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Comparison of Pulsed-Neutron Sources for Time-of-Flight Neutron Spectroscopy

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Abstract

Performance figures are given for fourteen pulsed-neutron sources, including reactors and electron and proton accelerators. Data are included for proposed installations as well as for existing facilities. Counting rates for a typical experiment within a specified energy resolution are given for the following neutron energies in ev: 10^2 (0.5), 10^3 (1.6), 10^4 (5), 10^5 (50), and 10^6 (500). The figures in parentheses show the assumed resolutions in ev. In addition, figures of merit are calculated which reflect the number of experiments which may be conducted simultaneously and the fractional availability of the accelerator sources for pulsed-neutron measurements. The graph showing the figures of merit illustrates that the accelerators have overwhelming advantages in count rate in the most important kev neutron-energy region. Proposed accelerators give improvements in the kev region of ten to one hundred times in counting rates over existing facilities.

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I. INTRODUCTION

In the course of justifying an electron linear accelerator to be used as a pulsed-neutron source for neutron cross-section measurements, the authors of this report have had innumerable discussions with proponents of other types of pulsed-neutron sources. After eliminating the inevitable confusion which arises in establishing satisfactory criteria of performance, it was usually possible to reach agreement on the relative basic capabilities of each source. We have assembled here data to calculate a figure of merit for the various pulsed sources of neutrons at five energies from 100 ev to 1 Mev. We hope that the combination of these data into the figures of merit is without substantial bias, but, in any event, the input numbers are included in order to permit other treatments. More subjective, but perhaps equally important, factors have been graded for each of the sources in Table III. Similar comparisons have been made in the past by E. B. Paul,[1] R. G. Fluharty,[2] and E. R. Rae.[3]

The values given throughout this document are only intended to indicate the order of magnitude of the performance of the neutron source and should not be considered as pretending great accuracy.

II. NEUTRON INTENSITY

With the increased strength of pulsed-neutron sources and the narrow pulse widths, neutron cross-section measurements are now being made with a neutron resolution of 0.5 nanoseconds/meter. This corresponds to an energy resolution of 14 ev at 10 kev computed from the formula,

$$\Delta E \text{ (in ev)} = 2.8 \times 10^{-5}\, E^{3/2} \cdot R \text{ (in nanoseconds/meter)}.$$

Although this resolution is very good it is still several times the Doppler broadening of resonances at this energy. Hence, the experimental data can be improved by decreasing the energy resolution of the spectrometer. The counting rate per resolution width is proportional to the third or fourth power of the resolution depending on whether the frequency is a limiting factor. Hence, the counting rate per resolution width decreases an order of magnitude for every factor of 2 improvement in the resolution. The width at half maximum of the Doppler broadening is

$$(\Delta E)_{\text{Doppler}} = 0.53\sqrt{\frac{E(\text{in ev})}{\text{mass number}}} \ .$$

In general, there is no reason to make the experimental resolution much less than this Doppler broadening.

The counting rate per second in an energy interval ΔE is given by the formula:

$$I(E)\ \Delta E = \left(\frac{Y}{10^9}\right)\left(\frac{n(E)\ \Delta E}{\int_0^\infty n(E)\ dE}\right)\cdot \ell_1 \cdot w \cdot \ell_2 \cdot f\left(\frac{\epsilon \cdot A}{4\pi \cdot L^2}\right)$$

where

- E is the neutron energy;
- Y is the peak neutron production rate with the optimum target (neutrons/second);
- ℓ_1 is the loss factor since the target is not always optimum size or material for maximum neutron production;
- w is the width of the unmoderated neutron pulse (nanoseconds);
- ℓ_2 is the loss factor in producing moderated neutrons;
- $n(E)$ is the intensity distribution of the unmoderated or moderated neutrons;

$\left(\frac{n(E)\ \Delta E}{\int_0^\infty n(E)\ dE}\right)$ is the fraction of the neutrons in the energy interval ΔE;

f is the repetition rate (pulses/second);

ϵ is the neutron detector efficiency;

A is the area of the detector (meters^2); and

L is the flight path (meters).

Values for some of these parameters are given in Table I. Many of these parameters are obviously energy dependent, such as the efficiency of the neutron detector, while others may be independent.

III. FIGURE OF MERIT

Some accelerators, such as LINACS, are inherently suited for multiple flight paths with simultaneous experiments since the beam is inherently extracted from the accelerator. The factor N is the increase in usefulness due to multiple flight paths. Some of the accelerators considered would be available only part time for neutron time-of-flight experiments. The factor D is the estimation of the fraction of time available for time-of-flight experiments. Hence, the over-all figure of merit $M(E)\ \Delta E$ is equal to:

$$M(E)\ \Delta E = [I(E)\ \Delta E]\cdot N\cdot D.$$

It must be emphasized that the existing accelerators may not now be capable of producing count rates equal to those shown in Table II (especially at the higher energies). The count rates given there are those that would result if the most advanced detectors and time analyzers were used in conjunction with the accelerators operating at their maximum output.

IV. COMMENTS ON TABLE II

Values of [I(E) ΔE] and [M(E) ΔE] are computed for neutron energies of:

1. 100 ev (with moderator) ΔE = 0.5 ev, the Doppler broadening for mass number 100, (~20 nanoseconds/meter).
2. 1 kev (with moderator) ΔE = 1.6 ev, the Doppler broadening for mass 100, (~6 nanoseconds/meter).
3. 10 kev (with moderator) ΔE = 5.0 ev, the Doppler broadening for mass number 100, (~0.2 nanoseconds/meter).
4. 100 kev (no moderator) ΔE = 50 ev, $\sim\sqrt{10}$ times larger than the Doppler broadening for mass number 100, (~0.06 nanoseconds/meter).
5. 1 Mev (no moderator) ΔE = 500 ev, ~10 times larger than the Doppler broadening for mass number 100, (~0.02 nanoseconds/meter).

For the calculations at 10 kev, it was found that the maximum counting rate occurred when the flight time in the source and that in the detector were each equal to burst width, w. At 1 Mev the time spread, ΔT, is almost all due to the burst width even for quite thick sources and detectors. At 100 ev the flight time in the source and detector are the main contributors and the burst width from the accelerator is not important in determining the resolution. If the neutron yield can be increased by increasing the pulse width, it should be widened until it is approximately equal to the contribution from the source or the detector, whichever is larger.

The following are comments on the various parameters:

Y, the values were taken from Table I;

ℓ_1, for the electron LINAC the data were taken from Barber and George,[4] for the proton accelerators unpublished data by

Kinney[5] at 400 Mev and extrapolations were used;

w, the values were taken from Table I;

ℓ_2, the data in Fig. 3 of Ribon and Michaudon[6] were used;

$\mathcal{L} = \ell_1 \ell_2$ is shown in Table II;

n(E), for the unmoderated neutron spectrum, a fission spectrum was assumed:

$$n(E) = 0.453\ (10^{-6})\ e^{-\frac{10^{-6}E}{0.965}} \sinh \sqrt{2.29\ (10^{-6})\ E}$$

where E is in ev.

For the moderated spectrum for the pulsed accelerators, the following equation was used:

$$n(E) = 0.1 \times \frac{10^{-3}}{\sqrt{\pi}} E^{-\frac{1}{2}} e^{-10^{-6}E}$$

where E is in ev. The coefficient 0.1 represents the fraction of unmoderated neutrons which are put in a $1/\sqrt{E}$ resonance spectrum. This $1/\sqrt{E}$ resonance spectrum is estimated for a moderator thickness of ~1 cm. For thicker moderators it will more nearly approach a 1/E spectrum, thus enhancing the lower energy neutrons, but the fraction of the neutrons which will be put into a 1/E spectrum, however, will decrease. For the moderated spectrum from a reactor, a 1/E was assumed.

Deflection or extraction efficiencies were not taken into account for the cyclotrons. In some cases this might lead to count rates which are optimistic by a factor of 10. On the other hand, some of this possible loss might be recovered by additional RF pulsing of the ion source.

f values were taken from Table I but less than

$$\frac{10^6}{10 \times \text{flight time of neutrons}}.$$

$\epsilon(E)$, a B^{10}-NaI detector was assumed with an efficiency,

$$\epsilon(E) = 0.3\ (1 - e^{-72\ x\ (\text{in cm})/\sqrt{E}}),$$

where a maximum value x of 5 cm was assumed;

A, was assumed to be 0.05 meters^2; and

L, was computed from the uncertainty in time ΔT and the required resolution.

V. COMMENTS ON FIGURE 1

The figures of merit from Table II are shown as a function of neutron energy in Fig. 1 for most of the pulsed-neutron sources.

Data are not shown in the figure for nuclear explosions because counting is not possible at the rates indicated in Table II. Other techniques, such as current measurement, may be feasible with the nuclear explosion but these would require other methods of evaluation. Thus, the explosion is included in the tables only to show that it provides a very intense neutron burst which may be useful if satisfactory detecting equipment can be developed.

The very intense and infrequent neutron bursts which would be produced by the ZGS would also give rise to serious count-loss problems. It is not clear whether these are so great as to render impractical the use of this accelerator as a pulsed-neutron source.

Among the accelerators with clearly tolerable count-loss situations, the proposed ORNL LINAC gives calculated count rates per specified energy interval which exceed those of operating neutron time-of-flight facilities by factors of ~25 to 100. Other proposed accelerators fall about 10 times below the ORNL proposal for neutron energies above 10 kev. The reactor-

associated sources are not competitive in this energy region.

The counting rates for the ORIC are not included since they are about one hundred times less than the Mc^2 cyclotron for all neutron energies. The Yale LINAC figures also are not included since they are quite close to those for the Mc^2 cyclotron.

The kev-energy region is considered to be the most important for the measurement of neutron cross sections for reasons which are described in detail elsewhere.[7] Briefly, these include the fact that existing sources are generally adequate for the lower energy region. Accurate measurements in the kev-energy region will yield information on p-wave strength functions and level spacings, which is significant for nuclear theories. Finally, the few-kev-energy region has increased in importance for fast reactors as their sizes have increased and average neutron energies have decreased.

REFERENCES

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3. E. R. Rae and W. M. Good, AERE-NP/GEN 21 (1962).
4. W. C. Barber and W. D. George, Phys. Rev. 116, No. 6, 1551-9 (1959).
5. W. E. Kinney, private communication, ORNL.
6. P. Ribon and A. Michaudon, Neutron Time-of-Flight Methods, EAEC (1961), p. 362.
7. "Proposal for a High-Intensity Short-Burst Electron Linear Accelerator for the Oak Ridge National Laboratory," ORNL, July 9, 1962.

Table I. Characteristics of the Neutron Sources

	E_0 Particle Energy (Mev)	I_p Peak Current (amps)	w Minimum Burst Width (nsec)	f Maximum Rep. Rate (sec^{-1})	y Neutron Yield (n/particle)	Y Peak Neutron Yield/sec (neutrons/sec)	References and Comments
EXISTING							
ORR Chopper			1,000	1325		3×10^{14}	Measurement for a $1/E$ spectrum.
USSR Pulsed Reactor			36,000	88			Physics of Fast and Intermediate Reactors III, IAEA, Vienna, 1962, p. 399.
Pulsed Van de Graaff	1.9	0.003	1	10^6			J. H. Neiler and W. M. Good, *Fast Neutron Physics*, Part I, Vol. IV, Interscience, New York, 1960, p. 509.
Nevis Cyclotron	400	0.3	25	60	6	1.1×10^{19}	J. Rainwater, Neutron Time-of-Flight Methods, EAEC, Brussels, 1961, p. 321; W. W. Havens, Jr., *Neutron Physics*-Proc. Sym. RPI, Academic Press, NY (1962), p. 91; and J. Rainwater *et al.*, NEVIS-81, 1959.
Harwell LINAC (no booster)	25	0.5	10	600	0.01	3×10^{16}	M. J. Poole and E. R. Wiblin, U.S. Intern. Conf. Peaceful Uses Atomic Energy, 2nd. Geneva, 1958, Paper 15/P/59; and E. R. Rae and W. M. Good, AERE-NP/GEN 21 (1962).
(with booster)	25	0.5	250	600	0.1	3×10^{17}	
RPI LINAC	60	1.5	100	600	0.03	2.8×10^{17}	E. R. Gaerttner, M. L. Yeater, and R. R. Fullwood, *Neutron Physics*-Proc. Sym. RPI, Academic Press, NY (1962); p. 263.
FUTURE							
HFIR Chopper (ORNL)			1,000	1325		3×10^{15}	Estimate for a $1/E$ spectrum.
Nuclear Explosion			80	(0.5/yr) = 6.4×10^{-8}	10^{24} fissions ~ 10 kT	5×10^{30} {0.15 leakage}	G. A. Cowan, Neutron Time-of-Flight Methods, EAEC, Brussels, 1961, p. 367.
ORIC (ORNL)	75	10^{-3}	5	20×10^6	0.25	1.5×10^{15}	J. A. Martin, ORNL, private communication, and ORNL-3324, "The Mc^2 Isochronous Cyclotron," June 15, 1962. Additional current might be obtained by pulsing the ion source.
Mc^2 Cyclotron	800	10^{-3}	7	1.4×10^7	10	6.2×10^{16}	
Yale Proton LINAC	750	1.4	0.07	25	10	8.4×10^{19}	"Yale Study of High Intensity Proton Accelerators," Internal Rept. Y-6, Prog. Rept. on Design of a Very High Intensity Linear Accelerator for Protons at an Energy of 750 Mev, Oct. 30, 1962.
ZGS (ANL)	10^4	160	10	0.25	50	4.8×10^{22}	A. B. Smith, ANL, private communications.
Electron LINAC (ORNL)	100	10	3	1.5×10^3	0.05	3×10^{18}	"Proposal for a High-Intensity Short-Burst Electron Linear Accelerator for ORNL," July 9, 1962.
El. LINAC and Booster (NRTS)	60	1.5	700	1000	0.03×100	1.0×10^{19}	R. G. Fluharty, *Neutron Time-of-Flight Methods*, EAEC, Brussels, 1961, p. 383.

Table IIa. Figures of Merit for 10^2-ev Pulsed-Neutron Sources

$\Delta E = 0.5$ ev $\frac{\Delta E}{E} = 5 \times 10^{-3}$ $n(E)\Delta E = 2.8 \times 10^{-6}$ $\epsilon = 0.3(1-e^{-7.2x})$ $A = 0.05\ m^2$	Neutron Yield	Loss Due to Finite Target and Moderator Size	Usuable Burst Width	Time Spread Due to Burst Width, Target Thickness, Moderation Time, Detector Thickness, and Electronics	Flight Path for Energy Resolution Equal to Doppler Broadening for $A = 100$	Maximum Usuable Repetition Rate	Combined Maximum Target Moderator plus Detector Thickness	Detector Efficiency	Number of Flight Paths Used Simultaneously	Availability for Pulsed Neutron Experiments	Figure of Merit for One Experiment Equals Counting Rate, I	Over-all Figure of Merit for Facility, $M = IND$
	$n(E)\Delta EY$ $(n \cdot sec^{-1} \cdot \Delta E^{-1})$	$\mathfrak{C}$	w (nsec)	ΔT (nsec)	L (meters)	f (sec^{-1})	ΔL (cm)	$\epsilon(E)$	N	D	I	M
EXISTING												
ORR Chopper	9.3×10^{10}	1.0	1,000	1,000	55	1250	5.0	0.3	1	1.0	46	46
USSR Pulsed Reactor (IBR)	4.2×10^{13}	1.0	36,000	36,000	(1900)	7.3	<<360	0.3	3	1.0	3.7	11
Pulsed Van de Graaff					NOT APPLICABLE							
Nevis Cyclotron	3.1×10^{13}	0.18	25	200	10.5	60	2.0	0.3	1	0.15	91	14
Harwell LINAC (with booster)	8.4×10^{11}	1.0	250	250	14.0	600	1.0	0.3	3	1.0	770	2,400
RPI LINAC	7.8×10^{11}	0.45	100	200	10.5	600	2.0	0.3	1	1.0	280	280
FUTURE												
HFIR Chopper	9.3×10^{11}	1.0	1,000	1,000	55	1250		0.3	1	1.0	460	460
Nuclear Explosion	1.4×10^{25}	0.5	100	200	((10.5))	6.4×10^{-8}	2.0	0.3	2	0.5	485,000[a]	485,000
Oak Ridge Isochronous Cyclotron	4.2×10^{9}	0.1	4×5[b]	220	12.2	1130	2.2	0.3	1	0.15	0.076	0.011
Mc^2 Cyclotron	1.7×10^{11}	0.1	3×7[b]	230	12.6	1100	2.2	0.3	1	0.15	3.0	0.44
Yale Proton LINAC	2.3×10^{14}	0.03	20×0.07[b]	150	8.3	25	1.5	0.3	1	0.15	4.2	0.63
Zero Gradient Sychrotron	1.3×10^{17}	0.08	10	160	8.5	0.25	2.2	0.3	1	0.15	430	64
Electron LINAC	8.8×10^{12}	0.45	100	200	10.5	1500	2.0	0.3	3	1.0	6,400	19,000
Electron LINAC and Booster	2.8×10^{13}	1.0	700	700	39.0	1000	1.0	0.3	3	1.0	15,000	45,000

[a]Count losses preclude pulse measurements for a nuclear explosion.
[b]A neutron burst consists of multiple accelerator cycles.
Note: Values in ( ) may not be realistic.

Table IIb. Figures of Merit for 10^3-ev Pulsed-Neutron Sources

$\Delta E = 1.6$ $\frac{\Delta E}{E} = 1.6 \cdot 10^{-3}$ $n(E)\Delta E = 2.8 \times 10^{-6}$ $\epsilon = 0.3(1-e^{-2.3x})$ $A = 0.05\ m^2$	Neutron Yield	Loss Due to Finite Target and Moderator Size	Usable Burst Width	Time Spread Due to Burst Width, Target Thickness, Moderation Time, Detector Thickness, and Electronics	Flight Path for Energy Resolution Equal to Doppler Broadening for $A = 100$	Maximum Usable Repetition Rate	Combined Maximum Target Moderator plus Detector Thickness	Detector Efficiency	Number of Flight Paths Used Simultaneously	Availability for Pulsed Neutron Experiments	Figure of Merit for One Experiment Equals Counting Rate, I	Over-all Figure of Merit for Facility, $M = IND$
	$n(E)\Delta EY$ $\{n \cdot sec^{-1} \cdot \Delta E^{-1}\}$		w (nsec)	ΔT (nsec)	L (meters)	f (sec^{-1})	ΔL (cm)	$\epsilon(E)$	N	D	I	M
EXISTING												
ORR Chopper	3×10^{10}	1.0	1,000	1,000	550	400	5	0.3	1	1.0	0.048	0.048
USSR Pulsed Reactor (IBR)	4.2×10^{13}	1.0	36,000	36,000	((20,000))	2.3	<<1100	0.3	3	1.0	0.014	0.031
Pulsed Van de Graaff					NOT APPLICABLE							
Nevis Cyclotron	3.1×10^{13}	0.25	25	80	44	60	2.5	0.29	1	0.15	7.0	1.0
Harwell LINAC (with booster)	8.4×10^{11}	1.0	250	250	140	600	2.5	0.3	3	1.0	7.7	22.0
RPI LINAC	7.8×10^{11}	1.0	100	160	88	600	5.0	0.3	1	1.0	7.2	7.2
FUTURE												
HFIR Chopper	3×10^{11}	1.0	1,000	1,000	550	400		0.3	1	1.0	0.47	0.47
Nuclear Explosion	1.4×10^{25}	0.5	80	130	71	6.4×10^{-8}	(4.1)	0.3	2	0.5	8500[a]	8500
Oak Ridge Isochronous Cyclotron	4.2×10^{9}	0.10	2×5[b]	100	55	800	2.2	0.29	1	0.15	0.0013	1.9×10^{-4}
Mc^2 Cyclotron	1.7×10^{11}	0.006	7	14	7.7	6000	0.45	0.16	1	0.15	0.5	0.075
Yale Proton LINAC	2.3×10^{14}	0.07	8×0.07[b]	60	33	25	1.8	0.28	1	0.15	0.23	0.035
Zero Gradient Synchrotron	1.3×10^{17}	0.005	10	20	11	0.25	0.65	0.19	1	0.15	11	1.6
Electron LINAC	8.8×10^{12}	0.30	36	56	31	1500	1.8	0.26	3	1.0	150	450
Electron LINAC and Booster	2.8×10^{13}	1.0	700	700	390	1000	2.5	0.3	3	1.0	150	450

[a] Count losses preclude pulse measurements for a nuclear explosion.
[b] A neutron burst consists of multiple accelerator cycles.
Note: Values in ( ) may not be realistic.

Table IIc. Figures of Merit for 10^4-ev Pulsed-Neutron Sources

$\Delta E = 5$ ev $\frac{\Delta E}{E} = 5 \times 10^{-4}$ $n(E)\Delta E = 2.8 \times 10^{-6}$ $\epsilon = 0.3(1-e^{-0.72x})$ $A = 0.05\ m^2$	Neutron Yield	Loss Due to Finite Target and Moderator Size	Usable Burst Width	Time Spread Due to Burst Width, Target Thickness, Moderation Time, Detector Thickness, and Electronics	Flight Path for Energy Resolution Equal to Doppler Broadening for $A = 100$	Maximum Usable Repetition Rate	Combined Maximum Target Moderator plus Detector Thickness	Detector Efficiency	Number of Flight Paths Used Simultaneously	Availability for Pulsed Neutron Experiments	Figure of Merit for One Experiment Equals Counting Rate, I	Over-all Figure of Merit for Facility, $M = IND$
	$n(E)\Delta EY$ $(n \cdot sec^{-1} \cdot \Delta E^{-1})$	C	w (nsec)	ΔT (nsec)	L (meters)	f (sec^{-1})	ΔL (cm)	$\epsilon(E)$	N	D	I	M
EXISTING												
ORR Chopper	9.3×10^9	1.0	1,000	1,000	(5,500)	125	5	0.3	1	1.0	4.6×10^{-5}	4.6×10^{-5}
USSR Pulsed Reactor (IBR)	4.2×10^{13}	1.0	36,000	36,000	((190,000))	0.7	<<3600	0.3	3	1.0	3.5×10^{-5}	1.0×10^{-4}
Pulsed Van de Graaff	3.6×10^7	1.0	1.4	2.0	11	5×10^4	0.15	0.03	1	1.0	0.0025	0.0025
Nevis Cyclotron	3.1×10^{13}	0.5	25	40	210	60	4.0	0.26	1	0.15	0.55	0.082
Harwell LINAC (with booster)	8.4×10^{11}	1.0	250	250	(1,400)	500	5.0	0.3	3	1.0	0.064	0.19
RPI LINAC	7.8×10^{11}	0.45	10	20	105	600	2.0	0.19	1	1.0	0.14	0.14
FUTURE												
HFIR Chopper	9.3×10^{10}	1.0	1,000	1,000	(5,500)	125		0.3	1	1.0	4.6×10^{-4}	4.6×10^{-4}
Nuclear Explosion	1.4×10^{25}	1.0	80	100	530	6.4×10^{-8}	10.0	0.3	2	0.5	300[a]	300
Oak Ridge Isochronous Cyclotron	4.2×10^9	0.08	5	12	64	2200	1.2	0.12	1	0.15	4.3×10^{-4}	6.5×10^{-5}
Mc^2 Cyclotron	1.7×10^{11}	0.10	7	14	70	1900	1.4	0.15	1	0.15	0.028	0.0041
Yale Proton LINAC	2.3×10^{14}	0.2	3×0.07[b]	18	97	25	2.0	0.19	1	0.15	0.019	0.0029
Zero Gradient Synchrotron	1.3×10^{17}	0.08	10	20	105	0.25	2.0	0.19	1	0.15	1.8	0.27
Electron LINAC	8.4×10^{12}	0.32	8	17.5	92	1500	1.7	0.17	3	1.0	2.6	7.7
Electron LINAC and Booster	2.8×10^{13}	1.0	700	700	(3,900)	180	5.0	0.3	3	1.0	0.28	0.83

[a]Count losses preclude pulse measurements for a nuclear explosion.
[b]A neutron burst consists of multiple accelerator cycles.
Note: Values in ( ) may not be realistic.

Table IId. Figures of Merit for 10^5-ev Pulsed-Neutron Sources

$\Delta E = 50$ ev $\frac{\Delta E}{E} = 5 \times 10^{-4}$ $n(E)\Delta E = 1.0 \times 10^{-5}$ $\epsilon = 0.3(1-e^{-0.23x})$ $A = 0.05\ m^2$	Neutron Yield	Loss Due to Finite Target Size	Usable Burst Width	Time Spread Due to Burst Width, Target Thickness, Detector Thickness, and Electronics	Flight Path for Energy Resolution Equal to Doppler Broadening for $A = 100$	Maximum Usable Repetition Rate	Combined Maximum Target Plus Detector Thickness	Detector Efficiency	Number of Flight Paths Used Simultaneously	Availability for Pulsed Neutron Experiments	Figure of Merit for One Experiment Equals Counting Rate, I	Over-all Figure of Merit for Facility, $M = IND$
	$n(E)\Delta EY$ $(n \cdot sec^{-1} \cdot \Delta E^{-1})$	$\mathcal{L}$	w (nsec)	ΔT (nsec)	L (meters)	f (sec^{-1})	ΔL (cm)	$\epsilon(E)$	N	D	I	M
EXISTING												
ORR Chopper	9.3×10^9	1.0	1000	1000	(17,000)	26	5	0.17	1	1.0	5.6×10^{-7}	5.7×10^{-7}
USSR Pulsed Reactor (IBR)					NOT APPLICABLE							
Pulsed Van de Graaff	10^8	1.0	1.4	2.0	35	13,000	0.6	0.02	1	1.0	1.2×10^{-4}	1.2×10^{-4}
Nevis Cyclotron	1.1×10^{14}	0.75	25	30	(520)	60	5	0.17	1	0.15	0.31	0.046
Harwell LINAC (no booster)	3×10^{11}	0.9	10	15	260	600	5	0.17	3	1.0	0.016	0.048
RPI LINAC	2.8×10^{12}	0.9	10	15	(260)	600	5	0.17	1	1.0	0.15	0.15
FUTURE												
HFIR Chopper	9.3×10^{10}	1.0	1000	1000	(17,000)	26	5	0.17	1	1.0	5.7×10^{-6}	5.7×10^{-6}
Nuclear Explosion	5×10^{25}	1.0	80	90	(1,600)	6.4×10^{-8}	(20)	0.3	2	0.5	120[a]	120
Oak Ridge Isochronous Cyclotron	1.5×10^{10}	0.3	5	8	140	3,100	2	0.09	1	0.15	0.0013	1.9×10^{-4}
Mc^2 Cyclotron	6.2×10^{11}	0.6	7	14	240	1,800	3	0.12	1	0.15	0.039	0.0058
Yale Proton LINAC	8.4×10^{14}	0.15	0.07	3	52	25	0.8	0.04	1	0.15	0.013	0.0019
Zero Gradient Synchrotron	4.8×10^{17}	0.3	10	15	260	0.25	5	0.17	1	0.15	3.6	0.54
Electron LINAC	3×10^{13}	0.9	7	11	200	1,500	3	0.12	3	1.0	3.4	10
Electron LINAC and Booster					NOT APPLICABLE							

[a]Count losses preclude pulse measurements for a nuclear explosion.
Note: Values in ( ) may not be realistic.

Table IIa. Figures of Merit for 10^6-ev Pulsed-Neutron Sources

$\Delta E = 500$ ev $\frac{\Delta E}{E} = 5.0 \times 10^{-4}$ $n(E)\Delta E = 1.7 \times 10^{-4}$ $\epsilon = 0.3(1 - e^{-0.072x})$ $A = 0.05\ m^2$	Neutron Yield	Loss Due to Finite Target Size	Usable Burst Width	Time Spread Due to Burst Width, Target Thickness, Detector Thickness, and Electronics	Flight Path for Energy Resolution Equal to Doppler Broadening for $A = 100$	Maximum Usable Repetition Rate	Combined Maximum Target Plus Detector Thickness	Detector Efficiency	Number of Flight Paths Used Simultaneously	Availability for Pulsed Neutron Experiments	Figure of Merit for One Experiment Equals Counting Rate, I	Over-All Figure of Merit for Facility, $M = IND$
	$n(E)\Delta EY$ $(n \cdot sec^{-1} \cdot \Delta E^{-1})$	$\mathfrak{L}$	w (nsec)	ΔT (nsec)	L (meters)	f (sec^{-1})	ΔL (cm)	$\epsilon(E)$	N	D	I	M
EXISTING												
ORR Chopper					NOT APPLICABLE							
USSR Pulsed Reactor (IBR)					NOT APPLICABLE							
Pulsed Van de Graaff					NOT APPLICABLE							
Nevis Cyclotron	1.9×10^{15}	1.0	25	26	(1,440)	60	10	0.09	1	0.15	0.49	0.074
Harwell LINAC (no booster)	5.1×10^{12}	1.0	10	12.5	680	600	10	0.09	3	1.0	0.024	0.071
RPI LINAC	4.8×10^{13}	1.0	10	12.5	(680)	600	10	0.09	1	1.0	0.22	0.22
FUTURE												
HFIR Chopper					NOT APPLICABLE							
Nuclear Explosion	8.5×10^{26}	1.0	80	85	(4,500)	6.4×10^{-8}	10	0.09	2	0.5	78[a]	78
Oak Ridge Isochronous Cyclotron	2.5×10^{11}	0.5	5	5.8	320	4,600	4	0.054	1	0.15	0.0060	9.05×10^{-4}
Mc^2 Cyclotron	1.1×10^{13}	1.0	7	9.0	500	2,900	8	0.09	1	0.15	0.32	0.048
Yale Proton LINAC	1.4×10^{16}	0.2	0.07	0.88	49	25	1.0	0.015	1	0.15	0.12	0.018
Zero Gradient Synchrotron	8.2×10^{18}	0.5	10	12.3	680	0.25	10	0.09	1	0.15	7.9	1.2
Electron LINAC	5.1×10^{14}	0.9	3	4.2	230	1,500	4	0.054	3	1.0	8.4	25
Electron LINAC and Booster					NOT APPLICABLE							

[a]Count losses preclude pulse measurements for a nuclear explosion.
Note: Values in ( ) may not be realistic.

TABLE III

QUALITATIVE EVALUATION OF PROBLEM AREAS

	Signal / Background	Count Losses	Radio-activity	Small Samples	Cost of Operating	Development Required
EXISTING:						
ORR Chopper	C	A	A	A	A	n. a.
USSR Pulsed Reactor	D	B	D	D	A	↓
Pulsed Van de Graaff	A	A	A	A	A	↓
Nevis Cyclotron	D	B	C	D	B	↓
Harwell LINAC	D	B	C	C	B	↓
RPI LINAC	C	B	B	B	B	↓
FUTURE:						
HFIR Chopper	C	A	A	A	B	A
Nuclear Explosion	B	E	C	D	D	B
ORIC	D	B	C	C	C	C
Mc^2 Cyclotron	D	C	D	D	D	C
Yale Proton LINAC	D	C	D	D	D	C
ZGS	C	D	D	D	D	D
Electron LINAC	C	B	B	B	B	B
Electron LINAC and Booster	D	C	D	D	D	D

A = most favorable
⋮
E = least favorable

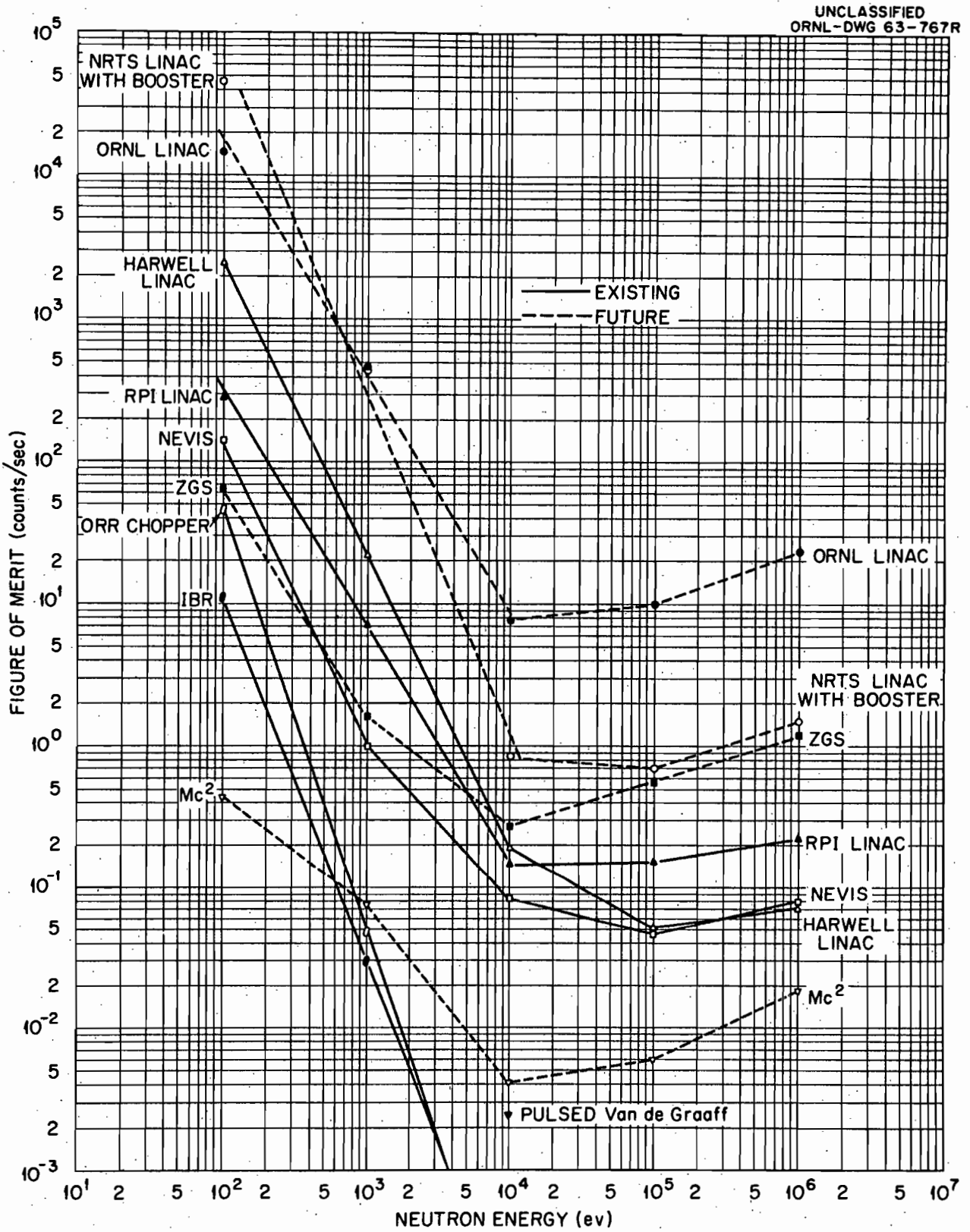

Fig. 1. Figure of Merit for Pulsed Neutron Sources.

Internal Distribution

1. E. P. Blizard
2. R. C. Block
3. G. T. Chapman
4. G. de Saussure
5. J. L. Fowler
6. R. Gwin
7-31. J. A. Harvey
32. W. H. Jordan
33. J. D. Kington
34. R. L. Macklin
35-59. F. C. Maienschein
60. R. W. Peelle
61. E. G. Silver
62. G. M. Slaughter
63. A. H. Snell
64. V. V. Verbinski
65. A. M. Weinberg
66. L. W. Weston
67-68. Central Research Library
69-70. Document Reference Section
71-105. Laboratory Records
106. Laboratory Records (ORNL-RC)
107. ORNL Patent Office
108-122. DTIE, AEC
123. Research and Development, ORO