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ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

THERMAL NEUTRON SOURCE STUDY

Etude des sources de neutrons thermiques

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Chalk River, Ontario

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Résumé

On traite, dans ce rapport, de la valeur des faisceaux neutroniques intenses pour étudier les matières condensées en mettant l'accent sur la nature complémentaire des sources de neutrons pulsées ou en régime constant. On y résume, par ailleurs, une vaste documentation relative aux sources de neutrons existantes ou projetées et, ce, sous quatre rubriques: réacteurs à fission, accélérateurs d'électrons dont les cibles sont en métaux lourds, sources pulsées de spallation et sources de spallation en régime constant. Bien que l'on puisse s'attendre à ce qu'une source de spallation coûte deux fois plus cher qu'un réacteur à fission ayant le même flux, une installation de spallation comme celle proposée sous le sigle EMTF (Electronuclear Materials Test Facility) aurait de grands avantages.

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Abstract

The value of intense neutron beams for condensed matter research is discussed with emphasis on the complementary nature of steady state and pulsed neutron sources. A large body of information on neutron sources, both existing and planned, is then summarized under four major headings: fission reactors, electron accelerators with heavy metal targets, pulsed spallation sources and "steady state" spallation sources. Although the cost of a spallation source is expected to exceed that of a fission reactor of the same flux by a factor of two, there are significant advantages for a spallation device such as the proposed Electronuclear Materials Test Facility (EMTF).

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I Introduction

This report presents a compilation of neutron sources suitable for thermal neutron scattering experiments in condensed matter physics, covering not only existing pulsed and steady state sources but also those in the construction or planning stages, so that their advantages and disadvantages can be easily assessed. The cost of these facilities, where available, has also been included with their physical characteristics. The purpose of the present survey is to summarize the current status of intense neutron sources in order to provide the background information for decisions on the next generation neutron source and associated experimental programs. Although these matters are discussed within the Canadian context, the conclusions are believed to have much wider application.

Section II summarizes data for steady state nuclear reactors. Accelerator-based pulsed sources are dealt with in sections III and IV. A discussion of accelerator-based steady state sources in section V is followed by a brief summary and concluding remarks in section VI. Technical details of neutron beam currents and fluxes from different moderators are discussed in an appendix. In this introductory section, we comment briefly on the need for new neutron sources, of both the steady state and pulsed varieties, and on the way in which the direction of scientific research may be influenced by the characteristics of these sources.

Neutron scattering has always been an intensity limited technique where improvements in source intensity have invariably led to new and exciting discoveries in basic condensed matter science. In the past fifteen years there has been a rapid increase in the number of papers published in this field[1] and the start of this growth coincides with the start-up of the major high-flux reactors, HFBR at Brookhaven (1965), HFIR at Oak Ridge (1966) and the HFR at the Institut Laue-Langevin (1971). The neutron scattering technique has been applied in an increasing number of scientific disciplines, both pure and applied, and the demand for carrying out experiments in these new areas has shown remarkable growth. Demand has been particularly stimulated in Europe by the well-funded and well-staffed program for developing and upgrading instruments and methods which has continued since the Institut Laue-Langevin was built. This growth shows no sign of levelling off and is confidently expected to increase well into the future. Perception of this demand has led to a number of reports in the last few years[2-4] that have documented existing facilities and programs and have identified promising areas of science where important advances could be made if higher fluxes were available. New neutron sources of the same flux as is currently at our disposal will also be essential in the future, not only to accommodate the increasing demands for neutron scattering research but also to replace existing sources as these reach the end of their working lives. The continuing need for reliable supplies of commercially valuable isotopes and for fast flux irradiation facilities must also be kept in mind.

In the past decade promising alternatives to high flux reactors have been developed that produce pulsed beams of neutrons from accelerated electrons or protons. These can overcome the heat transfer problem that ultimately limits high flux reactor technology since the average power developed in the core or target is substantially reduced by the pulsed nature of the source. However, as expected, while the peak flux can be made much higher than the average flux of a reactor, the time-averaged flux of these pulsed sources is usually less than that from a reactor.

Continuous beams of neutrons can be produced by spallation induced by a continuous-wave accelerator. If neutron intensities are limited by heat transfer difficulties, as appears to be the present case for reactors, then in principle accelerator-based spallation sources are capable of higher fluxes than reactors because the energy released per neutron is much less in spallation than in fission.

To make best use of a pulsed facility it is logical to employ time-of-flight methods to define the neutron energy. Resolution requirements then dictate that the fast neutron pulses should be of short duration, less than about 10 μs. The pulse repetition rate should not exceed about 500 pulses per second to avoid frame-overlap problems. Perhaps the most significant advantage of these pulsed sources is that it is relatively easy to tailor the moderator surrounding the target so as to increase the flux of energetic neutrons in the range 0.1 to 2 eV. This feature could permit, in principle, high energy inelastic scattering and high spatial resolution diffraction experiments which cannot be done with thermal neutron fluxes from conventional reactors.

Time-of-flight methods involving tens or even hundreds of detectors around the samples are best suited to measuring the scattering law $S(Q,\omega)$ for materials like liquids and amorphous solids, where there is a significant response at every wavevector $|\underset{\sim}{Q}|$ and energy $\hbar\omega$. On the other hand it has long been known that the energy-wavevector dispersion relations for phonons and magnons in crystalline solids are better studied by means of triple-axis crystal spectrometers operating at steady state sources.

It is thus clear that the character of the source, steady state or pulsed, determines to a considerable degree the nature of the scientific problems that can best be tackled. The conclusion to be drawn is that if the Chalk River condensed matter physics program is to continue to emphasize investigations of lattice dynamics and magnetic excitations in solids, and of the highly specific properties of quantum fluids such as ^4He, then a steady-state source, based on a reactor or a cw accelerator is the major requirement. On the other hand, if investigations of amorphous materials and liquids were to become major elements of the program, then a pulsed neutron source, based on a pulsed accelerator or on a storage ring device would become more attractive. Although it is extremely difficult to predict future trends in physics, our best guess indicates that liquids and amorphous solids will probably represent less than 25% of our future research effort.

II **Reactors**

Table I sets out the power, maximum thermal flux, estimated operating costs, neutron scattering program costs and capital costs of steady state reactors covering the range useful for neutron scattering research. Three examples of proposed reactors are given which are thought to be within the capabilities of existing technology. There is some uncertainty about the capital cost of new reactors, but there is little uncertainty about the operating cost and the cost of running an appropriate neutron scattering program.

For reactor neutron sources, besides maximum thermal neutron flux, factors such as fast/thermal ratio in the beam, the solid angle subtended at the source-block, the existence of hot or cold sources and the number of beam tubes are also important parameters in the effectiveness of the experimental effort. The ILL and HFBR reactors were designed as beam tube reactors and the thermal/fast ratio is optimized by having beam tubes tangential to the reactor core, directed at regions of maximum thermal flux in the moderator. Data on the 4 MW pulsed reactor at Dubna (IBR-II) are included in Table 1. The design peak flux is 2×10^{16} cm^{-2}sec^{-1} in a 230 μs pulse at a repetition rate of 5 Hz. A pulse length of 100 μs or longer is not useful for time-of-flight applications, so that IBR-II is essentially a steady-state neutron source with an intensity less than 10% of that of the NRU reactor.

III **Electron Accelerators**

Table 2 gives three examples of neutron sources based on electron bombardment of heavy metal targets. The ORELA source at Oak Ridge has been in operation since 1967 and the new Harwell linac source is almost up to full power operation. None of these sources has a time-averaged flux that approaches the present flux of NRU within a factor x 40. They would not be competitive in doing the same kinds of experiments as are presently performed. A further difficulty is that in several cases the experimental hall would be inaccessible during machine operation due to high radiation hazards from the beams. All sample manipulations, for example during the setting-up and calibration phase of experiments, servicing and filling of cryostats, and so on, would necessarily be carried out by remote control. For some applications, however, such as measurements of the total scattering S(Q) at high Q, a source of this kind may be useful.

IV Neutron Production at Pulsed Spallation Neutron Sources

The principal parameters of pulsed neutron sources built or planned are given in Table 3. At present WNR, IPNS-1 and KENS are operating, SNS and WNR-PSR are being built and IPNS-II and SNQ are in the discussion stage. High energy, high current facilities dominate since neutron production increases with proton current and energy. As long as the pulse width of the fast neutrons is less than the pulse width of neutrons in a moderator or moderator reflector combination (15-45 μs in practical cases), there is no severe degradation of the time resolution necessary for time-of-flight spectroscopy. The SNQ facility does not meet this criterion so the first SNQ machine is in effect a steady state source. A compressor ring producing 0.7 μs pulses in the SNQ(PSR)variant would make time-of-flight spectroscopy practical.

The peak neutron flux, the principal design goal of a pulsed spallation source, is limited by the moderation time rather than the source pulse width in general. Two different neutron flux figures can be calculated for each source: (1) the maximum thermal neutron current in a standard[14], Be reflected, heterogeneously poisoned moderator for intercomparison between pulsed sources and (2) the flux in an optimized moderator[13,15] for comparison with steady state spallation sources and reactors. Provided that the 100 μA average current can be extracted routinely, and that a U^{238} target can be used, the WNR(PSR) promises to be the most powerful near-term spallation source. On the other hand only the flux at the SNQ source exceeds the flux at NRU and is comparable with the existing highest flux reactors.

Of all the pulsed spallation sources, the most detailed cost figures[11] have been given for the SNS source at the Rutherford Laboratory. If the savings which accrued by use of the hard-ware left at the Nimrod site are added in, it is hard to avoid the conclusion that a comparable spallation neutron source at a new site would cost more than M $ 200. The cost of the SNQ source without a compressor ring is estimated[12] to be M $ 363. It is notable that with a liquid Pb-Bi target and optimised moderator[13,15] SNQ would give a steady flux of 10^{15} $n_{th}cm^{-2}$ s^{-1}, which is comparable to that of the ILL reactor, for twice the price of a new ILL reactor.

VI Neutron Production at "Steady" Spallation Neutron Sources

Table 4 gives the parameters for steady spallation sources, of which only the TRIUMF source is operating. The targets for steady sources are characterized by heavy liquid Pb-Bi targets[18], with forced convection[15] if the deposited power density is high. For comparison the figures for the ING[5,19] and the EMTF[20] neutron source are included in Table 4. The flux at the EMTF[20] (Electronuclear Materials Test Facility) source would be as high as any spallation source recently proposed and is comparable with the best high flux reactor.

VI **Summary and Conclusions**

It is anticipated that substantially more than half of CRNL neutron scattering research will continue to require a neutron source of high time-averaged flux for the forseeable future. The long-term health of this research would thus be best guaranteed by a steady state proton accelerator such as the EMTF (Table 4) or a subsequent development of this device to increase the proton beam energy and current. The steady state neutron flux available from EMTF would represent a significant improvement over that available from the NRU reactor, and, if extrapolated to 1 GeV, would exceed the highest flux attainable from the most advanced reactor so far envisaged (Advanced HFIR II, Table 1). In addition, provision of a suitable storage ring facility and a modified target/moderator would not be an easy task but might permit pulsed beam operation with little reduction in time-averaged flux, simultaneously optimising a wide range of neutron scattering experiments. It should be mentioned that construction of a new accelerator based neutron source would not eliminate our requirements at the best existing Canadian neutron source, the NRU reactor, where many excellent experiments could continue to be performed. Indeed, the pulsed spallation source and the steady state reactor are in many respects complementary, each having its own advantages for different kinds of neutron scattering experiments.

The cost per neutron for an accelerator-spallation source probably exceeds that for a high-flux research reactor by a factor of about 2. Thus, if considerations of cost are paramount, it seems clear that an advanced research reactor offers the best buy from the viewpoint of Canadian neutron scattering research. On the other hand, there are several compensating advantages for the accelerator, such as: (1) potential for pulsed neutron production as well as steady state operation (2) probably less serious licensing problems (3) potential development of the accelerator-breeder for production of fissile fuel (4) potential commercial spin-off developments in the industries associated with radio-frequency power and other accelerator components.

In conclusion, therefore, this report strongly favours the implementation of a program to develop a high current, high energy proton accelerator and heavy metal target to produce intense, continuous beams of neutrons. Subsequent addition of a storage-ring device might, if a suitable target could be developed, permit production of pulsed neutron beams which would be highly desirable for research in certain areas of condensed matter science. The report also supports consideration of a new research reactor, since this remains probably the least expensive device for the production of intense steady state neutron beams.

Acknowledgements

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Appendix Neutron Beam Currents and Neutron Fluxes From Pulsed Sources.

The spatial average number of fast neutrons leaving the target, the fast neutron leakage rate, is denoted by $\bar{S}$ and the performance of the moderator as a neutron source is expressed in terms of the target strength $\bar{S}$. Moderator performance is specified as the spatial average thermal neutron current, including all neutron energies, $\bar{I}_{th}(sr^{-1}\ n_f^{-1})$ flowing within 1 steradian of the normal from the whole viewed surface of the moderator of area A cm^2. The angular current from a moderator decreases as a chosen direction deviates from the normal so that to calculate the flux $\bar{\Phi}$ leaving the moderator (the number of thermal neutrons of all energies leaving 1 cm^2 of moderator surface in all directions) the angular distribution must be integrated. It is then found[14] that the thermal flux per incident fast neutron is related to the thermal neutron current and the moderator area by the expression

$$\frac{\bar{\Phi}}{\bar{S}} = \frac{4.29}{A}\frac{\bar{I}_{th}}{\bar{S}}\ cm^{-2} n_f^{-1}$$

The thermal neutron beam current for a given fast neutron production rate which may be extracted from a practical moderator, has been given by Carpenter et al[14]. Two cases are considered (a) a bare poisoned CH_2 moderator and (b) a beryllium reflected moderator.

(a) Bare moderator

The arrangement is shown in Fig. 1a in which thermalized neutrons stream away from the moderator in a direction tangential to the source. The angular current[14] from the 10 x 10 cm^2 face of the moderator is given empirically by

$$\frac{\bar{I}_{th}}{\bar{S}} = 1.5 \times 10^{-4}\ sr^{-1} n_f^{-1}.$$

To calculate the number of neutrons passing through 1 cm^2 at distance L from the moderator, per source neutron, we multiply by the element of solid angle $1/L^2$. In practice the maximum flux at the centre of the moderator exceeds the average flux by about a factor 2. The important number for neutron beam applications is the average flux.

The measured distribution[14] in energy of the neutron beam current, I(E), is shown in Fig. 2 normalized to $\bar{I}_{th}$. The current at 1 eV for this bare poisoned moderator exceeds the current in a Maxwellian spectrum by several orders of magnitude. The pulse width of the neutrons in the moderator is typically 15 μs at an energy 0.5 eV.

(b) Beryllium reflected moderator

The arrangement of the source, moderator and the Be reflector which completely surrounds both is shown in Fig. 1b. In the sense that a practical spallation source would not be surrounded entirely by Be but by other moderators for different beam tubes, this arrangement is optimistic. However it indicates the gains to be obtained. The <u>measured</u> beam current from the reflected moderator, signified by superscript R, was found to be

$$\frac{I^R_{th}}{\bar{S}} = 4.1 \times 10^{-3} \text{ sr}^{-1} \text{ n}_f^{-1}$$

which is a factor of about 30 larger than the unreflected case.

Hobbis et al.[6] suggested that practical reflected moderators of dimension 10 x 10 x 7.65 cm would provide about ten times more flux than bare moderators. Their estimates of the thermal neutron beam current and the current of 1 eV neutrons were

$$\frac{I^R_{th}}{\bar{S}} = 1.6 \times 10^{-3} \text{ sr}^{-1} \text{ n}_f^{-1}$$

and $$\frac{I^R(E=1eV)}{\bar{S}} = 3.6 \times 10^{-4} \text{eV}^{-1} \text{ sr}^{-1} \text{n}_f^{-1}$$

Finally the pulse width of the neutrons is larger for the reflected moderator case and is measured to be ≈ 30 μs at 0.5 eV. Of course this broadening of the peak lessens (by a factor of 2) the maximum flux seen during the burst compared with the bare moderator case, so the realizable gain in peak flux is of the order of x 5 with a Be reflector.

For steady neutron sources such as TRIUMF, SIN or the ING source, the considerations in moderator design are different since there is no requirement for neutron pulse sharpening by adding poisons to make the time resolution acceptable for time-of-flight spectroscopy. The task is one of optimising the moderator size and material to maximize the thermal or epithermal flux. Coleman[13] gave the flux at the face of an optimized moderator, per incident 500 MeV proton on the target, to be

$$\frac{\bar{\Phi}_{th}}{S_p} = 0.03 \text{ cm}^{-2} \text{ proton}^{-1}$$

This figure was confirmed by the Swiss group[15,18] who found that for a neutron source surrounded by a Be reflector the maximum useful flux is approximately

$$\frac{\bar{\Phi}_{th}}{S_p} = 0.02 \times \frac{E_p}{600} \text{ cm}^{-2} \text{ proton}^{-1}$$

where E_p is the proton energy in MeV.

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Table 1 Operating and Proposed Reactors

Reactor	Power (MW)	Average thermal flux (10^{15} $cm^{-2}s^{-1}$)	Annual operating cost (M $)	Annual neutron scattering program cost (M $)	Capital replacement cost (M $)
ILL Grenoble	57	1.5	31.8[a]		150-200[b]
HFIR Oak Ridge	100	1.3	4.1[c] 5.0[d]	1.1[c] 2.7[d]	
HFBR Brookhaven	40 60	0.8 1.2	2.8[c] 3.6[d]	2.5[c]	
NBSR Washington	10	0.1	12[c]	1.6[a]	
NRU Chalk River	100	0.25			
ORPHEE Saclay	14	0.3			
INP Leningrad	100	1.3			
IBR II Dubna	4	0.02			
Advanced HFIR I Oak Ridge	100 MW	3	5.5[c]		125[c]
Advanced HFIR II Oak Ridge	200 MW	6	6.0[c]		150[c]
Medium Flux Reactor	25	0.3	2[c]		45[c]

a. Ref. 4 Annual ILL operating cost (1980 $). The reactor operating costs alone are probably comparable with those for HFIR and HFBR.
b. Estimates given by W. Schmatz and G. Bauer (private communications).
c. Ref. 3 (1977 $).
d. Ref. 4 p. 81 (1980 $).

Table 2. Sources based on electron linacs

	Harwell Linac[a,b]	Orela[b]	Harwell plus Pu^{239} booster[b]	Orela plus U^{233} booster[c]	Purpose built linac[b]
Energy (MeV)	60	140	60	140	450
Average Current (mA)	0.75	0.50	0.75	0.5	1.0
Target	U^{238}	Ta	Pu^{239}	U^{233}	U^{238}
Repetition rate (sec^{-1})	300	600	300	500	150
Fast neutron pulse width (μsec)	5	0.2		0.2	
Peak neutron leakage rate (10^{17} sec^{-1})	2	10		500	
Average neutron leakage rate ($10^{14} sec^{-1}$)	3	1	40[d]	50[d]	20
Average flux ($10^{12} cm^{-2} sec^{-1}$)[e]	0.36	0.12	4.8	6.0	2.4
Capital cost (M $)			15[f]	12.5[f]	29.0
Operating cost (M $)				0.6	

a. Ref. 5
b. Ref. 6
c. Ref. 3
d. According to Ref. 6 a Pu^{239} booster gives a factor × 10 in neutron production rate. According to Ref. 3 a U^{233} booster gives a factor × 50 in neutron production rate.
e. A reasonable value for the thermal neutron flux at a well-designed moderator is ≈ 1.2×10^{-3} × average neutron leakage rate.
f. Incremental cost of booster.

Table 3(a) Operating pulsed spallation sources

	WNR Design[a,b]	WNR Operation[c]	IPNS-I	KENS[f,g]
Energy (MeV)	800	800	500	500
Average current (μA)	20	6	22	1.9
Target	U^{238}	W	U^{238}	W
Repetition rate (sec^{-1})	120	120	45	15
Protons per pulse (10^{11})	10	3	50	6
Neutrons per proton	35	12	20	16
Neutrons per pulse (10^{12})	35	3.6	100	10
Fast neutron pulse width (μsec)	10	8	0.1	0.1
Peak neutron leakage rate ($10^{18}sec^{-1}$)	2-4	0.4	600	130
Average neutron leakage rate ($10^{15}sec^{-1}$)	2-4	0.4	3	0.15
Average thermal flux ($10^{12}cm^{-2}sec^{-1}$)	2	0.7	5	0.2
Maximum thermal neutron current ($10^{12}sr^{-1}sec^{-1}$)	7	0.7	7	0.2
Accelerator[m]	L	L	RCS	S
Capital cost (M $)	200(1980)		6.4[d]	
Annual operating cost			2.0[d]	

Table 3(b) Spallation sources planned (P) or in construction(C).

	WNR(PSR)[c,e] C	IPNS-II P	SNS[g,h] C	SNQ[i] P	SNQ(PSR) P
Energy (MeV)	800	800	800	1100	1100
Average current (μA)	100	480	200	5000	5000
Target	U^{238}	U^{238}	U^{238}	Pb	Pb
Repetition rate (sec^{-1})	12	60	53	100	100
Protons per pulse (10^{11})	500	500	250	3000	3000
Neutrons per proton	35	35	35	22	22
Neutrons per pulse (10^{12})	1500	1800	600	6700	6700
Fast neutron pulse width (μsec)	0.25	0.25	0.25	500	0.7
Peak neutron leakage rate ($10^{18} sec^{-1}$)	5000	6000	3000	13	9000
Average neutron leakage rate ($10^{15} sec^{-1}$)	10-20	100	40	670	670
Average thermal flux ($10^{12} cm^{-2} sec^{-1}$) [j]	100	90	40	1000	1000
Maximum thermal neutron current ($10^{12} sr^{-1} sec^{-1}$) [k]	30	200	50	110	1100
Accelerator [m]	L	S	S	L	L
Capital cost (M $)	17 (PSR) 2 (shielding)		200	363	100(PSR)
Annual operating cost				30	

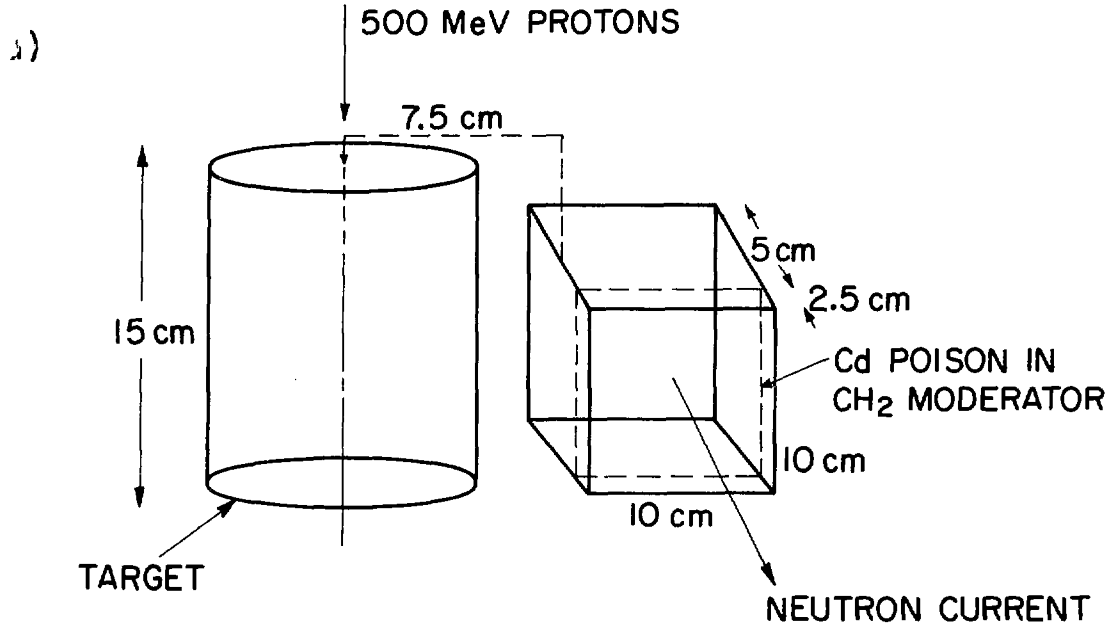
Table 3 footnotes

a. Ref. 5
b. Ref. 7
c. Ref. 4
d. Ref. 3
e. Ref. 8
f. Ref. 10
g. Ref. 6
h. Ref. 11
i. Ref. 12
j. Calculated for Pb-Bi target as in Ref. 13
k. Thermal neutron current per pulse times the pulse rate
m. L = Linac, S = Synchrotron, RCS = Rapid Cycling Synchrotron

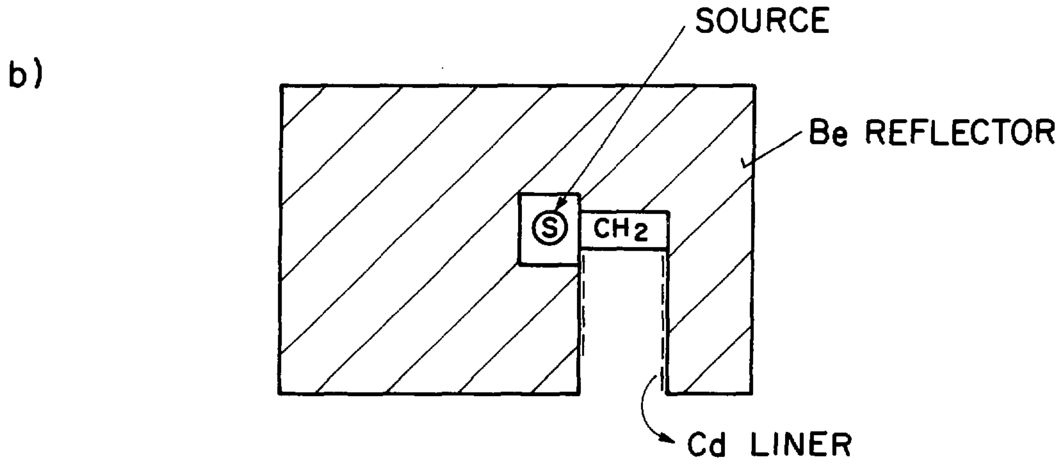
Table 4. Steady spallation sources

	TRIUMF[a,b]	SIN[c]	ING[d]	EMTF[e]
Energy (MeV)	550	600	1000	200
Average current (μA)	100	2000	65000	70000
Target	Pb-Bi	Pb-Bi	Pb-Bi	Pb-Bi
Protons(10^{14}sec^{-1})	6	120	3900	4000
Neutrons per proton	8	8	25	2-3
Average neutron leakage rate (10^{15}sec^{-1})	5	100	10000	10000
Estimated thermal flux (10^{12}cm^{-2}sec^{-1})	6	100-200	10000	1000
Accelerator[f]	C	IRC	L	L
Capital cost (M $)	0.4 (target)			

a. Ref. 16
b. Ref. 17
c. Ref. 15
d. Ref. 5
e. Ref. 19
f. Ref. L = Linac, C = Cyclotron, IRC = Isochronous ring cyclotron



BARE MODERATOR



SCHEMATIC BERYLLIUM REFLECTED MODERATOR

Fig. 1 (a) Schematic arrangement of a target and a bare poisoned moderator in a spallation source. (b) Schematic arrangement of a target and a moderator when surrounded by a beryllium reflector.

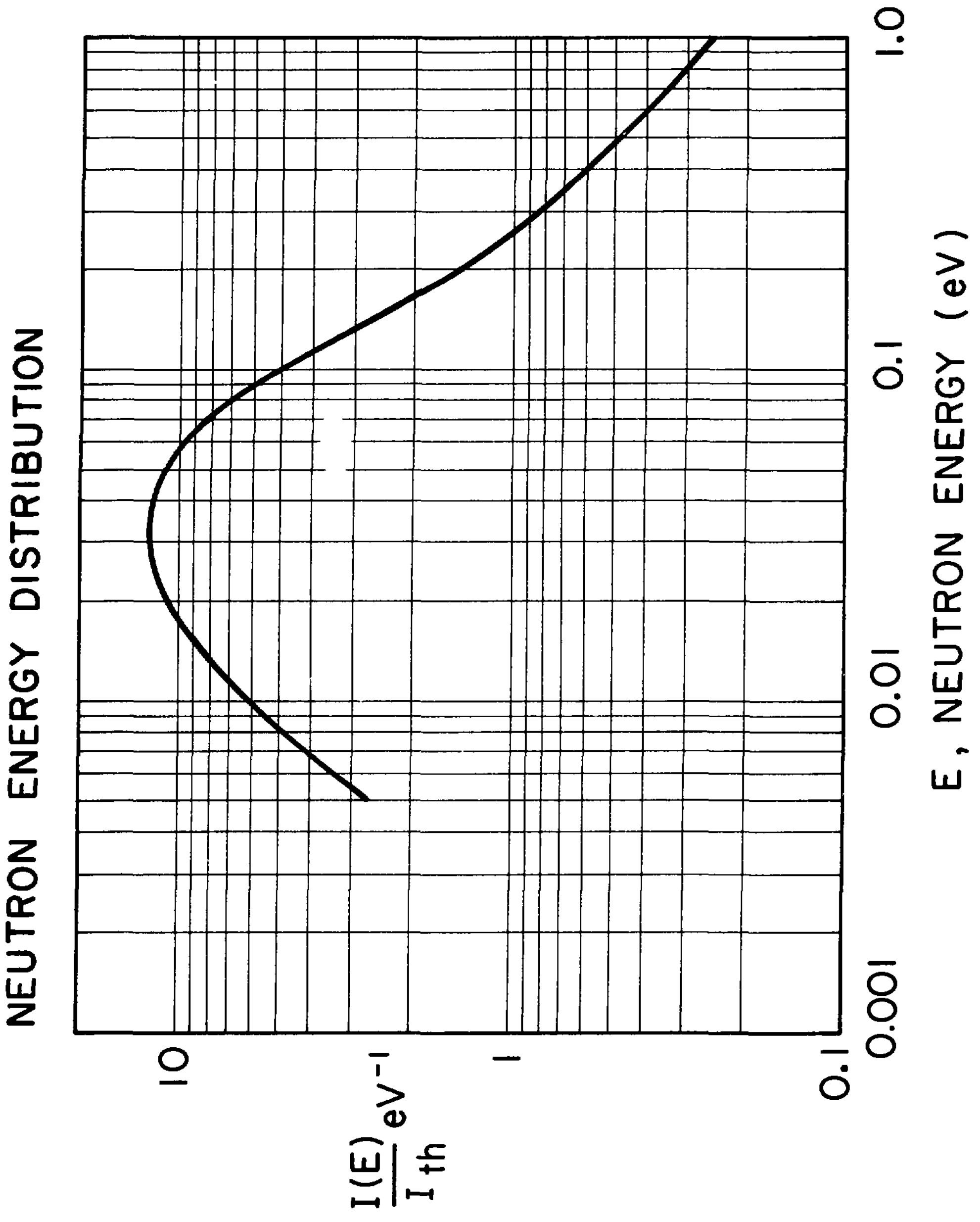


Fig. 2 Measured distribution in energy of the neutron beam current, I(E), normalized to the total angular current for a bare poisoned moderator.

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