NEANDC-274-U

SUMMARY REPORT OF THE NEANDC WORKING GROUP ON INTENSE NEUTRON SOURCES FOR NEUTRON PHYSICS AND NUCLEAR DATA MEASUREMENTS

September 1990

Edited by
S. Cierjacks (Chairman)
Kernforschungszentrum Karlsruhe
Institut für Material- und Festkörperforschung
Federal Republic of Germany

NOTE

This is the approved version of the Report NEANDC-174-A (December 1989) which was restricted for distribution to NEANDC Committee and NEANDC Working Group Members only. The present version of the Report includes final updatings of source specifications or design goals which have been significantly altered since 1989.

LEGAL NOTICE

C O N T E N T S

SUMMARY REPORT OF THE NEANDC WORKING GROUP ON INTENSE NEUTRON SOURCES FOR NEUTRON PHYSICS AND NUCLEAR DATA MEASUREMENTS

Edited by
S. Cierjacks (Chairman)
Kernforschungszentrum Karlsruhe
Institut für Material- und Festkörperforschung
Federal Republic of Germany

Working Group Members and Liaison Persons:

K.H. Böckhoff, CEC Geel; S. Cierjacks (Chair), FRG; H. Conde, Sweden; D.A. Gray, UK; J.A. Harvey, USA; S. Igarasi, Jpn; S. Katcoff, USA; A.J. Leadbetter, UK; P.W. Lisowski, USA; R.M. Moon, USA; L. Nilsson, Sweden; R.W. Peelle, USA; H. Sasaki, Jpn; A.B. Smith, USA; M.G. Sowerby, UK; S. Tanaka, Jpn; T. Ward, USA; N. Watanabe, Jpn; C.D. West, USA; S.L. Whetstone, USA; R.M. White, USA; and P.G. Young, USA.

Additional Ad-hoc Members during the 26th and 27th NEANDC Meetings:

C. Coceva, Italy; W. Cross, Canada; E. Fort, France; A. Michaudon, France; C. Nordborg, NEA; S.M. Qaim, FRG; F.G.J. Perey, USA; and H. Vonach, Austria.

1. INTRODUCTION

The neutron-physics and nuclear-data community has, over several decades, efficiently provided state-of-the-art experimental- and theoretical-determined neutron-nuclear data which were needed in various scientific disciplines extending from engineering applications to the most fundamental investigations. This service to a wide variety of different users has for a long time been coordinated and organized on an international and a world-wide basis by the two Nuclear Data Committees, the NEANDC of OECD's Nuclear Energy Agency (Paris) and the INDC of IAEA's Nuclear Data Section (Vienna). Presently, this community offers one of the best international-organized services to various research programs like those relevant to fission and fusion reactor technologies, radiotherapy, astrophysics research, cosmogenic and meteoritic investigations, high-energy accelerator technology, etc.

In the provision of up-to-date neutron-nuclear data, neutron sources play an important and indispensable role. In order to provide all required differential data, modern sources must cover the total neutron energy range extending from subthermal to more than 500

MeV. The measurement of well-resolved total and differential cross sections in this range requires sources, operating in the time domain from steady state to picosecond pulsing. Being aware that the steadily increasing needs of complex nuclear data require a continuous consideration of available sources and experimental equipment, the Nuclear Data Committees have routinely reviewed the main trends in technological developments relevant to possible improvements or replacements of existing facilities.

In this context, the NEANDC discussed at its 25th Meeting in 1985 (Paris/Grenoble), recent developments in this field. Especially, the new spallation neutron sources, which had primarily been built, planned, or studied for use in condensed matter research were considered. These seemed to have important future potential for largely increased neutron intensities over the entire energy range from (sub)thermal to ~500 MeV. Therefore, the NEANDC decided to set up a Working Group on Neutron Sources with the task of investigating the source capabilities in more detail. In order to broaden the expertise available in the Committee, the Group was advised to seek additional assistance from accelerator and source experts, more closely related to relevant programs in the OECD service area. This report primarily covers the situation in the years 1986 and 1987. Final updatings of source specifications were made after the 27th NEANDC Meeting (Los Alamos) at the end of 1988.

2. TERMS OF REFERENCE

At its 25th Meeting the NEANDC defined the following tasks for the Working Group on Intense Neutron Sources:

- Compile information on intense sources recently put into operation as well as on more advanced projects under construction or under study.

- Assess the potential use of these sources for neutron physics and nuclear data measurements and make a detailed comparison of their "quality" with those of neutron sources actually used for such purposes.

- Find out whether these sources can actually be used with or without modification for neutron physics and nuclear data measurements.

- Define what should be an (the) ideal neutron source(s) for neutron physics and nuclear data measurements.

Even though the initial discussion at the 25th Meeting was primarily on new spallation neutron sources, the Group felt that there was also some development in the field of special monoenergetic sources, and of some user-oriented high-flux reactors, which deserved attention. Since these were, however, sources for limited energy regions, they were considered in the compilation of information and the assessment of their use for neutron physics and nuclear data measurement only.

Furthermore, it was felt that the task of defining an (the) "ideal" source(s) for neutron-physics and nuclear-data measurements was formulated in a to ambitious manner in this generality. Therefore, this question was tackled in a more modest way.

3. METHOD OF WORK

According to the mandate from NEANDC, work was started by the end of 1985 to set up a Working Group and, at the same time, to compile information on intense new, projected, studied and hitherto-used intense neutron sources. In order to start work rapidly from scratch, the chairman prepared the necessary questionnaires to facilitate uniform and complete coverage of specifications for the mentioned types of sources. These were sent out in January 1986 to all NEANDC members working close to those laboratories that were involved in important activities. These members were then invited to either serve themselves as group members or to nominate other colleagues from their countries, who were more directly involved in the operation, design, planning, and use of such sources. To familiarize scientists outside of NEANDC with the objectives of the Committee, a General Information Sheet was also prepared which went out together with the letter to NEANDC members. The questionnaires, their accompanying letters and the General Information Sheet are attached in Appendices I-III.

In a second step, the action was complemented by approaching those colleagues who had been nominated by NEANDC members as either additional Working Group members or liaison persons. This action added important additional information to that received after the first call. The Working Group met again in 1987 during the 26th NEANDC Meeting in Rome, with a majority of Group Members present. After receipt of most of the information on new/improved and hitherto used sources, the Group discussed the various aspects of the potential use and the availability of these sources. Clarifications of final problems and open questions were left to discussions between individual experts, and the outcome was communicated by correspondence.

In performing this work, the Group made a few restrictions which were as follows:

- The discussion of the potential and the availibility of new sources concentrated mainly on that for intense spallation sources, since these seemed to be the most promising ones for potential use over a wide energy range.

- A detailed comparison of the "quality" of new sources with that of sources hitherto used in our field was only performed for the accelerator-based continuous-spectrum ('white') pulsed sources. More detailed comparisons of the other sources have been made elsewhere (Moo86, CS88).

- The NEANDC investigation on Neutron Sources was, on purpose, restricted to the OECD service area. Therefore, it excludes sources from Russia, the East-European countries, China etc.

4. COMPILED INFORMATION

4.1 New or Upgraded Sources and Advanced Projects or Studies

Following the procedure described above, the Group received information on twenty sources recently upgraded, put into operation, being under construction or being (have been) under study. Separating them according to the three main types of sources, the information belongs to:
The thirteen **spallation neutron sources**

IPNS, ANL, Argonne, USA
ISIS, RAL, Culham, UK
KENS, KEK, Tsukuba, Japan
LANSCE, LANL, Los Alamos, USA
WNR, LANL, Los Alamos, USA
MEIN, BNL, Brookhaven, USA
TTNF, TRIUMF, Vancouver, Canada
SINQ, SIN, Villigen, Switzerland
SNQ, KFA, Jülich, FRG
LIRIC, ORNL, Oak Ridge, USA
TKF, TRIUMF, Vancouver, Canada
GEMINI, KEK, Tsukuba, Japan
ASPUN, ANL, Argonne, USA

From these the first seven were operational at the end of 1988. Specifications collected for all above sources are given in Table I. For the sake of a uniform coverage of source specifications, all stated neutron intensities were commonly normalized to the measured numbers of neutrons per proton given by Fraser and Bartholomew (FB83).
The four special-purpose **monoenergetic sources**

IBF, LANL, Los Alamos, USA
PNS, TSL, Uppsala, Sweden
PIENF, BNL, Brookhaven, USA
LL Van-de-Graaff, LLNL, Livermore, USA

Except for the IBF source, none of the other three sources was in operation by the end of 1988. The LL Van-de-Graff facility has even not yet been envisaged for use as a neutron source. But with a hydrogen target similar as that of the IBF source, this facility with its

TABLE I. Specifications of Spallation Neutron Sources (Operating, Under Construction or Under Study)

Source, Laboratory, Country	Proton Energy (MeV)	Target, (Target Option)	Acc.Pulse Width (ns)	Rep. Rate (Hz)	Peak Current (mA)	Avg. Current (mA)	Fast [1] Neutr. Prod.Rate in Pulse (n_f/s)	Avg. Fast [1] Neutron Prod.Rate (n_f/s)	Status End 1988	Group Reporter, (Ref.)
IPNS, ANL, USA	500	U ^{235}U a)	100 100	30 30	5,000 5,000	0.015 0.015	5.6×10^{20} 1.7×10^{21}	1.7×10^{15} 5.1×10^{15}	operating, und. constr.	Smith 87, (Bro + 88)
ISIS, RAL, UK	800	U	100 b)	50	10,000	0.200 [2]	1.9×10^{21} b)	3.7×10^{16}	operating	Gray 86, (FG88)
KENS, KEK, Jpn	500	W,(U)	50	20	10,000	0.010 [3]	5.6×10^{20}	5.6×10^{14}	operating	Watanabe 88, (Wat88)
LANSCE, LANL, USA	800	W,(U)	270	12	31,000	0.100 [4]	2.9×10^{21}	9.3×10^{15}	operating	Lisowski 87, (Pyn88)
WNR Source c) LANL, USA	800	W	0.3 0.3	5.8×10^{4} 5.8×10^{4}	23 340	0.0004 0.006	2.2×10^{18} 3.2×10^{19}	3.8×10^{13} 5.6×10^{14}	operating, planned	Lisowski 86, (Bow87)
MEIN, BNL, USA	200	U	0.5 4.5×10^{5}	1×10^{5} 5	380 40	0.00005 0.090	9.6×10^{18} 1.0×10^{18}	1.3×10^{12} 2.3×10^{15}	operating	Ward 86, (War + 88)
TTNF, Can.	520	Pb	-	cw	-	0.135	-	6.2×10^{15}	operating	Cross 86, (Tho + 84)
SINQ, PSI, CH	590	Pb-Bi	-	cw	-	2.0	-	1.1×10^{17}	und. constr.	(Fis88)
SNQ, KFA, FRG	1,100	Pb,(U)	700	100	61,400	4.3	8.8×10^{21}	6.2×10^{17}	study, aborted 86	Cierjacks 86, (Bau + 81)
LIRIC, ORNL, USA	250	Ta	1 400	5,000 120	9,600 1,600	0.048 0.075	1.4×10^{20} 2.3×10^{19}	6.9×10^{14} 1.1×10^{15}	study, aborted 87	Peelle 86, (OMH86)
TKF, TRIUMF, Can.	3,500 3,000	unspecif.	220 320	1×10^{4} 9	45 35,000	0.100 0.100	1.7×10^{19} d) 1.3×10^{22} d)	3.7×10^{17} d) 3.7×10^{17} d)	study	Cross 86, (Bla84)
GEMINI, KEK, Jpn	800	U,(W)	200	50	50,000	0.500 e)	9.4×10^{21}	9.4×10^{16}	study	Watanabe 86, (GEM87)
ASPUN, ANL, USA	1,100 1,500	unspecif.	136 150 f)	220 50	117,000 128,000 f)	3.5 4.8	3.1×10^{22} d) 4.6×10^{22} d,f)	9.4×10^{17} d) 1.7×10^{18} d)	study, modif. study	(KK84) (Kus88)

[1] Fast neutrons before moderation; [2] End of 1988 100 μA realized; [3] End of 1988 5 μA realized; [4] End of 1988 30 μA realized; a) New ANL booster target; b) Values for one of two successive pulses in 400 ns; c) Target-4 source; d) Assuming a U target; e) Only half of the current to be used for condensed matter work; f) Values for one of five succesive pulses in 1.5 μs.

intense triton beam capability could, in principle, be also used as a very attractive $^{1}H(t,n)^{3}He$ source for the energy range between ~ 6-14 MeV. Achieved or estimated source specifications are given in Table II.
The three **high-flux reactor sources**

HFR, ILL, Grenoble, France
ANS, ORNL, Oak Ridge, USA
FRM, TUM, Munich, FRG

While for the first source a considerable upgrading had been finalized in 1987, the other two ones refer to contemporary projects of new fission research reactors. The main specifications of these sources are given in Table III. A more broadened survey of research reactor concepts considered before 1985 can be found in a survey article of Moon (Moo86).

4.2 Hitherto Used Pulsed 'White' Neutron Sources

Due to the primary task of the Group to compare spallation neutron sources with sources hitherto used in our field, information was compiled for the major white neutron sources which represent the most flexible ones, in that they can cover a wide energy range of the total required region from (sub)thermal to ~500 MeV. Such sources are chiefly electron-linac-based ones which can continuously cover the range from thermal (with cryogenic moderators from subthermal) to more than 20 MeV. Two other efficient sources for energies above ~300 keV or ~3 MeV, respectively, are the KfK-cyclotron and the WNR sources which deserve particular attention due to their sub-nanosecond burst characteristics. Updates for such sources have been requested, and were received for the following nine facilities:

GELINA, Geel, Belgium
HELIOS, Harwell, UK
ORELA, Oak Ridge, USA
JAERI Linac, Tokai, Japan
WNR, Los Alamos, USA
LLNL Linac, Livermore, USA
NBS Linac, Washington D.C., USA
RPI Linac, Troy, USA
KfK Cyclotron, Karlsruhe, FRG

While, in the past, all of these sources have been extensively used for neutron physics and neutron-nuclear data work, by the end of 1988 only the first five of these were still in essential use for this purpose. Updated information for all sources is summarized in Table IV.

TABLE II. Specifications of Some Special-Purpose High-Eenergy Monoenergetic Neutron Sources

Source, Name, Laboratory	Type of Particles	Acceler. Energy (MeV)	Neutron Energy (MeV	Target	Target Thickness (g/cm^2)	Avg. Current (μA)	0° Neutron Yield (n/sr-s)	Status End 1988	Group Reporter, (Ref.)
IBF, LANL, US	tritons	0.1-25	6-17 8 12	^1H	$3.9x10^{-3}$	20 [1]	$1.7x10^{10}$ $1.3x10^{10}$	operating	Young 87, (Hai88)
PIENF, BNL, USA	protons	93-200	93-200	^7Li	0.21	10-50	$2.5x10^{10}$ - $7.5x10^{10}$	under construction	Ward 86, (War + 88)
PNS, TSL, Swe	protons	50-185	50-185 100 185	^7Li	0.10 0.17	10	$1.7x10^{10}$ $3.2x10^{10}$	under construction	Conde 87, (TSL87)
LL VdG, * LLNL, US	tritons	2-20	(6-14) (8) (12)	(^1H)	($3.9x10^{-3}$)	20	($1.7x10^{10}$) ($1.3x10^{10}$)	t-beam capability available	White87

[1] End of 1988 10 μA realized; * Not yet available as neutron source; all numbers in parentheses for the assumption that an IBF type of target were used.

TABLE III. Specifications of Some Upgraded/Planned User-Oriented High-Flux Reactors

Source, Laboratory, Country	Reactor Power (MW)	Max.Pow. Density (MW/dm^3)	Fuel, Moderat., Reflect.	Thermal Peak Flux ($cm^{-2} s^{-1}$)	Numb. of Beam Tubes	Numb. of Neutron Guides	Number of Hot-Cold Sources	Numb. of Instrum.	Concept, Status End 1988	Group Reporter, (Ref.)
HFR, ILL, France	57	1.3	^{235}U, D_2O, D_2O	$1.2x10^{15}$	17	11	1 2	69	reactor upgrade, completed 87	Michaudon 87, (ILL86)
ANS, ORNL, USA	350	5.2	^{235}U, D_2O, D_2O	$8\text{-}10x10^{15}$	13	16	1 2	50	new reactor concept, pursued	Peelle 86, (Dif+86)
FRM, TUM, FRG	20	1.9	^{235}U, D_2O, D_2O	$7x10^{14}$	13 a)	13 a)	1 2	unspecif.	new reactor concept, pursued	(Boe86), (TUM87)

a) Arbitrary at present stage of development

TABLE IV. Accelerator-based Pulsed White Neutron Sources (Updated Information on Hitherto Used Facilities)

Source, Laboratory, Country/Instit.	Type of Particles	Target	Part. Energy (MeV)	Pulse Width (ns)	Peak Current (mA)	Maxim. p.r.f. (Hz)	Neutron Prod. Rate in Pulse (n/s)	Flight Path Length (m)	Best Nominal Resolut. (ns/m)	Group Reporter, (Ref.)
GELINA CBNM, CEC	electrons	U	100 120 100	0.67 4 2,000	>100,000 10,000 220	900 900 215	$3.7x10^{19}$ $4.5x10^{18}$ $1.0x10^{17}$	8-400	.0017	Böckhoff 86, (TSB85)
HELIOS AERE, UK	electrons	U ^{235}U a) U	94 128 60	5 100 5,000	6,000 1,000 1,000	2,000 390 300	$2.2x10^{18}$ $7.6x10^{18}$ $2.4x10^{17}$	4-300	.0167	Sowerby 86, (Lyn80)
ORELA ORNL, USA	electrons	Ta	160 140 140	3 40 1,000	25,000 10,000 500	1,000 1,000 1,000	$7x10^{18}$ $2.5x10^{18}$ $1.2x10^{17}$	10-200	.0150	Peelle 86, Harvey 87
Linac * LLNL, USA	electrons	Ta	115 100	5 3,000	10,000 350	1,140 360	$2.3x10^{18}$ $6.0x10^{16}$	7-250	.0200	White 87
Ab.-Gr. Linac * NBS, USA	electrons	Ta	120 100	5 1,000	4,000 300	720 200	$1x10^{18}$ $6x10^{16}$	20-200	.0250	Carlson 88
Linac * RPI, USA	electrons	Ta	80 45	10 4,500	1,000 900	720 360	$1.6x10^{17}$ $8x10^{16}$	10-250	.0400	(Blo88)
Linac JAERI, Jpn.	electrons	Ta	120 120	10 2,000	6,000 600	600 600	$1.4x10^{18}$ $1.4x10^{17}$	20-190	.0526	Igarasi 86, Tanaka 88
Cycl. Source ** KfK, FRG	deuterons	U	50 50	0.8 0.8	1,500 150	$2x10^{4}$ $2x10^{5}$	$1.2x10^{18}$ b) $1.2x10^{17}$ b)	12-190	.0042	Cierjacks 86, (Cie83)
WNR Source c) LANL, USA	protons	W	800 800	0.3 0.3	23 d) 344 f)	$5.8x10^{4}$ $5.8x10^{4}$	$2.2x10^{18}$ d) $3.2x10^{19}$ f)	4-(250)	.0020 e)	L isowski 86, (Bow87)

a) Harwell booster target; b) 0°-differential yield (n/sr-s); c) Short pulse (Target 4) source; d) Existing source; e) Assuming a detector limitation of 0.5 ns; f) Planned upgrade; * Since several years only scarcely used; ** Shut down in 1988.

5. POTENTIAL AND/OR AVAILABILITY OF NEW OR UPGRADED SOURCES

5.1 Spallation Neutron Sources

New intense pulsed spallation sources have come into operation within the past few years at the Argonne National Laboratory (IPNS), the KEK Laboratory (KENS), the Rutherford-Appleton Laboratory (ISIS), the Los Alamos National Laboratory (LANSCE, previously WNR/PSR) and the Brookhaven National Laboratory (MEIN). While the installation of these sources and the study of potential future sources was (or is) primarily driven by condensed matter research, aiming at intense fluxes of thermal and epithermal neutrons, these sources can, with certain modifications, become also very good tools for neutron physics and neutron-nuclear data work. Many of the existing and planned sources utilize pulsed proton beams with energies between 500 and 800 MeV and burst widths of the order of a few hundred ns. The involved pulse structure of these sources is, in principle, directly applicable to high-resolution nuclear data work in the energy range from subthermal to ~1 keV. If full advantage is taken of present accelerator and target techniques, some of these sources may also become outstanding facilities for high-resolution neutron work in the keV- and the MeV-range up to several hundred MeV (in the range from 3-500 MeV already realized for the Los Alamos WNR (Target-4) source). The useful spectrum from spallation sources ranges from thermal (or even subthermal, if cryogenic moderator techniques were used) to more than 500 MeV, and the energy-dependent fast neutron yields exceed those of any hitherto employed 'white' source increasingly with increasing energy. Around 20 MeV energy-dependent neutron yields are already ~4 orders of magnitude higher than those of the best r.f. electron linac sources (comp. Sect. 6.1). For fast-neutron nuclear-data work there is, however, the problem of suitably shaping the proton beam in time structure, while maintaining a high average beam intensity. The problem of optimizing the time structure for our purposes depends chiefly on the type of accelerator employed, and thus must be considered separately for different machines. The three main types of accelerators, presently involved, are r.f. linear accelerators, rapid-cycling synchrotrons and high-energy isochronous (AVF) cyclotrons.

Concerning r.f. linear accelerators, the pulsed proton beam is typically formed in two steps: Protons are in a first step accelerated to full energy at high duty cycles (~1:10 for LANSCE or the aborted SNQ source concept). This beam is then damped into a storage ring, and after suitable accumulation, ejected in one revolution period. Inside the ring, the beam can be in a continuous ribbon or may be stored in one or more separated bunches. In the first case, which is most suitable for condensed matter applications, the pulse is typically compressed into bursts of a few hundred nanoseconds width and ejected at pulse repetition rates of ~10-50 Hz. In the other case, individual pulses can be ejected one at a time, and pulse widths of the order of ~1 ns are possible. Unfortunately, both kinds of accumulator-ring operations cannot be achieved simultaneously. Thus any parallel (or parasitic) operation for condensed matter work and our purposes requires at least different compressor rings. Not only but also this fact, led to the drastic consequence taken for the abandoned

ORNL conceptional design study for the LIRIC source, which aimed at a completely new installation, including the accelerator. For this source concept, all components were particularly optimized to the needs in neutron physics and nuclear data measurements. In principle, this consequence must not be drawn so drastically. From present practice at LAMPF, it appears possible to structure a reasonable fraction of a H^- beam in a linac, while maintaining the gross pulse structure of the beam needed for main purpose operations. At least the share of the accelerator would save the high costs for this component. A different, less ambitious approach, has been adopted and realized, for the WNR (Target-4) neutron source at LAMPF which does not include a compressor ring. The WNR source takes advantage of the inherent micropulse structure of the LAMPF beam which consists of intense subnanosecond bunches of H^--ions spaced by about 5 ns. Taking only one in 200 of these microbunches, provides ~0.3 ns wide pulses with a spacing of about 1 μs, which is an appropriate condition for time-of-flight measurements in the 3 to 500 MeV neutron-energy range. In a planned upgrading, the WNR neutron source is expected to provide a largely increased average beam current of 3 μA which may still be doubled by bunching twice as many H^--ions into each burst (Bow87). But even with the hitherto realized average beam current of 400 nA for a pulse repetition frequency of 58 kHz, this installation is already a very good high-energy source for extended MeV-neutron physics. The combined use of the WNR (Target-4) source together with the LANSCE (previously WNR/PSR) facility provides a source system which is superior to (or at least comparative with) all sources previously used in our domain for work below ~1 keV, and many-MeV neutron investigations. The combined system, however, can not yet significantly outperform the hitherto used neutron sources for the intermediate energy range from ~1 keV to about 3 MeV.

For rapid-cycling synchrotrons pulsed proton beam provision is different. An injection linac is used for pre-acceleration to an energy of ~100 MeV. The pre-accelerated beam is then injected into the synchrotron ring and accelerated to maximum energy. The bunch length provided by the injector is largely conserved during further acceleration in the synchrotron, and the full-energy beam is ejected during a small fraction of the revolution period and damped directly onto the spallation target. This method provides, for the existing sources, typically ~50-100 ns wide pulses at repetiton rates of ~20-100 Hz. For such sources, there has not yet been any broader attempt to use them for neutron physics and nuclear data measurements (mainly because existing sources are, for many years, oversubscribed with suitably screened experiments in basic-physics and condensed-matter research). An interesting possibility for using these sources in a parasitic (or parallel) mode for our purpose has been pointed out by Sasaki (Sas88): Using non-adiabatic damping for injection of the pre-accelerated beam into the synchrotron, allows to produce narrow pulses of the order of ~1 ns with only moderate reduction in intensity (linear decrease in intensity with decreasing pulse length; see Fig. 1). Combining this damping method with alternate injection of a long and a short pulse in two successive r.f. periods, would enable a parasitic (or parallel) operation of synchrotron-based sources. Ejection of the long pulse well in advance of the short one, could bring a favourable final pulse compression due to a rapid rise of the r.f. amplitude from minimum to maximum value. Such a possibility makes these sources very attractive

as flexible high-intensity pulsed white sources for neutron physics and nuclear data work. Parasitic operation over the whole range from subthermal to more than 500 MeV could be boosted at minimum costs, especially if planned in the early design phase of a new source project. This applies e.g. for the projected GEMINI source which is expected to involve the non-adiabatic damping method for injection. It is, however, not yet clear, whether, and if so at what expense, such a damping method can be applied for already existing synchrotron-based sources.

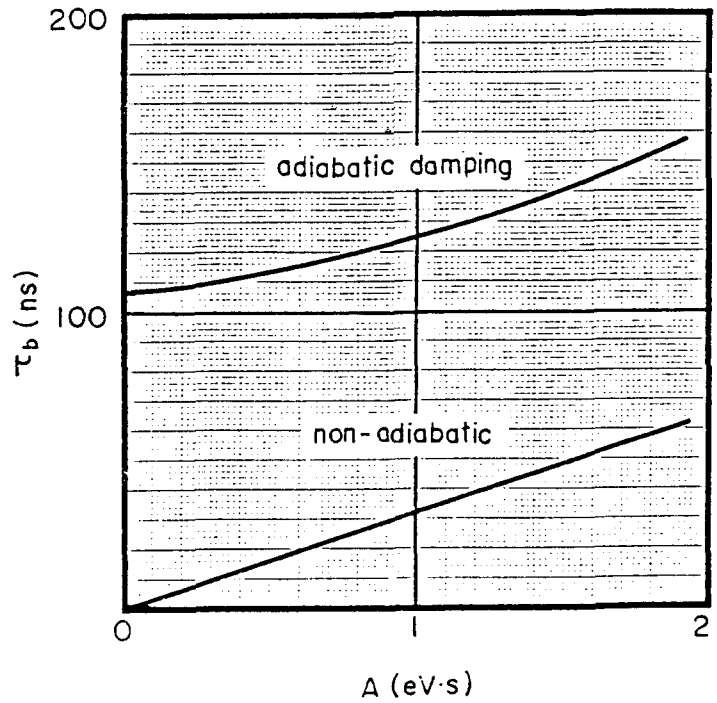

Fig. 1. Time characteristics of proton bunches in synchrotrons for adiabatic and non-adiabatic pulse injection modes (Sas87).

For isochronous (AVF) cyclotrons there does not yet exist any obvious, simple scheme to obtain attractive pulse conditions for our purposes. High average beam intensities are achieved by operating the accelerators in the cw mode, and the only available pulse structure is due to microstructure bunching. This consists typically of ~ 300-ps wide proton bunches with ~10-50 ns spacings. The elimination of one out of three microstructure bunches before injection into the main ring accelerator has been practised at the SIN cyclotron since many years (Fis78). This provided an interesting neutron source for time-of-flight work in the range from ~100 to 600 MeV; special unfolding methods have been applied to separate up to 8 overlaps in flight time from successive microstructure pulses. Reduced micropulse operation is, however, an unpopular usage of the SIN (PSI) machine, since it reduces the average beam current drastically for all other users. Thus any further reduction in pulse repetition rate for more improved specifications does not appear very feasible for this machine, since it would heavily affect the main research activities, which are primarily in meson physics. This situation seems to be similar for other spallation neutron sources based on this accelerator type (e.g. TTNF or SINQ).

5.2 Special High-Energy Monoenergetic Sources

The new monoenergetic sources PIENF and PNS, under construction at BNL (USA) and TSL (Sweden), respectively, are special-purpose sources primarily built for basic neutron-nuclear work in the range from 50/100 to 200 MeV, an early goal of which was (n,p) isovector excitation (IVE) studies. The prime monoenergetic source reaction to be used for these facilities is the ^{7}Li(p,n) reaction. In the 50-200 MeV region, the ^{7}Li(p,n) reaction is again an attractive, nearly monoenergetic source, since the high forward-peaked neutron yield is largely concentrated in the relatively close-spaced two groups from the ^{7}Li(p,n)^{7}Be (0.00 and 0.43 MeV) charge-exchange reactions. The favourable situation, that there exists a rather small secondary neutron-spectrum contamination, consists from ~ 10 MeV to several hundred MeV. The two new neutron sources, presently under construction, will provide a remarkable extension of monoenergetic source capabilities for increased neutron intensity in the energy range from ~50-200 MeV.

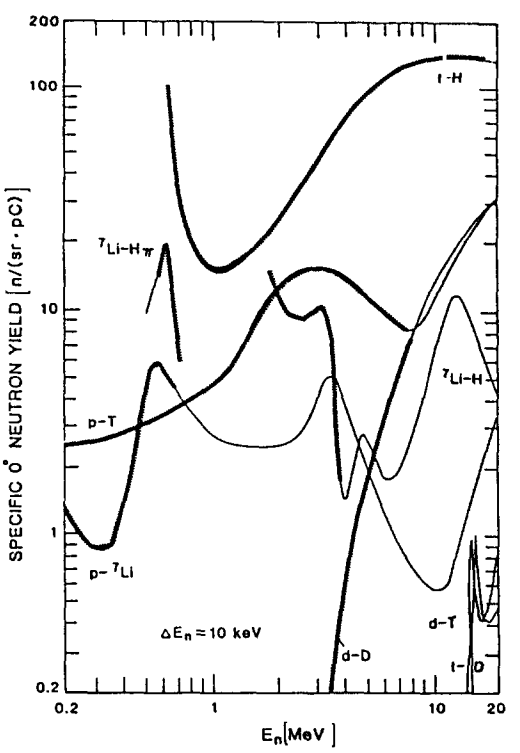

Fig. 2. 0° Neutron yields from some important monoenergetic source reactions (Dro87). Monoenergetic regions are rendered by fat lines.

The two other facilities, the Los Alamos IBF source and the LLNL Van-de-Graaf deserve particular interest with respect to high-intensity monoenergetic neutron production by the ^{1}H(t,n)^{3}He reaction in the energy range from ~6-17 MeV. While the IBF source is already effectively utilized for neutron work (Hai88), the LLNL Van-de-Graaff is not yet envisaged as a neutron facility, but is capable of providing an intense triton beam of 20 μA

dc current. Among the major monoenergetic neutron source reactions for the range between ~4-17 MeV, the $^{1}H(t,n)^{3}He$ reaction has by far the highest 0° yield (see Fig 2), and is intrinsicly a monoenergetic source up to 17.6 MeV. In addition, neutrons are only emitted into a narrow forward cone (kinematic collimation). Employment of rotating gas-target techniques and maximum triton beam capabilities are finally expected to provide neutron fluxes of the order of $1x10^{10}$ cm^{-2} s^{-1} in volumes of ~ 1 cm^{3}.

5.3 High-Flux Fission Reactor Sources

For a long time, user-oriented high-flux fission reactors have suffered from oversubscription by suitably screened experiments from different research fields (mainly condensed matter research), and from lack in intensity for some special types of experiments (e.g. double- and triple-axis spectrometer measurements). This has often limited the approval of important neutron physics and neutron-nuclear data work at these sources. Therefore, the upgrading of the HFR and the two proposals for new reactors at ORNL and TUM deserve special attention, in that they can possibly also provide enlarged capability for fundamental and applied neutron work in the range from subthermal to ~1 keV. The improvements of the high flux reactor in Grenoble (HFR), completed in 1987, concern increases in available flux, the installation of new and improved facilities (e.g. cold and/or hot sources), and the enlargement of instruments and beam lines providing increased neutron flux. For the project of a new reactor (ANS) at ORNL the goal is a factor of at least 5 increase in neutron flux, compared to that achieved contemporarily with the HFR. In case of the new 'Forschungsreaktor München' (FRM), the goal is a thermal peak flux of $\sim 7x10^{14}$ cm^{-2} s^{-1} from a novel type of a compact-core construction. While in an early concept (Boe + 86) the reconstruction of the existing core was considered, recently a completely new reactor was proposed. By placing the new reactor close to the old one, it is expected that a large fraction of the already existing facilities and instruments can be further used in their present positions. In early 1990, licensing of the new reactor had been requested (Was90).

6. COMPARISON OF HITHERTO USED AND POTENTIAL FUTURE SOURCES

6.1 General Considerations

The main types of nuclear reactions which can be used for neutron production are listed in Table V. Also given are the numbers of neutrons per particle or reaction, both of which represent a good measure for the utmost attainable source strengths. In the last column also the type of spectrum is indicated. It can be seen that neutron production for broad continuous spectra is clearly superior to production of monoenergetic neutrons. (The T(d,n) reaction with 200 keV deuterons is already the most effective one, due to its large cross section of 5 b in the 150 keV resonance, and large plasma sources based on the D-T fusion reaction cannot be realized, except for future large fusion facilities). Specific neutron yields for medium-energy electrons or light ions are already more than two orders of magnitude

higher than that for the T(d,n) reaction. This factor increases drastically for fission and even more for spallation reactions with ~1-GeV protons. In addition to the large increase in

TABLE V. Specific Yields and Deposited Heat for Some Major Types of Neutron Source Reactions

Neutron Source Reaction	Particle Energy or Spectrum	Yield n/particle or event	Deposited Heat (MeV/n)	Neutron Energy or Type of Neutron Spectrum
T(d,n)	0.2 MeV	8×10^{-5} n/d	2500	14 MeV
W(e,n)	100 MeV	3.2×10^{-2} n/e	3100	evap. + (direct)
Li(d,n)	35 MeV	4.8×10^{-2} n/d	730	d break-up + (evap.)
^{235}U(n,f)	fission	1 n/fission [a)]	200	fission
D-T	fusion	1 n/fusion	3	14 MeV
Pb spallation	1 GeV	20 n/p	50	evap. + cascade
U spallation	1 GeV	40 n/p	55	evap. + cascade

a) The yield per fission event is 2.4., but ~1.4 neutrons are required to maintain the chain reaction and compensate for parasitic losses.

specific yield, the heat deposited per particle decreases rapidly, so that target problems for high-intensity sources become less restrictive. There is, however, one glaring penalty to be paid for using the more favourable source reactions: These require rather large and expensive accelerators. The neutron spectra for the different types of continuous-energy source reactions are shown in Fig. 3 which was redrawn from Böckhoff's work and updated for 800 MeV protons incident on a thick U-target (LWA86). As can be seen, these are all of the evaporation type, i.e. very similar to the fission spectrum, with some more or less important contributions from direct (high-energy) neutrons. The latter contribution is rather small for 120 MeV electron linac sources and most pronounced for 800 MeV spallation sources. All primary neutron spectra can easily be softened at the low-energy end by neutron moderation. There is, however, only little possibility to considerably harden the almost pure evaporation spectra e.g. from (e,n) reactions. Here the usage of heterogeneous mixtures of a light and a heavy element for the target material can modestly enhance the neutrons yields in the many-MeV range in favourable cases (Boe87).

For pulsed "white" neutron sources, another important quantity is timing, when the source should be used as a neutron spectrometer. In time-of-flight measurements spectral intensity and resolution are anticorrelated, i.e. the better the resolution the lower the neutron flux at the detector position and vice-versa. Thus high-resolution measurements require short intense pulses and long flight paths. Moreover, for a given pulse length and a given flight path, the resolution decreases with energy as the square root. Thus, improved accelerators with shorter pulse lengths and/or higher beam intensities are required, if correspondingly high resolutions should be achieved at higher neutron energies.

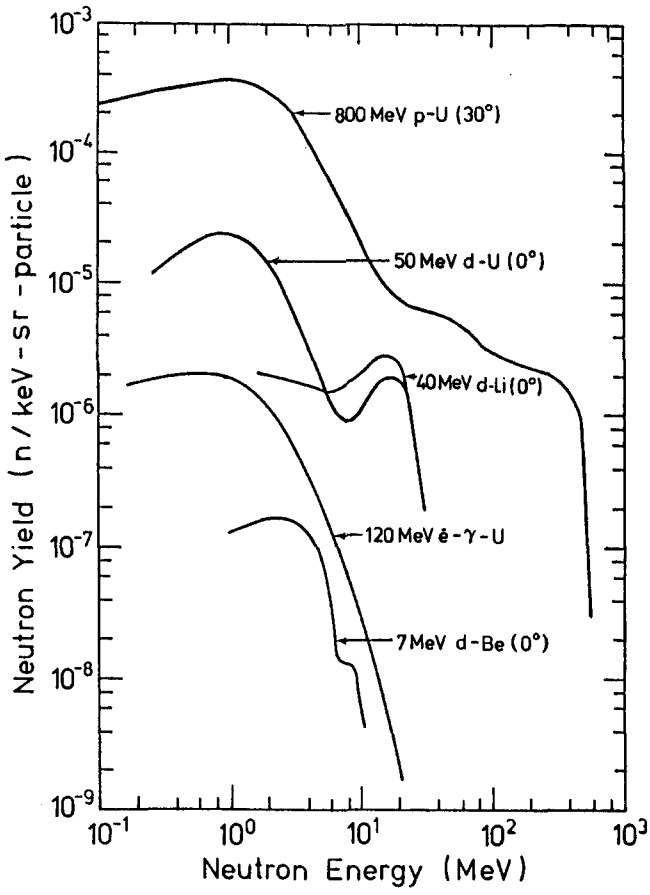

Fig. 3. Energy-dependent neutron yields per incident particle, keV, sr for some important neutron source reactions in thick targets. (Redrawn from Böckhoff (Boe87) and updated for 800 MeV protons on uranium).

6.2 Comparison of Accelerator-Based Pulsed 'White' Neutron Sources

From comparisons of Tables I and IV it can be seen that spallation neutron sources are superior in neutron intensity to sources traditionally used in our field. This applies not only to the time-averaged neutron intensities, but also to the instantaneous intensities produced in short pulses. While the highest average neutron intensities for operating spallation sources are of the order of 10^{16} n/s (increasing to $\sim 10^{18}$ for the next generation of sources presently under study); the corresponding values for the hitherto used sources at linacs and cyclotrons range between $\sim 10^{13}$-10^{15} n/s. The difference in instantaneous intensities is similar, and ranges between $\sim 10^{18}$-10^{23} n/s for the present and the next generation of spallation sources, and between $\sim 10^{17}$-10^{19}n/s for our actually utilized sources. Although useful for a rough characterization of neutron sources, time-average and instantaneous neutron yields alone are no suitable means for appropriate source intercomparisons. Presently, several well established criteria exist for this purpose, and the most useful ones can be divided into two categories: (1) Criteria which employ a few quantities in parallel for source characterization such as energy-dependent yields of neutrons per particle or reaction, number of neutrons per pulse, neutron flux at the detector for a given spectrometer resolution etc. (2) Criteria which

try to combine all different aspects in one single energy-dependent "figure of merit". Both methods have their particular virtues, but give, of course, slightly different results. A broad comparison of actually used 'white' fast neutron sources based on method (1) has been performed by Böckhoff (Boe87). Inspection of this work is suggested as a good complementary information to the different approach adopted here, which is based on method (2).

The method applied here is that first proposed by Rae and Good (RG70). In the past, this method has been widely used for source comparisons, because it takes care of all important source parameters and inherent limitations in a particularly useful manner. As a measure of the quality of a 'white' pulsed source the neutron flux at the detector position for a constant fractional energy resolution $\Delta E/E$ is chosen. In estimating this flux, not only the differential neutron yield in the pulse, but also the geometry and efficiency of the moderator, the limitation in intensity imposed by the use of overlap filters, and necessary reductions of pulse repetition rates due to time-overlap problems are all well taken into account. Using this scheme of comparison, the following assumptions have been made: (1) The value of $\Delta E/E$ is chosen to correspond to the minimum value of a moderated source at minimum flight path. The fractional energy resolution is held constant at all energies by varying the flight path correspondingly. Rather than introduce new conditions, a minimum flight path of 50 m, and a 2.2 cm flight path uncertainty for the moderation process was kept; these give $\Delta E/E = 8.8 \times 10^{-4}$ for the fractional energy resolution. (2) The flight path was allowed to increase up to 400 m to maintain this resolution. (3) for the transmission of a 1/v overlap filter a value of 1% was assumed. (4) Standard pulse repetition rates were reduced correspondingly, when the flight time was greater than three times the overlap time of neutrons from previous bursts.

Comparisons of potential advanced sources with those actually used for neutron-nuclear data measurements are shown in Figs. 4 and 5. In Fig. 4 the energy range from 1 eV to 200 keV is covered, for which moderated neutron sources are used. The GELINA, HELIOS, ORELA sources, hitherto extensively used in our field, are compared with the LANSCE source and two different operation options for a possible advanced sychrotron-based spallation neutron source (ASSNS). Operation conditions of the latter source are taken from the GEMINI proposal with (1) standard specifications, and (2) specifications for a reduced pulse width of 5 ns according to Sasaki's concept of pulse-length reduction in non-adiabatic damping. The pertinent parameters used to calculate the neutron flux within the given energy resolution are listed in Table VI *. In the diagram the number in parentheses behind

* N(E) data for the different sources were taken from Auchampaugh's work (Auc79), except for GELINA, where Böckhoff's results (Boe87) were used. For the electron linac sources, allowing for largely different pulse conditions, a pulse length was chosen that was optimum for operation over the entire energy range from 1 eV to 200 keV. It should, however, be noted that other choices of accelerator burst lengths do, of course, improve the source specifications in particular energy subintervals.

Table VI. Neutron Source Parameters Used for Flux Calculations in the Range 1 eV - 200 keV

Neutron Source	Repet. Rate (Hz)	Pulse Width (ns)	Average Beam Current or Power	N(E) (n/eV-sr-s)
GELINA	900	10	10.8 kW	$1.3\times10^{10}\ E^{-0.75}$
HELIOS *	390	100	5 kW	$5.9\times10^{10}\ E^{-0.78}$ *
ORELA	1000	35	50 kW	$1.3\times10^{10}\ E^{-0.75}$
LANSCE	12	270	30 μA	$1.9\times10^{12}\ E^{-0.90}$
ASSNS	50	100	250 μA	$3.0\times10^{13}\ E^{-0.90}$
	50	5	12.5 μA	$1.5\times10^{12}\ E^{-0.90}$

* Harwell booster target

the source symbols is the machine pulse length. The two quantities in the parantheses attached to all curves at a few energies are the pulse frequency (Hz) and the flight path length (m) necessary to achieve the assumed energy resolution. From the comparison in Fig. 4 it can be seen that the three electron linac sources are all very similar, but with the chosen pulse widths have special advantages in different subinterval energy regions. The LANSCE

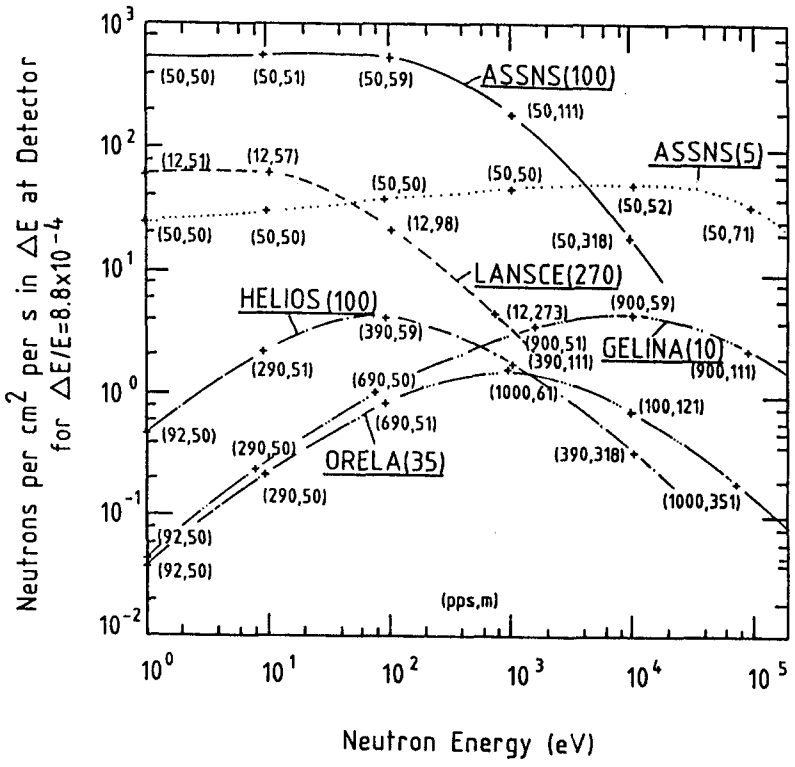

Fig. 4. Comparison of 'white' pulsed neutron sources for the energy range 1 eV - 200 keV. The numbers in parentheses behind the source symbols refer to accelerartor pulse lenths (ns). The two quantities in parentheses attached to the curves are the pulse frequency (Hz) and the flight path length (m). For details see text.

source obviously outperforms the electron linacs below ~1 keV, but requires already a 400 m flight path to maintain the assumed resolution at 2 keV. The potential ASSNS source shows an important improvement over the existing source, especially when operated with 100 ns burst length for the range from 1 eV to 5 keV, and with 5 ns in the range from 5-200 keV. For the LANSCE source, specifications are expected to increase further by a factor of 3, when the facility finally reaches the design goal of 100 μA dc current. The implications of pulse frequency reduction on neutron flux is also evident from Fig. 4. For instance the LANSCE and the ASSNS sources can run at their maximum frequencies of 12 and 50 Hz, respectively, for energies down to 1 eV. All three electron linac sources have to reduce their frequencies to 92 Hz at 1 eV with a corresponding reduction in neutron intensity.

In Fig. 5 the GELINA, KfK, ORELA, WNR (Target-4) sources are compared with ASSNS for the energy region 10^{-2}-10^{3}MeV *. Special source data used for flux calculations

Table VII. Neutron Source Parameters Used for Flux Calculations in the Range 0.01 - 1000 MeV

Neutron Source	Repet. Rate (Hz)	Pulse Width (ns)	Average Beam Current or Power	$\int E \cdot N(E)\, dE$ (n/sr-s)
GELINA	900	0.7	10.8 kW	3.4×10^{12}
ORELA	1000	3.0	10.5 kW	1.6×10^{12}
KfK	20,000	0.8	10 μA	7.6×10^{12}
WNR	58,000	0.5	400 nA	3.0×10^{12}
ASSNS	50	1.0	5 μA	7.6×10^{13}

are given in Table VII. For the two electron linac sources, neutron-spectrum shape data have been taken from those measured by Böckhoff (Boe87) for uranium, assuming that the shape is independent of whether the target material is uranium or tantalum. Total yields were, however, adjusted to measured power-dependent yields for Ta and U, respectively (Cie83). Spectrum shape data for the two spallation sources were taken from the work of Lisowski et al. (LWA86), and from this work the 800-MeV 30° data were selected. In the calculations flight path uncertainties of 2.2 cm have been kept for all sources except KfK, since target dimensions are of the order of several centimeters. For the KfK source the flight path uncertainty introduced by the source extension is less than 1 mm; thus this worse-case value has been used to determine the energy resolution of this facility. From Fig. 5 it can be seen that WNR can outperform the electron linac sources above ~1 MeV. The planned upgrade for an increased dc current from presently 0.4 μA to possibly 6 μA could bring another order of magnitude in neutron flux. But the inherent limitation to energies higher

* The HELIOS source is not included here. Its specifications are similar to those of the ORELA source. But above ~100 keV neutron fluxes decrease more rapidly due to the longer flight paths required to compensate for the deteriorated pulse width of 5 ns.

than ~1 MeV for WNR can, however, not be avoided due to the high pulse repetition rate of 58 KHz, which is required to achieve the stated dc currents. The restriction to MeV neutron work would not exist for the potential ASSNS source, since such a facility is expected to operate at 50 Hz pulse repetition rate.

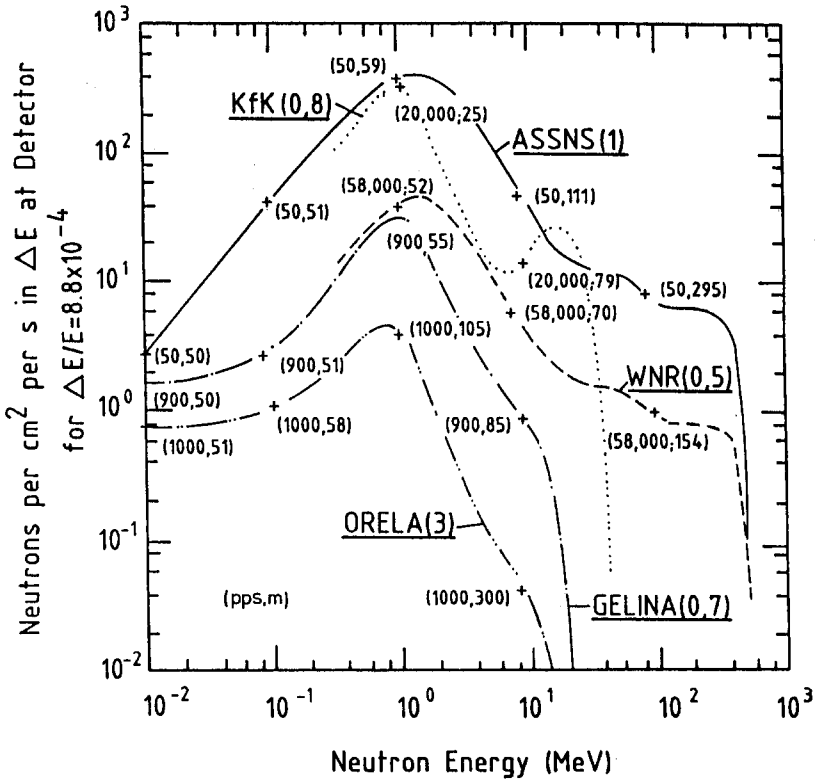

Fig. 5. Comparison of white pulsed neutron sources for the energy range 0.01-1000 MeV. Indications of accelerator pulse lengths, pulse frequencies, and flight path lengths are the same as in Fig. 4. The pertinent source parameters used to calculate neutron flux data are given in Table VII.

7. SUMMARY

The NEANDC Working Group on Neutron Sources has considered the status and assessed the potential of intense sources recently put into operation, under construction or under study. The majority of these belongs to sources of the spallation-neutron type. The interesting feature of spallation neutron sources is a total neutron intensity gain of a few orders of magnitude over the hitherto used pulsed white neutron sources, depending on the neutron energy range. This advantage can, of course, be best taken by building own spallation neutron sources, particularly optimized for use in neutron physics and neutron-nuclear data measurements. It seems, however, that such an approach will be prevented by present financial limitations. Therefore, a more realistic approach seems to be the consideration of possible parasitic (parallel) uses of spallation sources optimized for other purposes (mainly condensed matter research). For this approach, it has already been demonstrated by the WNR (Target-4) source, that neutron physics and nuclear data work can be substantially

boosted at low costs by parasitic use of the existing LAMPF/LANSCE facility. For the WNR source major advantage is presently gained for the energy range from 3 to 500 MeV. For spallation sources involving rapid-cycling synchrotrons, Sasaki has outlined a possible scheme, which promises a more global parasitic (parallel) use with good conditions all over the range from (sub)thermal to more than 500 MeV. Such a scheme could be best introduced in an early design phase of a new source, but may, in principle, be also possible for already existing synchrotron-based sources. Such sources would offer important intensity gains over hitherto used white sources, all over the energy range from 10^{-3} to 10^{9} eV, of interest to our research domain.

Important recent developments of some special-purpose monoenergetic neutron sources and a few high-flux fission research reactors have been considered, in addition. More complete assessments of these sources have been performed by Smith (CS88) (monoenergetic sources) and Moon (Moo86) (fission research reactors). The monoenergetic sources considered by the Group concern facilities for efficient use in the energy range from ~6-17 and ~50-200 MeV, respectively. The use of the $^{1}H(t,n)^{3}He$ reaction and of the $^{7}Li(p,n)^{7}Be$ reaction provides high intensities of monoenergetic neutron beams in the corresponding energy regions. The consideration of some high-flux reactor sources indicate that there is continuing activity to provide improved thermal and epithermal neutron fluxes, and thus enlarged experimental capability, from which the neutron physics and nuclear data community could gain in the future.

Admittedly, the Working Group considered and compared the specifications of neutron sources only. Although representing an important presupposition for high-quality measurements of neutron-nuclear data, neutron source specifications alone do not govern the accuracy and quality of experimental results. These depend also on many other factors, such as the intelligent use of excisting facilities, experimental techniques and methods, the broad knowledge and experience of well skilled scientific and technical personal etc. Finally, it should be repeated that the Group was aware, that a single type of source certainly cannot replace, in the future, the many different types of actually used high-quality neutron sources: The various powerful monoenergetic sources have made, and will continue to make, major contributions to applied and basic neutron work. The high-flux fission research reactors will clearly maintain their important role in the thermal and epithermal energy region over many coming years. Moreover, the various pulsed white neutron sources, especially the electron linac sources, have been for a long time, the most prolific sources for high-quality measurements all over the range from (sub)thermal to more than 20 MeV, and this will clearly remain so in the foreseeable future. Nonetheless, where more powerful sources exist or are under construction or under study, their potential should be seriously considered for future work in the neutron physics and neutron-nuclear data field. With respect to spallation neutron sources, the future potential is at least in most, and for some sources possibly in all of the energy range from 10^{-3} to 10^{9} eV, markedly superior to that of the hitherto used pulsed 'white' sources.

References

Auc80 G.F. Auchampaugh; Status and Comparison of New, Planned, and Upgraded Pulsed 'White' Neutron Source Facilities since 1970; Proc. Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, NBS Special Publication 594, p. 920, (1980).

Bau+81 G.S. Bauer, H. Sebening, J.E. Vetter and H. Willax; Realisierungsstudie zur Spallations-Neutronenquelle; Kernforschungsanlage Jülich/Kernforschungszentrum Karlsruhe Report, Jül-Spez-113/KfK-3175, Part I, (1981).

Bla84 E.W. Blackmore; TRIUMF Kaon Factory as a Potential Neutron Source; Proc. Intern. Collaboration on Advanced Neutron Sources (ICANS-VII), AECL Report, AECL-8488, p. 55, 1984.

Blo88 R.C. Block; Rensselaer Polytechnic Institute, Troy; private communication, 1988.

Boe87 K.H. Böckhoff; Electron Linac Based Pulsed White Neutron Sources for High Resolution Neutron Time-of-Flight Spectroscopy - Status and Perspectives; in Properties of Neutron Sources, IAEA-TECDOC-410, p. 35 (1987).

Boe+86 K. Böhning, W. Gläser, J. Meier, G. Rau, A. Röhrmoser, and L. Zhang; Upgrading of the Munich Reactor with a Compact Core; in Proc. Conf. on Neutron Scattering in the 'Nineties, Jülich, IAEA-CN-46/53, p. 165 (1986).

Bow87 C.D. Bowman; Spallation Sources for Neutron Nuclear Physics; in Properties of Neutron Sources, IAEA-TECDOC-410, p. 396 (1987).

Bro+88 B. S. Brown, J.M. Carpenter, R.K. Crawford, A.V. Rauchas, A.W. Schulke, and T.G. Worlton; Status of the Intense Pulsed Neutron Source; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 27, 1989.

Cie83 S. Cierjacks; Accelerator-Based Pulsed White Neutron Sources; in Neutron Sources for Basic Physics and Applications, ed. S. Cierjacks, Pergamon Press, Oxford, p. 81 ff, 1983.

CS88 S. Cierjacks and A.B. Smith; Neutron Sources: Present Practice and Future Potential; in Proc. Intern. Conf. on Nuclear Data for Science and Technology, Mito 1988, ed. S. Igarasi, Japan Atomic Research Institute, p. 325 (1988).

Dif+86 F.C. Difilippo, W.R. Gambill, R.M.Moon, R.T. Primm, and C.D. West; A Preliminary Reactor Design for the Center for Neutron Research; Nucl. Instrum. Meth. in Phys. Res. A249, 58 (1986).

Dro87 M. Drosg; Production of Fast Neutrons with Targets of the Hydrogen Isotopes - Source Properties and Evaluation Status of the Cross Sections; in Properties of Neutron Sources, IAEA-TECDOC-410, p. 239 (1987).

FB83 F.S. Fraser and G.A. Bartholomew; Spallation Neutron Sources; in Neutron Sources for Basic Physics and Applications, ed. S. Cierjacks, Pergamon Press, Oxford, p. 217 ff, 1983.

FG88 J.L. Finney and D.A. Gray; ISIS Status Report; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 11, 1989.

Fis78 Th. Fischer, G. Hammel, W. Hürster, K. Kern, R. Kettle, M. Kleinschmidt, L. Lehmann, E. Rössle, H. Schmitt, and D.M. Sheppard, SIN Newsletter 10, 29 (1978).

Fis88 W.E. Fischer; Status Report of SINQ: A Continuous Spallation Neutron Source; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 67, 1989.

GEM87 GEMINI Design Report; National Laboratory for High Energy Physics KEK, KEK-Report 86-4, 1987

Hai88 R.C. Haight; Los Alamos National Laboratory; private communication, 1988.

ILL86 Neutron Research Facilities at the ILL High Flux Reactor; Institut Max von Laue Paul Langevin, Grenoble, Edition June 1986.

Joh87 R. Johnson; White Neutron Sources: Primarily Pulsed; in Properties of Neutron Sources, IAEA-TECDOC-410, 29 (1987).

KK84 T.K. Khoe and R.L. Kustom; ASPUN, Argonne Super Intense Pulsed Spallation Neutron Source; Proc. Intern. Collaboration on Advanced Neutron Sources (ICANS-VII), AECL Report, AECL-8488, p. 46, 1984.

Kus88 R.L. Kustom; The ASPUN Project; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 239, 1989.

LWA86 P.W. Lisowski, S.A. Wender, and G.F. Auchampaugh; The WNR/PSR Facility - Neutron Physics Capabilities from Subthermal to 800 MeV; Radiation Effects 95, 239 (1986).

Lyn80 J.E. Lynn; HELIOS: The new Harwell Electron Linear Accelerator and its Scientific Program; Contemp. Physics 21, 5, 483 (1980).

Moo86 R.M. Moon; A Review of Current and Proposed Reactor Upgrades; in Proc. Conf. on Neutron Scattering in the 'Nineties, Jülich 1985, IAEA-CN-46/28, p. 119 (1986).

OMH86 D.K. Olsen, J.A. Martin, and D.J. Horen; A Preliminary Study of possible ORELA Replacement Options; ORNL Report, ORNL/TM-8669 (1986).

Pyn88 R. Pynn; Recent Progress on LANSCE; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 47, 1989.

RG70 E.R. Ray and W.M. Good; Pulsed Accelerator Time-of-Flight Spectrometers, in Experimental Neutron Resonance Spectroscopy, ed. J.A. Harvey, Academic Press, New York, p. 1 ff, 1970.

Sas87 H. Sasaki; Shortening of Bunch Length - Proposal of the Experiment at the 500 MeV Booster Synchrotron; in GEMINI Design Report, Nat. Laboratory for High Energy Physics, KEK, Japan, p. 87, (1987).

Sas88 H. Sasaki, Nat. Laboratory for High Energy Physics KEK, Japan; private communication, 1988.

Tho+84 I.M. Thorson, J.J. Burgerjon, R.E. Blaby, and T.A. Hodges; TRIUMF Thermal Neutron Facility; Proc. Intern. Collaboration on Advanced Neutron Sources AECL Report, AECL-8488, 31 (1984).

TSB85 D. Tronc, J.M. Salome, and K.H. Böckhoff; A New Pulse Compression System for Intense Relativistic Electron Beams; Nucl. Instrum. Meth. in Phys. Res. 228, 217 (1985).

TSL87 THE SWEDBERG LABORATORY, Uppsala University; (Description of New Instruments and Facilities); The Swedberg Institute Uppsala., 1987; H. Conde, S. Crona, A. Hakansson, O. Jonsson, A. Lindholm, L. Nilsson, P.-U. Renberg, G. Tibell, I. Bergqvist, and P. Ekstöm; The Uppsala (n,p) Facility; Can. J. Phys. 65, 643 (1987).

TUM87 30 Jahre FRM, Forschungsreaktor München in Garching, Vergangenheit und Zukunft; ed. by Fakultät für Physik der TU München, p. 39 ff, October 1987.

War+88 T.E. Ward, J. Alessi, J. Brennan, P. Grand, R. Lankshear, P. Montemurro, C.L. Snead, and N. Tsoupas; Pulsed-Neutron Production at the Brookhaven 200-MeV Linac; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 27, 1989.

Was89 W. Waschkowski, Technische Universität München, Fachbereich Physik, private communication, 1990.

Wat88 N. Watanabe; Progress at the Pulsed Spallation Neutron Facility KENS; in Advanced Neutron Sources 1988, ed. D.K. Hyer, Institute of Physics Conf. Series No 97, Institute of Physics, Bristol and New York, p. 27, 1989.

LIST OF ABBREVIATIONS

AERE	Atomic Energy Research Establishment (U.K.)
ANL	Argonne National Laboratory (U.S.A.)
ANS	Advanced Neutron Source Project (U.S.A.); formerly CNRR
ASPUN	Argonne Super Intense Pulsed Neutron Source (U.S.A.)
ASSNS	Advanced Synchrotron-Based Spallation Neutron Source (Potential Source)
BNL	Brookhaven National Laboratory (U.S.A.)
CBNM	Central Bureau for Nuclear Measurements (CEC Geel)
CNRR	Center for Neutron Research Reactor (U.S.A.)
FRM	Forschungsreaktor München (Fed. Rep. Germany)
GELINA	Geel Electron Linear Accelerator (CEC Geel)
GEMINI	Generator of Meson-Intense and Neutron-Intense Beams (Japan)
HELIOS	Harwell Electron Linac for the Investigation of Neutron Radiation Sciences (U.K.)
HFR	High-Flux Reactor Grenoble (France)
IAEA	International Atomic Energy Agency (Vienna)
IBF	Ion Beam Facility (U.S.A.)
ILL	Institut Max von Laue Paul Langevin, Grenoble (France)
INDC	International Nuclear Data Committee, (IAEA Nuclear Data Section, Vienna)
INST	International Institute for Standards and Technology (U.S.A.); formerly NBS
IPNS	Intense Pulsed Neutron Source (U.S.A.)
JAERI	Japan Atomic Energy Research Institute (Japan)
KFA	Kernforschungsanlage Jülich (Fed. Rep. Germany)
KfK	Kernforschungszentrum Karlsruhe (Fed. Rep. Germany)
KEK	High Energy Physics Institute (Japan)
KENS	High Energy Neutron Source (Japan)
LAMPF	Los Alamos Meson Production Factory (U.S.A.)
LANL	Los Alamos National Laboratory (U.S.A.)
LANSCE	Los Alamos Neutron Scattering Centre (U.S.A.)
LIRIC	Linac Ring Compressor (U.S.A.)
LLNL	Lawrence Livermore National Laboratory (U.S.A.)
MEIN	Medium Energy Intense Neutron Facility (U.S.A.)
NEANDC	NEA Nuclear Data Committee of OECD (Paris, France)
NBS	National Bureau of Standards (U.S.A.)
OECD	Organisation for Economic Co-operation and Development (Paris, France)
ORELA	Oak Ridge Electron Linear Accelerator (U.S.A.)
ORNL	Oak Ridge National Laboratory (U.S.A.)
PIENF	Pulsed Intermediate Energy Neutron Facility (U.S.A.)
PNS	Physics Neutron Source (Sweden)
PSI	Paul Scherrer Institute (Switzerland); formerly SIN
PSR	Proton Storage Ring (LANSCE, U.S.A.)
RAL	Rutherford-Appleton Laboratory Culham (U.K.)
RPI	Rensselaer Polytechnic Institute (U.S.A.)
SIN	Schweizerisches Institut für Nuklearforschung (Switzerland)
SINQ	SIN Spallationsneutronenquelle (Switzerland)
SNQ	Spallationsneutronenquelle (Fed. Rep. Germany)

TKF	TRIUMF Kaon Facility (Canada)
TRIUMF	Triuniversity Meson Factory (Canada)
TSL	The(odor) Swedberg Laboratory, Uppsala (Sweden)
TTNF	TRIUMF Thermal Neutron Facility (Canada)
TUM	Technische Universität München (Fed. Rep. Germany)
WNR	Weapons Neutron Research Facility (U.S.A.)
WNR/PSR	WNR/Proton Storage Ring (U.S.A.)

Appendix I

Kernforschungszentrum Karlsruhe
Gesellschaft mit beschränkter Haftung

Kernforschungszentrum Karlsruhe GmbH Postfach 3640 D 7500 Karlsruhe 1

Institut für Kernphysik

To: Drs. Böckhoff, Condé, Cross, Igarasi, Peele, Smith, Sowerby, Whetstone, White, Young

Datum: Dec. 27, 1985
Bearbeiter:
Telefon: 07247/ 824243
Ihre Mitteilung:

From: S. Cierjacks

Subject: Action N° 18 of the 25th NEANDC Meeting, Working Group on Neutron Sources for Nuclear Data Measurements

You gentlemen have been appointed as members of the above Working Group, or agreed to act as liaison persons to other scientists in your country who are more closely involved in the operation, design or planning of advanced neutron sources. Since our group is expected to work between regular Meetings, it is timely to call for your collaboration. According to the Terms of Reference our first task is to collect information on specifications or design objectives of relevant sources presently in operation, under construction or under study. During the last NEANDC Meeting first attention was focussed on spallation-type of sources involving medium-energy (> 100 MeV) proton or deuteron accelerators. Sources falling into this category are the existing facilities ISIS (Rutherford), IPNS I,(II) (ANL), KENS I,(II) (Tsukaba), TNF (Vancouver), WNR/PSR (LANL), and the projects of ASPUN (ANL), GEMINI (Tsukaba), PSR-LANCE (LANL), SINQ (Switzerland) and the TRIUMF Kaon Facility (Canada). Also the concepts of a ∿ 100 MeV proton-induced source in Sweden for medical applications and of a ∿ 300 MeV proton machine at BNL for radiation damage studies belong to this type.

Even though spallation sources have recently most rapidly advanced, I strongly feel that also some other types of sources must

be considered: As mentioned during the 25th Meeting thoughts are presently given to 'super' high-flux reactor concepts (e.g. at ILL) which can provide further increased fluxes from the subthermal to the epithermal range in the future. Moreover, largely increased intensity of monoenergetic neutrons can be obtained in the previous problem area between 13 and 17 MeV from electrostatic accelerator sources employing the H-1(H-3,n)- and the H-1(Li-7,n)-reactions, with the conventional projectile and target nuclei interchanged. A few powerful sources of this type have come into operation or under construction (e.g. at LANL and LLNL).

In order to get work started, I would like to request information on the mentioned facilities, projects or studies. Suggestions of other sources (or source concepts) of interest to our group, but not yet taken into account, are also much appreciated. For collection of specifications and design objectives of advanced sources I have prepared questionnaires which should preferably be used to facilitate uniform and complete coverage. Of course, updated 1- or 2-page summaries of source characteristics are, in principle, also acceptable, if those are already available from other recent work. For comparison of sources with those presently used in our field, I suggest to update the corresponding tables from my book which are attached for those of you who are concerned. I would be grateful, if you could care particularly for obtaining information on the

source(s),

and return the filled form(s) or updated tables to me before February 15, 1986. In case you are planning to send the questionnaire(s) to other scientists (not familiar with the objectives of our Working Group), it may be worthwhile to use the attached information sheet which explaines our intentions in some more detail. If you wish to nominate (an)other colleague(s) from your country for membership in the group, please let me know at your earliest convenience. In that case I would appreciate, if you could care for the initial contact, and forward the attached material to these individuals in the mean time. I will then continue correspondence with the new members at a later stage.

I look forward to your response. Best wishes for this Season and the New Year.

H. Liskien

Enclosure

QUESTIONNAIRE

on Advanced Neutron Sources

Origin: Nuclear Energy Agency Nuclear Data Committee (NEANDC), Working Group on Advanced Neutron Sources

---

General Information Page

Facility (Name, laboratory): _____

Name of member, liaison person: _____

Name of respondent: _____

Main field of source application: _____

Percentage of machine time for main application: _____ (%)

Other fields of application, and percentage of machine time presently scheduled or foreseen:

1. _____ _____ (%)
2. _____ _____ (%)
3. _____ _____ (%)

Present status of the source: _____

Last-date ref.: _____

Type of neutron source:

a) Spallation neutron source ☐

b) Advanced monoenergetic neutron source ☐

c) User-oriented advanced high-flux reactor source ☐

d) Other type of source _____ ☐

Special Information Page, Form A.1

(Spallation neutron sources)

Facility (Name, lab.): _____

Accelerator type
(Linac, cyclotron etc.): _____

Particle characteristics:	Part. type	Energy (MeV)	Avg. current (μA)	For application
Include here also data for intermediate target stations	1.			
	2.			
	3.			

Target(s) (material):
For main application _____ Oth.options _____

For spec. applications _____ " " _____

Time structure in application type	1.	2.	3.
Pulse width (μs):			
Rep. rate (pps):			
Peak current (μA):			
Peak intensity (n/s):			

Micropulse time structure (of R.F.-driven accelerators)

Microstr. pulse rep. rate (pps): _____

Microstr. pulse width (ns): _____

Possible uses for neutron physics and nuclear data measurements

a) Without modifications: _____

b) With modifications: _____

Type of modification: _____

Special Information Page, Form A.2

(Advanced monoenergetic neutron sources)

Facility (Name, lab.): _____

Accelerator type
(Van-de-Graaff, cyclotron etc.): _____

Accelerated particles:	^{1}H	^{2}H	^{3}H	^{7}Li	Other
Energy range (MeV):					
Avg. current (μA):					
Avg. neutron intensity (n/s):					

Neutron source reactions:	$^{1}H(t,n)$	$^{1}H(^{7}Li,n)$	$^{2}H(d,n)$	$^{3}H(d,n)$	Other
Avg. current on targ. (μA):					
Intens. on sample ($n \cdot sr^{-1} \cdot s^{-1}$):					

Time structure for reaction(s):			
Pulse width (ns):			
Rep. rate (pps):			
Peak current (μA):			
Peak intensity (n/s):			

Special uses in neutron physics and nuclear data measurements

Type of investigation	Energy range	Intens. on sample
1.		
2.		
3.		
4.		

Special Information Page, Form A.3

(User-oriented advanced high-flux reactor sources)

Reactor (Name, lab.): _____

Type of fuel: _____

Reactor power (MW): _____

Max. heat flux density at fuel surface (W cm^{-2}): _____

Total max. neutron flux (n cm^{-2} s^{-1}): _____

Max. thermal peak flux ($n \cdot cm^{-2} \cdot s^{-1}$): _____

Max. epitherm. peak flux ($n \cdot cm^{-2} \cdot s^{-1}$): _____

Number of beam tubes _____ and neutron guides: _____

Cold neutron source: YES ☐ NO ☐

Specifications: _____

_____

Hot neutron source: YES ☐ NO ☐

Specifications: _____

_____

Anticipated uses for neutron physics and nuclear data work:

Type of investigation	Neutron flux on target
1. _____	_____ ($n \cdot cm^{-2} \cdot s^{-1}$)
2. _____	_____ "
3. _____	_____ "

General Information Sheet

Dear Colleague:

The situation in neutron sources available for neutron physics investigations and nuclear data measurements gives rise to some serious concern. Several of the important sources presently used in these fields are more than fifteen years old. Even though there are still possibilities for future improvements of such sources, corresponding upgradings do not promise enough potential for drastically increased neutron intensity. In contrast, much more powerful neutron sources have been (or being) developed for use in other research fields. This applies particularly to expensive spallation neutron source installations built or envisaged for condensed matter studies. Such sources provide highly increased intensity of neutrons over a wide energy range from subthermal to several hundreds of MeV. These are thus, in principle, also excellent tools for advanced studies in neutron physics and nuclear data measurements. The nuclear data community is, however, quite small, so that it cannot possibly expect enough support on funds for own spallation neutron sources, at least not at the time being. In any case the nuclear community cannot expect serious interest in corresponding requests, before it has not carefully looked into the possibility to share sources of the new types with other scientific disciplines. Unfortunately, source specifications especially useful in solid or liquid state physics are often largely different from those required in nuclear data measurements, and source applications for the latter purpose are typically only scarcely considered in early planning stages of advanced sources.

To obtain a more complete picture of the actual situation in intense neutron source development for various research fields, the OECD's Nuclear Energy Agency Nuclear Data Committee (NEANDC) has set up a Working Group on Neutron Sources for Nuclear Data Measurements. Its main task is to consider appropriate neutron source concepts which could fit the future needs in this field. In this context a first step is to collect reliable information on advanced sources presently in operation, under construction or under study. This provides a suitable basis for studying their possible use (without or with possible modifications) for our purposes. For the planned survey of advanced sources it appears adequate to cover in a first stage the following three types:

1. Spallation neutron sources, i.e. accelerator-based pulsed or steady-state white sources involving medium-energy ($\gtrsim$100 MeV) proton or deuteron accelerators and typically heavy-element targets.

2. Advanced monoenergetic neutron sources, i.e. sources employing new powerful low-energy accelerators (especially electrostatic machines) and advanced types of source reactions such as H-1(H-3,n) or H-1(Li-7,n), with the conventional projectile and target nuclei interchanged, etc.

3. User-oriented advanced high-flux reactor sources, i.e. new high-flux reactor concepts as that presently considered at ILL Grenoble for provision of increased thermal and epithermal neutron fluxes.

The questionnaire which you find annexed is primarily addressed to those laboratories which are actively involved in the use, design or study of advanced neutron sources. The structure of the questionnaire is kept intentionally broad, to serve the intended purpose. In addition to a common general information page three different forms (A.1 - A.3) are provided for collection of source parameters. It is understood that only one of the latter forms is used for a particular source.

The NEANDC is aware of the fact that presently operating advanced sources are often, for the years to come, oversubscribed by suitably screened experiments from research fields other than those of interest here. Nonetheless, information on these sources is also essential for the success of our undertaking, because its final intent is more long-term oriented.

The NEANDC Working Group would be grateful, if you could help to fulfill the mentioned task, and return the filled forms to the requestor in your country before February 15, 1986. Your collaboration in this respect is very much appreciated.

S. Cierjacks
Chairman