LA-6020

UC-34c

Issued: March 1977

Parametric Studies of Target/Moderator Configurations for the Weapons Neutron Research (WNR) Facility

by

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7408-ENG. 16

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$5.00 Microfiche \$3.00

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PARAMETRIC STUDIES OF TARGET/MODERATOR CONFIGURATIONS FOR THE WEAPONS NEUTRON RESEARCH (WNR) FACILITY

by

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ABSTRACT

Parametric studies, using continuous-energy Monte Carlo codes, were done to optimize the neutronics of the Weapons Neutron Research (WNR) target and three possible target/moderator configurations; slab-target / slab-moderators, cylindrical-target / cylindrical-moderator, and cylindrical-target / double-wing-moderators. The energy range was 0.5 eV to 800 MeV. A general figure-of-merit (FOM) approach was used. The WNR facility performance can be doubled or tripled by optimizing the target and target/moderator configurations; this is more efficient than increasing the Clinton P. Anderson Meson Physics Facility (LAMPF) accelerator power by an equivalent factor. A bare target should be used for neutron energies above ~100 keV. The FOM for the slab-target/slab-moderator is the best by a factor of at least 2 to 3 below ~1 keV. The total neutron leakage from 0.5 eV to 100 keV through a 100- by 100-mm area centered at the peak leakage is largest for the slab moderator, exceeding that of the cylindrical moderator and double-wing moderator by factors of 1.7 and 3.4, respectively. The neutron leakage at 1 eV from one 300- by 150-mm surface of a slab moderator is 1.5 times larger than that from one 155- by 150-mm surface of a cylindrical moderator. When compared with the 1-eV leakage from two 100- by 150-mm surfaces of a double-wing moderator, that from the slab moderator is 3.4 times larger.

1. INTRODUCTION

A facility designed as a source of neutrons for time-of-flight (TOF) experiments should provide a short, intense burst of neutrons. The neutrons should have the particular energy and repetition rate needed for the experiment to be performed. Also, multiple experiments should be served. The Weapons Neutron Research (WNR) facility, which has been built at the Los Alamos Scientific Laboratory (LASL), is such a pulsed neutron

source.^{1,2} The WNR will provide polyenergetic neutron pulses with energies from ~800 Mev down to subthermal. Neutrons will be produced from the interaction of 800 MeV protons from the Clinton P. Anderson Meson Physics Facility (LAMPF)^{3,4} with the WNR target.

The two neutron-producing target areas of the WNR are shown in Fig. 1. The high-current area (target 1) uses a vertical target and should accept up to 2% of the LAMPF proton beam. The low-current area (target 2) utilizes a horizontal target to accept

Fig. 1.

The WNR facility. The high-current target is located in a vertical beam, allowing absorption of the forward high-energy neutrons in the earth. This high-current target has 1' horizontal neutron flight paths and requires a massive shield. The low-current target area provides for minimal neutron return from the walls.

up to 0.01% of the proton beam or to act as a scattering chamber using neutrons from target 1.

Figure 2 shows target 1 in more detail. The target is surrounded by a cylindrical void ~2 m in diameter and ~2 m high, then by a laminated iron-concrete shield ~3.7 m thick. Eleven horizontal flight paths view target 1. Six of them can be extended beyond the walls of the target-1 building. Target 2 is further illustrated in Fig. 3. The central target area is at least 6 m from any wall, floor, or ceiling to reduce backscattered neutrons.

The computational study done to determine the target and target/moderator configurations for the WNR is the subject of this report. The energy range

of the calculations was 0.5 eV to 800 MeV. The topics that are discussed include:

- neutron yields and leakage spectra from targets as a function of target geometry, material, and proton beam spot size,
- neutron yields and leakage spectra from moderators as a function of target/moderator geometry and moderator materials,
- figure of merit, pulse widths and mean emission times of leakage neutrons, and
- time, space, and angular distributions of leakage neutrons.

The target/moderator geometries studied are shown in Fig. 4. The sizes have been optimized

Fig. 2.

The high-current target area and flight paths.

Fig. 3.

The low-current target area and flight paths.

neutronically for each configuration, but collimation or neutron and gamma-ray background considerations could affect the moderator dimensions. Without these constraints, the width dimension of the slab and wing moderators could be reduced without serious consequences.

A general figure-of-merit (FOM) approach was used in this study (see Appendix A). The FOM is useful to compare the neutronics of different targets and target/moderators, to estimate the optimized neutron intensity (in a time bin Δt) a distance L away from the target/moderator, and to intercompare facilities. The optimized (for energy E) neutron intensity $J(E)$ (in a time bin Δt) a distance L away from the target/moderator is related to the FOM by (see Appendix A)

$$J(E) = \left(\frac{\Delta E}{E} \right)^2 \text{FOM}(E) \quad (\text{n/cm}^2 \cdot \text{s}) \quad (1)$$

where $\Delta E/E$ is the desired relative energy resolution at energy E . For a fixed $\Delta E/E$, increasing the FOM by a factor of 2 doubles the neutron intensity in an optimized time bin Δt .

The 800-MeV proton macropulse from the LAMPF accelerator is 500 μs long and repeats 120 times a second to form the LAMPF beam. Each LAMPF macropulse consists of 100 000 micropulses, 5 ns apart. The WNR can use up to 2% of the LAMPF beam. Thus, the proton pulse for the WNR,

or WNR macropulse, varies in duration, consists of 1-2000 micropulses and repeats at 120 pps.

The variable width of the WNR macropulse allows the proton pulse duration to be matched with the time response of the WNR target or target/moderator so that a specific resolution can be achieved. Single micropulse capability will make possible high-resolution experiments. A proton storage ring (PSR) is being proposed for the WNR which could provide more intense WNR macropulses having a 2-ns width at 600 Hz or 250 ns at 1 Hz.*

The FOM for the WNR has a different relationship to the standard deviation τ (ns) of the overall time-resolution function depending upon whether the width of the WNR macropulse is assumed to be variable or fixed (see Appendix A). For a variable-width WNR macropulse with no neutron overlap considerations,

$$\text{FOM} \propto \frac{1}{\tau} \quad (2)$$

If the width of the WNR macropulse is fixed, then

$$\text{FOM} \propto \frac{1}{\tau^2} \quad (3)$$

When PSR effects are included in this report, a proton pulse having a width of 5 ns at 600 Hz was assumed.

Fig. 4.
The WNR target/moderator configurations studied.

The FOM is also directly proportional to the neutron leakage. It is important, therefore, to produce as many neutrons as possible in the shortest time when maximizing the FOM.

FOM maximization is a multiparameter process and involves primarily* the target material and geometry for a bare target, and the target and moderator materials and target/moderator geometry for a target/moderator configuration. Criteria to be considered in assessing the overall effectiveness of a target/moderator configuration are:

- neutronics (FOM),
- the effect of a shadow bar used to block out unwanted neutrons and gamma rays emitted from the target area,
- the intensity of background neutrons,
- the intensity of gamma rays emitted from the target/moderator.

*The energy of the protons is an additional consideration, however, for the present work it was fixed at 800 MeV.

- the number of beam ports served,
- the neutron leakage intensity ($n/cm^2 \cdot s$) for those experiments which do not use the entire area of the target and/or moderator,
- the angular and spatial distribution of leakage neutrons and related time delays,
- the thermal neutron leakage from the moderator, and
- the energy deposition in the target/moderator and the resulting cooling problems.

The computational and analysis methods employed in the study are discussed in Sec. II. Section III describes possible WNR target/moderator configurations. The section includes examples of the use of the FOM in estimating neutron intensities at various flight-path distances and relative energy resolutions. Conclusions are discussed in Sec. IV. The development of the optimization technique used in the work (the figure of merit) is described in Appendix A. The bulk of the data acquired in the

 

Appendix F describes the solid angle nomenclature used in these studies. Energy deposition in targets and moderators are given in Appendix G.

The results for the decoupled moderators and bare targets are presented such that the feasibility of potential WNR experiments can be assessed. Examples of how to use the FOM are given.

A. Slab-Target/Slab-Moderators

1. General Results. The neutronics of a 50-mm-thick by 300-mm-wide by 150-mm-high depleted-uranium, metal target and two 40-mm-thick by 300-mm-wide by 150 mm-high H_2O moderators were studied (see Fig. 4). Each slab moderator was 17.5 mm from the target and decoupled by a 7.5-mm-thick $^{10}B_4C$ layer located 10 mm from the target. No parametric studies were done to optimize the thickness or type of decoupler. However, the need for and effect of decouplers are briefly discussed in Appendixes B and E.

The energy spectrum of leakage neutrons from such a slab/slab configuration is shown in Fig. 5. The spectrum of neutrons above 100 keV is included because these neutrons may represent a problem to experiments which only use neutrons below 100 keV. The spectrum in Fig. 5 consists of a $1/E$ -type component below ~ 20 keV, a softened, evaporation component which peaks around 2 MeV, and a high-energy cascade component above ~ 10 MeV. In addition, there is a low-energy component (not shown) below 0.5 eV. The moderator efficiency, defined as the leakage neutrons at 1 eV per electron volt per steradian per incident fast-neutron,¹¹ is $\sim 2.0 \times 10^{-3}$ for this slab moderator. About 21.9 leakage neutrons per incident proton are produced by the bare target itself. The leakage neutrons per unit energy, $n(E)$, is related to the leakage per unit lethargy, $n(u)$, by

$$n(E) = \frac{n(u)}{E}, \quad (4)$$

where E is the energy of interest and u is the lethargy corresponding to E .

The optimized FOM for leakage neutrons from the slab moderator is shown in Fig. 6, with and without the PSR effect included in the calculation. The FOM improves substantially with the PSR. For the energies shown, the ratio of the FOM with the PSR to that without the PSR increases with energy.

Fig. 5.

Neutron leakage spectrum, (averaged over a 1-sr conical solid angle below 10 MeV and a 0.5-sr conical solid angle above 10 MeV) from one 300- by 150-mm surface of the H_2O slab moderator. A least squares fit to the spectrum was made for energies less than 10 keV. A smooth curve has been drawn through the spectrum for energies above 10 keV. The lethargy interval is 0.230.

The differences in the FOM curve shapes are due to a variable-width WNR macropulse (and a $1/r$ dependence) without the PSR, and a fixed-width WNR macropulse (and a $1/r^2$ dependence) with the PSR [see Eqs. (2) and (3) and Appendix A]. The phrase, optimized FOM, denotes that the FOM has been maximized with a parametric study involving target and moderator sizes. The FOM alone implies maximization of the WNR macropulse and time bin at each energy.

The number of micropulses in an optimized WNR macropulse for the slab moderator is shown in Fig. 7. In actual practice, however, the number of micropulses in a WNR macropulse would be chosen to obtain the FOM at a given energy for the principal experiment. On a fixed, the number of

Fig. 6

Optimized figure of merit (averaged over a 1-sr conical solid angle) for one 300- by 150-mm surface of the H_2O slab moderator, with and without the PSR. Smooth curves have been drawn through the FOM results.

micropulses is not the optimized value at other energies.

Figure 8 shows the effective FOM for a fixed WNR macropulse at six energies versus the number of micropulses. The effective FOM macropulse is without the PSR. The effective FOM data in Fig. 8 are useful in obtaining neutron intensities at energies where the WNR macropulse is not optimized; the FOM data in Fig. 7 are useful under optimized conditions.

Fig. 7

Number of μ micropulses in an optimized WNR macropulse for the slab-target/slab-moderator configuration. A smooth curve has been drawn through the results.

The standard deviation σ_{eff} of the neutron leakage pulse from the slab moderator (delta function response) is shown in Fig. 9. The overall standard deviation σ at optimized conditions, that is, an optimized WNR macropulse and an optimized time bin is also illustrated in Fig. 9. Figure 10 shows the optimized σ and the overall standard deviation at six energies for a fixed number of micropulses in a WNR macropulse.

Fig. 8.

Effective FOM (averaged over a 1-sr conical solid angle) for one 300- by 150-mm surface of the H_2O slab moderator vs the number of micropulses in the WNR macropulse, without the PSR, at six energies.

The mean emission time t_{lm} is the average time for neutrons of a given energy to leak from a target/moderator for an input delta-function proton pulse. Mean emission times t_{lm} (delta-function response) and $\bar{t}$ (t_{lm} with the effect of the WNR macropulse included) for the decoupled slab moderator are shown in Fig. 11. Note that a constant flight-path correction to account for $\bar{t}$ is not accurate because the slope of $\bar{t}$ varies with energy.

Figure 12 shows the optimized time bin as a function of energy. The average neutron surface flux* is shown in Fig. 13. The surface flux, integrated from 0.5 eV to 800 MeV, for 2000 micropulses is 1.2×10^{13} n/cm²·s. The neutron surface flux should be used to determine neutron activation rates at the surface of the moderator or target.

The spatial distribution of the integrated (over energy and angle) neutron leakage from one large moderator surface versus the axial direction z is shown in Fig. 14. The distribution peaks slightly above the moderator centerline. This spatial dis-

*Determined by dividing the weight of each escaping neutron by the absolute value of its direction cosine with respect to the surface normal and the sum divided by the moderator area involved.

Fig. 9.

Standard deviation of the neutron leakage pulse (averaged over a 1-sr conical solid angle) from one 300- by 150-mm surface of the H_2O slab moderator, without the PSR. Smooth curves have been drawn through the results.

tribution should be considered in collimator and experiment design. The decoupler reduces the neutron leakage from the moderator by ~17%.

Figure 15 shows the spatial distribution of the integrated neutron leakage from one large moderator surface as a function of the width dimension x . The distribution is not strictly a cosine function and must be considered in collimator design. About 90% of the total leakage comes from the 200-mm-wide central part of the moderator. Reducing the moderator width from 300 to 200 mm decreases the leakage by only ~2%.

Fig. 10.

Standard deviation of the neutron leakage pulse (averaged over a 1-sr conical solid angle) from one 300- by 150-mm surface of the H_2O slab moderator vs the number of micropulses in a WNR macropulse, without the PSR, at six energies.

Energy-dependent spatial, angular, and time distributions of the leakage neutrons from the slab moderator are given in Appendix B. The time distribution of leakage neutrons with an average energy of ~ 8.9 keV from the slab moderator, is compared with those from decoupled cylindrical and wing moderators in Fig. 16. A line has been drawn through each distribution for ease of comparison. The distributions are only in qualitative agreement with results given in Ref. 12. In general, the timing is dependent upon the target/moderator geometry and the source energy distribution. Be careful applying the results for a specific configuration to other geometries.

Appendix E compares H_2O and TiH_2 slab moderators. Changing the moderator from water to a material of higher hydrogen density can significantly increase the FOM below ~ 10 eV and the low-energy (< 1 eV) neutron leakage.

The slab-target/slab-moderator configuration can effectively provide, simultaneously, moderated neutron beams to six beam ports in the WNR high current target area (see Fig. 2).

Fig. 11.

Mean emission time of leakage neutrons (averaged over a 1-sr conical solid angle) from one 300- by 150-mm surface of the H_2O slab moderator, without the PSR. Smooth curves have been drawn through the results.

2. FOM Use. We will illustrate the use of the FOM and τ curves with two example calculations. We estimate (1) the flight-path length L , the time bin Δt , and the neutron intensity J at three energies when $\Delta E/E$ equals 0.001, and (2) $\Delta E/E$, Δt , and J for a 30-m flight path. The relative energy resolution $\Delta E/E$ is related to the overall standard deviation τ and the flight-path length L by

$$\frac{\Delta E}{E} = \frac{2\sqrt{E - \Delta}}{72.398L} \quad (5)$$

Fig. 12.

The optimized width of a square time bin for the slab-target/slab-moderator configuration.

where E is in millions of electron volts, τ is in nanoseconds, and L is in meters. Both computations are made with the optimized number of micropulses in the WNR macropulse. The fixed flight-path calculation is also made with a fixed number of micropulses. The results are shown in Tables I and II.

In Table I, the flight-path length increases with energy to maintain $\Delta E/E$ at 0.001. For the optimized number of micropulses and optimized time bins, $\Delta E/E$ increase with energy in Table II. When we compare these resolution values to those in Table I, we find that if $\Delta E/E$ is larger than 0.001, the flight-path lengths are shorter, and the neutron intensities are higher. Table II also shows that if the fixed value

Fig. 13.

Average neutron surface flux (all angles) at a 300- by 150-mm surface of the H_2O slab moderator, without the PSR. A least squares fit to the surface flux was made below 10 keV. Above 10 keV, a smooth curve has been drawn through the results. The lethargy interval is 0.230.

of M (number of micropulses) is smaller than its optimized value, then $J(E)$ and $\Delta E/E$ are smaller and if the fixed value of M is larger than its optimized value, then $J(E)$ and $\Delta E/E$ are larger.

Note that in estimating the neutron intensities in Tables I and II, we assume that neutrons emitted from the entire 300- by 150-mm moderator surface were usable for experiments. Because of collimation and shadow bar requirements this assumption may not be true, and the neutron intensities would be

Fig. 14.

Vertical distribution of neutrons leaking from a 300- by 150-mm surface of the H_2O moderator (all angles and energies >0.5 eV), with and without a decoupler.

lower. For example, if a shadow bar is not used but collimation reduces the (centralized) moderator area viewed to 150 by 150 mm, the neutron intensities in Tables I and II should be multiplied by 0.70 (see Fig. 15). Also, the FOM and J values in Tables I and II were based on the assumption that LAMPF would be operating at its design level of 1-mA average current.¹

B. Cylindrical-Target/Cylindrical-Moderator

The neutronics of a cylindrical moderator decoupled from a cylindrical target were studied (see Fig. 14). The depleted-uranium metal target had an o.d. of 20 mm. The H_2O decoupler had an i.d. of 70 mm and an o.d. of 65 mm. The H_2O moderator had an o.d. of 65 mm and an i.d. of 155 mm. The

Fig. 15.

Horizontal distribution of neutrons leaking from a 300- by 150-mm surface of the H_2O moderator (all angles and energies >0.5 eV), with and without a decoupler.

height of the target/moderator was 150 mm. To account for the effects of target and moderator curvature in the FOM calculation, the neutrons were projected to a spatially-limited plane* tangent to the cylinder, and conical solid angles (see Appendix F) were used for energies less than 10 MeV. Above 10

*The plane was limited to the o.d. and height of the target or moderator.

Fig. 16.

Time distributions of leakage neutrons from slab, cylindrical, and wing moderators at ~ 8.9 keV. Smooth curves have been drawn through the points. The leakage interval is 0.001 ns.

TABLE I

**FLIGHT-PATH LENGTH, TIME BIN, AND NEUTRON
INTENSITY WITH A SLAB MODERATOR WHEN $\Delta E/E$ EQUALS 0.001**

<u>E</u>	<u>Number of Micropulses M^a</u>	<u>τ^b (ns)</u>	<u>τ_{tm}^b (ns)</u>	<u>FOM^c (n/cm²·s)</u>	<u>L^d (m)</u>	<u>Δt^e (ns)</u>	<u>J^f (n/cm²·s)</u>
10 eV	157	395	230	2.25×10^{10}	34.6	791	22.5
100 eV	51	128	75	6.35×10^9	35.4	257	8.4
1 keV	22	54	31	2.35×10^9	47.2	109	2.4

^aFrom Fig. 7 - optimized.^bFrom Fig. 9.^cFrom Fig. 6.^dUsing Eq. (5).^eFrom Fig. 12.^fUsing Eq. (1) and the time bin Δt indicated.

TABLE II

**RELATIVE ENERGY RESOLUTION, TIME BIN, AND NEUTRON INTENSITY
FOR A 30-m FLIGHT PATH AND A SLAB MODERATOR**

<u>E</u>	<u>Number of Micropulses M</u>	<u>τ (ns)</u>	<u>τ_{tm}^b (ns)</u>	<u>FOM (n/cm²·s)</u>	<u>$\Delta E/E$^c</u>	<u>Δt^e (ns)</u>	<u>J^d (n/cm²·s)</u>
10 eV	157 ^a	395 ^b	230	2.25×10^{10} ^d	0.00115	791	34.2
100 eV	51 ^a	128 ^b	75	6.35×10^9 ^d	0.00118	257	13.7
1 keV	22 ^a	54 ^b	31	2.35×10^9 ^d	0.00157	109	9.1
10 eV	60	287 ^c	230	1.40×10^{10} ^e	0.000836	602	8.2
100 eV	60	140 ^c	75	8.00×10^9 ^e	0.00129	281	17.2
1 keV	60	116 ^c	31	1.55×10^9 ^e	0.00338	225	59.9

^aFrom Fig. 7 - optimized.^bFrom Fig. 9.^cFrom Fig. 10.^dFrom Fig. 6.^eFrom Fig. 8.^fUsing Eq. (5).^gUsing Eq. (A-66) and τ_{tm} from Fig. 9 (rounded to nearest nanosecond).^hUsing Eq. (1) and the time bin Δt indicated.

Fig. 17.

Neutron leakage spectrum (averaged over a 0.5-sr conical solid angle below 10 MeV and a 1-sr conical-shell solid angle above 10 MeV) from the H_2O cylindrical moderator. A least squares fit to the spectrum was made for energies less than 10 keV. A smooth curve has been drawn through the spectrum for energies above 10 keV. The lethargy interval is 0.230.

MeV, conical-shell solid angles with no spatial projection were used.

The energy spectrum of neutrons leaking from the decoupled cylindrical moderator is shown in Fig. 17. The cascade and $1/E$ -type components are similar to those of the slab moderator. The evaporation component is slightly harder for this cylindrical moderator. The cylindrical moderator efficiency at 1 eV is 5.4×10^{-4} n/eV·sr·incident-fast-neutron. About 16.8 leakage neutrons per incident proton are produced by the bare target itself.

The optimized FOM with and without the PSR is shown in Fig. 18. The number of micropulses in an optimized WNR macropulse is illustrated in Fig. 19. Below ~ 10 keV, the optimized number of micropulses is larger than that for the slab moderator. Fig. 20 shows the effective FOM at six energies versus the number of micropulses in a WNR macropulse.

Fig. 18.

Optimized figure of merit (averaged over a 0.5-sr conical solid angle) for a 155- by 150-mm plane surface tangent to the H_2O cylindrical moderator, with and without the PSR. Smooth curves have been drawn through the FOM results.

The standard deviation σ_{im} (delta-function response) and the overall standard deviation σ (optimized conditions) are depicted in Fig. 21. The standard deviations for the cylindrical moderator are slightly larger than those for the slab moderator. The overall standard deviation at six energies for a fixed number of micropulses in a WNR macropulse is illustrated in Fig. 22; the optimized σ is also shown.

Fig. 19.

Number of micropulses in an optimized WNR macropulse for the cylindrical-target/cylindrical-moderator configuration. A smooth curve has been drawn through the results.

Fig. 20.

Effective FOM (averaged over a 0.5-sr conical solid angle) for a 155- by 150-mm plane surface tangent to the H_2O cylindrical moderator vs the number of micropulses in a WNR macropulse, without the PSR, at six energies.

Fig. 21.

Standard deviation of the neutron leakage pulse (averaged over a 0.5-sr conical angle) from a 155-by 150-mm plane surface tangent to the H_2O cylindrical moderator, without the PSR. Smooth curves have been drawn through the results.

The mean emission time $\bar{\tau}_{tm}$ (delta-function response) and the overall $\bar{\tau}$ (optimized conditions) are depicted in Fig. 23. Note that $\bar{\tau}$ has a slightly different energy dependence above ~ 1 keV than below. The mean emission times for the cylindrical moderator are larger than those for the slab moderator. Figure 24 shows the optimized time bin versus energy.

The average neutron surface flux is shown in Fig. 25. The surface flux between 0.5 eV and 800 MeV is $\sim 1.3 \times 10^{12}$ n/cm²·s for 2000 micropulses. Below 100 keV the surface flux from the slab moderator is

Fig. 22.

Standard deviation of the neutron leakage pulse (averaged over a 0.5-sr conical solid angle) from a 155-by 150-mm plane surface tangent to the H_2O cylindrical moderator vs the number of micropulses in a WNR macropulse, without the PSR, at six energies.

larger than that from the cylindrical moderator; above 100 keV the surface flux from the cylindrical moderator is larger. However, because different moderators have dissimilar spatial distributions of leakage neutrons, be careful comparing surface fluxes and leakage intensities between moderators.

The spatial distribution of the integrated neutron leakage versus the axial direction z is shown in Fig. 26. The distribution peaks ~ 60 mm from the top of the moderator. The decoupler reduces the moderator neutron leakage by $\sim 8\%$. Figure 27 shows the spatial distribution of the integrated (over energy and angle) neutron leakage as a function of the width dimension x . The leakage-neutron spatial distributions need to be considered in collimator design. Energy-dependent spatial, angular, and time distributions from the cylindrical moderator are given in Appendix B.

The cylindrical-target/cylindrical-moderator configuration can simultaneously provide moderated neutron beams to all 12 beam ports in the WNR high-current target area (see Fig. 2).

Fig. 23.

Mean emission time of leakage neutrons (averaged over a 0.5-sr conical solid angle) from a 155- by 150-nm plane surface tangent to the H₂O cylindrical moderator, without the PSR. Smooth curves have been drawn through the results.

Fig. 24.

The optimized width of a square time bin for the cylindrical-target / cylindrical-moderator configuration.

Fig. 25.

Average neutron surface flux (all angles) at the outer cylindrical surface of the H_2O moderator, without the PSR. A least squares fit to the surface flux was made below 10 keV. Above 10 keV, a smooth curve has been drawn through the results. The lethargy interval is 0.230.

Fig. 26.

Vertical distribution of neutrons leaking from a 155- by 150-mm plane surface tangent to the H_2O moderator (all angles and energies > 0.5 eV), with and without a decoupler.

Fig. 27.

Horizontal distribution of neutrons leaking from a 155- by 150-mm plane surface tangent to the H_2O moderator (all angles and energies >0.5 eV), with and without a decoupler.

Using the technique described for the slab moderator, Figs. 18-22 and 24 can be used to estimate neutron intensities and relative energy resolutions.

C. Cylindrical-Target/Double-Wing-Moderators

The neutronics of two wing moderators decoupled from a cylindrical target were studied (see Fig. 4). The depleted-uranium metal target had a diameter of 30 mm. The $^{10}B_4C$ decoupler was 10 mm from the target and 7.5 mm thick. Each H_2O moderator was 50 mm thick and 100 mm wide. The target/moderator configuration was 150-mm high.

The energy spectrum of neutrons leaking from two 100- by 150-mm moderator surfaces is shown in Fig. 28. Neutrons from the target area (target, gap, and decoupler) are not included; this situation would occur when using a shadow bar. The peak of the energy distribution (at ~ 500 keV) is much softer than that for the slab moderator without a shadow bar shown in Fig. 5. The spectrum has no high-energy cascade component in Fig. 28. The $1/E$ -type component for the wing moderators has a steeper slope than that for the slab moderator. The moderator efficiency at 1 eV for the wing moderators is 7.2×10^{-4} n/eV $\cdot$ sr $\cdot$ incident-fast-neutron. About 16.9 leakage neutrons per incident proton are produced by the bare target itself.

Fig. 28.

Neutron leakage spectrum (averaged over a 1-sr conical solid angle below 10 MeV) from two 100- by 150-mm surfaces of the H_2O wing moderators. A least squares fit to the spectrum was made for energies less than 10 keV. A smooth curve has been drawn through the spectrum for energies above 10 keV. The lethargy interval is 0.230.

The optimized FOM with and without the PSR is shown in Fig. 29. Figure 30 shows the number of micropulses in an optimized WNR macropulse. Below ~ 200 eV, the number is the same for the slab and wing moderators. Above ~ 200 eV, the number is less for the wing moderators. The effective FOM versus the number of micropulses in a WNR macropulse at six energies is shown in Fig. 31.

The standard deviation of the target/moderator τ_{tm} (delta-function response) and the overall standard deviation τ (optimized conditions) are illustrated in Fig. 32. Below ~ 200 eV, the τ_{tm} for the slab and wing moderators are equivalent; above ~ 200 eV, the τ_{tm} for the wing moderators is smaller. The overall standard deviation for a fixed number of micropulses in a WNR macropulse is illustrated in Fig. 33; the optimized τ is also shown.

Fig. 29.

Optimized figure of merit (averaged over a 1-sr conical solid angle) for two 100- by 150-mm surfaces of the H₂O wing moderators, with and without the PSR. Smooth curves have been drawn through the FOM results.

Fig. 30.

Number of micropulses in an optimized WNR macropulse for the cylindrical-target/double-wing-moderator configuration. A smooth curve has been drawn through the results.

Fig. 31.

Effective FOM (averaged over a 1-sr conical solid angle) for two 100- by 150-mm surfaces of the H_2O wing moderators vs the number of micropulses in a WNR macropulse, without the PSR, at six energies.

Fig. 32.

Standard deviation of the neutron leakage pulse (averaged over a 1-sr conical angle) from two 100- by 150-mm surfaces of the H_2O wing moderators, without the PSR. Smooth curves have been drawn through the results.

Fig. 33.

Standard deviation of the neutron leakage pulse (averaged over a 1-sr conical solid angle) from two 100- by 150-mm surfaces of the H_2O wing moderators vs the number of micropulses in a WNR macropulse, without the PSR, at six energies.

The mean emission time for the target/moderator t_{tm} (delta-function response) and the overall mean emission time t (optimized conditions) are depicted in Fig. 34. Below ~ 10 eV, the t_{tm} values for the slab and wing moderators are equivalent; above ~ 10 eV the t_{tm} for the wing moderators is smaller. Note that t has a different energy dependence above ~ 1 keV than below.

Figure 35 shows the optimized time bin versus energy. The average neutron surface flux is shown in Fig. 36. The surface flux from 0.5 eV to 800 MeV is $\sim 1.4 \times 10^{12}$ n/cm²-s for 2000 micropulses in the WNR macropulse.

The spatial distribution of the integrated neutron leakage versus the axial direction z is shown in Fig. 37. The distribution peaks ~ 50 mm from the top of the moderator. The decoupler reduces the neutron leakage from the moderator by $\sim 32\%$. This reduction is larger than for the slab or cylindrical moderator, because wing moderators are more dependent on the distance between the target and moderator (see Appendix F).

Figure 38 shows the spatial distribution of the integrated (over energy and angle) neutron leakage as

Fig. 34.

Mean emission time of leakage neutrons (averaged over a 1-sr conical solid angle) from two 100- by 150-mm surfaces of the H_2O wing moderators, without the PSR. Smooth curves have been drawn through the results.

a function of the width dimension x . The wing-moderator spatial distribution is significantly different than those for the slab and cylindrical moderators and needs to be considered in collimator design. Energy-dependent spatial, angular, and time distributions from the wing moderator are described in Appendix B. The use of TiH_2 moderators instead of H_2O is given in Appendix E.

The cylindrical-target / double-wing-moderators configuration can effectively provide, simultaneously, moderated neutron beams to six beam ports in the WNR high-current target area (see Fig. 2).

Fig. 35.

The optimized width of a square time bin for the cylindrical-target/double-wing-moderator configuration.

Using the technique described for the slab moderator, Figs. 29-33 and 35 can be used to estimate the neutron intensities from two wing-type moderators.

D. Bare Targets

The parametric studies of the neutronics for various targets as a function of geometry, material, and proton beam spot size are described in Appendix C. The proton energy was 800 MeV.

The neutron production from a cylindrical target increases as the diameter and length become larger. In general, only neutrons leaking from the cylindrical surface into an appropriate solid angle are im-

Fig. 36.

Average neutron surface flux (all angles) at one 100- by 150-mm surface of the H_2O wing moderator, without the PSR. A least squares fit to the surface flux was made below 10 keV. Above 10 keV, a smooth curve has been drawn through the results. The lethargy interval is 0.230.

portant in target neutronics for TOF applications. The total neutron production, however, is important in shielding considerations. The neutron leakage spectrum from the cylindrical surface of a target becomes softer and the time response slower as the target diameter increases. The overall quality of the target neutronics, as indicated by the FOM, depends upon the intensity and time response of the

Fig. 37.

Vertical distribution of neutrons leaking from one 100- by 150-mm surface of the H_2O wing moderator (all angles and energies >0.5 eV), with and without a decoupler.

leakage neutrons as well as their energy. We found that the FOM increased as the target diameter decreased until the target diameter approached the size of the proton beam spot.

The choice of bare-target material and size should reflect

- target neutronics (spatial, angular, and energy distributions; yields; and pulse widths of leakage neutrons),
- direct experimental backgrounds (delayed neutrons from the target, high-energy neutron flash, and gamma-ray flash), and
- energy deposition in target, cooling requirements, target temperatures, material properties, target complexity and cost, etc.

Look at all these concurrently because the engineering considerations may force a compromise with the neutronic considerations in target design.

The initial WNR target material will be tantalum,¹² however, to be consistent with the target material and sizes used in the target/moderator con-

Fig. 38.

Horizontal distribution of neutrons leaking from one 100- by 150-mm surface of the H_2O wing moderator (all angles and energies >0.5 eV), with and without a decoupler.

figurations already discussed, the neutronics of a 30-mm-diam by 150-mm-long depleted-uranium target will be given.

The energy spectrum of neutrons leaking from the cylindrical surface of such a target is shown in Fig. 39. The solid angles used are described in Appendix F. The neutron leakage (all angles and energies) from the cylindrical surface is 15.5 n/p. The average energy is 64.5 MeV above 10 MeV and 2.5 MeV below 10 MeV. Of the 15.5 n/p, about 1.4 leak into π unit solid angle at 90° to the target axis. The total leakage from the target is 16.8 n/p, with 1.9 neutrons having energies greater than 10 MeV.

The FOM for the bare target with and without the PSR is shown in Fig. 40. The shape of the FOM curves are similar because the proton pulse width is essentially fixed for both situations. Above ~ 200 keV, single micropulses should be used when there is no PSR. The peak in the FOM curve with the PSR is at ~ 850 keV compared to ~ 2.5 MeV without the PSR.

Figure 41 shows the standard deviation for the target τ_t (delta-function response) and the overall standard deviation τ (optimized conditions*). The

*A single proton micropulse at the WNR target was assumed to have a standard deviation τ_n of 0.125 ns. If τ_n is significantly larger, the overall standard deviation τ and the FOM without the PSR can be affected dramatically, especially at higher energies [see Eqs. (A-46) and (A-47)].

Fig. 39.

Neutron leakage spectrum (averaged over a 0.5-sr conical solid angle below 10 MeV and a 1-sr conical-shell solid angle above 10 MeV) from a 30-mm-diam by 150-mm-high depleted-uranium target. A smooth curve has been drawn through the spectrum. The lethargy interval is 0.230.

mean emission time for the target t_i (delta-function response) and the overall mean emission time t (including WNR macropulse) are illustrated in Fig. 42. The optimized time bin versus energy is shown in Fig. 43.

The average neutron surface flux is illustrated in Fig. 44. The surface flux from ~ 1 keV to 800 MeV is

Fig. 40.

Figure of merit (averaged over a 0.5-sr conical solid angle below 10 MeV and a 1-sr conical-shell solid angle above 10 MeV) for a 30-mm-diam by 150-mm-high depleted-uranium target, with and without the PSR. Smooth curves have been drawn through the FOM results.

$\sim 1.6 \times 10^{10}$ n/cm²·s for 2000 micropulses in the WNR macropulse.

The spatial distribution of the integrated (over energy and angle) neutron leakage as a function of the axial direction z is shown in Fig. 45. The distribution peaks about 25 mm from the top of the target. This axial distribution of neutrons should be

Fig. 41.

Standard deviation of the neutron leakage pulse (averaged over a 0.5-sr conical solid angle below 10 MeV and a 1-sr conical-shell solid angle above 10 MeV) from a 30-mm-diam by 150-mm-high depleted-uranium target, without the PSR. Smooth curves have been drawn through the results.

Fig. 42.

Mean emission time of leakage neutrons (averaged over a 0.5-sr conical solid angle below 10 MeV and a 1-sr conical-shell solid angle above 10 MeV) from a 30-mm-diam by 150-mm-high depleted-uranium target, without the PSR. Smooth curves have been drawn through the results.

considered in designing collimators and vertically positioning the target.

Figures 40, 41, and 43 can be used to estimate neutron intensities from the bare target using the same procedure as for the target/moderators.

IV. CONCLUSIONS

The scoping and parametric studies done to determine the WNR target/moderator materials and the target and target/moderator configurations show that the overall problem is multiparameter and the

Fig. 43.

The optimized width of a square time bin for a 30-mm-diam by 150-mm-high depleted-uranium target.

Fig. 44.

Average neutron surface flux (all angles) from a 30-mm-diam by 150-mm-high depleted-uranium target, without the PSR. A smooth curve has been drawn through the results. The lethargy interval is 0.230.

choices are not clear-cut. In particular, definitive decisions cannot be made on leakage neutronics alone. Target design and the selection of material are influenced by

- heat transfer properties of both the target material and coolant,
- high-temperature properties of the target material,

Fig. 45.

Vertical distribution of neutrons leaking from the cylindrical surface of a 30-mm-diam by 150-mm-high depleted-uranium target (all angles and energies >0.5 eV).

- fabrication complexities and costs, and
- gamma-ray and delayed-neutron production in the target.

The choice of the moderator material and target/moderator configuration are affected by such experimental requirements as

- the feasibility of flight paths neutronically viewing the high-Z target material,
- the neutron energy and pulse widths required,
- gamma-ray production in the moderator, and
- the number of flight paths which are served simultaneously.

In addition to providing data for estimating neutron intensities when planning experiments, we supply here the information on three target/moderator configurations to which other designs can be compared.

The parametrically optimized FOM for the three target/moderator geometries studied are shown in Fig. 46. Neutrons emitted from the target area are included. The FOM for a bare, cylindrical, depleted-uranium spallation target is also given. A bare target is best for neutron energies above ~ 100 keV. The slab-target/slab-moderator is the best

target/moderator configuration by a factor of at least 2 to 3 below ~ 1 keV. Note in Fig. 46 that the FOM for the wing-type moderators is for a double-wing moderator with both moderators viewed by an experiment. If only one moderator can be viewed, the FOM for the slab moderator would then be better by a factor of 4 to 6 below ~ 1 keV. The FOM for a bare target increases with decreasing target diameter (see Appendix C). The optimized FOM with target-area neutrons omitted (a simulated shadow bar), is shown in Fig. 47. The slab moderator is still superior, the significance increasing with decreasing neutron energy.

The necessity and feasibility of using a shadow bar or another method to indirectly view the spallation target are important in moderator and collimator design. The decision is not clear-cut and depends upon experimental and radiological considerations.

In principle, the cylindrical moderator can effectively provide, simultaneously, moderated neutron beams to all 12 WNR beam ports in the high-current target area; the other 2 moderator geometries can effectively service 6 beam ports simultaneously.

The total neutron leakage from 0.5 eV to 100 keV through a 100- by 100-mm area centered at the peak leakage position is largest for the slab moderator, exceeding that for the cylindrical moderator and double-wing moderator by factors of 1.7 and 3.4, respectively. The neutron leakage at 1 eV from one 300- by 150-mm surface of the slab moderator is larger by a factor of 1.5 than that from one 155- by 150-mm surface of a cylindrical moderator. When compared with the 1-eV leakage from two 100- by 150-mm surfaces of a double-wing moderator, that from the slab moderator is 3.4 times larger. The relative magnitude of the 1-eV leakage should be indicative of the comparative ability of moderators to produce useful low-energy neutrons.¹⁴

The angular distributions of leakage neutrons from each of the three moderator geometries are similar. The spatial distributions of leakage neutrons from the bare target and the three target/moderator configurations described in this report have differences which must be considered in beam plug and collimator design for flight paths. The width dimension of the (H_2O) slab moderator can be reduced from 300 to 200 mm without seriously degrading the neutronics. Similarly, each wing of the (H_2O) double-wing moderator can be

Fig. 46.

Optimized WNR figure of merit (averaged over a 1-sr conical solid angle) for depleted-uranium targets, $^{10}\text{B}_4\text{C}$ decouplers, and H_2O moderators.

reduced in width from 150 to 100 mm without any serious consequences.

In general, the time dependence of leakage neutrons from a given moderator material varies with target/moderator configuration, and care should be exercised when comparing this information for different geometries.

The neutronics of moderators can be significantly improved, at least for energies less than ~ 10 eV, by using moderator materials with hydrogen density

higher than that of H_2O . A heterogeneous moderator arrangement may be essential to enhance neutronics at low energies for some moderator materials. Reflected moderator arrangements, reentrant geometry, heterogeneous and homogeneous poisoning, and lowered moderator temperature are additional ways to improve moderator neutronics for thermal and subthermal neutron energies.

The initial WNR target will be a solid cylinder of tantalum 25.4 mm in diameter by 150 mm high. The

Fig. 47.
Optimized WNR figure of merit (averaged over a 1-sr conical solid angle) for depleted-uranium targets, $^{10}\text{B}_4\text{C}$ decouplers, and H_2O moderators (target-area neutrons omitted).

target will be cooled by water. The initial WNR moderators will be polyethylene or water; other hydrides will be considered if they resist radiation damage and can be cooled effectively. Poisoned and low-temperature moderators may be used for special experimental applications. The WNR target/moderator handling system will be versatile and will take a variety of target/moderator configurations. The actual configuration will be the best combination of the geometries shown in Fig. 4. The use of decouplers between the target and moderators may not be necessary, especially when using a tantalum target. Further work has to be done to determine the need for decouplers and their effect on the moderator figure of merit and background. The neutronics of the final WNR target and target/moderator configuration will be described in a separate report.

Target and target/moderator design is a crucial component in the overall concept of a pulsed neutron source. Flight-path orientation can be dependent upon the design. Significant gains in the neutronics of a facility can be obtained by optimizing the target and target/moderator configurations.

ACKNOWLEDGMENTS

The authors wish to thank G. P. Lawrence, M. S. Moore, and J. J. Malanify for helpful discussions and encouragement during this work. The editorial assistance of M. DeLancy and typing help of V. Bennett and E. Wood are greatly appreciated.

APPENDIX A

FIGURE OF MERIT

1. TIME-OF-FLIGHT SPECTROMETER CONDITIONS

The number of neutrons of energy E at time $t + L/v(E)$ crossing an area normal to a distance L , measured from the neutron source, can be written

$$J[L, E, t + L/v(E)] = T(E) \int_{\text{source}} \int_{\text{area about } \vec{r}} S_0 \eta(\vec{r}, E, \vec{\Omega}, t) d\vec{\Omega} d\vec{r}, \quad (\text{A-1})$$

where

$\eta(\underline{r}, E, \underline{\Omega}, t)$ = production efficiency of the source
 S_0 = source term
 $\Delta\Omega$ = the average solid angle subtended by the area of interest at the source
 $v(E)$ = neutron speed corresponding to energy E .

The factor $T(E)$ has been introduced to allow for absorption losses and the effective reduction in solid angle from collimators or other apparatus between the neutron source and area of interest.^{10,16} Several interpretations can be given to the source term and the production efficiency:

- 1) If S_0 is the amount of energy produced during a pulse from a pulsed reactor,¹⁷ then $\eta(\underline{r}, E, \underline{\Omega}, t)$ would represent the number of neutrons leaving a moderator adjacent to the reactor at time t from a unit area located about $\underline{r}$ in a unit interval about E , traveling in a unit solid angle about the direction $\underline{\Omega}$, per unit energy produced in the reactor pulse.
- 2) If S_0 represents the total number of fast neutrons incident upon a moderator per pulse, then $\eta(\underline{r}, E, \underline{\Omega}, t)$ would be the number of neutrons leaving the moderator at time t from a unit area located about $\underline{r}$ in a unit energy interval about E , traveling in a unit solid angle about the direction $\underline{\Omega}$, per fast neutron incident upon the moderator.*
- 3) If S_0 is the number of protons per WNR macropulse incident upon a target with an adjacent moderator (as is true for the WNR facility) then $\eta(\underline{r}, E, \underline{\Omega}, t)$ would represent the number of neutrons leaving the moderator at time t from a unit area located about $\underline{r}$ in a unit energy interval about E , traveling in a unit solid angle about the direction $\underline{\Omega}$, per proton incident upon the target.

The production-efficiency factor for the WNR facility also carries the connotation of a "transform kernel" which transforms a proton introduced into the target at $\underline{r}_0$, traveling in the direction $\underline{\Omega}_0$, with an energy E_0 at time t_0 into neutrons at $\underline{r}$, traveling in the direction $\underline{\Omega}$, with an energy E at time t . The WNR target/moderator production-efficiency factor is a very complex function of proton energy and

beam spot size, target material and geometry, moderator material and geometry, and the target/moderator neutronic coupling. This factor, however, has been computed for various targets and target/moderator configurations using Monte Carlo techniques. The integral (over area and time) of the WNR production-efficiency factor is illustrated in this report by the graphs of leakage neutrons per proton per lethargy per steradian versus energy.

The number of counts per pulse recorded (neglecting deadtime effects in the detection system) in the i th time bin (relative to the start of the source pulse) of width Δt_i by a detector with an efficiency $\epsilon(E)$ located a distance L away from a pulsed neutron source can be written as

$$C_i = \int_{\text{source area}} d\mathbf{a} \int_{\Delta\Omega \text{ about } \underline{\Omega}} d\Omega \int_{t_i - \Delta t_i/2}^{t_i + \Delta t_i/2} \epsilon(E) T(E) S_0 \eta(\underline{r}, E, \underline{\Omega}, t) dt \quad (\text{A-2})$$

where

$$t_i = \bar{t}' + \bar{t}''(E_i) + \bar{t}'''(E_i) + \frac{L}{v(E_i)} \quad (\text{A-3})$$

and, for the WNR facility,

$\bar{t}'$ = the mean arrival time of the WNR macropulse

$\bar{t}''(E_i)$ = the mean emission time of neutrons leaking from the target or target/moderator configuration

$\bar{t}'''(E_i)$ = the mean detection time

$v(E_i)$ = neutron speed corresponding to energy E_i .

The quantity $\bar{t}'''$ represents the effects of the energy-dependent mean stopping distance of neutrons in a detector. The factors $\bar{t}''$ and $\bar{t}'''$ are usually accounted for by defining an effective energy dependent flight path as

$$L(E_i) = L + \bar{t}''(E_i) + \bar{t}'''(E_i) \quad (\text{A-4})$$

*In this context, the production efficiency is analogous to the absolute yield discussed in Ref. 18, p. 421.

where

$$\bar{T}''(E_i) = v(E_i) \bar{T}''(E_i) \quad (A-5)$$

and

$$\bar{T}'''(E_i) = v(E_i) \bar{T}'''(E_i) \quad (A-6)$$

The flight-path corrections given by Eqs. (A-5) and (A-6) are constants when t'' and t''' vary as $1/\sqrt{E}$. Equation (A-2) can be divided by the time bin to give the *instantaneous* counting rate in the i th time bin,

$$\dot{C}_i \equiv \frac{C_i}{\Delta t_i} \quad (\text{counts/s} \cdot \text{pulse}) \quad (A-7)$$

Equation (A-2) can also be multiplied by the pulse repetition rate of the neutron source, f (pps), to obtain an *average* counting rate in the i th time bin,

$$\bar{C}_i \equiv f C_i \quad (\text{counts/s}) \quad (A-8)$$

Appropriate average values of $\epsilon(E)$ and $T(E)$ can be defined and Eqs. (A-2) and (A-8) combined to give

$$\begin{aligned} \bar{C}_i &= f \bar{\epsilon}_i \bar{T}_i S_0 \int_{\text{source area}} da \int_0^\infty dE \\ &\times \int_{\text{about } \bar{E}} \frac{d\Omega}{\Delta\Omega} \int_{t_i - \Delta t_i/2}^{t_i + \Delta t_i/2} n(\underline{r}, E, \underline{\Omega}, t) dt \quad (A-9) \end{aligned}$$

An average production-efficiency factor is

$$\begin{aligned} n(\underline{\Omega}, t_i) &\equiv \frac{1}{\Delta\Omega \Delta t_i} \int_{\text{source area}} da \int_0^\infty dE \\ &\times \int_{\text{about } \bar{E}} \frac{d\Omega}{\Delta\Omega} \int_{t_i - \Delta t_i/2}^{t_i + \Delta t_i/2} n(\underline{r}, E, \underline{\Omega}, t) dt \quad (A-10) \end{aligned}$$

*Section III and Ref. 12 show that the slope of mean emission time versus energy changes and is not strictly proportional to $1/\sqrt{E}$.

Equations (A-9) and (A-10) can be combined to give

$$\bar{C}_i = \bar{\epsilon}_i \bar{T}_i f S_0 n(\underline{\Omega}, t_i) \Delta\Omega \Delta t_i \quad (\text{counts/s}) \quad (A-11)$$

Now,

$$n(\underline{\Omega}, t_i \pm \Delta t_i/2) \approx n(E_i, \underline{\Omega} \pm \Delta E_i) \quad (A-12)$$

and Eqs. (A-11) and (A-12) can be combined to give the average counting rate in the i th time bin,

$$\bar{C}_i = \bar{\epsilon}_i \bar{T}_i f S_0 n(E_i, \underline{\Omega}) \Delta\Omega \Delta E_i \quad (\text{counts/s}) \quad (A-13)$$

II. FIGURE-OF-MERIT DEVELOPMENT

We will now outline a method of determining an optimized average counting rate and neutron intensity in a time bin for a given relative energy resolution $\Delta E/E$. The procedure involves the development of a concept called the figure of merit (FOM). The concept is not new,¹⁹ and the approach does have "merit" (when equitably applied and interpreted) in comparing the neutronic capability of different facilities^{20,28,29} and for optimizing the neutronics of a given facility.

A. Yield Function and Optimized Neutron Intensity

For nonrelativistic neutrons,

$$E = \frac{1}{2} m_0 v^2 = \frac{1}{2} m_0 \frac{L^2}{\tau^2} \quad (A-14)$$

where m_0 is the rest mass of the neutron. Then,

$$\left| \frac{dE}{d\tau} \right| = m_0 \frac{L^2}{\tau^3} \quad (A-15)$$

If the time bin is small, then

$$\left| \frac{\Delta E}{\Delta \tau} \right| \approx \left| \frac{dE}{d\tau} \right| = m_0 \frac{L^2}{\tau^3} \quad (A-16)$$

If the flight path is relatively long so that all parts of the source can be considered equidistant from the detector, the solid angle subtended by a detector of area A can be written

$$\Delta\Omega \approx \frac{A}{L^2} \quad (\text{sr}) \quad (\text{A-17})$$

Equations (A-13), (A-16), and (A-17) can be combined to give

$$\begin{aligned} \bar{C}_1 &= 1.04539 \times 10^{-12} A \bar{E}_1 \bar{T}_1 \text{ fS}_0 \\ &\times \eta(E_1, \Omega) \frac{\Delta\tau_1}{\tau_1^3} \quad (\text{counts/s}) \quad (\text{A-18}) \end{aligned}$$

where the units of $S_0\eta(E_1, \Omega)$ are in neutrons per electron volt per steradian per pulse, A in square centimeters, f in pulses per second, and time in seconds. Equation (A-18) does not consider restrictions on the pulse repetition rate to account for neutron overlap from one pulse to another.²² The need for this restriction will be investigated later; Eq. (A-18) holds for neutron energies where overlap is not a problem.

The standard deviation* of the overall time resolution is

$$\tau(E) \equiv \left[\tau_a^2(E) + \tau_t^2(E) + \tau_m^2(E) + \tau_1^2(E) + \tau_k^2(E) \right]^{1/2} \quad (\text{A-19})$$

where

$\tau_a(E)$ = standard deviation of the accelerator pulse, for example, of the WNR macropulse or of the electron pulse for ORELA³⁰

$\tau_t(E)$ = standard deviation of the neutron pulse from the source, for example, the neutron pulse from the WNR target, or the neutron pulse from a pulsed reactor (τ_a would be zero for this latter situation)

$\tau_m(E)$ = standard deviation of the neutron pulse from the moderator

$\tau_i(E)$ = standard deviation of the *i*th time bin

*For a normal distribution, the full width at half maximum (FWHM) is $\sim 2.35\tau$.¹¹

$\tau_k(E)$ = standard deviation of all other unresolved experimental time spreads, for example, detector response, flight-path uncertainty, Doppler broadening, etc.

The standard deviation τ_k will be ignored in the FOM development.* Therefore, the present development is limited to energies at which the TOF in the detector is small compared to τ . All graphs of $\tau(E)$ versus E in this report neglect the contribution from τ_k .

Using Eqs. (A-14) and (A-16), the relative energy resolution $\Delta E/E$ is given by

$$\left| \frac{\Delta E}{E} \right| \approx 2 \frac{\Delta\tau}{\tau} = 2 \frac{\tau(E)}{\tau} \quad (\text{A-20})$$

Then,

$$\tau = \frac{2\tau(E)}{|\Delta E/E|} \quad (\text{A-21})$$

Equations (A-16) and (A-21) can be combined to give

$$\begin{aligned} \bar{C}_1 &= \frac{1.04539 \times 10^{-12}}{8} A \bar{E}_1 \bar{T}_1 \text{ fS}_0 \\ &\times \eta(E_1, \Omega) \frac{\Delta\tau_1}{\tau_1^3(E_1)} \left(\frac{\Delta E_1}{E_1} \right)^3 \quad (\text{counts/s}) \quad (\text{A-22}) \end{aligned}$$

For a square time bin of width Δt_i ,

$$\tau_i(E_1) = \frac{\Delta t_i}{\sqrt{12}} \quad (\text{A-23})$$

Equations (A-22) and (A-23) give

$$\begin{aligned} \bar{C}_1 &= 4.52667 \times 10^5 A \bar{E}_1 \bar{T}_1 \left(\frac{\Delta t_i}{E_1} \right)^3 \text{ fS}_0 \\ &\times \eta(E_1, \Omega) \frac{\tau_1(E_1)}{\tau_1^3(E_1)} \quad (\text{counts/s}) \quad (\text{A-24}) \end{aligned}$$

*The approach, however, is identical with or without τ_k .

where the standard deviations τ are in nanoseconds. Equation (A-24) shows that for a given detector, flight-path attenuation, and relative energy resolution, the average counting rate in the i th time bin is proportional to a yield function defined as

$$Y(E_i) \equiv 4.52667 \times 10^5 \text{ FS}_0$$

$$= \tau_i(E_i) \frac{\tau_i(E_i)}{\tau^3(E_i)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad (\text{A-25})$$

The result of maximizing Y with respect to $\tau_i(E_i)$ and $\tau_n(E_i)$ for a fixed $\Delta E/E_i$ will be called the figure of merit.²⁰ For the case where there is no accelerator, maximization would be done with respect to τ_i instead of τ_n . The average counting rate in the i th time bin is then given by

$$\bar{C}_i = A \bar{E}_i \bar{T}_i \left(\frac{\Delta E_i}{E_i} \right)^3 \text{FOM}(E_i) \quad (\text{counts/s}) \quad (\text{A-26})$$

An optimized FOM implies maximizing the FOM using parametric studies. The optimized neutron intensity (in the time bin Δt_i) is

$$J(E_i) = \left(\frac{\Delta E_i}{E_i} \right)^3 \text{FOM}(E_i) \quad (\text{n/cm}^2 \cdot \text{s}) \quad (\text{A-27})$$

Relationships for the figure of merit will be developed for several different source terms after considering the effect of the time bin.

B. Optimized Time Bin

The overall facility resolution is sometimes defined as^{19,22}

$$R(L, E) \equiv \frac{\tau(E)}{L} \quad (\text{ns/m}) \quad (\text{A-28})$$

The relative energy resolution $\Delta E/E$ is related to R by [see Eqs. (A-14) and (A-20)]

*Note that L is a variable

$$\frac{\Delta E}{E} = 2 \sqrt{\frac{2}{m_0}} \sqrt{E R(L, E)} \quad (\text{A-29})$$

Also,

$$\frac{\Delta E}{E} = \frac{2\sqrt{E} \tau(E)}{72.298L} \quad (\text{A-30})$$

where L is in meters, and the units of E and $\tau(E)$ can be electron volts and microseconds or millions of electron volts and nanoseconds.

Equation (A-30) shows that for a fixed energy, the relative energy resolution decreases with an increase in L or a decrease in τ . If $\tau(E)$ and L are constant, $\Delta E/E$ increases with increasing energy and varies by a factor of 10 over two decades of energy. It is often desirable during TOF experiments to keep $\Delta E/E$ constant.^{21,31} This results when $\tau(E)$ varies continuously as $1/\sqrt{E}$. One way to vary $\tau(E)$ [see Eq. (A-19)] is to not use constant time-bins. Multiple bins are available with an on-line computer for data acquisition during a TOF experiment. The widths are, however, not continuously variable. A variable time bin is also useful in maximizing the yield function $Y(E_i)$ [Eq. (A-25)] which is part of the FOM approach. Equation (A-25) will now be maximized with respect to $\tau_i(E_i)$.

The maximization of the yield function with respect to τ_i (assuming τ_i to be continuously variable) is found from

$$\frac{1}{Y(E_i)} \frac{\partial Y(E_i)}{\partial \tau_i(E_i)} = 0 \quad (\text{A-31})$$

The derivative of $\tau(E_i)$ with respect to any of its components $\tau_j(E_i)$ is [see Eq. (A-19)]

$$\frac{\partial \tau(E_i)}{\partial \tau_j(E_i)} = \frac{\tau_j(E_i)}{\tau(E_i)} \quad (\text{A-32})$$

Then, Eq. (A-31) becomes

$$\frac{\tau^3(E_i)}{\tau_i(E_i)} \left[\frac{1}{\tau^3(E_i)} - \frac{3\tau_i^2(E_i)}{\tau^5(E_i)} \right] = 0 \quad (\text{A-33})$$

and

$$\tau_i(E_i) = \frac{\tau(E_i)}{\sqrt{3}} \quad (\text{ns}) \quad , \quad (\text{A-34})$$

where

$$\tau(E_i) = \sqrt{\frac{3}{2}} \left[\tau_a^2(E_i) + \tau_t^2(E_i) + \tau_m^2(E_i) \right]^{1/2} \quad (\text{ns}) \quad . \quad (\text{A-35})$$

Equations (A-25) and (A-34) can be combined to give a yield function with an optimized time bin. Thus

$$Y(E_i) = 2.61347 \times 10^5 \frac{f S_0 \eta(E_i, \Omega)}{\tau^2(E_i)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad , \quad (\text{A-36})$$

where $\tau(E_i)$ is given by Eq. (A-35). The optimized time bin is found from [see Eqs. (A-23) and (A-34)]

$$\Delta t_i = 2\tau(E_i) = \sqrt{6} \left[\tau_a^2(E_i) + \tau_t^2(E_i) + \tau_m^2(E_i) \right]^{1/2} \quad (\text{ns}) \quad . \quad (\text{A-37})$$

To obtain the figure of merit, Eq. (A-36) needs to be maximized with respect to $\tau_a(E_i)$ for each source-term condition.

C. Source Term

1. Fixed Source Term. If S_0 is constant, or independent of the accelerator pulse width, the figure of merit becomes [see Eq. (A-36)]

$$\text{FOM}(E_i) = \frac{\eta(E_i, \Omega)}{\tau^2(E_i)} \quad , \quad \text{if } S_0 \text{ constant and no pulses overlap} \quad . \quad (\text{A-38})$$

As shown later, the WNR FOM for single micropulses and for a WNR macropulse of proton storage ring (PSR) pulses has the form of Eq. (A-38).

Equation (A-38) is similar to other relationships^{19, 24, 25} for the figure of merit when consistent definitions are used in the product $S_0 \eta(E_i, \Omega)$, when S_0 is constant, and when there is no neutron

overlap constraint. For low-energy neutrons, the constraint on the pulse repetition frequency is

$$\max f = \frac{1}{\tau_i} = \frac{(\Delta E_i/E_i)}{2\tau(E_i)} \quad (\text{pps}) \quad , \quad (\text{A-39})$$

and the figure of merit becomes

$$\text{FOM}(E_i) = \frac{\eta(E_i, \Omega)}{\tau^3(E_i)} \quad , \quad \text{if } S_0 \text{ constant and pulses overlap} \quad . \quad (\text{A-40})$$

Since FOM includes a factor of $\Delta E_i/E_i$, the neutron intensity is proportional to $(\Delta E/E)^4$ [see Eq. (A-27)].

2. Variable Source Term. If we assume that S_0 is proportional to the duration of the accelerator pulse τ_a and neutron overlap is not considered, then

$$\text{FOM}(E_i) = \frac{\eta(E_i, \Omega)}{\tau(E_i)} \quad , \quad \text{if } S_0 \propto \tau_a \text{ and no pulses overlap} \quad . \quad (\text{A-41})$$

If the additional constraint of neutron overlap is imposed,

$$\text{FOM}(E_i) = \frac{\eta(E_i, \Omega)}{\tau^2(E_i)} \quad , \quad \text{if } S_0 \propto \tau_a \text{ and pulses overlap} \quad . \quad (\text{A-42})$$

The FOM relationship as given by Eq. (A-42) is similar to that given in Ref. 22. The neutron intensity is proportional to $(\Delta E/E)^4$.

D. WNR Figure of Merit

The WNR macropulse has a variable duration from a fraction of a nanosecond to 10 μs . Before the FOM for the WNR with a variable macropulse is developed, two special cases will be discussed: (1) the WNR FOM with the PSR and (2) the WNR FOM with a single micropulse.

1. **WNR Macropulse of PSR Pulses.** One mode of operating the planned PSR is to provide a continuous series of WNR macropulses with a pulse repetition rate of 600 pps, a source term of 1×10^{11} p/pulse, and a proton pulse width $2\tau_a$ of 2 ns (see Ref. 32). However for the FOM curves in this report, a $2\tau_a$ of 5 ns was used.⁴

To simplify the notation, the standard deviation of the overall WNR target/moderator pulse will be defined as

$$\tau_{tm}^2(E) \equiv \tau_t^2(E) + \tau_m^2(E) \quad (A-43)$$

The FOM for the WNR with the PSR becomes [see Eq. (A-36)]

$$\text{FOM}(E_1) = 1.55808 \times 10^{13} \frac{n(E_1, \Omega)}{\tau^2(E_1)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad (A-44)$$

where

$$\tau(E_1) = \sqrt{\frac{3}{2} [2.5^2 + \tau_{tm}^2(E_1)]^{1/2}} \quad (\text{ns}) \quad (A-45)$$

With no neutron overlap constraint, the FOM with the PSR varies as $1/\tau^2$. The neutron intensity in the i th time bin is found from Eq. (A-27).

2. **WNR Macropulse of a Single LAMPF Micropulse.** A single LAMPF micropulse will contain 5×10^8 protons (Ref. 4). The WNR macropulse composed of a single micropulse is estimated to have a width $2\tau_a$ of 0.25 ns (Ref. 4). With a pulse repetition rate of 120 pps, the WNR FOM with single micropulses is given by [see Eq. (A-36)]

$$\text{FOM}(E_1) = 1.56808 \times 10^{16} \frac{n(E_1, \Omega)}{\tau^2(E_1)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad (A-46)$$

where

$$\tau(E_1) = \sqrt{\frac{3}{2} [0.125^2 + \tau_{tm}^2(E_1)]^{1/2}} \quad (\text{ns}) \quad (A-47)$$

With no neutron overlap restrictions, the FOM with a single micropulse in the WNR macropulse varies as $1/\tau^2$. The neutron intensity in the i th time bin is found from Eq. (A-27).

3. **WNR Macropulse of Multiple LAMPF Micropulses.** The LAMPF proton macropulse is 500 μs long and consists of 100 000 micropulses each 5 ns apart.² The WNR macropulse can contain up to 2000 micropulses, and therefore has a variable time width. Mathematically, the WNR macropulse can be described as a chain of delta functions 5 ns apart.³³

The source term is then given by

$$S_0 = \int_0^{t_p} S(t) dt = QM \quad (\text{p/pulse}) \quad (A-48)$$

where

$S(t) \equiv$ proton production rate per pulse,

$t_p \equiv$ the duration of the WNR macropulse,

$Q \equiv 5 \times 10^8$ p/micropulse, and

$M \equiv$ number of micropulses (assumed to be delta functions).

The mean emission time for an arbitrary function $I(t)$ is

$$\bar{\tau} \equiv \frac{\int_0^\infty \tau I(\tau) d\tau}{\int_0^\infty I(\tau) d\tau} \quad (A-49)$$

and the standard deviation is

$$\tau^2 \equiv \frac{\int_0^\infty (\tau - \bar{\tau})^2 I(\tau) d\tau}{\int_0^\infty I(\tau) d\tau} = \overline{(\tau^2)} - (\bar{\tau})^2 \quad (A-50)$$

where

$$\overline{(\tau^2)} \equiv \frac{\int_0^{\infty} \tau^2 I(\tau) d\tau}{\int_0^{\infty} I(\tau) d\tau} \quad (A-51)$$

If $I(t)$ is a chain of delta functions, the mean emission time and standard deviation of the WNR macropulse are

$$\bar{\tau}_a(M) = 2.5(M-1) \text{ (ns)} \quad , M \geq 2 \quad (A-52)$$

and

$$\tau_a(M) = \sqrt{\frac{25}{12}(M^2-1)} \text{ (ns)} \quad , M \geq 2 \quad (A-53)$$

A plot of Eq. (A-53) is shown in Fig. A-1 where a smooth curve is shown instead of a histogram to simplify the figure.

The source term for the WNR is given by Eq. (A-48) or, using Eq. (A-53),

$$S_0 = Q \left[1 + \frac{12}{25} \tau_a^2(M) \right]^{1/2} \text{ (p/pulse)} \quad (A-54)$$

The source term as given by Eq. (A-54) is not exactly linear with τ_a though it is within 1% for $\tau_a > 14$ ns. Equation (A-54) can be incorporated into the yield function which has been maximized with respect to the time bin [see Eq. (A-36)] giving

$$Y(E_1) = 1.56808 \times 10^{18} \left[1 + \frac{12}{25} \tau_a^2(M) \right]^{1/2} \times \frac{\eta(E_1, \Omega)}{\tau^2(E_1)} \text{ (n/cm}^2\text{-s)} \quad (A-55)$$

where $\tau(E_1)$ is from Eq. (A-35).

The maximization of Y with respect to τ_a [where τ_a is assumed to be a continuous variable, that is, $\tau_a(M) \rightarrow \tau_a(E_1)$] is found from

$$\frac{1}{Y(E_1)} \frac{\partial Y(E_1)}{\partial \tau_a(E_1)} = 0 \quad (A-56)$$

The result is

Fig. A-1.

Standard deviation of WNR macropulse vs the number of micropulses in a WNR macropulse. A smooth curve has been drawn instead of a histogram.

$$\tau_a(E_1) = \left[\tau_{tm}^2(E_1) - \frac{25}{6} \right]^{1/2} \text{ (ns)} \quad (A-57)$$

(The solution $\tau_a(E_1) = 0$ is invalid since $M \geq 2$.) Then, using Eqs. (A-35) and (A-57), we get

$$\tau_a(E_1) = \left[\frac{\tau^2(E_1)}{3} - \frac{25}{12} \right]^{1/2} \text{ (ns)} \quad (A-58)$$

where

$$\tau(E_1) = \left[3\tau_{tm}^2(E_1) - \frac{25}{4} \right]^{1/2} \text{ (ns)} \quad (A-59)$$

Equations (A-55) and (A-58) can be combined to give

$$\text{FOM}(E_i) \approx 6.27232 \times 10^{15} \frac{n(E_i, \Omega)}{\tau(E_i)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad (\text{A-60})$$

if $\tau_a(E_i)$ is continuous and $\tau(E_i)$ is given by Eq. (A-59). Since τ_a is not a continuous variable here, the number of micropulses M in a WNR macropulse will be chosen as the integer which most nearly satisfies

$$\tau_a(M) \approx \tau_a(E_i) \quad (\text{A-61})$$

A plot of $\tau_a(E_i)$ versus $\tau_{tm}(E_i)$ is shown in Fig. A-2. As $\tau_{tm}(E_i)$ increases, $\tau_a(E_i)$ approaches $\tau_{tm}(E_i)$ as in Eq. (A-57). A plot of $\tau_a(M)$ is also illustrated in Fig. A-2 as well as the range of $\tau_{tm}(E_i)$ for each $\tau_a(M)$. The points of discontinuity $\tau_{tm}^\dagger$ in $\tau_{tm}(E_i)$ are found from [see Eq. (A-57)]

$$\tau_{tm}^\dagger = \left[\frac{[\tau_a(M+1) + \tau_a(M)]^2}{2} + \frac{25}{6} \right]^{1/2} \quad (\text{ns}) \quad (\text{A-62})$$

Note that M equals 1 (a single micropulse) for $\tau_{tm}(E_i) \leq 2.4$ ns and M equals 2 for $\tau_{tm}(E_i) \leq 3.9$ ns. For larger values of $\tau_{tm}(E_i)$, M can be determined from

$$M = \text{Int} \left[\frac{12}{25} \tau_{tm}^2(E_i) - 1 \right]^{1/2}, \quad M \geq 3 \quad (\text{A-63})$$

If $\tau_a(E_i)$ is approximated by $\tau_a(M)$, Eqs. (A-35) and (A-53) can be combined to give

$$\tau(E_i) \approx \left[\frac{25}{8}(M^2 - 1) + \frac{3}{2} \tau_{tm}^2(E_i) \right]^{1/2} \quad (\text{ns}), \quad M \geq 2 \quad (\text{A-64})$$

The WNR FOM without the PSR is then [see Eq. (A-60)]

$$\text{FOM}(E_i) \approx 6.27232 \times 10^{15} \frac{n(E_i, \Omega)}{\tau(E_i)} \quad (\text{n/cm}^2 \cdot \text{s}) \quad (\text{A-65})$$

where $\tau(E_i)$ is given by Eq. (A-64). The WNR FOM without the PSR varies as $1/\tau$, but the WNR FOM with the PSR varies as $1/\tau^2$ [see Eq. (A-44)]. The neutron intensity in the i th time bin can be found using Eq. (A-27). For a square time bin, the optimized width of the i th bin is given by [see Eqs. (A-37) and (A-64)]

Fig. A-2.

Optimized standard deviation of WNR macropulse assuming it is continuously variable, $\tau_a(E_i)$, and composed of delta-function pulses, $\tau_a(M)$, vs the standard deviation of the target/moderator neutron leakage pulse $\tau_{tm}(E_i)$.

$$\Delta t_i \approx \left[\frac{25}{2}(M^2 - 1) + 6\tau_{tm}^2 \right]^{1/2} \quad (\text{ns}) \quad (\text{A-66})$$

III. EFFECT OF A TIME-DEPENDENT PROTON PULSE

The WNR macropulse without the PSR is time dependent. If $\psi(\underline{r}, E, \Omega, t)$ represents the neutron leakage from a particular target/moderator configuration for a time-dependent WNR macropulse, then, in general,

$$\psi(\underline{r}, E, \Omega, t) = \int_{-\infty}^t S(\xi) G(\underline{r}, E, \Omega, t; \underline{r}_0, E_0, \Omega_0, \xi) d\xi \quad (\text{A-67})$$

where G is the Green's function.^{34,35} Physically a Green's function corresponds to the solution of a problem for a delta-function source, for example, a delta-function proton pulse in space, energy, angle, and time. For the WNR target/moderator

$$G(\underline{r}, E, \underline{\Omega}, t; \underline{r}_0, E_0, \underline{\Omega}_0, \xi) \equiv \begin{array}{l} \text{the neutron leakage at } \underline{r}, \\ \text{at time } t, \text{ in a unit energy} \\ \text{interval about } E, \text{ in a unit} \\ \text{solid angle about the direc-} \\ \text{tion } \underline{\Omega}, \text{ resulting from one} \\ \text{proton introduced at } \underline{r}_0 \\ \text{with energy } E_0, \text{ in the} \\ \text{direction } \underline{\Omega}_0, \text{ at time } \xi. \end{array} \quad (\text{A-68})$$

The Green's function in Eq. (A-68) is related to the production-efficiency factor $\eta(\underline{r}, E, \underline{\Omega}, t)$ discussed previously. The two functions only differ because the proton beam is assumed to be uniformly spread over a beam spot of finite size in the Monte Carlo calculations, from which $\eta(\underline{r}, E, \underline{\Omega}, t)$ is extracted. Thus

$$G(\underline{r}, E, \underline{\Omega}, t; \underline{r}_0, E_0, \underline{\Omega}_0, \xi) = \eta(\underline{r}, E, \underline{\Omega}, t - \xi) \quad (\text{A-69})$$

and

$$\psi(\underline{r}, E, \underline{\Omega}, t) = \int_0^{\infty} S(\xi) \eta(\underline{r}, E, \underline{\Omega}, t - \xi) d\xi \quad (\text{A-70})$$

(from Ref. 22), where time zero is the time when the protons first strike the WNR target. A convolution of the production efficiency and the WNR source term is necessary to obtain $\psi(\underline{r}, E, \underline{\Omega}, t)$. The mean emission time for the actual neutron leakage from a WNR target/moderator is

$$\bar{t} = \frac{\int_0^{\infty} t \psi(\underline{r}, E, \underline{\Omega}, t) dt}{\int_0^{\infty} \psi(\underline{r}, E, \underline{\Omega}, t) dt} \quad (\text{A-71})$$

IV. ENERGY, LETHARGY, AND DECADE INTERVAL

The lethargy variable, denoted by the symbol u , is defined as²⁰

$$u \equiv \ln \frac{E^*}{E}, \quad (\text{A-72})$$

where E^* is some arbitrary reference energy and $\ln$ is the symbol for a natural logarithm. The highest energy of interest in a particular problem is usually chosen to be E^* . The lethargy is then zero for particles with energy E^* and increases with decreasing energy. From Eq. (A-72), the lethargy interval Δu is

$$|\Delta u| = \left| \frac{\Delta E}{E} \right|. \quad (\text{A-73})$$

The magnitude of the lethargy interval is equal to the magnitude of the relative energy resolution [Eq. (A-20)].

The decade variable, which will be denoted by the symbol u_{10} , is a lethargy-type variable defined as

$$u_{10} = \log \frac{E^*}{E}, \quad (\text{A-74})$$

where $\log$ is the symbol for a logarithm base 10. The decade interval Δu_{10} is related to the lethargy interval by

$$\Delta u_{10} = \frac{\Delta u}{\ln(10)}. \quad (\text{A-75})$$

Then

$$|\Delta u_{10}| = \frac{1}{\ln(10)} \left| \frac{\Delta E}{E} \right|. \quad (\text{A-76})$$

APPENDIX B

VARIOUS NEUTRON LEAKAGE DISTRIBUTIONS FROM SPECIFIC TARGET/MODERATOR CONFIGURATIONS

Spatial distributions of leakage neutrons from moderators for three target/moderator geometries were discussed in the main text. Certain energy-dependent neutron leakage distributions will now be described for the three configurations (same geometries as in main text, see Fig. 4).

- 1) Slab-target/slab-moderator
 target: 50-mm-thick by 300-mm-wide by 150-mm-high depleted-uranium metal
 decouplers: two, 7.5-mm-thick by 300-mm-wide by 150-mm-high $^{10}\text{B}_4\text{C}$, 10 mm from target
 moderators: two, 40-mm-thick by 300-mm-wide by 150-mm-high H_2O , each moderator 17.5 mm from target
- 2) Cylindrical-target/cylindrical-moderator
 target: 30-mm-diam by 150-mm-high depleted-uranium metal
 decoupler: 50-mm-i.d. by 65-mm-o.d. by 150-mm-high $^{10}\text{B}_4\text{C}$
 moderator: 65-mm-i.d. by 155-mm-o.d. by 150-mm-high H_2O
- 3) Cylindrical-target/double-wing-moderator
 target: 30-mm-diam by 150-mm-high depleted-uranium metal
 decouplers: two, 50-mm-thick by 7.5-mm-wide by 150-mm-high $^{10}\text{B}_4\text{C}$, each decoupler 10 mm from target
 moderators: two, 50-mm-thick by 150-mm-wide by 150-mm-high, each moderator 17.5 mm from target

I. SPATIAL DISTRIBUTIONS

The vertical and horizontal distributions of leakage neutrons with energies of 1 eV, 100 eV, and 1 keV are shown in Figs. B-1 and B-2 for the slab-target/slab-moderator configuration. For the energies shown, the leakage neutrons tend to peak slightly above the target/moderator centerline. In the horizontal plane, the leakage neutron distributions are symmetric but appear to fall off more rapidly than cosine functions.

The vertical and horizontal leakage neutron distributions at energies of 1 eV, 10 eV, and 1 keV for a double-wing-moderator geometry are depicted in Figs. B-3 and B-4. The vertical distributions tend to be skewed above the target centerline. For the horizontal distributions at the lower energies, the peak tends to be more toward the interior of the moderator. However, because of the added dimensions of space, angle, and time, better statistics are needed before definite conclusions can be reached about any of the energy-dependent distributions discussed in this appendix; only trends are indicated.

II. ANGULAR DISTRIBUTIONS

The angular distributions of leakage neutrons about the normal to the moderator surface are shown in Figs. B-5 and B-6 for a slab moderator and a double-wing moderator, respectively. In addition to a loss of neutron intensity with angle, the pulse

Fig. B-1.

Vertical distributions of neutrons leaking from a 300- by 150-mm surface of an H_2O moderator in a slab-target/slab-moderator geometry with a $^{10}\text{B}_4\text{C}$ decoupler. Depleted-uranium target. Three neutron energies with all leakage angles included. The lethargy interval is 0.230.

Fig. B-2.

Horizontal distributions of neutrons leaking from a 300- by 150-mm surface of an H_2O moderator in a slab-target/slab-moderator geometry with a $^{10}B_4C$ decoupler. Depleted-uranium target. Three neutron energies with all leakage angles included. The lethargy interval is 0.230.

widths increase and the FOM can decrease significantly. Also, when flight paths are not perpendicular to the moderator surface, the distance uncertainty resulting from the inclination of the moderator causes another distortion and further degrades the widths of the neutron leakage pulses.^{10,27} Inclined flight paths were not specifically considered in this report because the WNR moderator can be positioned at right angles to any of the 11 horizontal flight paths in target 1.

III. TIME DISTRIBUTIONS

The time distributions of leakage neutrons from the slab moderator are shown in Fig. B-7 for six energy groups. The upper and lower bounds of each group are indicated as well as the average energy. The standard deviation and mean emission time of the leakage pulse are also shown. Similar distributions are shown in Fig. B-8 for cylindrical moderators and in Fig. B-9 for double-wing moderators. All the time distributions are for a delta-function proton pulse.

Energy-dependent time distributions are the basic characteristics of a pulsed neutron source.

Fig. B-3.

Vertical distributions of neutrons leaking from one 100- by 150-mm surface of an H_2O wing moderator in a cylindrical-target/double-wing-moderator geometry with a $^{10}B_4C$ decoupler. Depleted-uranium target. Three neutron energies with all leakage angles included. The lethargy interval is 0.230.

Fig. B-4.

Horizontal distributions of neutrons leaking from one 100- by 150-mm surface of an H_2O wing moderator in cylindrical-target/double-wing-moderator geometry with a $^{10}B_4C$ decoupler. Depleted-uranium target. Three neutron energies with all leakage angles included. The lethargy interval is 0.230.

Fig. B-5.

Angular distributions (from the normal to the moderator surface) of neutrons leaking from a 300- by 150-mm surface of an H₂O moderator in a slab-target/slab-moderator geometry with a ¹⁰B₄C decoupler. Depleted-uranium target. The lethargy interval is 0.230.

Fig. B-6.

Angular distributions (from the normal to the moderator surface) of neutrons leaking from one 100- by 150-mm surface of an H₂O moderator in a cylindrical-target/double-wing-moderator geometry with a ¹⁰B₄C decoupler. Depleted-uranium target. The lethargy interval is 0.230.

Fig. B-7.

Time distributions of neutrons leaking from a 300- by 150-mm surface of an H_2O moderator in a slab-target/slab-moderator geometry with a $^{10}\text{B}_4\text{C}$ decoupler. Depleted-uranium target, all leakage angles included. The lethargy interval is 0.230.

Fig. B-8.

Time distributions of neutrons leaking from a 155- by 150-mm plane surface tangent to an H_2O moderator in a cylindrical-target/cylindrical-moderator geometry with a $^{10}\text{B}_4\text{C}$ decoupler. Depleted-uranium target, all leakage angles included. The lethargy interval is 0.230.

Fig. B-9.

Time distributions of neutrons leaking from one 100- by 150-mm surface of an H_2O wing moderator in a cylindrical-target/double-wing-moderator geometry with a $^{10}\text{B}_4\text{C}$ decoupler. Depleted-uranium target, all leakage angles included. The lethargy interval is 0.230.

APPENDIX C

CHARACTERISTICS OF BARE TARGETS

The neutronics of targets bombarded by high-energy protons depend upon the target material and geometry as well as the proton energy and beam spot size. The energy of leakage neutrons produced by 800-MeV protons striking a target can be as high as 800 MeV and, depending on target material and size, can extend into the 10- to 100-keV range. All computations reported here are for 800-MeV incident protons.

The computed neutron leakage spectrum from a cylindrical depleted-uranium target is shown in Fig. C-1. The leakage neutron spectrum is depicted as the "transported neutrons" curve. The evaporation component of the spallation process is depicted as the "nontransported neutrons" curve. The difference between the two curves (below 20 MeV) results from transporting the evaporation neutrons from their points of origin within the target to the target surface. The spectrum of the "transported neutrons" is softer and more intense than the evaporation spectrum because of inelastic scattering, fission, and (n,2n)-type processes. The increase in the total number of "transported neutrons" over the "nontransported neutrons" is ~10% for this target. Essentially 93% of the leakage neutrons have energies below 20 MeV. The amount of "leakage enhancement" depends upon the target material and size.

I. NEUTRON YIELDS FROM TARGETS

The total number of leakage neutrons (important for shielding calculations) and the neutron leakage from pertinent target surfaces (important for target/moderator neutronics) have been computed for various target geometries and materials.

A. Cylindrical Targets with Pencil and Circular Proton Beam Spots

The total and cylindrical-surface leakage from ^{238}U targets, for protons uniformly distributed over a 15-mm-diam circle, is shown in Fig. C-2 as a function of target diameter and height. The total neutron leakage increases with target height and

levels off at a target diameter of ~150 mm. The neutron leakage from the cylindrical surfaces goes through a maximum as the leakage from the ends of the target increases. The peaking is more pronounced for the shorter targets. The neutron leakage intensity (neutrons per proton per square centimeter) from the cylindrical surface decreases with increasing target diameter for all the target heights shown. In general, unless the target/moderator is reflected,¹⁴ only neutrons leaking from the cylindrical surface can contribute to the neutronics of a moderator placed adjacent to the target.

Fig. C-1.

Neutron leakage and evaporation spectra for a 30-mm-diam by 150-mm-high depleted-uranium target. The lethargy interval is 0.230

Fig. C-2.

Neutron leakage from ^{238}U targets bombarded by 800-MeV protons distributed uniformly over a 15-mm-diam beam spot.

The neutron yields for other cylindrical targets with pencil and other circular proton beam spot sizes are given in Table C-I.

B. Cylindrical Targets with Gaussian Proton Beam Spot

The total and cylindrical-surface neutron leakage from various 150-mm-high targets were computed for protons distributed in a truncated Gaussian beam spot with one standard deviation in a radius of 7.5 mm. The Gaussian was truncated at the radius of the target. The results are given in Table C-II.

C. Rectangular Targets with Circular Proton Beam Spot

The total neutrons leakage from tungsten and depleted-uranium rectangular targets was computed for protons distributed uniformly over a circular beam spot. The results are shown in Table C-III.

II. NEUTRON LEAKAGE SPECTRA, PULSE WIDTHS, AND MEAN EMISSION TIMES FOR CYLINDRICAL TARGETS

The neutron leakage spectrum from the cylindrical surface of 150-mm-high ^{238}U targets is shown in Fig. C-3 for three target diameters. The spectrum becomes softer as the target diameter increases.

As shown in Fig. C-4, the pulse widths of leakage neutrons below ~100 MeV become larger as the target diameter increases. The leakage neutrons above ~100 MeV tend to have narrower pulse widths for the larger target diameters.

The mean emission times (the average time for neutrons of a given energy to leak from a target) increase as the target diameter becomes larger. This effect is illustrated in Fig. C-5.

The energy, angular, spatial, and time distributions, as well as yield and intensity, of neutrons leaking from a target not only determine target neutronics but also affect the neutronics of a moderator placed adjacent to the target.

III. AXIAL, ANGULAR, AND ENERGY DISTRIBUTIONS FROM CYLINDRICAL TARGETS

The range of 800-MeV protons in depleted uranium is ~250 mm.¹⁴ The calculated total yield of leakage neutrons from a 30-mm-diam by 250-mm-high cylinder of depleted uranium bombarded with 800-MeV protons is ~18.3 n/p (see Table C-I). Of these 18.3 neutrons, 17.2 leak from the cylindrical surface and the remaining 1.1 leak from the target

TABLE C-1
NEUTRON LEAKAGE FROM CYLINDRICAL TARGETS BOMBARDED
BY 800-MeV PROTONS ON AXIS AND DISTRIBUTED
UNIFORMLY OVER CIRCULAR BEAM SPOTS

			Neutron Leakage (n/p)																	
Target ^a	Target Diameter (mm)	Target Length (mm)	Pencil Beam Spot on Axis		5-mm-diam Beam Spot		10-mm-diam Beam Spot		15-mm-diam Beam Spot		20-mm-diam Beam Spot		30-mm-diam Beam Spot		50-mm-diam Beam Spot		70-mm-diam Beam Spot		100-mm-diam Beam Spot	
			T ^b	C-S ^b	T	C-S	T	C-S	T	C-S	T	C-S	T	C-S	T	C-S	T	C-S	T	C-S
²³⁸ U	10	150	11.8	11.5	11.3	10.9	9.8	9.5	---	---	---	---	---	---	---	---	---	---	---	---
U	15	150	---	---	---	---	13.3	12.8	11.7	11.2	---	---	---	---	---	---	---	---	---	---
²³⁵ U	20	150	15.1	14.3	14.9	14.0	14.9	14.1	14.1	13.4	12.8	12.1	---	---	---	---	---	---	---	---
U	20	150	---	---	15.3	14.4	15.2	14.4	14.5	13.7	---	---	---	---	---	---	---	---	---	---
²³⁵ U	30	150	17.0	15.7	16.5	15.4	17.0	15.5	16.5	15.2	16.3	15.0	14.7	13.6	---	---	---	---	---	---
U	30	150	---	---	---	---	---	---	16.9	15.5	---	---	---	---	---	---	---	---	---	---
U	30	200	---	---	---	---	---	---	18.0	16.8	---	---	---	---	---	---	---	---	---	---
Cu	30	250	---	---	---	---	---	---	4.8	4.5	---	---	---	---	---	---	---	---	---	---
U	30	250	---	---	---	---	---	---	18.3	17.2	---	---	---	---	---	---	---	---	---	---
U	40	150	---	---	---	---	---	---	18.2	16.3	---	---	---	---	---	---	---	---	---	---
U ^c	50	150	---	---	---	---	---	---	19.5	16.8	---	---	---	---	---	---	---	---	---	---
U	50	150	---	---	---	---	---	---	19.3	16.7	---	---	---	---	---	---	---	---	---	---
U	60	150	---	---	---	---	---	---	20.1	16.9	---	---	---	---	---	---	---	---	---	---
U ^c	100	150	22.6	16.6	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
U	100	150	22.7	16.6	---	---	---	---	22.3	16.4	---	---	---	---	22.3	16.6	21.9	16.6	19.2	15.0
U	100	300	26.6	22.6	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
²³⁸ U	150	250	---	---	---	---	---	---	25.8	20.6	---	---	---	---	---	---	---	---	---	---
²³⁵ U	200	250	---	---	---	---	---	---	25.9	18.5	---	---	---	---	---	---	---	---	---	---

^aThe symbol ²³⁸U refers to a ²³⁸U target with an atom density of 4.73×10^{22} atoms/cm³. The symbol U refers to a depleted-uranium (0.2 wt% ²³⁵U) target with a ²³⁸U atom density of 4.80×10^{22} atoms/cm³ and a ²³⁵U atom density of 9.74×10^{19} atoms/cm³.

^bThe total neutron leakage from the target is designated by "T". The neutron leakage from the cylindrical surface is designated by "C-S".

^cNo ²³⁸U but a ²³⁵U atom density of 4.80×10^{22} atoms/cm³.

TABLE C-II

**NEUTRON LEAKAGE FROM CYLINDRICAL
TARGETS BOMBARDED BY 800-MeV
PROTONS IN A TRUNCATED
GAUSSIAN^a BEAM SPOT**

Target	Target Diameter (mm)	Target Length (mm)	T ^b (n/p)	C-S ^b (n/p)
W ^c	20	150	10.6	10.1
W	25	150	11.5	10.7
Be	30	150	0.1	0.6
Ta	30	150	11.5	10.6
W	30	150	12.0	11.0
Pb	30	150	9.0	8.3
U ^d	30	150	16.6	15.3
W	30	300	12.9	12.1
W	40	150	12.8	11.4
W	50	150	13.5	11.7
W	60	150	13.7	11.5
W	80	150	14.3	11.2
W	100	150	14.8	10.7

^aOne standard deviation in 7.5 mm and truncated at radius of target

^bThe total neutron leakage from the target is designated by "T". The neutron leakage from the cylindrical surface is designated by "C-S"

^cThe density of the tungsten targets was assumed to be 92% of the theoretical density.

^dDepleted uranium with a ²³⁵U content of 0.2 wt%.

ends. Of the 17.2 neutrons, 15.8 (or 92%) leak from the first 150 mm of the 250-mm-high target. If the target height is 150 mm, the neutron leakage from the cylindrical surface is ~15.5 n/p (see Table C-I). Therefore, the neutron leakage from the cylindrical surface of a 150-mm-high target is ~90% of that from a 250-mm-high target. Similar ratios hold for tungsten targets (see Table C-II). In addition to neutronics, the size of the collimation system which views the target can influence the height of the target. The height of the WNR target was set at 150 mm.

The axial distribution of leakage neutrons from a 30-mm-diam by 150-mm-high depleted-uranium target is shown in Fig. 45. The distribution peaks between 20 and 30 mm from the end of the cylinder

TABLE C-III

**NEUTRON LEAKAGE FROM RECTANGULAR
TARGETS BOMBARDED BY 800-MeV
PROTONS IN A 15-mm-DIAM
CIRCULAR BEAM SPOT**

Target	Target Size ^a (mm)	Total Leakage (n/p)
W ^b	30 x 200 x 150	14.4
W	40 x 200 x 150	14.8
W	50 x 200 x 150	15.6
U ^c	50 x 50 x 150	19.8
U	50 x 100 x 150	21.1
U	50 x 200 x 150	21.7
U	50 x 250 x 150	21.8
U	50 x 300 x 150	21.9
U	50 x 400 x 150	21.9

^aThickness by width by height.

^bThe density of all tungsten targets was assumed to be equal to the theoretical density.

^cIn all the uranium targets, the ²³⁵U content was assumed to be 0.2 wt%.

the protons strike. Essentially 50% of the leakage from the cylindrical surface comes from the first 54 mm of the 150-mm-high target. The fraction of neutrons leaking from the cylindrical surface, above and below any energy, is illustrated in Fig. C-6. About 50% of these leakage neutrons have energies less than 2 MeV.

The angular distribution of leakage neutrons from the preceding target is shown in Fig. C-7. The high-energy (>100-MeV) leakage neutrons are strongly forward peaked. This latter effect can have significant implications for shielding problems.² The lower energy neutrons tend to have a more isotropic distribution.

IV. FIGURE OF MERIT FROM CYLINDRICAL TARGETS

As seen in Figs. C-2, C-3, and C-4, the yield, intensity spectrum, and pulse widths of neutrons leaking from cylindrical targets vary with the target diameter. The FOM for depleted-uranium targets is

Fig. C-3.

Neutron leakage spectra (at all angles) from the cylindrical surface of 150-mm-high ^{238}U targets as a function of target diameter. The lethargy interval is 0.230.

shown in Fig. C-8 for three target diameters. The FOM of the 20-mm-diam target is larger by about 50% to 60% over the peak than that of the 30-mm-diam target. The FOM is larger for the 20-mm-diam target than for the 30-mm-diam target because, even though the neutron yield (n/p) from the cylindrical surface of the 20-mm-diam target is smaller by $\sim 12\%$, the neutron leakage intensity (n/p $\cdot$ cm 2) for the 20-mm-diam target is larger by $\sim 7\%$. The pulse widths of leakage neutrons from the

Fig. C-4.

Standard deviation of neutron leakage pulses from the cylindrical surface of 150-mm-high ^{238}U targets.

20-mm-diam target are narrower than those of the other two targets.

The FOM for a 20-mm-diam by 150-mm-high depleted-uranium target is shown in Fig. C-9 for two sizes of proton beam spots. There does not appear to be any overall trend in the differences between the two curves, and, except for a few energies, the dissimilarities appear to be relatively small. The effect on the FOM of various proton beam spot sizes should become more pronounced at larger target

Fig. C-5.

Mean emission time of leakage neutron pulses from the cylindrical surface of 150-mm-high ^{238}U targets.

diameters where differences in proton beam spot sizes can be appreciable.

The detailed requirements for cooling a target are important in target design and neutronics. In par-

Fig. C-6.

Fraction of leakage neutrons from the cylindrical surface of a depleted-uranium target which have energies above or below energy E . The target was 30 mm in diameter by 150 mm high.

ticular, cooling of uranium metal is difficult and proper design to effect cooling can significantly change the neutronics.¹⁵

V. NEUTRON LEAKAGE SPECTRA FROM DIFFERENT TARGET MATERIALS

The neutron leakage spectrum and intensity from a target is dependent upon the target material as well as target geometry for a fixed proton energy. There is a certain amount of "spectrum shaping" which can be achieved by varying the target material.

Fig. C-7.

Angular distribution of leakage neutrons from a 30-mm-diam by 150-mm-long depleted-uranium target using a conical-shell solid angle at 90° to the target axis.

The neutron leakage spectra from a copper target and a depleted-uranium target are compared in Fig. C-10. The targets had diameters of 30 mm and heights of 250 mm. The protons were uniformly spread over a circular beam spot 15 mm in diameter. The neutron yield is decreased and the spectrum is harder for the copper target.

The neutron leakage spectrum from a tungsten target is compared to a depleted-uranium target in Fig. C-11. The targets were 30 mm in diameter by 150 mm high. The protons were assumed to be in a

truncated Gaussian beam spot. The neutron yield from the tungsten is 1.0 n/p·sr and that from the uranium is 1.4 n/p·sr. The spectrum from tungsten is slightly harder than that from uranium.

Computations were done to determine the leakage neutron spectrum from small, thin targets. The targets were 10 mm in diameter and 20 mm high. The proton beam spot diameter was 5 mm. The results are shown in Fig. C-12. The peak of a spectrum moves toward higher energies as the target nuclei becomes lighter.

Fig. C-8.

Figure of merit (averaged over a 1-sr conical-shell solid angle at 90° to the target axis) for 150-mm-high depleted-uranium targets of various diameters.

Fig. C-9.

Figure of merit (averaged over a 0.5-sr conical solid angle) for a 20-mm-diam by 150-mm-high depleted-uranium target using two proton beam spot diameters.

Fig. C-10.

Neutrons leakage spectra from the cylindrical surface of 30-mm-diam by 250-mm-high targets of copper and depleted uranium into a 1-sr conical-shell solid angle at 90° to the target axis. The decade interval is 0.10.

Fig. C-11.

Neutron leakage spectra from the cylindrical surface of 30-cm-diam by 150-mm-high targets of tungsten and depleted uranium into a 1-sr conical-shell solid angle at 90° to the target axis. The lethargy interval is 0.230.

Fig. C-12.
Total neutron leakage from 10-mm-diam by
20-mm-high targets of different materials. The
numbers in parentheses are the total neutron
leakage values.

APPENDIX D

NEUTRONICS OF VARIOUS TARGET/MODERATOR GEOMETRIES AND MODERATOR MATERIALS

The energy, angular, spatial, and time distributions as well as the intensity of leakage neutrons from a high- Z target bombarded with 800-MeV protons depend upon the target material and geometry.* The energy, spatial, and angular distributions of neutrons leaking from the target affect

the neutron yields from an adjacent moderator. The time distribution affects the moderator pulse widths. We did scoping studies of the neutronic coupling for several target/moderator configurations to determine the magnitude of the effects. We also did preliminary studies to determine the extent of the effects on moderator neutronics of changing the

*See Appendix C for a discussion of bare target neutronics.

moderator material. This appendix discusses this early work.

I. WING MODERATORS

The geometry of wing-type moderators is illustrated in Fig. 4 for a double-wing moderator adjacent to a cylindrical target. A single-wing (one moderator) geometry was used to investigate target/moderator neutronic coupling. Double-wing and cruciform (four moderator wings) geometries were used to look at the effect of moderator/moderator neutronic coupling. No decoupler was used in these neutronic-coupling studies.

A. Vertical Positioning of Moderator Relative to Target

The axial distribution of leakage neutrons from a cylindrical target is shown in Fig. 45. We computed the yield of neutrons leaking from a single-wing moderator as a function of its vertical position relative to the top of the target. For this variation in target/moderator configuration, the changes in the leakage neutron yield were not large. Additional studies with other target/moderator geometries should establish the optimum relative heights between the target and the moderator. For the results given in this report, the top of the moderator was level with the top of the target.

B. Target/Moderator Neutronic Coupling

The energy distribution and intensity of neutrons leaking from a bare target vary with the target diameter (see Appendix C). The neutron leakage from a moderator adjacent to a target depends on the geometry of the target/moderator configuration (geometric coupling) as well as the energy distribution, angle of incidence, and intensity of the neutrons leaking from the target. The interplay between these factors was investigated by computing the neutron leakage from the 150- by 150-mm surface of a 50-mm-thick by 150-mm-wide by 150-mm-high H_2O single-wing moderator as a function of target diameter. The results are shown in Fig. D-1 for two energy ranges. There is a slight peaking in

Fig. D-1.

Leakage neutrons (all angles) from one 150- by 150-mm surface of a 50-mm-thick by 150-mm-wide by 150-mm-high H_2O moderator located 10 mm from a ^{238}U target.

the neutron leakage at a target diameter between 50 and 60 mm. At the larger target diameters, geometric effects become important and the moderator yield decreases.

The thermal neutron source (represented by the number of neutrons falling below some reference energy, e.g. 1 eV, in the moderator for each proton incident upon the target) for the H_2O moderator is shown in Fig. D-2. The thermal neutron source peaks at a target diameter between 50 and 60 mm. The thermal neutron source should be a good indicator of relative neutron leakage intensities at thermal and subthermal energies from a moderator of a fixed size and material.¹⁴

In general, the pulse width of neutrons leaking from a cylindrical target increases as the target diameter increases (see Appendix C). In addition to moderator neutron yields, the time response of a target/moderator configuration is very important in judging moderator effectiveness. The figure-of-merit approach accounts for both. The FOM for the H_2O single-wing moderator is illustrated in Fig. D-3. The peaks in the FOM are energy dependent and rather flat at low energies. The peaks are sharper and occur

Fig. D-2.

Thermal neutron source (neutrons falling below 1 eV in the moderator) in one 50-mm-thick by 150-mm-wide by 150-mm-high H_2O moderator located 10 mm from a ^{235}U target.

at smaller target diameters as the neutron energy increases. Appendix E shows that the thickness of the moderator should be maximized for each target diameter.

Heterogeneous and homogeneous poisoning of moderators is a way to alter the neutronics.^{18,24} The energy cutoff, or level below which the poison affects the neutronics, depends on the poison used; the cutoff is ~ 0.4 eV and ~ 500 eV for Cd and ^{10}B , respectively.¹⁴ Heterogeneous poisoning of a moderator in a wing-type configuration is a way to enhance the neutronics for relatively large target diameters. Poisoned moderators were not considered in this study.

C. Moderator/Moderator Neutronic Coupling

For two or more moderator wings, there is neutronic coupling (crosstalk) between the wings. The extent is important because crosstalk degrades the characteristics of the neutron pulse from the moderator wings. For a double-wing configuration, the crosstalk occurs through the moderator ends facing the target. It is a function of moderator thickness and the separation between the moderators, or the target diameter. Crosstalk between moderators is more severe for a cruciform configuration, because the crosstalk depends on the area of the moderator

Fig. D-3.

Figure of merit for neutrons leaking from one 150- by 150-mm surface of a 50-mm-thick by 150-mm-wide by 150-mm-high H_2O moderator located 10 mm from a ^{235}U target.

sides as well as moderator thickness and target diameter.

Table D-I compares the amount of moderator crosstalk in cruciform and double-wing configurations with a single-wing configuration for a 40-mm-diam by 150-mm-high ^{235}U target and 50-mm-thick by 150-mm-wide by 150-mm-high H_2O moderators. In the energy range 1 eV to 10 MeV, the number of leakage neutrons from one 150- by 150-mm moderator surface in a cruciform geometry is larger by $\sim 10\%$ than that from a similar moderator surface in single-wing geometry. Because the crosstalk is energy dependent, the relative increases are $\sim 20\%$ from 1 to 100 keV and $\sim 49\%$ from 1 eV to 1 keV. Thus, for the cruciform geometry, about half the neutrons leaking from one moderator in the energy range 1 eV to 1 keV come from the other three moderators. Moderated rather than target neutrons should be used if neutrons with energies less than ~ 100 keV are needed. The cruciform moderator configuration was not studied extensively because of the

TABLE D-I

NEUTRONIC COUPLING IN DOUBLE-WING AND CRUCIFORM MODERATOR CONFIGURATIONS RELATIVE TO A SINGLE-WING CONFIGURATION*

Energy Range	Single-Wing	Per Cent Increase of Leakage Neutrons	
		Double-Wing	Cruciform
<1 eV ^b	reference	4.2	57.4
1 eV - 1 keV	reference	1.9	49.1
1 keV - 100 keV	reference	0.0	20.4
100 keV - 10 MeV	reference	0.4	3.3
1 eV - 10 MeV	reference	0.4	9.8

*A 40-mm-diam by 150-mm-high ²³⁵U target and 50-mm-thick by 150-mm-wide by 150-mm-high H₂O moderators 10 mm from the target. Leakage neutrons from one 150- by 150-mm moderator surface.

^bThermal neutron source in one moderator.

amount of crosstalk between the moderators at energies less than ~100 keV.

The amount of crosstalk between moderators is also dependent upon the moderator material. The crosstalk in a cruciform geometry versus moderator material is shown in Fig. D-4. The atom densities of some moderator materials are given in Table D-II. A heavy element in the moderator can cause peaks in the crosstalk for leakage. With the exception of ZrH₂, the change in the thermal neutron source for H₂O is larger than for some of the more dense hydrogenous moderators for the thickness shown. Crosstalk between moderators in a cruciform configuration can be reduced by increasing the target diameter, decreasing the thickness and size of the moderators, and using a decoupling material at the moderator surfaces.

II. SLAB MODERATORS

The slab-target/slab-moderator geometry with neutron decouplers is depicted in Fig. 4. Scoping studies of slab-moderator neutronics were done with a single slab moderator and no decoupler. A slab and a cylindrical target were used.³⁸

The number of neutrons into a 70-mm-thick by 360-mm-wide by 150-mm-high H₂O moderator placed 10 mm away from a 40-mm-thick by 360-mm-wide by 150-mm-high ²³⁵U slab target was 39%

greater than for the same moderator placed 10 mm from a 40-mm-diam by 150-mm-high ²³⁵U cylindrical target. The number of leakage neutrons from the 360- by 150-mm moderator surface with

Fig. D-4.

Relative increase of leakage neutrons from one 100- by 100-mm surface and thermal neutron source (neutrons falling below 1 eV in one moderator) of a 50-mm-thick H₂O moderator in cruciform configuration to that of an H₂O moderator in a single-wing geometry. All moderators were 10 mm from a 40-mm-diam by 150-mm-high ²³⁵U target. The NiH₂ values marked with an asterisk were obtained using VH₂ atom densities.

TABLE D-II
ATOM DENSITIES OF VARIOUS MODERATOR MATERIALS

Moderator	Atom Densities (atoms/cm ³)							
	H	C	N	O	Ti	Ni	Zr	²³⁵ U
H ₂ (LH) ^a	0.0424 x 10 ²⁴	---	---	---	---	---	---	---
H ₂ (H ₂ O) ^b	0.0669 x 10 ²⁴	---	---	---	---	---	---	---
H ₂ O	0.0669 x 10 ²⁴	---	---	0.0334 x 10 ²⁴	---	---	---	---
NiZrH _{1.1}	0.0679 x 10 ²⁴	---	---	---	---	0.0251 x 10 ²⁴	0.0251 x 10 ²⁴	---
ZrH ₁	0.0726 x 10 ²⁴	---	---	---	---	---	0.0363 x 10 ²⁴	---
CH ₄	0.0780 x 10 ²⁴	0.0195 x 10 ²⁴	---	---	---	---	---	---
CH ₃	0.0800 x 10 ²⁴	0.0400 x 10 ²⁴	---	---	---	---	---	---
UH ₃	0.0819 x 10 ²⁴	---	---	---	---	---	---	0.0273 x 10 ²⁴
NH ₃ ^c	0.0890 x 10 ²⁴	---	0.0297 x 10 ²⁴	---	---	---	---	---
TiH ₂	0.0947 x 10 ²⁴	---	---	---	0.0476 x 10 ²⁴	---	---	---
TiH ₃ ^d	0.103 x 10 ²⁴	---	---	---	0.0513 x 10 ²⁴	---	---	---
NiH ₂ ^d	0.103 x 10 ²⁴	---	---	---	---	0.0513 x 10 ²⁴	---	---

^aHydrogen density for liquid hydrogen.

^bHydrogen density for H₂O (without including oxygen).

^cSolid ammonia.

^dAtom densities for VH₂ with Ti and Ni substituted for V for computational convenience.

energies from 1 eV to 100 keV was 56% greater for the slab target than for the cylindrical target. Also, the thermal neutron source in the moderator was 76% larger for the slab target. The neutronics of the slab-target/slab-moderator were studied in detail and are discussed in Appendix E.

III. CYLINDRICAL MODERATORS

The cylindrical-target/cylindrical-moderator configuration with a decoupler is shown in Fig. 4. Preliminary computations were performed for cylindrical-targets/cylindrical-moderators with no decoupler. Three target diameters were used with no separation between the target and moderator. Computations were done for two moderator thicknesses with the 20-mm-diam target. The results are given in Table D-III.

For a fixed target diameter, the thermal neutron source increases with moderator thickness. For a fixed moderator thickness, the thermal neutron source increases with target diameter. About 37% of the neutrons which enter a 70-mm-thick H₂O moderator from a 150-mm-diam ²³⁵U target fall below 1 eV in the moderator. For a 20-mm-diam target, the neutron leakage from a 70-mm-thick H₂O moderator is less than that from a 50-mm-thick H₂O moderator, suggesting a strong dependence on moderator thickness. The neutron leakage from a moderator of a fixed thickness behaves the same as that from a single-wing moderator (Fig. D-1), however, the peaking appears to be more severe for the cylindrical moderators. There is an "optimum" moderator thickness for leakage neutrons for each target diameter (see Appendix E for more detail).

In Table D-III, the results of computations for slab-target/slab-moderator and cylindrical-target/double-wing-moderator configurations have been included for comparison purposes.* None of the moderator thicknesses have been "optimized" for a given target diameter or target thickness. The thermal neutron source with the 40- by 150-mm target and the 70-mm-thick cylindrical moderator is ~1.1 times that for the slab moderator and ~5.1 times that for the double-wing moderator. Factors which partly account for the ~1.6 increase in

*The results for the slab-target/slab-moderator have been doubled to account for a second moderator.

leakage neutrons when comparing a cylindrical and slab moderator of the same thickness are

- the separation of the slab moderator and slab target,
- the disregard of leakage neutrons from the ends of the slab moderator, and
- the differences in neutron leakage from the top and bottom of each moderator configuration.

IV. PARTIALLY REFLECTED MODERATORS

Computations were made to study the neutronics of reflected moderators with a re-entrant hole for beam extraction.³⁹ Such a configuration has been considered for low-energy (<0.5-eV) neutron sources.^{14,40} The computations were done for a polyethylene moderator with Be, D₂O, and Fe reflectors. The geometry is given in Ref. 40 and is illustrated in Fig. D-5. The cadmium liner was not included in the problem; a 0.5-eV energy cutoff was employed instead. The increase of the thermal neutron source below 0.5 eV in the polyethylene moderator for the Be, D₂O, and Fe reflected systems was ~11.6, ~7.4, and ~6.4, respectively, relative to the unreflected polyethylene moderator. The neutron leakage between 0.5 eV and 100 keV is larger for the Be and Fe reflected systems; the relative leakage varies from ~4.9 to ~1.1 for the Be reflector and from ~2.1 to ~1.3 for the Fe reflector at 0.5 eV and 100 keV, respectively. The neutron leakage from the D₂O reflected system at 0.5 eV is higher by a factor of ~2.9 than that from the unreflected moderator, and the same at ~20 keV. The computed pulse widths of leakage neutrons for the unreflected moderator are consistently smaller than the pulse widths from any of the reflected systems at all energies above 0.5 eV. However, care must be exercised in interpreting the *computed* standard deviations of neutron leakage pulses from the polyethylene moderator.^{11,14,39} The standard deviations can be *artificially* broadened when neutrons are delayed in the reflector and then re-enter and leak from the moderator. The increased neutron production in a partially reflected moderator configuration may be useful for experiments above 0.5 eV in which resolution is not a critical factor.⁴¹

TABLE D-III

**COMPARISON OF CYLINDRICAL MODERATORS TO SLAB
AND DOUBLE-WING MODERATORS**

Target Size (mm)	H ₂ O Moderator Thickness (mm)	Thermal Neutron Source ^a (n/p)	Thermal Neutron Source Efficiency ^b	Neutron Leakage (All Angles) Per Proton Into Target ^c	
				1 eV-1 keV	1 keV-100 keV
20 x 150 ^d	50	2.08	0.156	0.840	0.868
20 x 150 ^d	70	3.31	0.247	0.633	0.580
40 x 150 ^d	70	4.51	0.282	0.793	0.702
40 x 360 x 150 ^e	70	4.14	0.256	0.502	0.424
40 x 150 ^f	70	0.88	0.112	0.379	0.538

^aNeutrons falling below 1 eV in the moderator per proton into target.

^bNeutrons falling below 1 eV in the moderator per neutron incident upon the moderator.

^cNeutron leakage from top and bottom of moderators are not included. Neutron leakage from the ends of slab and double-wing moderators are not included.

^dCylindrical-target/cylindrical-moderator with no gap between target and moderator.

^eSlab-target/slab-moderator with a 10-mm gap between target and moderators. Two 70-mm-thick by 30-mm-wide by 150-mm-high moderators.

^fCylindrical-target/double-wing moderator with a 10-mm gap between target and moderators. Two 70-mm-thick by 150-mm-wide by 150-mm-high moderators.

V. HYDROGENOUS MODERATOR MATERIALS

Scoping studies were done to ascertain the effect of moderator materials on the figure of merit, the thermal neutron source in the moderator, and the neutron leakage for various WNR target/moderator configurations. Only materials containing hydrogen (to keep the moderator time response as short as possible) and a cylindrical-target/double-wing-moderator configuration are discussed here. Other target/moderator geometries are described in Appendix E. The WNR FOM, thermal neutron source, and neutron leakage from a moderator can be significantly altered by varying the moderator material and thickness.

The present results refer to a fixed ²³⁵U target size (40-mm-dia. by 150-mm-high) and a fixed moderator size (70-mm-thick by 150-mm-wide by 150-mm-high). For a fixed target and moderator size, differences in moderator neutronics can be

more readily attributed to dissimilarities in the moderator material. The results will vary with moderator thickness (see Appendix E).

The moderator materials used in the computations are summarized in Table D-II. High-energy neutrons can interact with the heavy element component in a moderator by inelastic scattering, fission, and (n,2n) processes to aid in the neutron slowing-down and production processes.

A. Figure of Merit

FOM versus hydrogen density in the moderator is shown in Fig. D-6. The FOM is dependent upon both the hydrogen density and type of heavy element in the moderator (as well as moderator thickness and target/moderator geometry). The following are observations on the results in Fig. D-6 and are in the order of ascending hydrogen density.

Fig. D-5.
Geometry for reflected moderator.

- As the hydrogen density alone is changed, the FOM increases at all energies below ~ 100 keV. For example, $H_2(LH)$ and $H_2(H_2O)$.

- For a fixed hydrogen density and the inclusion of a heavy element, the FOM tends to decrease. For example, $H_2(H_2O)$, H_2O , and $NiZrH_{2.7}$. This is similar to the conclusion of Michaudon.¹⁹

- If the hydrogen density increases, the heavy element changes, and the density of the heavy element decreases, the FOM can either increase or decrease. For example, $NiZrH_{2.7}$, ZrH_2 , and CH_4 , or CH_2 and UH_3 .

- The FOM can increase at low energies and decrease at high energies when the hydrogen and heavy element densities increase and the heavy element is the same. For example, CH_4 and CH_2 , or TiH_2 and TiH_3 (with VH_2 atom densities).

- If the heavy element changes and the hydrogen and heavy element densities increase, the FOM can essentially not change, increase or decrease depending upon energy. For example, UH_3 and NH_3 , or NH_3 and TiH_3 , or TiH_2 and NiH_2 (with VH_2 atom densities).

Fig. D-6.
Figure of merit for leakage neutrons from one 150- by 150-mm surface of 70-mm-thick by 150-mm-wide by 150-mm-high single-wing moderators of different materials. The moderators were 10 mm from a 40-mm-diam by 150-mm-high ^{235}U target. The TiH_3 and NiH_2 values marked with asterisks were obtained using VH_2 atom densities.

- The FOM can vary if both the hydrogen and heavy element densities are the same and the heavy elements differ. For example, TiH_2 and NiH_2 both with VH_2 atom densities.

B. Thermal Neutron Source in the Moderator

A plot of the thermal neutron source in the moderator (number of neutrons falling below 1 eV per proton into target) versus hydrogen density is given in Fig. D-7. The thermal neutron source varies with hydrogen density and the heavy element in the moderator. It is also a function of moderator

Fig. D-7.

Thermal neutron source (neutrons falling below 1 eV in the moderator) in 70-mm-thick by 150-mm-wide by 150-mm-high single-wing moderators of different materials. The moderators were 10 mm from a 40-mm-diam by 150-mm-high ^{235}U target. The TiH_2 and NiH_2 values marked with asterisks were obtained using VH_2 atom densities.

thickness and target/moderator geometry (see Appendix E). The thermal neutron source is an upper limit to the thermal and subthermal neutron leakage from the moderator.

C. Neutron Leakage at 90°

The 1-eV neutron leakage at 90° from one 151- by 150-mm moderator surface is shown in Fig. D-8.

Fig. D-8.

Leakage neutrons at 1 eV and 90° from one 150-mm-wide by 150-mm-high moderator surface. The moderator was 70-mm-thick and 10 mm from a 40-mm-diam by 150-mm-high ^{235}U target. The TiH_2 and NiH_2 values marked with asterisks were obtained using VH_2 atom densities. The lethargy interval is 0.230.

This leakage should be indicative of the useful thermal and subthermal neutron leakage from the moderator.¹⁴ The 1-eV neutron leakage has a different overall dependence on hydrogen density and moderator material than does the thermal neutron source in the moderator (see Fig. D-7). The 1-eV leakage is also dependent upon moderator thickness and target/moderator geometry (see Appendix E). The data shown in Fig. D-8 were obtained from linear least squares fits of the computed neutron leakage from 1 eV to 10 keV. The fits and leakage neutrons at other energies are given in Table D-IV.

TABLE D-IV
LEAKAGE NEUTRONS AT 90° FROM ONE 150- BY
150-mm MODERATOR SURFACE^a

Moderator	Fit ^b	Leakage Neutrons (n/p · lethargy · sr)				
		1 eV	10 eV	100 eV	1 keV	10 keV
H ₂ (LH)	0.00291 E ^{0.170}	2.01 x 10 ⁻³	2.96 x 10 ⁻³	4.38 x 10 ⁻³	6.48 x 10 ⁻³	9.57 x 10 ⁻³
H ₂ O	0.00348 E ^{0.0810}	3.48 x 10 ⁻³	4.20 x 10 ⁻³	5.08 x 10 ⁻³	6.13 x 10 ⁻³	7.40 x 10 ⁻³
NiZrH _{2.7}	0.00283 E ^{0.0448}	2.83 x 10 ⁻³	3.52 x 10 ⁻³	4.37 x 10 ⁻³	5.44 x 10 ⁻³	6.76 x 10 ⁻³
ZrH ₂	0.00332 E ^{0.0926}	3.32 x 10 ⁻³	4.11 x 10 ⁻³	5.09 x 10 ⁻³	6.30 x 10 ⁻³	7.80 x 10 ⁻³
CH ₄	0.00322 E ^{0.107}	3.22 x 10 ⁻³	4.12 x 10 ⁻³	5.28 x 10 ⁻³	6.76 x 10 ⁻³	8.65 x 10 ⁻³
CH ₂	0.00331 E ^{0.0884}	3.31 x 10 ⁻³	4.06 x 10 ⁻³	4.98 x 10 ⁻³	6.10 x 10 ⁻³	7.47 x 10 ⁻³
UH ₃	0.00263 E ^{0.126}	2.63 x 10 ⁻³	3.52 x 10 ⁻³	4.70 x 10 ⁻³	6.29 x 10 ⁻³	8.42 x 10 ⁻³
NH ₃	0.00277 E ^{0.109}	2.77 x 10 ⁻³	3.56 x 10 ⁻³	4.57 x 10 ⁻³	5.88 x 10 ⁻³	7.55 x 10 ⁻³
TiH ₂	0.00355 E ^{0.117}	3.55 x 10 ⁻³	4.07 x 10 ⁻³	4.67 x 10 ⁻³	5.36 x 10 ⁻³	6.14 x 10 ⁻³
TiH ₂ ^c	0.00347 E ^{0.0876}	3.47 x 10 ⁻³	3.96 x 10 ⁻³	4.53 x 10 ⁻³	5.17 x 10 ⁻³	5.90 x 10 ⁻³
NiH ₂ ^c	0.00256 E ^{0.0839}	2.56 x 10 ⁻³	3.11 x 10 ⁻³	3.77 x 10 ⁻³	4.57 x 10 ⁻³	5.55 x 10 ⁻³

^aModerator was 70 mm thick and 10 mm away from a 40-mm-diam by 150-mm-high ²³⁵U target.

^bLinear least squares fit from 1 eV to 10 keV.

^cUsing VH₂ atom densities.

APPENDIX E

PARAMETRIC STUDIES FOR SPECIFIC TARGET/MODERATOR GEOMETRIES

Parametric studies were done to determine the dimensions of slab-target/slab-moderator and cylindrical-target/double-wing-moderator geometries for specific target and moderator materials. The FOM was used in these studies for intercomparing the various target/moderator sizes.

First, the target size was fixed and the moderator thickness varied to obtain the "best" FOM.^{*} Second, the thickness or diameter of the target was changed and the moderator thickness again varied to obtain the "best" FOM. An optimized FOM was determined and the target thickness (or diameter) and the moderator thickness were fixed. Third, the width of the moderator (and the target as well in the slab/slab case) was varied and ultimately fixed such

that the FOM was ~90% of that for an essentially infinitely wide moderator. We studied the effect of varying the gap between the target and moderator, as well as the improvements in the FOM, the thermal neutron source, and the neutron leakage at 1 eV obtainable by changing the moderator material.

I. SLAB-TARGET/SLAB-MODERATOR

The slab-target/slab-moderator geometry with neutron decouplers and two moderators is shown in Fig. 4. However, the parametric studies reported here were done with bare ²³⁵U slab targets, one H₂O slab moderator, and no decoupler. Target and moderator canisters were not included in the calculations. The effect of ²³⁵U in a target and the

^{*}The width of the moderator was effectively infinite.

resulting need to decouple the moderator from the target were investigated.

A. Target/Moderator Thickness

Bare ^{238}U slab targets of four thicknesses, ranging from 30 to 60 mm, were used. The thickness of the single H_2O slab moderator was varied from 20 to 70 mm for each target. The moderator was 10 mm from the target in all the computations. The width of each target/moderator system was effectively infinite (350–380 mm) and the height was 150 mm.

The FOM and thermal neutron source for each target thickness as a function of moderator thickness are shown in Figs. E-1 through E-4. There is no one moderator thickness at which the FOM is maximum for all the energies shown. A moderator thickness of 40 mm appears to yield the maximum FOM for leakage neutrons above ~ 1 eV and below ~ 10 keV. Above ~ 10 keV, the moderator should be thinner. In Ref. 42 the maximum stationary epithermal neutron leakage from an H_2O slab moderator was obtained with a moderator thickness of 40 to 50 mm, which generally agrees with our results.

As shown in Figs. E-1 through E-4, the number of neutrons falling below 0.5 eV or 1 eV in the moderator (the thermal neutron source) increases with moderator thickness. These neutrons must still be transported to the moderator surface and can be absorbed in the process. The thermal neutron source represents an upper limit to the total number of thermal and subthermal leakage neutrons.

In order to be useful for TOF experiments, neutrons should leak from the moderator surface which is viewed by the flight paths. Neutron leakage from the top and bottom of the slab moderator is not useful and increases as the moderator becomes thicker. The 1-eV neutron leakage at 90° from a moderator surface viewed by a flight path should indicate the useful thermal and subthermal neutron leakage.¹⁴ The 1-eV neutron leakage from H_2O slab moderators coupled to a 40-mm-thick ^{238}U slab target versus moderator thickness is illustrated in Fig. E-5. The thermal neutron source is also shown. The 1-eV neutron leakage peaks at a moderator thickness slightly larger than 50 mm. This thickness is thinner than the 65 mm mentioned in Ref. 42 as the thickness at which the thermal neutron leakage peaked for an H_2O slab moderator.

Fig. E-1.

Figure of merit (averaged over a 1-sr conical solid angle) for one 350-mm-wide by 150-mm-high surface of H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 30-mm-thick by 350-mm-wide by 150-mm-high ^{238}U slab target.

The FOM of a 40-mm-thick H_2O slab moderator as a function of target thickness is shown in Fig. E-6. The FOM for each target thickness is slowly varying and slightly energy dependent. At the higher energies, 10 to 100 keV, the thinner targets are better. A target thickness of 50 mm was chosen for further study.

Fig. E-2.

Figure of merit (averaged over a 1-sr conical solid angle) for one 360-mm-wide by 150-mm-high surface of H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 40-mm-thick by 360-mm-wide by 150-mm-high ^{238}U slab target.

B. Target/Moderator Width

The width of a 50-mm-thick ^{238}U slab target and a 40-mm-thick H_2O slab moderator was varied from 50 to 400 mm and the FOM computed. The 400-mm width was assumed to essentially represent the infinite width. The results are shown in Fig. E-7. The

Fig. E-3.

Figure of merit (averaged over a 1-sr conical solid angle) for one 370-mm-wide by 150-mm-high surface of H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 50-mm-thick by 370-mm-wide by 150-mm-high ^{238}U slab target.

FOM and thermal neutron source increase rapidly up to a target/moderator width of ~ 200 mm. For widths greater than ~ 200 mm, the FOM and thermal neutron source are relatively flat. The target/moderator width was set at 300 mm for further studies.

C. Separation Between Target and Moderator

For the design of the WNR target/moderator, we felt that the moderator should be as close to the

Fig. E-4.

Figure of merit (averaged over a 1-sr conical solid angle) for one 380-mm-wide by 150-mm-high surface of H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 60-mm-thick by 380-mm-wide by 150-mm-high ^{238}U slab target.

target as possible; a 10-mm gap between the bare target and moderator was arbitrarily specified. The sensitivity of the neutron leakage to the size of this gap was checked by changing the gap from 10 to 5 mm and from 10 to 20 mm. For a gap of 5 mm, the integrated (over energy and angle) neutron leakage from a 300- by 150-mm moderator surface increased by 5.1% relative to that from the surface with a 10-mm gap. Changing the gap to 20 mm decreased the

Fig. E-5.

Leakage neutrons at 1 eV and 90° from one 360-mm-wide by 150-mm-high surface of H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 40-mm-thick by 360-mm-wide by 150-mm-high ^{238}U slab target. The lethargy interval is 0.230.

relative neutron leakage by 7.7%. Thus, the integrated leakage from the moderator face is relatively insensitive to modest changes in the distance between the target and moderator.

D. TiH_2 and H_2O Moderators

The neutronics of TiH_2 slab moderators as a function of moderator thickness were studied to compare with those of H_2O moderators. The target/moderator was 150 mm high and 300 mm wide. The moderator was 10 mm from a 50-mm-thick ^{238}U target.

The thickness of the TiH_2 moderator was varied from 20 to 50 mm. The FOM and thermal neutron source versus moderator thickness are shown in Fig. E-8. In general, the FOM is more sensitive to the thickness of a TiH_2 moderator than to that of an H_2O moderator.

The "best" FOMs for 300-mm-wide TiH_2 and H_2O slab moderators are compared in Fig. E-9. The FOM of TiH_2 is better than that of H_2O below ~ 100 eV (a factor of ~ 1.4 at 1 eV).

The thermal neutron source of TiH_2 and H_2O moderators as a function of moderator thickness is shown in Fig. E-10. The thermal neutron source for TiH_2 is better than that for H_2O by factors of ~ 1.6 to ~ 2.5 for the moderator thicknesses given.

Fig. E-6.

"Best" figure of merit (averaged over 1-sr conical solid angle) for 40-mm-thick H_2O slab moderators 10 mm from ^{238}U slab targets of different thicknesses.

Fig. E-7.

Figure of merit (averaged over a 1-sr conical solid angle) for 40-mm-thick by 150-mm-high H_2O slab moderators of different widths. Each moderator was 10 mm from a 50-mm-thick by 150-mm-high ^{238}U slab target of the same width as the moderator.

The neutron leakage at 90° to the 300-mm-wide by 150-mm-high surface of TiH_2 and H_2O moderators versus moderator thickness is shown in Figs. E-11 and E-12. The peak neutron leakage from TiH_2 occurs at a lower thickness value than that from H_2O . The peak neutron leakage is higher from the H_2O moderators above ~ 100 eV. The peak 1-eV neutron leakage from TiH_2 is larger than that from H_2O by a factor of ~ 1.2 . The pulse widths from TiH_2 are shorter than those from H_2O . The neutron leakage at 1 eV from the H_2O moderator in Fig. E-11

Fig. E-8.

Figure of merit (averaged over a 1-sr conical solid angle) for one 370-mm-wide by 150-mm-high surface of TiH_2 slab moderators of different thicknesses. Each moderator was 10 mm from a 50-mm-thick by 370-mm-wide by 150-mm-high ^{235}U slab target.

for a 50-mm-thick target peaks at a slightly thinner moderator than that for the 40-mm-thick target (see Fig. E-5).

Fig. E-9.

"Best" figure of merit (averaged over a 1-sr conical solid angle) for a 35-mm-thick TiH_2 and a 40-mm-thick H_2O slab moderator 10 mm from a 50-mm-thick by 300-mm-wide by 150-mm-high ^{235}U slab target.

E. Neutron Decoupler with a Depleted-Uranium Target

We ran calculations of the FOM for a 40-mm-thick H_2O slab moderator placed 10 mm from a 50-mm-thick slab target, one with 0.2 wt% ^{235}U in the

Fig. E-10.

Thermal neutron source in 300-mm-wide by 150-mm-high TiH_2 and H_2O slab moderators of different thicknesses. Each moderator was 10 mm from a 50-mm-thick by 300-mm-wide by 150-mm-high ^{235}U slab target.

the target and one without any ^{235}U in the target (the ^{235}U content was the same in both cases). The height and width of the slabs were 150 and 300 mm, respectively. The FOM was used to indicate the effect of ^{235}U . Fission in ^{235}U caused by neutrons leaking back into the target from the moderator would produce neutrons on a different time scale than those produced directly from proton-induced reactions.

Fig. E-11.

Neutron leakage at 90° from one 300-mm-wide by 150-mm-high surface of TiH_2 and H_2O slab moderators of various thicknesses. Each moderator was 10 mm from a 50-mm-thick ^{235}U slab target. The lethargy interval is 0.230.

The neutrons from fission in the ^{235}U could artificially dominate the computed standard deviations of pulse widths for leakage neutrons at various energies.

The resulting FOMs are shown in Fig. E-13. The dips in the FOM are due to neutrons produced from ^{235}U fissions caused by low-energy neutrons. With better statistics, the FOM over the entire energy range shown would be degraded when ^{235}U is present in the target. A 7.5-mm-thick layer of $^{10}\text{B}_4\text{C}$ between

Fig. E-12.

Neutron leakage at 90° from one 300-mm-wide by 150-mm-high surface of TiH_2 and H_2O slab moderators of various thicknesses. Each moderator was 10 mm from a 50-mm-thick ^{238}U slab target. The lethargy interval is 0.230.

the target and moderator neutronically decoupled the low-energy neutrons and eliminated this effect.

II. CYLINDRICAL-TARGET/DOUBLE-WING-MODERATOR

The cylindrical-target/double-wing-moderator geometry with neutron decouplers is shown in Fig. 4. However, the parametric studies reported here were done with bare ^{238}U targets (no ^{235}U included) and

Fig. E-13.

Figure of merit (averaged over a 1-sr conical solid angle) for one 300- by 150-mm surface of a 40-mm-thick by 300-mm-wide by 150-mm-high H_2O slab moderator. The moderator was 10 mm from a 50-mm-thick by 300-mm-wide by 150-mm-high ^{238}U slab target, with and without 0.2 wt% ^{235}U .

without decoupler material. Target and moderator canisters were not included in the calculations.

A study was made to ascertain the magnitude of moderator crosstalk for a fixed target diameter as a function of moderator thickness. The target was a 40-mm-diam by 150-mm-high cylinder of ^{238}U . The neutron leakage from a 150- by 150-mm surface of an H_2O moderator and the thermal neutron source in the moderator were computed for both the single-wing and double-wing configurations as a function of moderator thickness. The moderators were 10 mm from the target. The results are depicted in Fig. E-14. The coupling is most pronounced for the lower energy (≤ 100 -keV) neutrons. The crosstalk is less

Fig. E-14.

Relative increase in neutron leakage from one 150- by 150-mm surface of an H_2O moderator in double-wing configuration to that of one in single-wing geometry.

than ~3% for moderator thicknesses of 50 mm or less. See Appendix D for more information on wing-moderator neutronic coupling.

A. Target Diameter and Moderator Thickness

Three bare cylindrical targets with diameters of 20, 30, and 40 mm were studied in combination with two H_2O moderators. The thickness of the moderators was varied from 30 to 100 mm for each bare target. The moderators were 10 mm from the target. The width of each moderator was 150 mm and the height of the target/moderator systems was 150 mm.

The FOM and thermal neutron source for each target diameter versus moderator thickness are shown in Figs. E-15 through E-17. The FOM curves reflect neutron leakage from two 150- by 150-mm moderator surfaces only. No target-area neutrons are included, that is, a shadow bar is assumed. There is no one moderator thickness at which the FOM is maximum for all the energies shown. A moderator thickness of 50 mm was selected as a

Fig. E-15.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of H_2O wing moderators of different thicknesses. Each moderator was 10 mm from a 20-mm-diam by 150-mm-high ^{235}U target.

reasonable compromise. The FOM curves for the double-wing moderators are not as sensitive to moderator thickness as those for the slab moderators (see Figs. E-1 through E-4).

The 1-eV neutron leakage at 90° to one 150-mm-wide by 150-mm-high moderator surface is shown in Fig. E-18. The thermal neutron source is also given. The target diameter was 30 mm. For the thicknesses shown, the 1-eV neutron leakage for the double-wing moderator does not go through a maximum as it did for the slab/slab geometry (see Fig. E-5).

The FOM of a 50-mm-thick H_2O double-wing moderator versus target diameter is illustrated in Fig. E-19. The FOM is a slowly varying function of target diameter. A target diameter of 30 mm was selected for further study.

Fig. E-16.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of H_2O wing moderators of different thicknesses. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{235}U target.

B. Figure of Merit With Target Area Neutrons Included

The FOM curves for cylindrical targets (Figs. E-15 through E-17) did not include target-area neutrons. The FOM for the H_2O double-wing moderator including target-area neutrons is shown in Fig. E-20. The FOM for neutrons with energies less than ~ 10 keV is larger when there is a shadow bar than when there is not a shadow bar. For energies greater than ~ 100 keV, the FOM is larger

Fig. E-17.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of H_2O wing moderators of different thicknesses. Each moderator was 10 mm from a 40-mm-diam by 150-mm-high ^{235}U target.

without a shadow bar than with a shadow bar, because target neutrons can directly contribute to the FOM.

C. Moderator Width

The width of each 50-mm-thick H_2O moderator was varied from 50 to 300 mm. Each moderator was 10 mm from a 30-mm-diam ^{235}U target. The results are shown in Fig. E-21. The width of the moderators was set at 100 mm each for further studies.

D. Separation Between Target and Moderators

The sensitivity of the total neutron leakage from a 100-mm-wide by 150-mm-high H_2O moderator surface to the separation distance between the

Fig. E-18.

Leakage neutrons at 1 eV and 90° from two 150- by 150-mm surfaces of H_2O wing moderators of different thicknesses. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{238}U target. The lethargy interval is 0.230.

moderator and target is shown in Fig. E-22. The 50-mm-thick double-wing moderators were coupled to a 30-mm-diam ^{238}U target. As the separation between the target and moderators increases, the neutronic coupling between the target and moderators decreases. Significant losses in neutron leakage from the moderator can result at relatively large separation distances.

E. TiH_2 and H_2O Moderators

The neutronics of TiH_2 double-wing moderators were studied as a function of moderator thickness to compare with those of H_2O moderators. Each moderator wing was 150 mm wide and 10 mm away from a 30-mm-diam by 150-mm-high ^{238}U target.

The thickness of the TiH_2 moderators was varied from 30 to 70 mm. The FOM and thermal neutron source are shown in Fig. E-23. The FOM for TiH_2 moderators in a double-wing configuration is not too sensitive to moderator thickness.

The "best" FOMs for 150-mm-wide TiH_2 and H_2O double-wing moderators are compared in Fig. E-24. The FOM for TiH_2 is significantly better than that for H_2O at all the energies shown. Note that above ~ 1 keV, the FOM for the TiH_2 double-wing

Fig. E-19.

"Best" figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of 50-mm-thick H_2O wing moderators 10 mm from ^{238}U targets of different diameters.

Fig. E-20.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of H_2O wing moderators, including target neutrons. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{235}U target.

moderator is significantly better than that for the TiH_2 slab moderator (see Fig. E-9).

The thermal neutron source for TiH_2 and H_2O moderators as a function of moderator thickness is depicted in Fig. E-25. The thermal neutron source for TiH_2 is better than that for H_2O by factors of ~ 1.6 to ~ 2.5 for the moderator thicknesses shown.

Fig. E-21.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of H_2O moderators of different widths. Each moderator was 10 mm from a 150-mm-diam by 150-mm-high ^{235}U target.

The neutron leakage at 90° to the 150-mm-wide by 150-mm-high moderator surfaces of TiH_2 and H_2O moderators versus moderator thickness is shown in Figs. E-26 and E-27. The neutron leakage is from two of the above surfaces. For the energies and thicknesses shown, there are significantly more neutrons from the TiH_2 moderators than from the H_2O moderators. The neutron leakage from the double-wing moderators is not as strongly dependent upon moderator thickness as that from the slab/slab geometry (see Figs. E-11 and E-12).

Fig. E-22.

Neutron leakage at 90° from one 100-mm-wide by 150-mm-high surface of H_2O moderators at various separation distances between the target and moderator. Double-wing moderator configuration with a 30-mm-diam ^{238}Pu target.

Fig. E-23.

Figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of TiH_2 wing moderators of different thicknesses. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{238}Pu target.

Fig. E-24.

"Best" figure of merit (averaged over a 1-sr conical solid angle) for two 150- by 150-mm surfaces of 40-mm-thick TiH_2 and 50-mm-thick H_2O moderators. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{235}U target.

Fig. E-25.

Thermal neutron source in two 150-mm-wide by 150-mm-high TiH_2 and H_2O wing moderators of different thicknesses. Each moderator was 10 mm from a 30-mm-diam ^{235}U target.

Fig. E-26.

Neutron leakage at 90° from two 150-mm-wide by 150-mm-high surfaces of TiH_2 and H_2O double-wing moderators of various thicknesses. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{235}U target. The lethargy interval is 0.230.

Fig. E-27

Neutron leakage at 90° from two 150-mm-wide by 150-mm-high surfaces of TiH_2 and H_2O double-wing moderators of various thicknesses. Each moderator was 10 mm from a 30-mm-diam by 150-mm-high ^{235}U target. The lethargy interval is 0.230.

APPENDIX F

SOLID ANGLE NOMENCLATURE

I. SOLID ANGLE - GENERAL

The differential solid angle $d\Omega$ is given by (see Fig. F-1a)

$$d\Omega \equiv \frac{dA}{r^2} = \sin \theta \, d\theta \, d\phi \quad (F-1)$$

Thus

$$\begin{aligned} \int_{\text{all solid angles}} d\Omega &= \int_0^{2\pi} d\phi \int_0^\pi \sin \theta \, d\theta \\ &= 2\pi(-\cos \theta) \Big|_0^\pi = 4\pi \end{aligned} \quad (F-2)$$

that is, there are 4π sr in a sphere.

II. CONICAL SOLID ANGLE

Consider an elemental conical solid angle $\Delta\Omega$ about the z-axis formed by letting θ' vary from 0 to θ and ϕ vary from 0 to 2π (see Fig. F-1b). Then,

$$\begin{aligned} \Delta\Omega &= \int_0^{2\pi} d\phi \int_0^\theta \sin \theta' \, d\theta' \\ &= 2\pi(-\cos \theta') \Big|_0^\theta = 2\pi(1 - \cos \theta) \end{aligned} \quad (F-3)$$

The angle θ as a function of $\Delta\Omega$ is illustrated in Table F-I.

III. CONICAL-SHELL SOLID ANGLE

Consider an elemental conical-shell solid angle $\Delta\Omega$ formed by letting θ vary from θ_1 to θ_2 and ϕ vary from 0 to 2π (see Fig. F-1c). Then,

$$\begin{aligned} \Delta\Omega &= \int_0^{2\pi} d\phi \int_{\theta_1}^{\theta_2} \sin \theta \, d\theta \\ &= 2\pi(-\cos \theta) \Big|_{\theta_1}^{\theta_2} = 2\pi(\cos \theta_1 - \cos \theta_2) \end{aligned} \quad (F-4)$$

or

$$\Delta\Omega = 2\pi \Delta\cos \theta \quad (F-5)$$

where

$$\Delta\cos \theta \equiv \cos \theta_1 - \cos \theta_2 \quad (F-6)$$

The angle θ_2 as a function of $\Delta\Omega$, and θ_1 , are illustrated in Table F-II.

IV. CONICAL-SHELL SOLID ANGLE ABOUT 90°

Consider an elemental conical-shell solid angle $\Delta\Omega$ formed by letting θ vary from $(90^\circ - \delta)$ to $(90^\circ + \delta)$ and ϕ vary from 0 to 2π (see Fig. F-1d). Then, from Eq. (F-4)

$$\Delta\Omega = 2\pi[\cos (90^\circ - \delta) - \cos (90^\circ + \delta)] \quad (F-7)$$

or

$$\Delta\Omega = 4\pi \sin^2 \delta \quad (F-8)$$

The angle δ as a function of $\Delta\Omega$ is illustrated in Table F-III.

a. General solid angle nomenclature.

b. Elemental conical solid angle.

c. Elemental conical-shell solid angle.

d. Elemental conical-shell solid angle about 90° .

Fig. F-1.
Solid angle nomenclature

TABLE F-I

ANGLE θ VS ELEMENTAL
CONICAL SOLID ANGLE $\Delta\Omega$

$\Delta\Omega$ (sr)	θ (deg)
0.25	16.2
0.50	23.0
1.0	32.8
2.0	47.0

TABLE F-II

ANGLE θ_2 VS ELEMENTAL CONICAL-
SHELL SOLID ANGLE
 $\Delta\Omega$ AND ANGLE θ_1

$\Delta\Omega$ (sr)	θ_1 (deg)	θ_2 (deg)	θ_1 (deg)	θ_2 (deg)
0.25	30.0	34.3	60.0	62.6
0.50	30.0	38.1	60.0	65.1
1.0	30.0	45.0	60.0	70.1
2.0	30.0	56.8	60.0	79.5

V. NEUTRON LEAKAGE SPECTRA USING CONICAL AND CONICAL-SHELL SOLID ANGLES

The neutron leakage spectrum from a 25-mm-diam by 150-mm-high tungsten target bombarded with 800-MeV protons was analyzed using a 1-sr conical solid angle and 1-sr conical-shell solid angle about 90° to the target axis. The results are shown in Fig. F-2. The disagreement is most severe at energies above ~100 MeV where the angular distribution of leakage neutrons is not isotropic (see Appendix C) and the angular aperture of the solid angle has an effect. As the aperture is reduced, the agreement improves.

TABLE F-III

ANGLE δ VS ELEMENTAL CONICAL-SHELL
SOLID ANGLE $\Delta\Omega$ ABOUT 90°

$\Delta\Omega$ (sr)	δ (deg)
0.25	1.1
0.50	2.3
1.0	4.6
2.0	9.2

Fig. F-2.

Neutron leakage spectrum at 90° to axis of 25-mm-diam by 150-mm-high tungsten target for a 1-sr conical solid angle and a 1-sr conical-shell solid angle. Smooth curves have been drawn through the spectra. The lethargy interval is 0.230

APPENDIX G

ENERGY DEPOSITION IN TARGETS AND MODERATORS

I. BARE TARGETS

The energy deposition resulting from impinging 800-MeV protons onto bare targets of tungsten and depleted uranium was computed using Monte Carlo techniques. The targets were 30 mm in diameter and 150 mm high. The protons were assumed to have a Gaussian distribution truncated at a radius of 15 mm with one standard deviation in a radius of 7.5 mm. The computations included:

- heating caused by atomic collisions of charged particles and recoil energy of residual nuclei for particles with energies greater than 20 MeV, and

- gamma-ray, charged-particle, and fission heating for neutron-induced reactions below 20 MeV.

The high-energy fission was estimated by assuming all nuclear interactions by protons or neutrons with energies above 20 MeV ultimately terminated in a fission.⁴⁸

The energy balance for the tungsten and uranium targets is given in Table G-I. A large fraction of the initial proton energy is carried from the target by escaping neutrons and protons. For 1% of the LAMPF beam (8.16 kW in the beam), the power generated in the tungsten target is 3.21 kW. The power generated in the depleted-uranium target is 3.89 kW when high-energy fission is excluded. An estimate of the *upper limit* to the high-energy (>20-MeV) fission contribution in depleted uranium increased the power in the target by ~50%.

II. SPECIFIC TARGET/MODERATOR CONFIGURATIONS

For a moderator adjacent to a target, the leakage neutrons and protons from the target interact in the moderator and deposit some of their energy. The energy deposition in a moderator is dependent upon the moderator material and the specific target/moderator configuration.

The total energy of leakage neutrons and protons from a 25-mm-diam by 150-mm-high tungsten target bombarded with 800-MeV protons has been computed to be about 362 MeV. This leakage energy is about 45% of the incident proton energy. The maximum* energy deposited in two H₂O wing moderators, each 33 mm thick by 100 mm wide by 150 mm high, was computed to be ~11.2 MeV/p. At 1% of the LAMPF beam, this amounts to a power generation in the moderators of ~115 W. If the tungsten target is centrally imbedded in a 70-mm-thick by 200-mm-wide by 150-mm-high H₂O moderator, the energy deposited in the moderator is ~25.9 MeV/p. At 1% of the LAMPF beam, this amounts to a power generation in the moderator of ~264 W.

*Neglecting neutron transport below 0.5 eV and proton transport below 20 MeV.

TABLE G-I

**ENERGY DEPOSITIONS IN AND LOSSES FROM 30-mm-DIAM BY 150-mm-HIGH
TUNGSTEN AND DEPLETED-URANIUM TARGETS BOMBARDED BY 800-MeV PROTONS***

Energy Accounting		Tungsten ^b	Depleted Uranium ^c
Energy in proton beam (MeV/p)	(A)	800	800
Energy deposited in target (MeV/p)			
Charged particles >20 MeV and recoil of residual nuclei		318.5	297.0
Charged particles (includes fission) induced by neutrons <20 MeV		0.3	99.9
Gamma rays <20 MeV		<u>5.6</u>	<u>8.0</u>
Subtotal (1)		324.4	404.9
Energy escaping (MeV/p)			
Neutrons		157.1	163.6
Protons		<u>170.2</u>	<u>193.1</u>
Subtotal (2)		327.3	356.7
(1) + (2)		651.7	761.6
Less fission & gamma		<u>-5.9</u>	<u>-107.9</u>
(B)		645.8	653.7
Separation energy available for neutrons and protons (MeV/p)	(A) - (B)	154.2	146.3

*Protons were distributed in a Gaussian truncated at a radius of 15 mm with one standard deviation in a radius of 7.5 mm.

^bTotal atom density was 0.0629×10^{24} atoms/cm³.

^cTotal atom density was 0.0481×10^{24} atoms/cm³. Includes 0.2 wt% ²³⁵U.

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