear data evaluation and examined the basic requirements and problems associated with establishing, maintaining, using and exchanging computer-based libraries of evaluated neutron data. It also reviewed still unsatisfied important needs for evaluated data in IAEA Member States, particularly in developing countries and compared in detail the main computer formats for evaluated neutron data whose knowledge is an indispensable prerequisite for an efficient international exchange of evaluated data.

In spite of the restrictions mentioned above quite some exchange of evaluated neutron data is taking place already in which also NDS takes part, on a bilateral or regional basis. There is a free exchange between countries in the OECD area of ENDF/B data and a free international exchange of the German and of parts of the UK evaluated neutron data files. Recently the U.S.A. released ENDF/B data for standard reference nuclides for free distribution and exchange.

NDS participates in the overall evaluation effort by reviewing selected neutron data of relevance and particular importance to the development of peaceful uses of nuclear energy. At present nuclear data of predominant importance for the development of fast reactors are reviewed such as

- the α Pu-239 values in the keV range [15],
- the fast fission cross section of Pu-239 [16],
- $\bar{\nu}$ standards like Cf-252 and $\bar{\nu}$ data for the heavy isotopes [17],
- the U-238 fast capture cross sections [18],
- the fast fission cross sections for the threshold isotopes Th-232, Np-237 and U-238 [19],
- the prompt fission neutron energy spectra of the main fissile nuclides and of the Cf-252 standard [20],
- neutron cross sections for reactor dosimetry [21].

These reviews aim at giving a comprehensive survey of the available experimental data (available through the Four-Centre cooperation mentioned before), they assess as far as possible the systematic errors of the individual experiments, they give weighted average curves through the experimental data, they assess the pointwise confidence level of these curves, and finally they indicate gaps and inconsistencies and needs for further measurements. These reviews are done in close cooperation with the experimental physicists who are the originators of the data considered and other relevant experts. This cooperation proceeds via extensive correspondence and via specialists meetings called for discussion of specific data subjects. Those meetings were for example held twice on the subject of α (Pu-239) at Winfrith in the United Kingdom in 1969 and at Studsvik in Sweden in 1970 [22,23]. Other similar expert meetings were held on $\bar{\nu}$ data including the Cf-252 $\bar{\nu}$ standard at Studsvik in 1970 [22,24], and on the status of prompt fission neutron spectrum measurements in Vienna in 1971 [25]. These meetings have proven to be a very powerful tool to understand the sources of discrepancies between different experiments and to foster measures for their explanation either by evaluation or by experiment.

B4. Consumption

In the following we quote the neutron data users serviced by the neutron data centres:

a. Main users of neutron data: reactor physicists and designers; they need evaluated data in the form of a computer library with rapid access in high density of (E,E',Θ) points so as to be usable in every conceivable application: such as reactor core and blanket design, reactor kinetics and dynamics, reactor burn-up, reprocessing, shielding, radiation damage, neutron flux dosimetry, interpretation of critical and subcritical facility measurements etc., mainly by multigroup and Monte Carlo methods.

b. Secondary users of neutron data: nuclear physicists. Experimenters need experimental and evaluated data in experiment planning. Theorists need both of these data for check of theories, fitting of nuclear models (e.g. optical model) and establishment of nuclear systematics (e.g. level density parameter a, 14 MeV reaction cross sections).

c. Further user fields: fusion reactors [26,27] (increasing), safeguards [28], activation analysis, astrophysics [29] (build-up of elements in stars by nucleosynthesis), industrial material quality and purity testing, etc.

B5. Meetings

The international neutron nuclear data effort as described in the preceding sections B1. through B4. is in all its phases strongly aided by national and international gatherings of various kinds. In the following we give a list of past and planned relevant meetings.

a. Conferences and Symposia

IAEA Conferences on Nuclear Data for Reactors, 1966 in Paris [30], 1970 in Helsinki [31], third Conference planned for about 1975 with a scope broadened to non-reactor applications and non-neutron nuclear data

Planned: IAEA Symposium on Applications of Nuclear Data in Science and Technology, Paris, March 1973

National Conferences:

USA: on Cross Sections and Technology, 1966 and 1968 in Washington [32,33], 1971 in Knoxville [34];

USSR: on Neutron Physics, in Kiev in 1971 [35] and May 1973;

UK: on Chemical Nuclear Data, Canterbury, 1971 [36];

EANDC sponsored topical conferences, the last one being held at Argonne National Laboratory in 1970 on Neutron Standards and Flux Normalization [37].

Neutron nuclear data are discussed also at

(i) national nuclear and physical society meetings,

(ii) national and international conferences on reactor physics and other application topics.

b. IAEA Panels

on Nuclear Standards for Neutron Measurements, Brussels, 1967 [38];

on Neutron Data Compilation, Brookhaven, 1969 [7,8];

on Neutron Data Evaluation, Vienna, 1971 [14];

(Second) on Neutron Standard Reference Data, Vienna, 1972

Planned: IAEA Panel on Fission Product Nuclear Data in November 1973

IAEA Study group meeting on nuclear data requirements for shielding in the middle of 1974.

c. IAEA Specialist Meetings

on α (Pu-239) at Winfrith/UK in 1969;

on α (Pu-239) at Studsvik/Sweden in 1970 [22,23];

on $\bar{\nu}$ data including the Cf-252 $\bar{\nu}$ standard at Studsvik in 1970 [22,24];

on status of prompt fission neutron spectrum measurements in Vienna in 1971 [25];

on second update of 2200 m/sec fission constants evaluation in Vienna in 1972.

d. Annual meetings of INDC, EANDC and meetings in regular intervals of regional and national nuclear data committees. For the minutes of the last meetings respectively of INDC and EANDC see references [39,40].

e. Annual Meetings of the Four Neutron Data Centres.

C. Neutron nuclear data requirements and confidence levels achieved

This chapter will deal specifically with accuracy requirements in neutron nuclear data and their basis mainly for fast reactors and a discussion of the status of fulfilment of these requirements including the more important neutron standard reference data. We start with a general review of pertinent references.

C1. Review of references

a. Fast reactors

Most of the available literature refers to Na, only a small part to steam or He cooled reactors; the strongest concern is on nuclear data requirements for large fast oxide fuelled power breeder reactors.

The following references contain discussions of neutron nuclear data implications on

- stationary parameters (K_{eff}, breeding ratio, critical mass, etc.) [41,43,45,54,63,64,67,75,78,80];
- kinetics and dynamics parameters (Doppler and Na void coefficients, etc.) [41-43,45,51,63,64,67,78,80];
- burnup [54,55];
- fuel processing including fuel handling, spent fuel transport, chemical reprocessing, etc. [41,51,55]
- reactor operation [53,63];
- fission product effects [54,55,74].

Specific discussion points in these and other references are:

- accuracy requirements versus achievements for stationary, unstationary and long-term reactor parameters including economic implications [41-43,45,51,54,58,60,61,63,64,75, 76,78,84-86];
- accuracy requirements for neutron data and related constants [41,45-47,51,54,58,63,72,74-76,78] and their derivation [42,75,78] including also future accuracy goals for neutron data;
- confidence level achieved of microscopic evaluated neutron data, progress in meeting requirements in evaluated data libraries and problem of systematic errors [15-17,40-43,45-47,51,54, 69,70,80];
- assessment of confidence level of neutron data by integral experiments [42-45,47,55,56,60-63,65,79,80] including also

  procedures of adjustment (physical and mathematical) of evaluated microscopic neutron data,

  role of integral experiments in evaluation,

  errors in calculational methods versus errors in microscopic evaluated data versus errors in measured integral parameters and accuracies credibly achieved in integral measurements;

- accuracy requirements for neutron standard reference data [41,46,67,75];
- confidence level achieved of neutron standard reference data, progress in meeting the requirements in evaluated data libraries [19,46,67-73,80,83]

b. Thermal reactors

The following references contain discussions on neutron data effects on

stationary and unstationary parameters [42,49,50,53,57];

burnup [53,54,57];

reprocessing [74] and

fission product effects [49,54,74].

Specific discussion points in these and other references are:

- accuracy requirements for reactor parameters [42,49,50,53,54,57,78];
- accuracy requirements for neutron data including effect of neutron data uncertainties on reactor parameters, etc. [42,49,54,57,72];
- assessment of neutron data accuracies by integral measurements in test reactors, etc. [42,53];
- confidence level of neutron data achieved, progress in meeting requirements in evaluated data libraries [49,54,57,72,73,81-83]

c. Other types of reactors

As typical example we may quote reference [52] in which the neutron nuclear data requirements and status for molten salt and gas cooled thermal reactors are discussed.

d. Shielding

Effects of neutron data uncertainties on reliability of shielding predictions are specifically being investigated and discussed by H. Goldstein and coworkers [48,59,66].

In the following we restrict our discussions to neutron data for fast reactors. For the checking of microscopic evaluated data by integral type measurements in critical assemblies we refer to the later talk by Professor Farinelli in this Seminar.

C2. Accuracy requirements versus achievements for fast reactor design parameters

For various fast reactor design parameters we compare accuracies required for their prediction with accuracies achieved, e.g. in fast critical assembly calculations, as a function of time. In extrapolation it is expected that design parameters of actual fast power reactors will be predicted to about the same confidence level as that achieved for a variety of fast critical assemblies.

a. K_{eff}

Country Reference	Year	Reactor considered	Accuracy (± %) required	Accuracy (± %) achieved
UK [58]	1966	typical fast power reactor	1	
UK [78]	1968	typical fast power reactor	1	
FRG [80]	1968	U criticals with hard spectra U subcriticals Pu criticals		2 -(0.8 - 2.4) -(1.0 - 3.5)
UK [61]	1969	PFR		0.87
FRG [60]	1969	U and Pu criticals		$\lesssim$ 2.0
FRG [43]	1970	U criticals Pu criticals		+ (1 - 2) - (1 - 2)
UK [42]	1970	PFR, adjusted data " unadjusted "		0.5 2.6 - 5.0
France [45]	1970	PHENIX MASURCA, U-core " , Pu-core	1	6 + 0.5 - 0.5
USA [63]	1971	1000 MWe LMFBR	1	4
USA [64]	1971	" " " " , U-238 $\Delta\sigma_\gamma$ (pessimistic assumption) " , Pu-239 $\Delta\sigma_{f+\gamma}$, < 30 KeV " , Pu-239 $\Delta\sigma_f$, > 30 KeV	1	 3 1 several
USSR [75]	1971	large Pu breeder	1	
USA [70]	1972	benchmark assemblies calculations with ENDF/B-III		$\leq$ + 0.9 - 1.3

<u>Observations:</u>

(i) The accuracy requirement for K_{eff} is the same for all requesting countries and constant as a function of time, viz. = 1%.

(ii) It is difficult to see <u>overall</u> progress in achieved accuracy, some numbers seem to be over-pessimistic estimates due to over-pessimistic judgement of neutron data accuracy:

the 6% uncertainty for PHENIX K_{eff} prediction results from exaggerated pessimistic assumptions for Pu-239 neutron data uncertainties: $\bar{\nu}$: 2%; σ_f: 10%; α: 30%;
similar, but weaker arguments hold for [63,64];

(iii) Progress can be seen for the UK and FRG as a result of repeated intensive studies of critical facilities and mathematical (UK) and physical (FRG) adjustment of microscopic evaluated data. The numbers for PFR are confidence levels expected in the prediction of PFR K_{eff} and extrapolated from the prediction of criticals' K_{eff}; they look good, there is, however, some doubt as to the validity of extrapolation from critical facilities to actual reactors with different properties, e.g. in neutron spectra. The numbers for MASURCA are also due to adjusted data and have also to be considered with some caution.

<u>Broad conclusion:</u>

1% seems not to be achieved with throughout confidence in the prediction of K_{eff} of fast reactors.

b. Breeding (BR) and internal conversion ratios (ICR)

Definition: BR = Amount of Pu $\frac{\text{produced}}{\text{destroyed}}$ in reactor per unit time

$= \eta_{eff} - 1 - L \qquad (L = \text{Leakage})$

The same definition holds for ICR. Difference: BR holds for the total reactor (core + blanket), ICR only for the core

Country Reference	Year	Reactor considered	Accuracies BR (+) required	Accuracies BR (+) achieved	Accuracies ICR (+) required	Accuracies ICR (+) achieved
UK [58]	1966	typical fast power reactor	≤0.05			
USA [41]	1966	300 and 1000 MWe LMFBR		0.13		
UK [78]	1968	typical fast reactor	0.03			
USA [41]	1970	300 and 1000 MWe LMFBR		0.10		
France [45]	1970	PHENIX			0.03	0.13
USA [41]	1971	300 and 1000MWe LMFBR	0.05			
USA [64]	1971	1000 MWe LMFBR	0.02			
		" U-238 $\Delta\sigma_\gamma$ (pess.ass.)		0.10		
		" Pu-239, $\Delta\sigma_{f+\gamma}$ < 30 KeV		0.05		
USSR [75]	1971	large Pu breeder	0.02			

On the average the requirements for BR and ICR have been sharpened with time, presently being ≅ 0.02, with the exception of [41] (= 0.05).

What seems to be realistically achieved is ≅ 0.10. [41] shows some improvement in prediction, which is certainly due to improved data accuracies for U-238 and Pu-239.

c. Doubling time T_d

T_d is closely related to the breeding gain G = BR - 1

$$T_d \sim \frac{1}{G}$$

The accuracy achieved is of the order 30-60% [41,51], the typical accuracy requested is 10% [75].

d. Fissile Pu inventory

Here we have only estimates from Greebler et al./USA [41]; his accuracy figures are:

1966: achieved: 10%
1970: " : 8%
1971: required: 3%

e. Doppler coefficient DC

Country Reference	Year	Reactor considered	Accuracy (±%) required	achieved
UK [58]	1966	typical fast power reactor	20	
USA [41]	"	300 and 1000 MWe LMFBR		30
FRG [86]	1969	DC-measurements in PuO_2-sample in SNEAK assembly 3B-2, 400-1000°K temperature range		+(20-30)
USA [41]	1970	300 and 1000 MWe LMFBR		20
"	1971	"	10	
USA [63]	1971	1000 MWe LMFBR	20	40
USA [64]	1971	1000 MWe LMFBR	5	
		" ,U-238 $\Delta\sigma_\gamma$ (pessimistic assumption)		20
		" ,Pu-239 $\Delta\sigma_{f+\gamma}$ < 30 KeV		12 (U-238)

Increasing accuracies achieved in the calculations are followed by increasing accuracy requirements; the present most stringent one, 5%, is not met by the presently available resonance data [64].

f. Total loss of Na coolant

According to Greebler et al./USA [41] accuracy achievements were in 1966: 2.3\$, in 1970: 2.0 \$; as short-term accuracy goal they state 1.5 \$, where 1 \$ ↔ 1.4% in K for the 1000 MWe LMFBR considered.

g. Reactivity worth of control rods

Requirements are ≤ 10% [58,63], achievement is estimated to 30% [63].

h. Burnup

Accuracy requirements for burnup predictions are given e.g. by Fudge and Foster/UK [54] for a typical fast reactor:

Use of burnup data	accuracy required (± %)
Fuel element design	2.5
reactor design and operation	2.5 - 5.0
physics measurements	2.5
reprocessing	10.

Burnup measurements have been done e.g. in the Dounreay Fast Reactor (DFR) [55]. Average agreement between measurement and calculation was found to within 4%, slightly worse than the most stringent requirement above. This rather good agreement seems to be due to the fact that burnup measurements were based on fission yield data which were measured in DFR and in regions where the fuel was irradiated. It is not clear whether these results can be extended to other fast reactors because of shortage of experimental data on the neutron energy dependence of the fission yields concerned.

i. Fuel cost

The only estimate of the economic disadvantage of neutron data uncertainties is available from Greebler et al./USA [41,51]. In 1968 they state a total fuel cost of

0.5 mills/KWh for low) neutron leakage
0.7 " " " high) 1000 MWe LMFBR

and uncertainties in the fuel cost of

$\left.\begin{matrix}-0.09\\+0.16\end{matrix}\right\}$ mills/KWh = $\left.\begin{matrix}-20\%\\+30\%\end{matrix}\right)$ low leakage reactor

$\left.\begin{matrix}-0.09\\+0.24\end{matrix}\right\}$ " = $\left.\begin{matrix}-15\%\\+35\%\end{matrix}\right\}$ high leakage reactor

for US \$ 10/g fissile Pu.

Required are

0.03 mills / KWh.

To illustrate these figures:

In 1970 [41] the uncertainties in the Pu inventory and in BR result in a fuel cost uncertainty of 0.13 mills/Kw(e)h. This uncertainty is equivalent to an uncertainty of US $ 900 000/year in operating cost for a single 1000 MWe breeder.

Summary

Figure 8 summarizes broadly estimates of the presently achieved accuracies and the short-term ($\leq$5 years) requirements for accuracies of the fast reactor design parameters discussed above.

C3. Accuracy requirements versus confidence levels achieved for fast neutron nuclear data

The accuracy requirements for fast neutron nuclear data are closely linked to the accuracy requirements for fast reactor design parameters. The progress in the prediction of these parameters is connected with the progress in the knowledge of these data. Both these aspects are considered below.

Figure 9 gives a historicalreview of fast neutron data accuracy requirements versus achieved confidence levels for the most important neutron data.

1. Explanation of "most important neutron nuclear data" requirements and of their historical development (see figure 9)

a. It was rather rapidly recognized what are the important data; certain data were only in 1961 not requested, from 1962 on almost all data were requested which also today are deemed important. An exception is fission product capture; fission product influence was only considered from the later sixties on in more mature and realistic fast reactor design studies.

b. Many requirements did almost not change over the years; they were obviously not met by the existing data and therefore maintained by the requestor. This happened in spite of the increasing number of more and more sophisticated studies of the influence of neutron data accuracy requirements. In some data, however, a drastic sharpening of accuracy requirements can be observed, viz. in

σ_f (Pu-239, Pu-240, Pu-241)
$\bar{\nu}$ (U-238)

and slight sharpening in

$\sigma_{n'}$ (U-238) and $\bar{\nu}$(Pu-240, Pu-241).

Reason: Pu-239 σ_f was recognised already in 1962 as the main fission quantity; Pu-240, 241 σ_f only in $\geq$ 1964, where more realistic fast reactor design studies took not only Pu-239, but the actually available (e.g. from thermal reactors) mixed-Pu-isotopes fuel into account. Also with the detection of subthreshold fission of Pu-240, σ_f of this isotope became more important. Note, however, the relaxing tendency towards 1975, because of the minor contribution (Pu-240: 0.004 mills/KWh, Pu-241: 0.003 mills/KWh for 10% uncertainty in σ_f) to the total requested fuel cost uncertainty for 1975 of 0.03 mills/KWh. Similar arguments hold for $\bar{\nu}$(Pu-240) and $\bar{\nu}$(Pu-241).

$\bar{\nu}$ and $\sigma_{n'}$(U-238): during the sixties an increasing trend could be observed towards design studies of large (mostly 1000 Mwe) fast power reactors with high U-238 proportion in the fuel ($\sim$ 80-90%); whereas σ_f was for a long time considered rather well known, only sparse data were available on $\bar{\nu}$. Theoretical (with increasing refinement in multigroup structure in computer programmes such as ELMOE/MC^2, MIGROS/200 group-P1-programme or GALAXY/GENEX) and experimental (critical facility measurements with time-of-flight, proton recoil, sandwich spectrometer, Li glass detector) studies of the neutron energy spectrum singled out the importance of the inelastic neutron scattering on U-238 for the neutron spectrum of fast reactors.

c. Some tendency towards sharpening of the accuracy requirements can be observed for the years $\geq$ 1964. This is mainly due to the very high accuracy (but priority 3) requests being put forward by UK at this time [58]. They were later (1970) withdrawn because of the technical impossibility to meet the requested accuracies (examples [58]: σ_γ(U-238), 40 KeV - 1 MeV, accuracy: 1%, σ_f(Pu-239), 40 KeV - 1 MeV, accuracy: 0.5%; α(Pu-240), 1 - 40 KeV, accuracy: 2%). Accuracy requirements were also relaxed because of the complementary role of integral data and adjustment of the microscopic evaluated data to integral measurements.

d. RENDA 72 [4] is different from all former request lists [3,87-92] since it contains also requests from the USSR and from developing countries. The accuracies requested by these additional countries are rather similar to those in Western requests, therefore there is no drastic change compared to previous requirements. Only the α(Pu-239) accuracy requirements were relaxed. Reasons for this are the many measurements after the "1967 α event" (the high α measurements by Schomberg et al. [98]), their tendency to convergence and the impossibility to measure α more accurately than about 10% in an individual experiment.

e. The accuracy requirements for neutron capture data in structural materials have slowly sharpened with time. RENDA 1970 [3] and an average over all request lists (1961-1972) show the relative importance of Cr, Fe, Ni: 1. Fe, 2. Ni, 3. Cr, in accord with their proportion in SS; Ni became more important also through INCONEL and other cladding materials with Ni as main constituent.

Material	Accuracy required (± %)	
	1970	1961 - 1972
Fe	10	13
Ni	13	21
Cr	20	24

f. The goals 1975 in figure 9 are due to one particular author group [41] interested in industrial design. This can, however, be taken as rather representative, as this group has continuously studied fast reactor designs in intimate connection with nuclear data requirements. They reflect the more mature and balanced opinions regarding the real neutron data needs, the possible achievements by microscopic experiments and the complementary role of integral measurements and data.

2. History of confidence level achievements

a. With few exceptions (at certain times $\bar{\nu}$(U-238) or σ_γ of structural materials) was never an accuracy requirement met by the then available experimental material. Comparison of the three columns 1966-1968-1970 in figure 9 shows an initial overestimate of confidence levels achieved, which, with more critical judgement of the experiments and with increasing physics knowledge (see e.g. α(Pu-239)) had afterwards to be corrected.

b. Definite progress was made in 1972 [15-17] due to many recent precision measurements and evaluations. $\bar{\nu}$ will be about 1% more accurate, when the $\bar{\nu}$(Cf-252) problem will have been solved (see below).

c. The numbers in the 1968 column of figure 9 reflect the influence of the first studies of integral facilities and of the "α event". The figures indicate changes in pertinent evaluated neutron data available at that time (KEDAK, ENDF/B first version etc.) suggested by discrepancies between measured integral data and their theoretically predicted values [51,80] such as K_{eff}, spectral indices, prompt neutron decay constants, reactivity changes due to assembly voiding and flooding.

d. Note the (mostly) great difference between the confidence levels achieved (taking the total volume of available experimental information together) and the accuracies which are claimed to be achieved in individual experiments. This reflects an underestimate by experimenters of systematic errors in their measurements and represents the main difficulty in the evaluation and derivation of "best" values of neutron data. This illustrates also the important role of integral measurements for data accuracy check.

3. More detailed discussion of RENDA 72 requests for fast reactors

On the example of RENDA 72 the requirements for important neutron data for fast reactors will be discussed below in more detail regarding

- energy subranges;
- accuracy requirement ranges;
- number of requests, requesting countries and priority.

Figure 10 contains a summary of RENDA 72 requests for important fast reactor neutron data.

Note: a. the high priority for the neutron fission and capture properties of Pu-239, U-238 and structural materials Fe and Ni ($\sim$1.2 - 1.3) and the somewhat smaller priorities for Pu-240, 241 data, the neutron aapture of fission products and Cr ($\gtrsim$1.4);

b. the generally large number of requests/quantity and of requesting countries;

c. the partly rather large accuracy ranges.

Figure 11 gives a breakdown of figure 10 for σ_f and α (Pu-239) and σ_γ (U-238) with regard to energy range and adds present confidence level figures, where available.

a. The average accuracies requested tend to sharpen between 10 KeV and 1 MeV, i.e. in the most important part of fast reactor neutron spectra.

b. For Pu-239 the accuracy ranges and the (average) priorities are not very different from one energy subrange to the other. The reason for this is that several requests do not discriminate between more and less important neutron energy ranges.

Examples: 1. σ_f(Pu-239), 100 eV - 14 MeV, 2%
for an indiscriminate request;

2. σ_f(Pu-239), 1 eV - 10 MeV;
$<$20 KeV: 3%; 20 KeV - 3 MeV: 2%;
3 - 6 MeV: 5%
for a more sophisticated request.

Ideally the accuracy requirements and the (average) priorities should follow a pattern about inversely to the neutron importance.

c. A comparison of the columns with average accuracy and present confidence level shows that the accuracies required are in no case achieved.

C4. Derivation of neutron data accuracy requirements from required accuracies in reactor design parameters

In the following the link between accuracy requirements in neutron data and reactor design parameters will be discussed. To establish this link there are in principle two possibilities:

a. "Experimental" possibility: one investigates in calculations with multigroup diffusion (or transport) theory codes the influence of neutron data uncertainties on the prediction of reactor design parameters, fixes accuracy requirements for the latter (e.g. 1% in K_{eff}, 0.02 in breeding ratio) and concludes "intuitively" on the requirements for data accuracy.

b. Mathematical derivation: one formulates a mathematical relationship between both requirements, with (more or less) due account of the correlation (direct or through neutron flux etc.) between neutron data changes and uncertainties, and solves the pertinent equations for given reactor requirements, for the individual data requirements.

In the following we describe an interesting mathematical procedure as suggested by Usachev and Bobkov [76, see also 75]. According to this procedure the uncertainties of the group cross sections $\delta\sigma/\sigma$ define the uncertainties of a reactor parameter C through the following linear relationship

$$\frac{\delta C}{C} = \sum_{\alpha ij} S_{\alpha ij} \left(\frac{\delta \sigma}{\sigma}\right)_{\alpha ij} \tag{1}$$

where

- α = cross section type,
- i = isotope,
- j = energy group,
- S = sensitivity coefficient (for its definition by generalized perturbation theory see [99])

Two extreme assumptions were made in the past in dealing with equ. (1): cross section errors were assumed to be either fully correlated or not at all. No correlation at all means that all non-diagonal elements of

$$\left(\sum_{\alpha ij} S_{\alpha ij} \left(\frac{\delta \sigma}{\sigma}\right)_{\alpha ij}\right)^2$$

vanish and that

$$\overline{\left(\frac{\delta C}{C}\right)^2} \cong \sum_{\alpha ij} S^2_{\alpha ij} \overline{\left(\frac{\delta \sigma}{\sigma}\right)^2_{\alpha ij}} \tag{2}$$

However, a comparison of results of various authors quoted in [76] showed that the derived required neutron data accuracies are strongly dependent on the correlation or non-correlation of the errors assumed. Greebler et al. [100] estimate differences by factors 3 to 5. The derived data accuracy requirements vary from values unsatisfiable in the foreseeable future to values already almost satisfied.

It is the new and more realistic feature of Usachev's approach [76] that the structure of cross section errors is taken into account, whose individual components differ from each other with regard to correlation.

The cross section errors are assumed to be composed of statistical and systematic errors and the error in the standard:

$$\left(\frac{\delta \sigma}{\sigma}\right)_{\alpha ij} = \left(\frac{\delta \sigma}{\sigma}\right)^{stat}_{\alpha ij} + \left(\frac{\delta \sigma}{\sigma}\right)^{norm}_{\alpha i} \cdot f_j + \left(\frac{\delta \sigma}{\sigma}\right)^{stand} \tag{3}$$

These three error components are uncorrelated, the squared standard deviation is therefore:

$$\overline{\left(\frac{\partial \sigma}{\sigma}\right)^2_{\alpha ij}} \equiv d^2_{\alpha ij} = (d^{stat}_{\alpha ij})^2 + (d^{norm}_{\alpha i})^2 f_j^2 + (d^{stand})^2 \tag{4}$$

$\underline{d^{stat}_{\alpha ij}}$: if the j-th group contains n experimental points each with a statistical error $\varepsilon_{\alpha ij}$, then

$$d^{stat}_{\alpha ij} = \frac{\varepsilon_{\alpha ij}}{\sqrt{n}} \; ; \; n = \text{number of experimental points in group } j \tag{5}$$

$\underline{d^{stand}}$: taken constant for all groups, substances and quantities where the same standard is used (examples: $\bar{\nu}$(Cf-252) error in $\bar{\nu}$ measurements; neutron flux measurement by the same method in a number of experiments). This error component is fully correlated over the energy range where the standard is used.

$\underline{d^{norm}}$: represents either systematic errors different from the error of the standard (error in determining amount of substance in sample, etc.) or the error of the standard if this is not separately considered under d^{stand}. This error is correlated in different energy groups. f_j is a vector which takes into account the calculated corrections for systematic errors ($0 \leq /f_j/ \leq 1$), $f_j = 1$ in group j with the maximum systematic error.

As a result the errors $d_{\alpha ij}$ are now only partially correlated.

Introducing equ. (3) into equ. (1) we get

$$\frac{\partial C}{C} = \sum_{\alpha ij} S_{\alpha ij} \left(\frac{\partial \sigma}{\sigma}\right)^{stat}_{\alpha ij} + \sum_{\alpha i} \left(\sum_j f_j S_{\alpha ij}\right) \left(\frac{\partial \sigma}{\sigma}\right)^{norm}_{\alpha i} \tag{6}$$

$$+ \left(\sum_{ij} S_{\bar{\nu} ij}\right) \left(\frac{\partial \sigma}{\sigma}\right)^{stand}_{\bar{\nu}} + \sum_{ij} (S_{fij} + S_{\gamma ij}) \left(\frac{\partial \sigma}{\sigma}\right)^{stand}_{flux}$$

The third term in equ. (3) is subdivided into three independent terms for $\bar{\nu}$, fission (f) and capture (γ). $\bar{\nu}$ is assumed to be measured throughout relative to the $\bar{\nu}$ (Cf-252) standard, $(\partial\sigma/\sigma)^{stand}$ is the error of this standard. In the fourth term it is assumed that the same method for the neutron flux measurement has been applied in both fission and capture cross section measurements. In equ. (6) each relative error is uncorrelated with the others.

Now m correlation intervals are assumed; the K-th of these intervals covers groups j between n_k and m_k ($n_k \leq j \leq m_k$). Thus the second and fourth term in equ. (6) can be broken down as follows:

$$\sum_{\alpha i}\Big(\sum_j f_j S_{\alpha i j}\Big)\Big(\frac{\partial\sigma}{\sigma}\Big)^{norm}_{\alpha i} = \sum_{\alpha i}\sum_{k=1}^{m}\Big(\sum_{j=n_k}^{m_k} f_j S_{\alpha i j}\Big)\Big(\frac{\partial\sigma}{\sigma}\Big)^{norm,k}_{\alpha i} \tag{7a}$$

$$\sum_{ij}\big(S_{fij} + S_{\gamma ij}\big)\Big(\frac{\partial\sigma}{\sigma}\Big)^{stand}_{flux} = \sum_{k=1}^{m}\sum_{i}\sum_{j=n_k}^{m_k}\big(S_{fij} + S_{\gamma ij}\big)\Big(\frac{\partial\sigma}{\sigma}\Big)^{stand,k}_{flux} \tag{7b}$$

In the first and third terms of equ.(6) the errors are uncorrelated. In (7a) and (7b) the errors in different correlation intervals are uncorrelated. Therefore it is possible to re-write the right-hand side of equ.(6) as one single sum over ℓ from 1 to N, where N is the total number of independent errors. With coefficients

$$z_\ell \equiv \begin{cases} S_{\alpha i j} & \text{first term} \\ \sum_{j=n_k}^{m_k} f_j S_{\alpha i j} & \text{second term, } K=1,\ldots,m \\ \sum_{ij} S_{\bar{\nu} ij} & \text{third term} \\ \sum_i \sum_{j=n_k}^{m_k}\big(S_{fij} + S_{\gamma ij}\big) & \text{fourth term } k=1,\ldots,m \end{cases} \tag{8}$$

we get

$$\frac{\partial C}{C} = \sum_{\ell=1}^{N} z_\ell \Big(\frac{\partial\sigma}{\sigma}\Big)_\ell \tag{9}$$

and, since all $(\partial\sigma/\sigma)$ are uncorrelated

$$\overline{\left(\frac{\delta C}{C}\right)^2} = \sum_{l=1}^{N} z_l^2 \, \overline{\left(\frac{\delta \epsilon}{\epsilon}\right)_l^2} \qquad (10)$$

where the average is taken over different experiments.

On the basis of the above it is possible to estimate the total cost of uncorrelated microscopic neutron data measurements to attain a predetermined accuracy of a given reactor parameter (experiment planning).

For this it is assumed that the weight of experiment l is equal to the reciprocal of its squared error

$$W_l = \frac{1}{d_l^2} \qquad (11)$$

The cost of the experiment l is $\lambda_l W_l$

where λ_l is a proportionality factor representing the cost of obtaining unit weight in experiment l. (Different error types in equ. (9) are counted as different experiments !)

Thus the total cost of a system of experiments needed to achieve a predetermined accuracy is

$$\text{Total cost} = \sum_{l=1}^{N} \lambda_l W_l \qquad (12)$$

It is now of interest to attain at a minimum total cost this predetermined accuracy in a given reactor parameter C:

$$\delta_0^2 = \overline{\left(\frac{\delta C}{C}\right)^2} = \sum_{l=1}^{N} \frac{z_l^2}{W_l} \qquad (13)$$

The problem of obtaining the minimum of expression (12) under condition (13) is solved by the method of Lagrangian multipliers in which the extremum of following expression is looked for:

$$B = \sum_{l=1}^{N} \lambda_l W_l + \lambda \sum_{l=1}^{N} z_l / W_l \qquad (14)$$

$$\frac{\partial B}{\partial W_l} = 0 \;\leadsto\; \frac{1}{\lambda} = \frac{z_l^2}{W_l^2 \lambda_l} \qquad (15)$$

Eliminating λ one gets (N-1) equations

$$\frac{W_1}{W_\ell} = \frac{Z_1}{Z_\ell}\sqrt{\frac{\lambda_\ell}{\lambda_1}} \tag{16}$$

Upon insertion into equ. (13) and with equ. (11) one gets:

$$\delta_0^2 = d_1^2 Z_1^2 + d_1^2 \sum_{\ell=2}^{N} \frac{Z_1}{Z_\ell}\sqrt{\frac{\lambda_\ell}{\lambda_1}}\, Z_\ell^2 \tag{17}$$

For a given δ_0^2, equ. (17) determines d_1. Then the total cost can be determined from equ. (12).

Example: Given the following accuracies to be attained of the following parameters of a 5000 l volume fast $(Pu,U)O_2$ reactor:

K_{eff} : 1%; BR: 0.02

Assuming three correlation intervals (0–0.1 MeV - 1.4 MeV - $\gtrsim$ 10 MeV) the following data accuracy requirements are derived:

σ_f(Pu-239) : 1.1 %

σ_γ(U-238) : 2.4 %

which is still outside the present achievements.

C5. Accuracy requirements versus confidence levels achieved for neutron standard reference data

Figure 12 displays accuracy requirements versus confidence levels achieved for the more important standard reference data used in neutron nuclear data measurements. The references chosen are representative and not compre‿nsive ! With the exception of thermal and epithermal values, σ_T(H-1), σ_T(C-12) and $\bar{\nu}$(Cf-252) (to be expected shortly) no accuracy requirement is so far met.

σ_T(H-1): No more problem; confidence level in 1966 [12] slightly overestimated. Precision experimental and careful evaluation work [107], later on only, established the present $\leq$1% confidence level.

σ_p(He-3): Below 100 KeV satisfactory, above not.

σ_α(Li-6): Below 10 KeV satisfactory, above not, particularly in 270 KeV resonance discrepancies between Cadarache and Harwell measurements not yet fully resolved [73].

σ_α(B-10): Below 100 KeV satisfactory, above not.

σ_T(C-12): Definite progress in accuracy since 1966 due to a number of precision measurements with generally good agreement. Below 0.5 MeV there are still discrepancies of 2% between "precision" measurements, but cross section probably known to about 1% also in this energy range [71].

σ_γ(Au-197): accuracy achieved about 10%, required are 3-5%, existing discrepancies still not solved. At EANDC Standards Symposium at Argonne [37,68,71] tendency to drop gold standard, at 5th INDC Meeting 1972 [73] again strong vote for gold standard, other KeV capture standards worse from measurement standpoint.

σ_f(U-235): Thermal: recent precision value by Deruytter [108] about 1% higher than "best" value of Hanna et al. [83]. New update of thermal fissile constants by IAEA/NDS in cooperation with outside consultants underway.

Fast: low Pönitz values seem to be ruled out by more recent absolute and normalized shape measurements and by Monte Carlo calculations of highly enriched criticals.

$\bar{\nu}$(Cf-252): Most recent measurements of Boldeman [104] with liquid scintillator technique yield preliminary result of about 3.73 with an accuracy of about 0.5% in close agreement with the most recent $MnSO_4$-bath results from Argonne [105] (3.725 ± 0.024) and National Physical Laboratory, Teddington, UK [106] (~3.72 ± (0.5–1.0)%).

C6. Relationship between standard data and fast reactor parameter accuracies

In the following in a very simple way relationships between uncertainties in standard reference data and accuracies required for certain fast reactor parameters are investigated [67]. We consider a fast reactor with Pu-239/U-238 fuel. We neglect for simplicity structural and coolant materials.

a. K_{eff}

K_{eff} is defined as

K_{eff} = Average number of neutrons produced in reactor per unit time/ [Average number of neutrons absorbed in, and leaking from, reactor per unit time]

This may be written as

$$K_{eff} = \frac{\bar{\nu}_9 \Sigma_f^9 + \bar{\nu}_8 \Sigma_f^8}{\Sigma_{f+r}^9 + \Sigma_{f+r}^8 + L} \qquad (13)$$

$$(\overline{\bar{\nu}\Sigma_f}) \equiv \langle\bar{\nu}\rangle \bar{\Sigma}_f \equiv \bar{\nu}\Sigma_f$$

where

Σ = energy and reactor space averaged macroscopic cross section for fission (f) and capture (γ);

R = effective reactor radius;

L = leakage term;

8,9 = Indices for U-238 and Pu-239.

Remembering that $\bar{\nu}$ measurements are usually made relative to the $\bar{\nu}$(Cf-252) standard and fission and capture cross sections relative to σ_f U-235 (with the exception of σ_γ(Pu-239)) we can rewrite equ. (18)

$$K_{eff} = \bar{\nu}_{252}\, \sigma_f^5 \frac{R_9 F_9 + R_8 F_8 y}{\sigma_f^5 \left(F_9(1+\alpha_9) + (F_8 + G_8) y\right) + L'} \tag{19}$$

where

$$\Sigma = N \cdot \sigma$$
$$R_{8,9} = \bar{\nu}_{8,9} \,/\, \bar{\nu}(\text{Cf-252})$$
$$F_{8,9} = \sigma_f^{8,9} / \sigma_f^5$$
$$G_8 = \sigma_\gamma^8 / \sigma_f^5$$
$$5 = \text{index for U-235}$$
$$y = N_8 / N_9$$
$$L' = L/N_9$$

Neglecting all other uncertainties equ. (19) shows first that $K_{eff} \sim \bar{\nu}_{252}$, i.e.

$$\frac{\Delta K_{eff}}{K_{eff}} = \frac{\Delta \bar{\nu}_{252}}{\bar{\nu}_{252}} \tag{20}$$

Now we consider two extreme cases:

a. $L' \simeq 0$; case of very large highly dilute fast power reactor. Then

$$K_{eff} = \bar{\nu}_{252} \frac{R_9 F_9 + R_8 F_8 y}{F_9(1+\alpha_9) + (F_8 + G_8) y} \tag{21}$$

In this case the dependence of K_{eff} upon σ_f (U-235) vanishes, and, besides $\bar{\nu}_{252}$, K_{eff} depends only upon the cross section ratios R,F,G and α.

b. $L' \gg$ absorption term; extreme case of highly enriched, very small critical assembly (GODIVA-type)

Then

$$K_{eff} = \text{const.} \cdot \bar{\nu}_{25i} \cdot \sigma_f^5 \left(R_9 F_9 + R_8 F_8 \gamma \right) \tag{22}$$

K_{eff} becomes directly proportional to σ_f^5. This explains, why small critical assembly calculations are so sensitive to σ_f^5.

b. Breeding ratio

The breeding ratio is defined as

$$BR = \text{Amount of Pu-239 } \frac{\text{produced}}{\text{destroyed}} \text{ in reactor per unit time}$$

Defining similar "effective" cross sections as in equ. (18) and differentiating between core and blanket quantities by subscripts C and B respectively, we get for the same Pu-239/U-238 fuelled fast reactor with U-238 blanket

$$BR = \gamma_C \frac{\sigma_{\gamma C}^8}{\sigma_{fC}^9 (1 + \alpha_C^9)} + \gamma_B \frac{\sigma_{\gamma B}^8}{\sigma_{fC}^9 (1 + \alpha_C^9)} \cdot K \tag{23}$$

where

$$K = \frac{\bar{\Phi}_B V_B}{\bar{\Phi}_C V_C}$$

$\bar{\Phi}$ = average neutron flux;

V = Volume.

BR does not depend upon σ_f^5 ! BR depends either on the absolute σ_f^9 and σ_γ^8 data only or on the ratios F_9 and G_8 only.

BR does, however, depend upon α_c^9 and, for example, on the error in α_c^9 due to normalisation errors. Neglecting uncertainties of all other quantities we have

$$\left| \frac{\Delta BR}{BR} \right| = \frac{\alpha_c^9}{1 + \alpha_c^9} \; \frac{\Delta \alpha_c^9}{\alpha_c^9} \tag{24}$$

We consider only the normalization error in α_c^9. Gwin et al. [109] quote typical errors, due to normalization of their metal foil data to thermal and resonance α values, in the quantity $1/(1+\alpha) = 0.8$ (corresponding to $\alpha = 0.25$). These correspond to errors of 1% and 6% in BR respectively.

Appendix

Statistics on RENDA 72 [4]

General:

1. Total number of countries requesting and measuring neutron nuclear data: 26.

2. Number of countries requesting: 23.

3. Number of countries measuring requested data: 19.

4. Country overlap (measuring and requesting): 16.

5. Total number of national laboratories (mostly) and industrial firms (fewer) requesting and/or performing neutron nuclear data measurements: 121.

6. 55 laboratories and industrial firms participate in requests with 89 requestors mostly associated with national reactor programmes.

7. 93 laboratories and industrial firms measure requested data.

8. There is an overlap of 27 laboratories and industrial firms who do both, request and measure nuclear data.

9. Two international organizations (IAEA and EURATOM with Ispra and Geel) participate with 7 requestors.

10. IAEA, Geel, Ispra and Dubna participate in measurements and evaluation of requested data.

The following table contains the breakdown by country.

Country	Category	requesting	measuring	requesting and measuring
Australia	A	x	x	x
Canada		x	x	x
France		x	x	x
FRG		x	x	x
Italy		x	x	x
Japan		x	x	x
Sweden		x	x	x
UK		x	x	x
USA		x	x	x
USSR	A	x	x	x
Belgium	B	x	x	x
Hungary		x	x	x
India		x	x	x
Netherlands		x	x	x
South Africa		x	x	x
Switzerland		x	x	x
Yugoslavia	B		x	
Argentina	C		x	
Brazil		x		
Bulgaria		x		
Denmark		x		
Eastern Germany		x		
Finland		x		
Pakistan		x		
Poland			x	
Taiwan	C	x		

In this table countries have been categorized into those having

substantial neutron nuclear data programmes (A)
smaller " " " " (B) and
very small " " " " (C).

Comments:

The category C countries are almost all developing countries; those under category C listed as requesting only have very small neutron data measuring programmes which are still not related to RENDA requests: this elucidates a future task of NDS and INDC to promote measurements of neutron data linked to RENDA requests in developing countries; the table also reveals qualitatively the immediate benefit of measurements in developed countries to developing countries provided the latter have the necessary infrastructure (computers, group constant generation and reactor physics programmes, etc.) to make effective use of these data.

The degree to which an internationalization of neutron data efforts has already been achieved can be expressed by the percentage of those requests which are being measured by other countries than the requesting ones. The following tables contain statistical details regarding measurements of requested data again on the basis of information contained in RENDA 72 [4].

Number of requestors per request	No. of measuring (or evaluating) laboratories per request	No. of requests measg. = requestg. countries	measg. ≠ requestg. countries
1	0	518	
	1	211	258
	2	56	104
	3	8	69
	4	8	34
	5	-	9
	6	-	8
	7	-	8
	8	-	1
	9	-	-
	10	-	4
2	0	94	
	1	35	23
	2	8	14
	3	4	12
	4	2	3
	5	-	1
	≥ 6	-	-
≥ 3	0	3	
altogether 28 requests	1	12	8
(25 USA, 2 UK,	2	4	7
1 EURATOM)	3	3	3
19 requests with 3 requestg. labs	4	-	2
8 " " 4 " "	5	3	-
1 " " 5 " "	6	-	-
	7	-	-
	≥ 8	-	-

Condensation of the last table

No. of requestors per request (= P)	no measurements	No. of requests being measured by laboratories in: requestg. country itself (A)	other countries (B)	total
1	518 40%	283 22% (36%)	495 38% (64%)	1296 100% (100%)
2	94 48%	49 25% (48%)	53 27% (52%)	196 100% (100%)
≥ 3	3 7%	22 49% (52%)	20 44% (48%)	45 100% (100%)
≥ 1	615 40%	354 23% (38%)	568 37% (62%)	1537 100% (100%)

P	Country Category	No. of measuring (or evaluating) laboratories per request: 1	2	3	4	5	6	7	8	9	10
1	A	27.2	7.2	1.0	1.0	-	-	-	-	-	-
	B	33.1	13.4	8.9	4.4	1.2	1.0	1.0	0.1	-	0.5
2	A	34.2	7.9	3.9	2.0	-	-	-	-	-	-
	B	22.5	13.7	11.8	2.9	1.0	-	-	-	-	-
≥ 3	A	28.5	9.5	7.2	-	7.2	-	-	-	-	-
	B	19.0	16.6	7.2	4.8	-	-	-	-	-	-
≥ 1	A	28.0	7.4	1.6	1.1	0.3	-	-	-	-	-
	B	31.4	13.5	9.1	4.2	1.1	0.9	0.9	0.1	-	0.4

The numbers in this table are % figures, they add up to 100% for each (C,A,B) combination.

Observations and explanations

Trivial observations:

a. The number of requests on which measurements are being performed is strongly decreasing as a function of the number of laboratories participating in those measurements (figure 2a - d).

b. The number of requests being measured is strongly decreasing as a function of the number of requestors per request and country (figure 3).

c. Note the high percentage of requests (40%) with "zero measurers" with a status comment "No measurements available" (referring to one of the primary purposes of RENDA, which is to make measurers aware of users' data needs) or with no status comments at all; the latter case may be interpreted in several ways, for example:

- no measurements available (as in the first case)
- laziness of requestor and/or reviewer to insert status comments
- available data insufficient.

At this point two warnings are indicated.

Warning 1

The fact that laboratories measure requested data does not necessarily mean that the measurements are initiated by the requests !

RENDA does not allow to discriminate between measurements done explicitly in fulfilment of RENDA requests and those done for a different purpose coinciding only incidentally with a requested measurement.

This is not true for big countries like USA and others whose measurement programme is determined by national request lists which form part of RENDA.

As a consequence it will be an important task of INDC, EANDC and other regional nuclear data committees to establish a better link between requestors and measurers.

Warning 2

RENDA has a certain randomness with regard to requesting countries. Often countries can be supposed not to enter their own requests when these are already entered by other requesting countries. This means that one can safely assume that many RENDA requests are backed by more countries than appear in the list, due to the similarity of their nuclear reactor programmes. This is not so much true of certain high priority requests for key fast reactor and standard data requested by many countries.

This randomness is also partly due to different levels of the requestor's knowledge of the status of the requested data and to different emphasis within different programmes: better knowledge or minor/diminishing emphasis leads to omission or non-entering of requests into RENDA.

Further observations:

(with the above two warnings in mind which somewhat restrict the validity of the statements below)

1. The percentage of the requests being measured outside the requesting country is a measure of international cooperation in the production of neutron nuclear data (figure 4):

   62% = 2/3 of all requests are being measured by laboratories outside the requesting country.

   If one considers this number as a function of the number of requestors per request (where ≥ 2 different requestors from the same laboratory have been counted as one requestor), it changes from

   64% for 1 requestor/request to
   52% " 2 " s/ " and to
   48% " 3 " s/ " .

   One would expect this tendency to be stronger: the more requestors per request, the more urgent the need and the greater the incentive for that country to measure the requested data itself.

2. The percentage of requests being measured by the requesting country itself illustrates

   a. the degree of financial and technical capabilities of that country to work in fulfilment of its own requests

   b. the degree of feedback between requestors (users) and producers in that country.

   38% = 1/3 of all requests are being measured by laboratories inside the requesting country.

   This number may be misleading as the ratio R of the number of laboratories outside to inside the country as appearing in RENDA 72 is strongly increasing when one goes from the bigger to the smaller countries as illustrated by the table below.

Country	R	Country	R	Country	R
USA	2 (35%)	Canada	29 (3.3%)	Argentina	119 (0.8%)
Germany	12 (7.5%)	Belgium	39 (2.5%)	Finland	
USSR	14 (6.7%)	Sweden	59 (1.7%)	Austria	
France	16 (5.8%)	Netherlands		Brasil	
UK	16 (5.8%)	Hungary		Yugoslavia	
India	19 (5.0%)	Japan		Pakistan	
Italy	23 (4.2%)	Switzerland	59 (1.7%)	Denmark	
South Africa	23 (4.2%)	Bulgaria	119 (0.8%)	Poland	119 (0.8%)
Australia	29 (3.3%)	Taiwan	119 (0.8%)		

Thus for one laboratory in the USA there are only about two laboratories in countries outside the USA, whereas for a medium country like Italy this number is greater than 20. The numbers in brackets are ratios of the numbers of laboratories inside the country concerned to the total number of laboratories appearing in RENDA 72.

As a conclusion of points 1 and 2 it seems that the rather high percentage (62%) of outside-the-requesting-country work illustrates the international character of nuclear physics research going on in many laboratories in the world rather than the willingness or capability of countries to measure other than their own requests.

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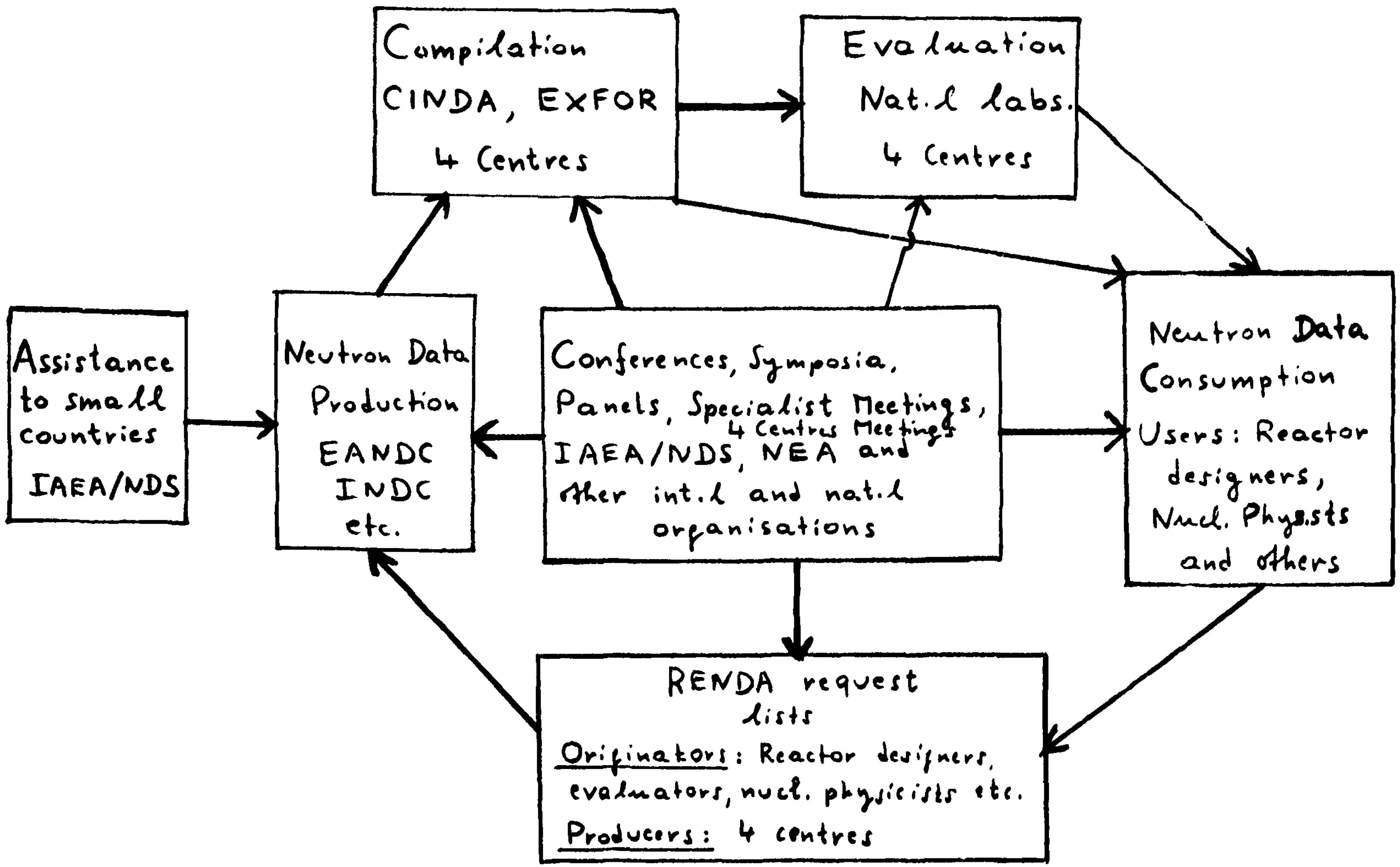
Figure 1

Organisational chart for the field of neutron nuclear data



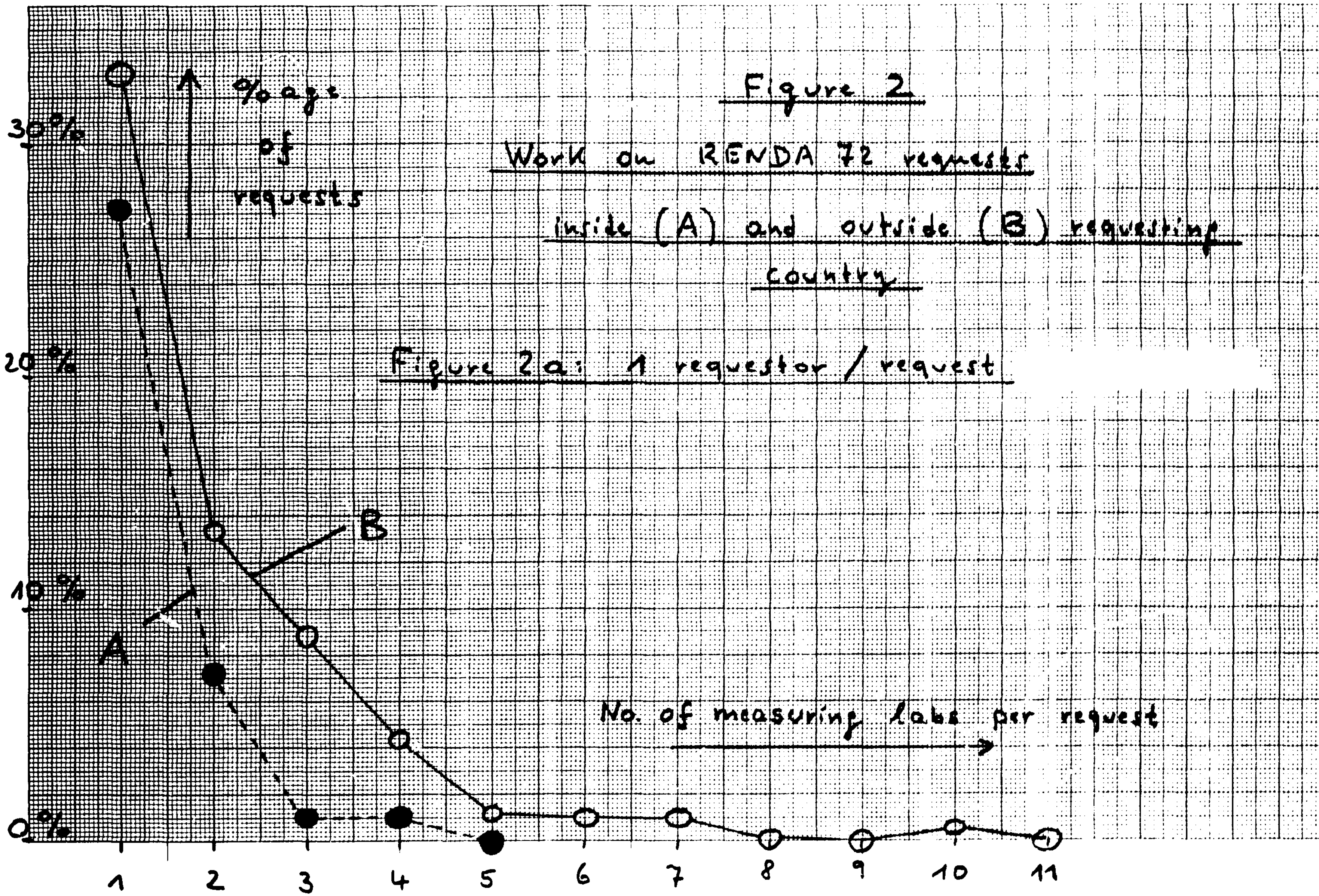


Figure 2
Work on RENDA 72 requests
inside (A) and outside (B) requesting country
Figure 2a: 1 requestor / request
%age of requests
30%
20%
10%
0%
A
B
No. of measuring labs per request
1
2
3
4
5
6
7
8
9
10
11

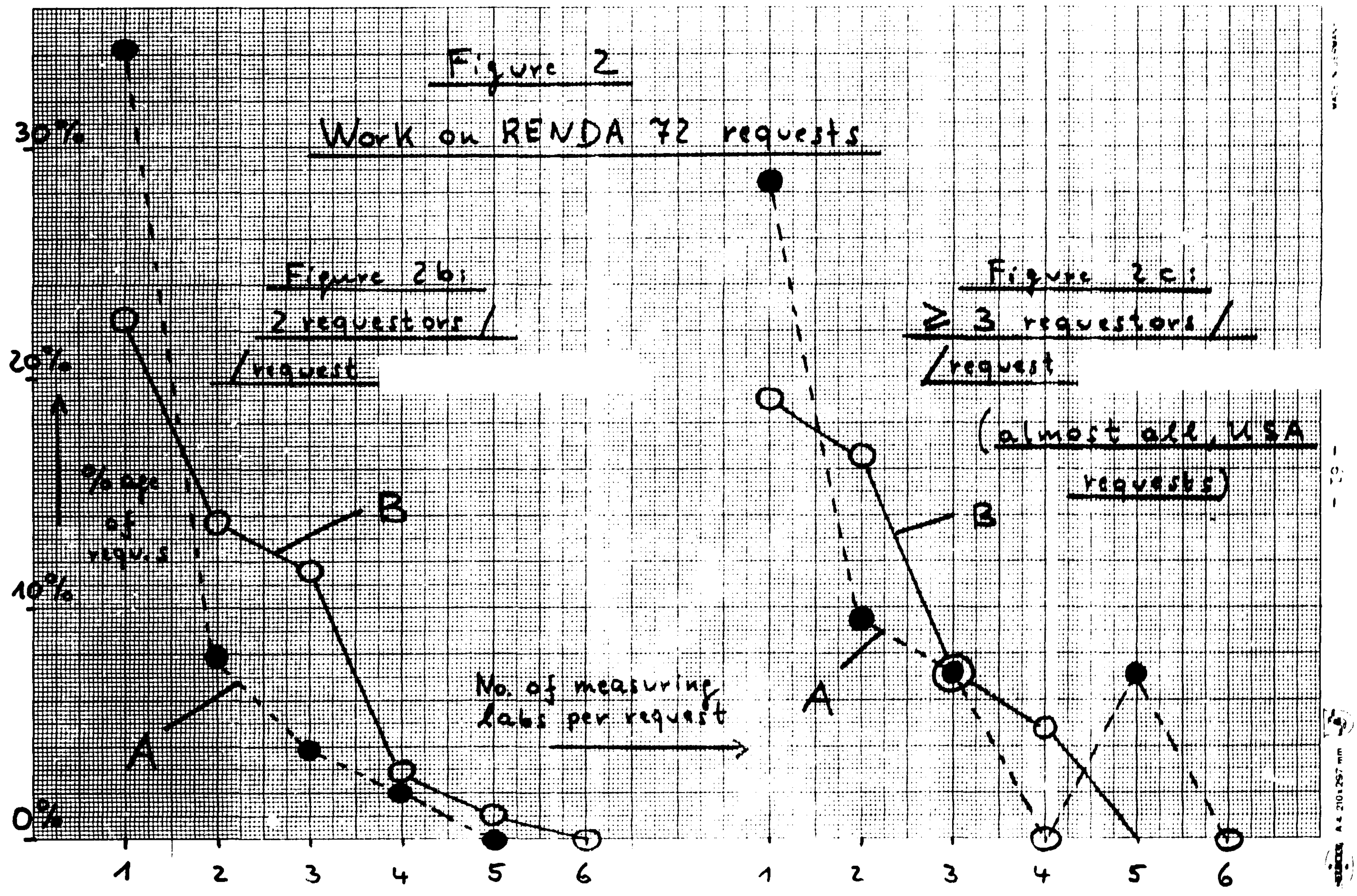


Figure 2
Work on RENDA 72 requests
Figure 2b:
2 requestors / /request
Figure 2c:
≥ 3 requestors / /request
(almost all USA requests)
30%
20%
10%
0%
% age of requ.s
No. of measuring labs per request
A
B
A
B
1
2
3
4
5
6
1
2
3
4
5
6

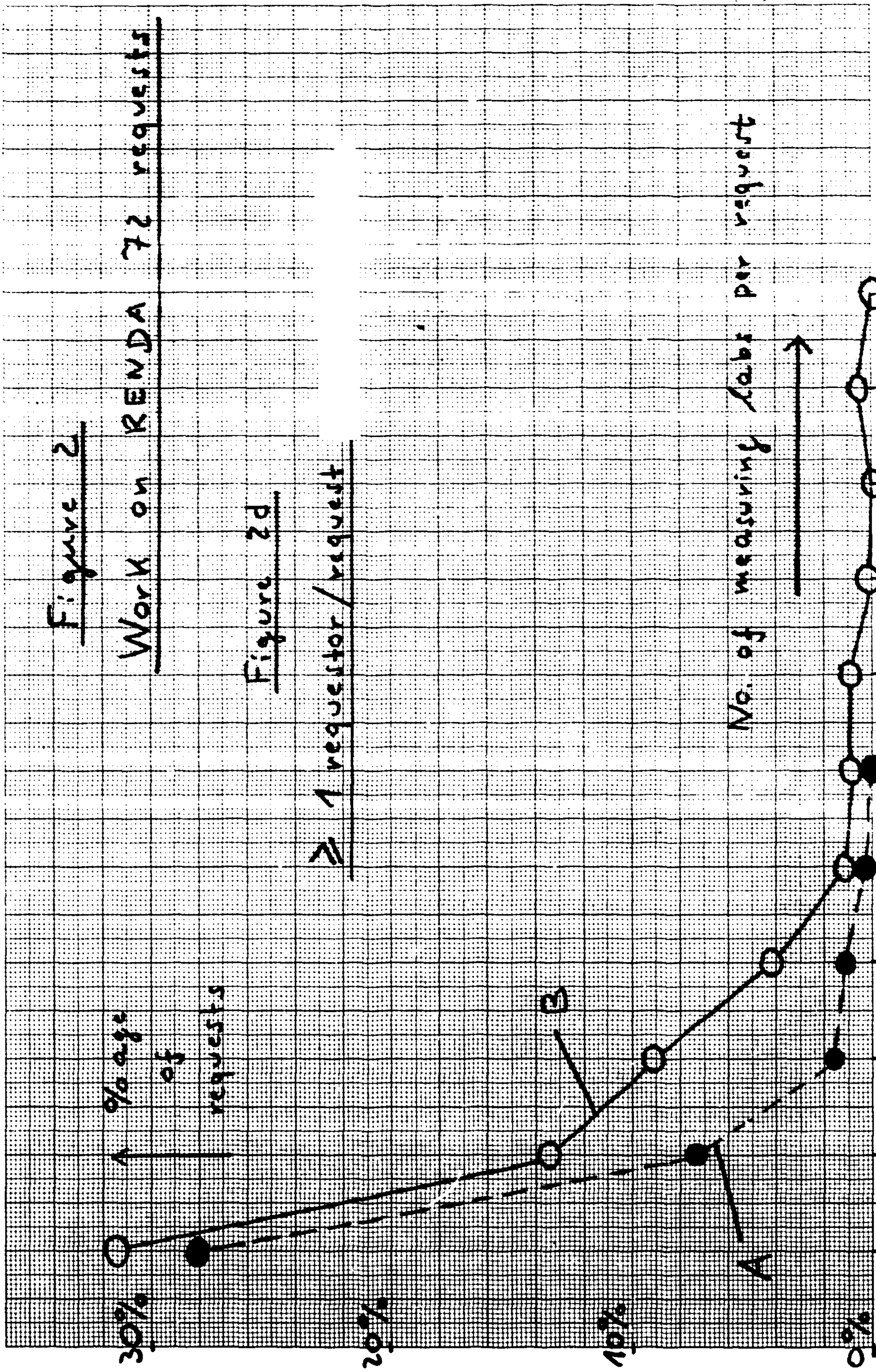


Figure 2
Work on RENDA 72 requests
Figure 2d
≥ 1 requestor / request
%age of requests
No. of measuring labs per request
30%
20%
10%
0%
1
2
3
4
5
6
7
8
9
10
11
A
B

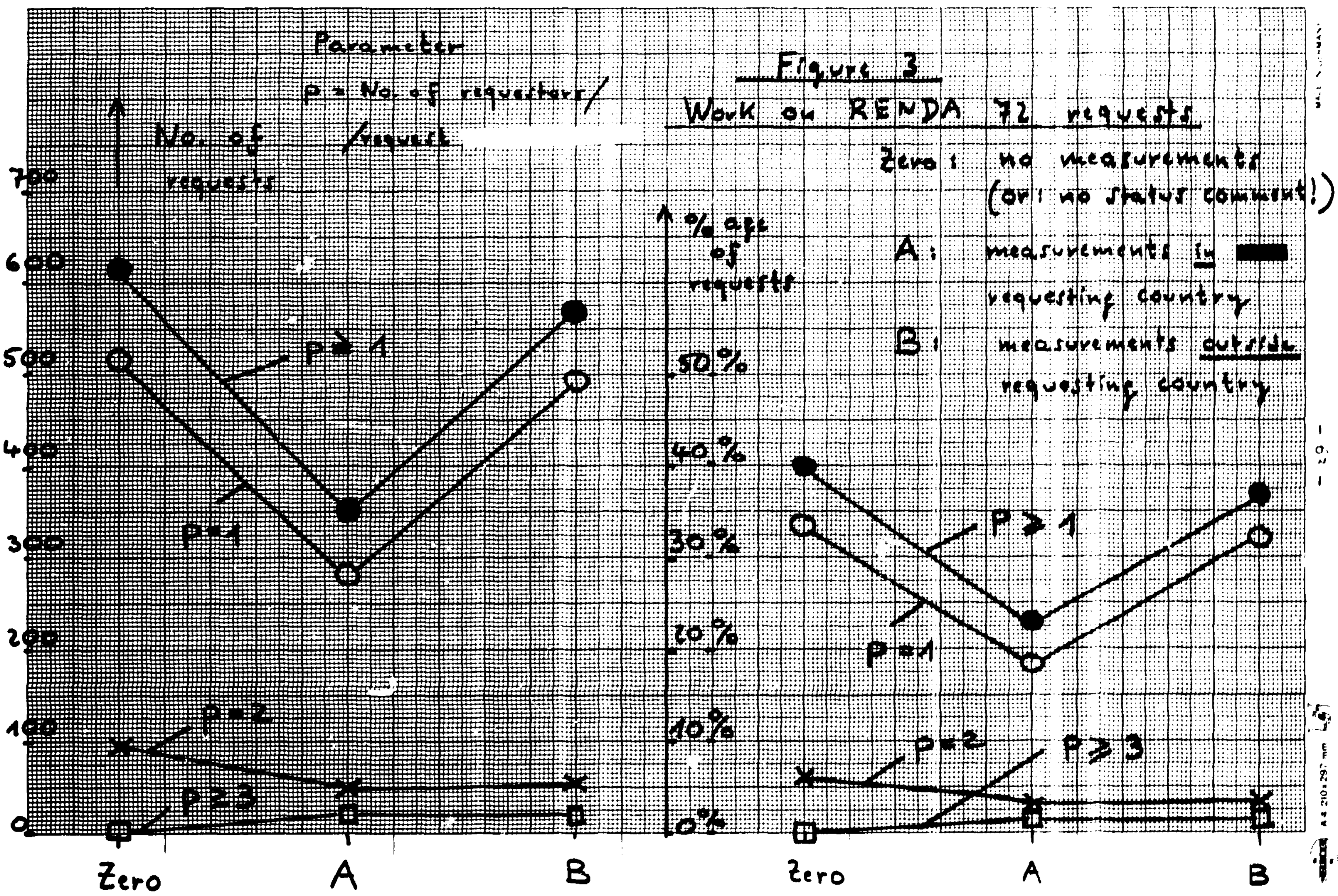


Figure 3
Work on RENDA 72 requests
Parameter
p = No. of requestors/
/request
No. of requests
700
600
500
400
300
200
100
0
p ≥ 1
p = 1
p = 2
p ≥ 3
Zero
A
B
% age of requests
50 %
40 %
30 %
20 %
10 %
0 %
Zero : no measurements
(or : no status comment!)
A : measurements in [redacted]
requesting country
B : measurements outside
requesting country

Figure 4
CINDA sample page

15 OCTOBER 1971 PAGE 319

92 Uranium 233 **92 Uranium 233**

Quantity	Type	Energy Min	Energy Max	Documentation Ref Vol Page	Date	Lab	Comments	Data
Fission	Theo-Conf		7. +3	70HELS 2 799	6/70	SDC	GARRISON.DISCUSSN. RESONANCE ANAL	
Fission	Expt-Jour	1.8-2	1.2+3	JNE 24 1?1	6/70	GEL	CAO+ MULTLVL FIT TO RES BELOW 65EV	
Fission	Theo-Jour	0.0+0	3. +6	YF 12 293	8/70	CCP	ZHMAILO. U233(D,P FISSN)GRPH CFD XPT	
2							= ENGLISH SNP 12 160 2/71	
Fission	Expt-Prog	NDG		BNL-50276 59	D/70	COL	FELVINCI+.ANAL TO BE COMPLETED.NDG	
Fission	Eval-Prog	2.5-2		BNL-50276 12	D/70	ANL	DE VOLPI.PRELIMINARY VALUE GIVEN	
Fission	Expt-Conf	3.2+5	2.5+6	70MADURAI 2 67	D/70	TRM	IYENGAR+ SIGMA EXPT TB CONT'D. NDG	
Fission	Theo-Jour	1. +2	1. +5	NP A159 305	D/70	GA	GARRISON.AVERAGE C.S.=NO RES INTERF	
Fission	Eval-Conf	2.5-2		71KNOX 560	3/71	ANL	DE VOLPI. ADJUSTED VALUE GIVEN	
Fission	Eval-Conf	2.5-2		71KNOX 566	3/71	BET	STEEN. BEST VALUE=524.0+-5.08	
Fission	Expt-Conf	8.0-1	1.0+2	71KNOX 855	3/71	COL	FELVINCI+ CURVES	
Fission	Expt-Conf	3.0+1	2.0+2	71KNOX 829	3/71	SAC	BLONS+. CURVE	
Fission	Expt-Prog	6.0-2	4.0+4	BNL-50298 61	5/71	COL	FELVINCI+.PRELIM CURVS.ANAL TBC	
Eta	Expt-Abst	THR	3. +0	BAP 5 33II1	1/60	ORL	SLAUGHTER+.ETA VARIATN WITH E. NDG	
Eta	Comp-Rept	2.5-2		AE- 11	4/60	AE	STORY+.DISCUSSION+TABULATN OF MEASTS	
Eta	Expt-Prog	9.5-2	2.6-1	NCSAC-31 72	5/70	MTR	SMITH+.MN BATH.ANAL TBC.REL MEAST	
Eta	Expt-Prog	6.0-2	2.6-1	IN- 1407 39	6/70	MTR	SMITH+. 4ES.MN BATH.TABLE+CURVE	
Eta	Expt-Conf	THR	2.6-2	70HELS 1 295	6/70	FAR	VIDAL+97. VAL GVN.OSCILLATN METHOD	
Eta	Theo-Conf	+0	1.0+1	70HELS 2 757	6/70	ORL	SAUSSURE+94. ETA(E) CRV.MULTILVL FIT	
Eta	Expt-Prog	6. -2	2.6-1	BNL-50276 87	D/70	MTR	SMITH+.4 ES.CURVE+TABLE	
Eta	Eval-Prog	2.5-2		BNL-50276 12	D/70	ANL	DE VOLPI.PRELIMINARY VALUE GIVEN	
Eta	Eval-Conf	2.5-2		71KNOX 560	3/71	ANL	DE VOLPI. ADJUSTED VALUE GIVEN	
Eta	Eval-Conf	2.5-2		71KNOX 605	3/71	BET	MITCHELL+.MONTE CARLO ANAL OKS SMITH	
Eta	Eval-Conf	2.5-2		71KNOX 566	3/71	BET	STEEN. BEST VALUE=2.2978+-0.007	
Eta	Expt-Jour	THR		NSE 44 266	5/71	ORL	MAGNUSON RE-ANAL GVES-MAGNUSON DATA	
Alpha	Comp-Rept	2.5-2		AE- 11	4/60	AE	STORY+.DISCUSSION+TABULATN OF MEASTS	
Alpha	Expt-Conf	THR	2.6-2	70HELS 1 287	6/70	CRC	LOUNSBURY+PPR2. VALUE GVN.THRML FLUX	
Alpha	Eval-Prog	2.5-2		BNL-50276 12	D/70	ANL	DE VOLPI.PRELIMINARY VALUE GIVEN	
Alpha	Eval-Conf	2.5-2		71KNOX 560	3/71	ANL	DE VOLPI. ADJUSTED VALUE GIVEN	
Alpha	Eval-Conf	2.5-2		71KNOX 566	3/71	BET	STEEN. BEST VALUE=0.0874+-0.0006	
Alpha	Expt-Jour	5. -1	UP	NSE 44 180	5/71	KAP	EILAND+ CD AND CD-RH FILTERS	
Alpha	Expt-Jour	PILE		NSE 45 37	7/71	ANL	KATO+.FAST REACTOR SPEC. INTEG MEAST	
Nu	Expt-Jour	8.0+4		PR 101.1012	2/56	LAS	DIVEN+.LIQ SCINT.+PROB EMISS	
Nu	Expt-Rept	THR	9.0+5	NP-TR-440	9/57	CCH	SAUNDERS. NDG NSA 14 2213 9/60	
Nu	Comp-Rept	2.5-2		AE- 11	4/60	AE	STORY+.DISCUSSION+TABULATN OF MEASTS	
Nu	Expt-Jour	THR	3.9+6	NP 48 433	0/63	LAS	HOPKINS+SCINT TANK.RELAT TO CF252	
2							SEE ALSO 61VIENNA 1 149 8/61 SUPERSEDED	
3							SUPERSEDES ALSO WASH-1028 29 5/60,	
4							WASH-1033 32 8/61, WASH-1034 22 D/61	
5							WASH-1039 26 5/62 AND WASH-1041 28 0/62	
Nu	Revw-Conf	THR	1.5+7	70HELS 2 195	6/70	HAR	COLVIN.PPR99. REPORT ON DATA STATUS	
Nu	Comp-Conf	THR		70HELS 2 93	6/70	AE	ALMEN+57. COMPILATN AND NU-TEMP-PLOT	
Nu	Revw-Rept	2.5-2	1.5+7	INDC(NDS)-19	6/70	IAE	KON'SHIN+NU(E)COMPIL+RENORM.CURV.TBL	
2							WORK BEING CONTINUED	
Nu	Eval-Prog	2.5-2		BNL-50276 12	D/70	ANL	DE VOLPI.PRELIMINARY VALUE GIVEN	
Nu	Theo-Jour	8.0+4		NST 7 635	D/70	TOK	HARA.CAL CFD C DIVEN EXP	
Nu	Eval-Conf	2.5-2		71KNOX 560	3/71	ANL	DE VOLPI. ADJUSTED VALUE GIVEN	
Nu	Eval-Conf	2.5-2		71KNOX 566	3/71	BET	STEEN. NU(T)=2.4986+-0.0076 REL U233	
Nu	Eval-Conf	2.5-2		71KNOX 566	3/71	BET	STEEN. NU(P)=3.774+-0.014 REL CF252	
Nu	Expt-Prog	NDG		BNL-50298 174	5/71	RPI	REED+. TO BE COMPLETED. NO DATA GIVN	
Nu	Eval-Jour	0. +0	1.5+7	NSE 44 345	6/71	ANL	DAVEY. PROMPT NEUTS PER FISSION	
Nu	Expt-Jour	2.5-2	2. +6	JNE 25 321	8/71	AUA	WALSH+ LIQ SCIN.	
Nu	Eval-Jour		5. +6	JNE 25 321	8/71	AUA	WALSH+ 2 LINE EN DEPENDENCE	
Delayd Neuts	Revw-Rept	THR	FISS	LA- 1970	0/55	LAS	KEEPIN. NEUT YLDS+SPECTRA.CURVS+TBL3	
Delayd Neuts	Revw-Jour	PILE		NPW 1 114	7/56	HAR	COX. YIELD+HALF LIFES OF DEL-NEUTS	
Delayd Neuts	Expt-Diss	THR		TID-25645	5/69	VPI	RAMBO.HALF-LIVES+REL ABUNDANCES	
Delayd Neuts	Expt-Abst			DA 30B 4749	4/70	VPI	RAMBO 5 NTN.GPS.YLD.HL.REL ABUNDS.	
Delayd Neuts	Expt-Prog	THR	1.5+7	NCSAC-31 156	5/70	LAS	KRICK+.PRELIMINARY NEUTRON YLDS GIVN	
Delayd Neuts	Revw-Rept	2.5-2	1.5+7	INDC(NDS)19.15	6/70	IAE	KON'SHIN+ REVIEW AND TABLES	
Delayd Neuts	Expt-Prog	1. +5	7. +6	BNL-50276 155	D/70	LAS	KRICK+.CURV ABSOL NEUT YLD VS. E	
Delayd Neuts	Expt-Jour	1.6+7	2.1+7	YF 13 293	2/71	CCP	MAKSUTENKO+ YIELD OF 11 GROUPS.TBL	
Delayd Neuts	Expt-Jour	THR		NSE 44 173	5/71	BNL	CONANT+ DELAYED NEUT FRACTION	
Frag Neuts	Theo-Conf	THR		70MADURAI2 619	D/70	SAH	SARKAR+ NU VS FRAGMASS GRPHS CFD XPT	
Spect Fiss N	Theo-Abst	THR		BAP 16 56CD5	1/71	CUA	LEE+. THEORETICAL EXPRESSION.NO DATA	
Spect Fiss G	Expt-Jour	PILE		JNE 25 1	1/71	SRC	SCOBIE+ BETA EN RELESE RATE REL U235	
Spect Fiss G	Theo-Jour	2.5-2		JNE 25 339	8/71	SRC	SCOBIE+ VAR BETA EN REL RATE WTH TME	

Figure 5

CINDU sample page

92 URANIUM 235

QUANTITY	ENERGY MIN	ENERGY MAX	LAB	YR	TYPE	DOCUMENTATION REF VOL PAGE	DATE	AUTHORS.COMMENTS	NEW
FISSION			LAS	65	EXPT	PETREL		HEMMENDINGER.A+BROWN.WK+BERGEN.DW+	
								+CRAMER.JD.	
	2.0+1	2.0+6			CONF	CONF660303 971	MAR/66	PPR F11. EXPT DESCRIBED. CURVES	
	2.0+1	2.0+6				66PARIS II 219	OCT/66	PPR 42.EXPT DESCRIBED.CURVS 20-400EV	
	2.0+1	2.0+6			REPT	LA-DC-7618	MAR/66	SAME AS CONF660303 895	
	2.0+1	2.0+6				LA-DC-7813	OCT/66	SAME AS 66PARIS II 219	
	2.0+1	9.8+5				LA- 3586	SEP/66	NORMALIZATION. GRAPHS. TABLES	
	2.0+1	9.8+5				LA- 3478 V.1+2	67	EXPT + DATA REDUCTION DESCRIBED	
					PROG	WASH-1064 93	OCT/65	SHORT NOTE. SUPERSEDED	
						WASH-1056 51	MAR/65	SHORT NOTE ON EARLIER 1964 SHOT	
					JOUR	PT 18 8 17	AUG/65	REVIEW AND PRELIM CURV FROM 1964SHOT	
	2.0+1	9.8+5			DATA	DASTAR-00128	MAR/67	3087 DATA LINES FROM BNL SCISRS TAPE	
FISSION			KUR	66	EXPT	LINAC TOF		MOSTAVAJA.TA+BESPALOV.DG.	
	8.0-1	1.7+2			REPT	IAE-1302	FEB/67	METHOD.ANALYSIS. CURVES. CFD OTHERS	
	8.0-1	1.7+2				ICD-3 10	OCT/66	SAME AS IAE-1302	
	8.0-1	1.7+2				INDSWG-152E 10	67	ENGL TRANSL OF ICD-3 10	
	8.0-1	1.7+2			DATA	DASTAR-00056	NOV/66	1860 DATA LINES.PR COM FROM OBNINSK	
	3.6-1	9.0-1				DASTAR-00068	JUN/69	15 DATA LINES.PR COM FROM OBNINSK	
FISSION			ORL	66	EXPT	TOF. LINAC		DE SAUSSURE.G+WESTON.LW+GWIN.R+	
								INGLE.RW+TODD.JH+HOCKENBURY.RW+	
								FULLWOOD.RR+LOTTIN.A	
	4.0-1	2.0+4			CONF	66PARIS II 233	OCT/66	PPR48.S.MULTAN FISSION+CAPTURE.GRPHS	
	4.0-1	2.0+4			PROG	WASH-1068 131	MAR/66	PRELIMINARY RESULTS. GRAPHS	
	4.0-1	2.0+4			REPT	ORNL-TM-1804	67	MORE DETAILS	
	4.0-1	2.0+4			PROG	WASH-1064 123	OCT/65	EXPERIMENT IN PROGRESS. NDG	
	4.0-1	6.3+1			DATA	DASTAR-00027	NOV/66	SIGMA-ROOT-E AT 2220ES. ALSO SIG ABS	
	1.7+2	2.0+4				DASTAR-00028	NOV/66	SIGMA-ROOT-E AT 3568ES. ALSO SIG ABS	
FISSION			LAS	69	EXPT	PERSIMMON		CRAMER.JD+BERGEN.DW.	*
	2.0+1	1.0+3			REPT	LA- 4285	DEC/69	NUCLEAR EXPLOSION.TOF. EXPER DETAILS	*
	2.0+1	1.0+3			DATA	INDA*10054.	JLY/71	CROSS SECT + ERR AT 2801 ENERGIES.	*
ETA			ITE	63	EXPT			IGNAT'EV.KG+KIRPICHNIKOV.IV+	
								SUKHORUCHKIN.ST.	
	2.5-2	2.0+1			JOUR	AE 16 110	FEB/64	SIMULTANEOUS ETA AND TOTAL.CURVES	
	2.5-2	2.0+1				SJA 16 121	FEB/64	ENGL TRANSL OF AE 16 110	
	2.5-2	2.0+1				JNE 18 719	NOV/64	ENGL TRANSL OF AE 16 110	
	2.5-2	2.0+1				EAF 16 2 19	FEB/64	TRADUCTION FRANCAISE DE AE 16 110	
	2.5-2	2.0+1			REPT	ITE-147	63	SAME CURVES AS AE 16. SIMILAR TEXT	
	2.5-2	2.0+1				INDSWG-7E	63	ENGL TRANSL OF AE 16 110	
	3.0-2	1.2+0			DATA	DASTAR-00058 *	NOV/66	ETA AT 58 ENERGIES	
	9.1-1	1.3+0				DASTAR-00059 *	NOV/66	ETA AT 35 ENERGIES	
ETA			MTR	64	EXPT			SMITH.JR+REEDER.SD+FLUHARTY.RG.	
	2.5-2				REPT	IDO-17083	FEB/66	CRYST SPEC.MN-BATH.FULL INFORMATION	
	2.5-2				PROG	WASH-1064 133	OCT/65	ABSTRACT. TABLE GIVEN	
	2.5-2					BAP 10 1099CD6	OCT/65	ABSTRACT. TABLE GIVEN	
	2.5-2				DATA	DASTAR-00554	APR/67	ABSOLUTE VALUE	
ETA			HAR	65	EXPT	TOF		BROOKS.FD+JOLLY.JE+SCHOMBERG.MG+	
								SOWERBY.MG.	
	3.5-2	2.0+2			REPT	AERE/NP/GEN-35	66	REPORT PLANNED BUT NOT ISSUED	
	3.5-2	2.0+2				AERE-M 1670	FEB/66	XPT DESCR.CFD OTHERS.INTEGRAL DATA.	
	3.5-2	2.0+2				EANDC(UK)42 L	64	PRELIM REPORT.SUPERSEDED.	
	3.3-2	1.1+2			CONF	66SDIEGO 3.3	FEB/66	EXPT + METHOD PRESENTED	
	3.5-2	4.0+0			DATA	DASTAR-00103 *	JAN/67	AT 206 ES.SEE AERE-M1670.FIGS 1.2A	
	1.8+0	2.0+2				DASTAR-00104 *	JAN/67	AT 2220ES.SEE AERE-M1670.FIGS 2A.3A	
	3.5-1	6.0+1				DASTAR-P0013	NOV/67	MEAN ETA CFD OTHRS.AERE-M1670.TBL1+3	
ALPHA			ANL	58	EVAL			SIGMA CENTER.BNL.	
	3.8-3	4.9-1			PRIV	*PO SIGMA-CNTR	58	ALF DEDUC FROM ETA/NU-BAR.BOLLINGER	
	3.8-3	4.9-1			DATA	DASTAR-00123	MAR/67	28 DATA LINES FROM SCISRS	
ALPHA			COL	58	EXPT			SAFFORD.GJ+MELKONIAN.E.	
	2.9-3				JOUR	PR 113 1285	MAR/59	SIMULTAN TRANSM+FISSION. CRYSTSPEC	
	2.9-3					PNL 2 189	FEB/59	ABSTRACT. VALUES SUPERSEDED BY PR113	
	2.9-3				CONF	60VIENNA 203	OCT/60	SHORT VERSION OF PR 113. SAME DATA	
	2.9-3				PROG	WASH-1013 24	NOV/58	ABSTRACT. VALUES SUPERSEDED BY PR113	
	2.9-3					WASH-1006 8	JUN/58	ABSTRACT. NO DATA	
	2.9-3				DATA	DASTAR-00692	JLY/68	ALFA AT 0.00291EV	
ALPHA			HAR	60	EXPT			CORNISH.FW.	
	PILE				REPT	NRDC-129	MAY/60	ACTIVATION AND MASS ANALYSIS	
	PILE				DATA	DASTAR-00706	JLY/68	ALFA FOR REACTORSPEC..0253 DEDUCED	

Figure 6

Example for EXFOR entry

```
ENTRY              30148
SUBENT          30148001
BIB
TITLE      INVESTIGATION OF THE REACTION T(N,2N)D AT EN=13.94 MEV
           AND THE NEUTRON-NEUTRON SCATTERING LENGTH
AUTHOR     (G.ADAM,F.BAR AVRAHAM,R.FOX,Y.PORAT)
INSTITUTE  (3ISLNFA)
REFERENCE  (J,NP/A,178,321,71) EXPER DETAILS,CFD THEORY,GRAPH ONLY
FACILITY   (ACCEL)200-KV KAMAN NUCLEAR A-1001 DEUTERON ACCELERATOR
N-SOURCE   (D-T) DEUTERIUM-TRITIUM
INC-SPECT  13.94+-0.22 MEV NEUTRONS EMITTED AT ANGLE OF 100 DEG.
SAMPLE     1) TRITIUM-TITANIUM 0.2 MG/CM2 ON GOLD BASE TO PRODUCE
              DEUTERONS FROM T(N,2N)D REACTION.
           2) TITANIUM 0.3 MG/CM2 FOR BACKGROUND SUBTRACTION.
           3) DEUTERATED-PARAFFIN 16.5 MG/CM2 FOR DIRECT
              MEASUREMENT OF RESOLUTION FUNCTION BY SIMULATION OF
              THE RESOLUTION OF A 7.69-MEV DEUTERON PRODUCED IN
              TARGET 1).
GEOMETRY   TARGETS WERE PLACED 20 CM FROM ACCELERATOR TIP AT AN
           ANGLE OF 100 DEG TO THE ACCELERATED DEUTERON BEAM.
DETECTOR   (TELES) COUNTER TELESCOPE (SEE NUCL.PHYS.A178,321 FOR
           SCHEMATIC OF TELESCOPE AND ELECTRONICS) CONSISTING OF
           (PROPC) SIX PROPORTIONAL COUNTERS. TWO FOR DELTA-E.
            THE OTHERS TO DETERMINE GEOMETRY AND DECREASE
            ACCIDENTAL COINCIDENCES. AND
           (SOLST) SOLID-STATE TOTAL ENERGY DETECTOR (1.7 CM DIAM)
           LOCATED 300 MM FROM TARGET.
METHOD     (DIDET,COINC) DIRECT DETECTION,COINCIDENCE.
           THE ELECTRONIC SYSTEM SEPARATED DEUTERONS FROM
           BACKGROUND BY
           1) TIME COINCIDENCE IN 5 COUNTERS
           2) LIMITATION OF E AND DELTA-E TO THE RELEVANT RANGES
           3) FINAL IDENTIFICATION OF PARTICLES BY E*DELTA-E
              MULTIPLICATION.PRODUCT APPROXIMATELY PROPORTIONAL
              TO M*(Z**2).M=PARTICLE MASS.Z=PARTICLE CHARGE.
           COUNTING RATE.0.3/MIN. DATA GIVEN REPRESENT 30 RUNS OF
           4-HR EACH.
COMMENT    THE NEUTRON-NEUTRON SCATTERING LENGTH HAS BEEN DERIVED
           AND COMPARED WITH THEORY.
STATUS     (PRIV) NUMERICAL DATA FROM R.FOX. LETTER OF 720323.
                  GRAPH IN NUCL.PHYS.A178,321(1971),FIG.5.
HISTORY    (720410C)

COMMON
EN         EN-RSL
MEV        MEV
13.94      0.22


SUBENT          30148002
BIB
ISO-QUANT  (1-T-3,N2N,DA/DE,REL,D)
STANDARD   (OTHER) DATA ARE RELATIVE NUMBER OF COUNTS AS FUNCTION
           OF DEUTERON ENERGY. ARBITRARY NORMALIZATION
PART-DET   (D) DEUTERONS
EN-SEC      (ANG) AND (ANG-RSL). DEUTERONS EMERGING AT 2.+-2. DEG
               WERE DETECTED.
            (E-RSL) DEUTERON ENERGY RESOLUTION FUNCTION GIVEN IN
               NUCL.PHYS.A178,321(1971),FIG.1. FWHM,485. KEV.
            (E-ERR) CALIBRATION ACCURACY,+-20.KEV.
ERR-ANALYS DATA ERROR IS STATISTICAL ONLY.

COMMON
ANG        ANG-RSL    E-RSL      E-ERR
ADEG       ADEG       KEV        KEV
2.         2.         485.       20.

DATA
E          DATA       DATA-ERR
MEV        ARB-UNITS  ARB-UNITS
6.16        58.        7.5
6.26        61.        8.
6.36        51.        7.
6.46        67.        7.5
6.55        70.        9.
6.65        74.        9.
6.74        86.        9.5
6.84        89.        9.5
6.93        90.        9.5
7.03        93.        9.5
7.13       107.       10.5
7.22       103.       10.
7.32       107.       10.5
7.42        90.        9.5
7.52        86.        9.
7.61        75.        9.
```

(Example only. The data table is incomplete.)

Explanations to Figure 6

Some notes on EXFOR

EXFOR is a computerized system of codes and formats used for the exchange of experimental neutron nuclear data between the Four Neutron Data Centres named on page vi. Each regional centre, having different computer facilities and user needs, operates its own internal storage-and-retrieval system (e.g. CSISRS, NEUDADA) optimized for its needs and facilities. EXFOR is compatible with these centre-internal systems so that all data compiled at one centre are easily transmitted, through EXFOR, into the internal systems of the other centres thus becoming available to users all over the world.

On the opposite page a sample of an EXFOR-entry is given for illustration. EXFOR is based, among others, on the following basic principles:

1. A numerical data table cannot be meaningful without a minimum of supplementary information on standard cross-sections used, measurement method, error analysis, origin of the data, and others.

This supplementary information can be found under a set of keywords such as AUTHOR, N-SOURCE, DETECTOR, METHOD, ERR-ANALYS and so on. Some information is given in coded form and is thus computer-retrievable. For example, the code (3ISLHFA) given under the keyword INSTITUTE means: 3 = responsible data centre is the IAEA Nuclear Data Section; ISL = country of origin is Israel; HFA = data were measured at the Technion, Haifa. In an output format such codes can be expanded to a readable text.

2. The results of an experiment given in one ENTRY may consist of several data tables given in separate SUBENTries. Each ENTRY or SUBENTry is identified by an International Neutron Data Accession (INDA-) number.

The present EXFOR entry has the accession-number INDA*30148 and is so indexed on page 7 of this catalogue. Its first SUBENTry (30148.001) gives information which is valid for the entire experiment, whereas the second SUBENTry (30148.002) gives a specific data table resulting from this experiment, and its definitions.

3. A SUBENTry may consist of three parts: text-information ("BIB"), parameters that are constant ("COMMON") throughout the data table, and the data-table itself ("DATA").

The format of the data-table is flexible, and the meaning and units of the columns are defined in their headings. The second column which is headed DATA/ARB-UNITS is defined above under ISO-QUANT (= isotope and quantity). In the present case the isotope considered is tritium and the quantity is: relative ("REL") double-differential ("DA/DE") cross-section for the T(n,2n)D reaction ("N2N"), and the term 'differential' is meant with respect to the resulting deuterons ("D"). The first column in the data-table (headed E/MEV) gives the deuteron-energy as explained in the text above. The incident neutron-energy EN and its resolution are given under "COMMON" in the first SUBENTry.

4. As with a conventional publication the author receives a proof-copy of the EXFOR entry.

When the author approves the EXFOR entry, this will be entered under the keyword STATUS. The present entry is so new that the approval was not yet received. However, it is said under STATUS that the numerical data had been received from one of the authors and that these data correspond to a published graph; compare above under REFERENCE. If the author regards his data as preliminary (or after some years as superseded), a note to this effect will be entered under STATUS. If the author submits corrections, the revised EXFOR entry will be sent to everyone to whom the IAEA Nuclear Data Section had sent the uncorrected version of the entry.

Figure 7

RENDA 72 Sample page

```
96                                                      RENDA 1972

 REQ  NUCLIDE  QUANTITY     ENERGY(EV) ACCURACY P  LAB  REQUESTER , COMMENTS                                   YEAR
[REG]                        MIN   MAX    (%)

1095  238U     N,GAMMA      5.0+2 1.0+7  <10    1  AI   Alter, H.                                               69
[2036 ]                                 2 TO 10%   ANL  Avery, R.
                                        see        GE   Snyder, T.
                                        comment.   ANL  Hennig, P.B.
                                                        Highest priority need for fast reactor calculation.
                                                        Accuracy 3% from 500 eV to 1keV.
                                                        Accuracy 2% from 1-300 keV.
                                                        Accuracy 3% from 300-500 keV.
                                                        Accuracy 10% from 500 keV to 10 MeV.
                                                        Accuracies of 10% from 1-300 keV and 20% from 0.3 to
                                                   ___  10 MeV would be useful.
                                                        Status: see REG 865 above.

1096  238U     N,GAMMA      5.0+2 1.0+6    3    1  CAD  Barre, J-Y.                                             69
[1484 ]                                  1% 10 to       For fast reactor calculations.
                                          400keV        Absolute values useful but request concerns mainly
                                                        relative values versus energy or relative values to
                                                        235U (accuracy 1% on this ratio).
                                                   SAC  Reuss, P.                                               70
                                                        Relative to sigma (n,g) (0.0253eV) .
                                                        Evaluation may suffice if it explains discrepancies.
                                                   ___  For calculations of Keff.
                                                        Status: see REG 865 above.

1097  238U     N,GAMMA      5.0+2 1.4+6    3.0  1  FEI  Nikolaev, M.N.                                          71
[2530+]        see comment                              For accuracies of 1.0 % in Keff and 1.6 % in BR  for
                                                        fast breeders.
                                                        Between 1 and 100 keV information on resonance self-
                                                        shielding factors (see book by Abagyan et al., Con-
                                                        sultants Bureau, New York,1964) with 2% accuracy
                                                        and averaged over 0.2 lethargy intervals desired.
                                                        Ratios of capture CS of U238 to fission CS of U235
                                                        wanted. For selfshielding evaluation transmission
                                                        measurements requested with flat response and cap-
                                                        ture detectors and with attenuations of primary beam
                                                        down to 1 and 0.1%. Experiments wanted at different
                                                        temperatures from 70 to 2500°K.  Temperature diffe-
                                                        rences of selfshielding factors must be known with
                                                   ___  7% accuracy.
                                                   ANL  Davey, NSE 39(1970),337, reviews status before HEL-
                                                        SINKI conference above resonance range. Several
                                                        relevant papers at HELS. conf. (CN-26/18, 43,77, 78,
                                                        111).
                                                   COL  Arbo et al. plan low keV  TOF measurement
                                                        (EANDC(US)-143U, P.50).
                                                   HAR  Moxon (AERE-R 6074) estimates accuracy of data bet-
                                                        ween 0.5 and 100 keV to 3-7%.
                                                   ORL  De Saussure et al., capture work in progress.
                                                   NPL  Ryves et al. plan activation meas. 120-600 keV.
                                                   KFK  Froehner et al. plan meas. rel. to (n,p),100-500keV.
                                                   IAE  Konshin, evaluation in progress.

1098  238U     N,GAMMA      1.0+3 1.0+6  < 5    1  JAE  Japanese Nuclear Data Committee (JNDC) .                70
[2312+]                                                 For fast reactor calculations.
                                                        Poenitz: NSE 40 383 (1970).
                                                        Menlove, Poenitz: NSE 33 24 (1968).
                                                        Moxon: AERE-R 6074 (1969).
                                                        Barry et al.: JNE A/B 18 481 (1964).

1099  238U     N,GAMMA      1.0+3 1.0+6  < 5.0  1  JAE  Japanese Nuclear Data Committee (JNDC).                70
[2209+]                                            ___  For fast reactor calculations.
                                                        Poenitz: NSE 40 383 (1970).
                                                        Menlove and Poenitz: NSE 33 24 (1968).
                                                        Moxon: AERE-R 6074 (1969).
                                                        Barry et al.: JNE A/B 18 481 (1964).

1100  238U     N,GAMMA      2. +3 2. +6    3    1  WIN  Campbell, C.G.
[ 8670]                                  (N-2E)         For fast reactors.
                                                   ___  Note changed energy range.
                                                   HAR  Moxon: data available below 100 keV.
                                                   NPL  Axton: activation measur. in progress.
                                                   HAR  Coates: scint. tank measur. in progress.
                                                        Evaluation shows that acc. requirement not met.
                                                        Status: see REG 865 above.
```

Figure 8

Accuracy requirements (R) versus achievements (A) for fast reactor design parameters

K_{eff} (± %)		BR(±), ICR(±)		T_d(± %)		Fissile Pu inventory (± %)		DC ± %	
R	A	R	A	R	A	R	A	R	A
1	$\gtrsim 1$	0.02	0.10	10	~30-60	3	$\lesssim 8$	5-10	20-30

Total loss of Na coolant (± $)		Reactivity worth of control rods (± %)		Burnup (± %)		Fuel cost $\left(\frac{\text{mills}}{\text{Kwh}}\right)$	
R	A	R	A	R	A	R	A
2.0	$\lesssim 1.5$	≤ 10	30	≥ 2.5	≥ 4	0.03	~0.15

ICR = internal (core) conversion ratio
T_d = doubling time
DC = Doppler Coefficient
1 $ ≅ 1.4 % $\Delta K/K$

Figure 9.

Accuracy requirements versus confidence levels achieved for neutron nuclear data (fast)

Isotope	Quantity	Accuracy requirements (±%) 1961 [87]	1962 [88]	1963 [89]	1964 [90]	1965 [91]	1968 [92]	1970 [3]	1972 [4]	1975 [40]	(± %) Confidence levels achieved. 1966 [12]	1968 [51,80]	1970 [16,41,46,47,96]	1971 [15-1?]	Acc.ies achd. in indiv. exp. ≤ 1970 [12,15-18, 81,93-97]
Pu-239	σ_f	10	3	3	2	2	2	2	2.5	2	15;5	15; 10	10	4-6	≳ 3
	α	5	4	5	4	4	5	4	7	5	15;10	≳ +50;-20; 20	10-30	10-30	10-20
	$\bar{\nu}$	–	1.0	1.0	<1.0	1.0	1.0	1.0	0.5	0.5	3	2	2	2	0.5-1.0
U-238	σ_γ	–	2	3	3	4	[illegible]	2.5	3	2	25;10	20;10-15	10	–	8-10
	σ_f	–	2	2	2	2	3	4	3	3	5-10	≳ 5	6	–	5
	$\sigma_{n'}$	10	10	7	8	6	7	8	7	5	15-20	15	20	–	10-20
	$\bar{\nu}$	–	4	4	0.5	0.5	0.5	2.0	1.2	–	2	2	–	3	1
Pu-240	σ_f	–	8	8	10	10	≥5	3	3	10	–	≲ 20	20	–	10
	σ_γ	10	10	10	10	10	10	10	8	10	–	~ 30	30 - [illegible]	–	10
	$\bar{\nu}$	5	5	5	4	5	4	4	3	–	–	–	4	3-5	2-5
Pu-241	σ_f	20	20	20	5	5	6	5	7	10	–	25	20	–	3
	α	10	10	10	10	15	10	20	15	–	–	–	100	–	–
	$\bar{\nu}$	–	5	–	5	5	4	4	2.5	–	–	–	5	3-5	3-4
Fiss. Prod.	σ_γ	–	–	–	–	–	–	–	15	10	–	–	40	–	–
Cr	σ_γ	–	20	20	30	30	20	20	17	10	20		30	–	5-10
Fe	σ_γ	–	15	15	10	10	10	10	10	10	≲ 20	+50 -30	30	–	5-10
Ni	σ_γ	–	20	20	30	25	20	13	10	10	≲ 10		30	–	5 - 10

Pu-239: σ_f: 1-100 keV ±15 %
σ_f: 0.1 - 1 MeV " 5 "
σ_γ: 1 - 100 keV " 15 "

Figure 10

Summary of RENDA 72 requests for important fast reactor neutron data

Isotope	Quantity	Energy range	Accuracy range (±%)	Average acc.y (±%)	No. of requ.g countries	No. of requests	Average priority
Pu-239	σ_f	100 eV - 15 MeV	1 - 5 (1 request: 10)	2.5 (3.0)	8 (incl. IAEA)	16	1.2
	α	100 eV - 10 MeV	3 - 10	7	6	7	1.7
	σ_γ	100 eV - 4 MeV	3 - 10	5.5	6	8	1.2
	$\bar{\nu}$	therm. - 15 MeV	0.1 - 1.0	0.5	6	7	1.3
U-238	σ_γ	500 eV - 14 MeV	1 - 10	3	8	9	1.2
	σ_f	thresh. - 20 MeV	1 - 5	3	7	8	1.3
	$\sigma_{n'}$	thresh. - 15 MeV	5 - 10	7	8	12	1.6
	$\bar{\nu}$	thresh. - 14 MeV	0.7 - 2	1.2	3	3	1.3
Pu-240	σ_f	100 eV - 15 MeV	2 - 5	3	4	6	1.5
	σ_γ	100 eV - 10 MeV	5 - 10 (1 request: 20)	8 (10)	6	8	1.4
	$\bar{\nu}$	"thresh." - 15 MeV	1 - 5	3	6	6	1.7

Figure 10, continued

Jsotope	Quantity	Energy range	Accuracy range (± %)	Average acc.y (± %)	No. of requ.g countries	No. of requests	Average priority
Pu-241	σ_f	100eV-15 MeV	3 - 10	7	4	4	1.5
	α	100eV - 2 MeV	10 - 20	15	4	4	2.3
	σ_γ	100eV - 10 MeV	3 - 10 (1 request: 20)	8 (10)	5	5	1.6
	$\overline{\nu}$	therm. - 14 MeV	1 - 5	2.5	4	4	1.8
Fiss. prod.	σ_γ	100eV - 1MeV	10 - 20	15	3	3	1.7
Cr	σ_γ	"	10 - 25	17	4	5	1.4
Fe	σ_γ	"	10	10	6	6	1.2
Ni	σ_γ	"	10 (1 request: 20)	10 (12)	4	6	1.3

Figure 11

Energy breakdown of RENDA 72 requests

11a. σ_f (Pu-239)

Energy range	Accuracy range (± %)	Average acc.y (± %)	No. of requ.g countries	No. of requests	Average priority	[16] Present confidence level (± %)
100 eV - 10 keV	1 - 5 (1 request: 10)	2.9 (3.5)	7 (incl. IAEA)	11	1.0	6
10 - 100 keV	1 - 5	2.6	"	13	1.1	~ 5
100 keV - 1 MeV	1 - 5	2.2	"	13	1.2	~ 5
1 - 5 MeV	1 - 5	2.9	"	13	1.2	8 - 10
> 5 MeV	1 - 5	3.6	4 (incl. IAEA)	8	1.1	8 - 10

Figure 11 continued

11 b. α or σ_γ (Pu-239)

Energy range	Accuracy range (± %)	Average acc.y (± %)	No. of requ.g countries	No. of requests	Average priority	[15] Present confidence level (± %)
100 eV – 10 KeV	· 3 – 10	6	12	15	1.5	10
10 – 100 KeV	3 – 10	5.5	12	14	1.5	15
100 KeV – 1 MeV	5 – 10	7	7	9	1.3	20
> 1 MeV	5 – 10	8	4	6	1.3	—

11 c. σ_γ (U-238)

0.5 – 10 keV	2 – 5	3	8	8	1.3	
10 – 100 KeV	1 – 3	2.3	8	9	1.2	
100 KeV – 1 MeV	2 – 5	3	7	8	1.1	
> 1 MeV	3 – 10	6	3	4	1.0	

Figure 12

Accuracy requirements versus confidence levels achieved for standard reference data

Isotope	Quantity	Energy range	Accuracies required (± %) 1968 [78]	1970 [3]	1972 [4]	Confidence levels achieved (± %) 1966 [12]	1970 [68,71]	1970 [38,46,101-108]	1972 [70]
H-1	σ_T	0.1 - 20 MeV	–	–	–	≤ 1	–	0.5 - 1.0	1
He-3	σ_p	thermal	–	–	–	–	0.2	–	–
		< 10 KeV	–	–	–	2	1 - 3	–	~ 3
		10 - 100 KeV	–	–	–	≳ 2	–	–	~ 5
		100 - 500 KeV	–	–	–	15	10	–	–
		> 500 KeV	–	–	–	10	10	–	–
		1 - 5 MeV	2	–	–	–	–	–	–
		all energies	–	1 - 3	1 - 10 (av.: 4)	–	–	3 - 10	–
Li-6	σ_α	thermal	–	–	–	–	0.5	–	0.5
		< 10 KeV	–	–	–	–	1	–	1 - 2
		10 - 100 KeV	–	–	–	–	2 (theory) 8 (exp.)	–	~ 3
		100 KeV - 1.7 MeV	–	–	–	–	5 - 15	–	–
		> 1.7 MeV	–	–	–	–	–	~ 20	–
		all energies	2	1 - 5	1 - 10 (av.: 4)	–	–	5 - 10	–
B-10	σ_α	thermal	–	–	–	–	0.5	–	–
		< 10 KeV	–	–	–	–	1 - 2	–	≳ 1
		10 - 100 KeV	–	–	–	–	2 - 3	–	2 - 3
		100 - 200 KeV	–	–	–	–	3 - 5	–	–
		all energies	2	1 - 5	1 - 10 (av.: 4)	–	–	3 - 10	–

Figure 12 continued

Isotope	Quantity	Energy range	Accuracies required (± %) 1968 [78]	1970 [3]	1972 [4]	Confidence levels achieved (± %) 1966 [12]	1970 [68,71]	1970 [38,46,101-103]	1972 [70]
C-12	σ_T	eV range	–	–	–		0.5	–	
		eV - 0.5 MeV	–	–	–	5-10	1-2	–	1
		0.5 - 2.0 MeV	–	–	–		1	–	
Au-197	σ_γ	10 - 500 KeV	–	–	–	–	–	–	8
		10 KeV - 3 MeV	–	1-5 (most)	–	–	–	5 - 18	–
		100 eV - 3 MeV	5	–	–	–	–	–	–
		thermal - 7 MeV	–	–	1-10 (av.: 5)	–	–	–	–
U-235	σ_f	thermal	–	–	–	2	1	–	–
		< 1 KeV				–	3	–	–
		1 - 30 KeV				5 - 6	6 - 8		
		30 - 400 KeV			1-5	+7; -3	5	≦ 10	5 - 10
		0.4 - 1.5 MeV	3	1-3	(av.: 2.5)	5 - 10	+4; -7		
		> 1.5 MeV				5 - 10	7	5 - 10	
Cf-252	$\bar{\nu}_{spont}$	–		0.25-0.5	0.1 - 0.5 (av.: 0.4)	1969 [72] Hanna et al. 3.765 ± 0.010		≳ 1	3.73 ± 0.5 % [17,73]