MODERATOR NEUTRON PULSE-SHAPE STUDY FOR THE *NXGENS* LONG-PULSE SPALLATION SOURCE

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We present results of MCNPX modeling of the neutron pulse time structure delivered by moderators under investigation for the proposed NxGENS long-pulse spallation neutron source at the Los Alamos Neutron Science Center. As envisioned at the time of this work, low-energy neutrons would be produced for the NxGENS flight path by a single "backscattering" moderator of either water or liquid hydrogen in proximity to a tungsten-reflected tungsten target bombarded by 800 MeV protons. Specifically, our results here pertain to a 9.2 cm thick water moderator, and a 5.2 cm thick liquid hydrogen moderator with ortho*:*para *ratio of 1:1. It was found that the Ikeda-Carpenter model accurately represents the storage of neutrons in these moderators, but that there are inaccuracies in the time region dominated by slowing-down. We suspect that inhomogeneity of the moderators, their limited size, and neutronic coupling of the moderators to their surroundings may be responsible for the observed disparities with this model.*

I. INTRODUCTION

Spallation neutron sources for neutron scattering research have traditionally operated in the so-called "short-pulse" regime, in which neutrons are generated in the target by intense, sub-microsecond proton beam pulses. However, significant practical impediments to the development of more powerful short-pulse sources (e.g. target thermal-mechanical stresses, beam space-charge effects) are driving interest in alternative long-pulse sources (LPSSs) that would have pulse durations on the order of 1 ms. LPSS technology could circumvent the average power ceiling imposed by extant SPSS technology, at the expense of more complicated flight path components.

This paper reports on a neutronics modeling study conducted for NxGENS,[1] a proposed prototype LPSS at the Los Alamos Neutron Science Center (LANSCE) that would provide experimental platform for testing the LPSS concept. As envisioned at the time of this work, NxGENS would be a beneficiary of leakage flux from the proposed Materials Test Station (MTS)–a tungsten target designed to be driven by 650-μs proton beam pulses from the 800-MeV LANSCE linac. The primary purpose of MTS is fast-neutron irradiation of advanced nuclear fuel samples, so unique care is necessary to integrate and harmonize the NxGENS flux-tailoring components with those of MTS.

Toward the goal of optimizing moderator brightness, we used MCNPX simulation to study how the materials and dimensions of a single "backscattering" moderator in proximity to the MTS target influence neutron flux in the NxGENS flight path. We also examined the impact of the moderator on adverse fission heating of the MTS fuel. These findings were presented in a companion publication.[2] *This* paper focuses on the time-dependence of the neutron pulses emitted from the moderators under investigation. Understanding of these pulse shapes will help guide the design for flight-path neutronics and NxGENS research instruments.

I.A. Target Station Materials and Geometry

I.A.1. Spallation Target

The spallation target under consideration for NxGENS is the Materials Test Station (MTS) planned at LANSCE.[3] This target station is envisioned to be two D_2O-cooled rectangular tungsten blocks sandwiching a payload of HEU fuel pellets, all of which is surrounded by a tungsten fast-neutron reflector (see Fig. 1, see also Fig. 12 in Ref. 1 for a 3D rendering). Beam pulses are magnetically switched between the two blocks. The model for MTS used in this study is not final and has evolved some since the study; however, it is useful for our scoping purposes.

I.A.2. Moderator, Pre-Moderator, and Decoupler

As illustrated in Fig. 1, the NxGENS moderator is intended to be situated within the target station reflector upstream of the target, with the neutron flight path at a right angle to the proton beamline.

The basic moderator design derives from that of the high-resolution water moderator on the 1L target at the

Manuel Lujan, Jr. Neutron Scattering Center, in which the moderator flows through a chambered aluminum tank. [4] Moderator thickness (vertical direction in Fig. 1) was a parameter discussed in our complementary paper (Ref. 2), as was the moderator composition (light water, liquid hydrogen over the range of *ortho* : *para* ratios).

The tungsten fast-neutron reflector is a strong absorber of low-energy neutrons. This fact serves the flux-tailoring needs of MTS but creates a lossy environment for the NxGENS moderator. One improvement we discussed previously in Ref. 2 is a beryllium pre-moderator of no more than 4 cm thickness surrounding the moderator tank to minimize the loss of low-energy neutrons back into the reflector. A 4-cm pre-moderator was found to improve the flight-path flux below 5 meV by 46% with a liquid hydrogen moderator and, in the case of a water moderator, to improve the flight-path flux below 0.4 eV by 60%. The pre-moderator is controversial, however, because of its deleterious impact upon MTS fuel heating.

Finally, a 0.1016-cm (40 mil) cadmium decoupler layer enclosing the moderator (and pre-moderator if present) attenuates leakage of low-energy neutrons that would soften the spectrum in the MTS fuel region and contribute to adverse heating. We found the decoupler to be a desirable feature: in the absence of a pre-moderator it reduces flux < 1 eV in the upstream fuel segments by nearly 50% while having no significant impact on NxGENS flux (again, see Ref. 2).

In this paper we only consider a 9.2 cm thick water moderator and a 5.2 cm thick liquid hydrogen moderator with *ortho* : *para* = 1:1. Neither contain the advantageous but controversial Be pre-moderator. Both do contain the Cd decoupler. The water moderator is at the optimal thickness determined in our study. The liquid hydrogen moderator is thinner than the 12 cm optimal thickness—unfortunately, the pulse-shape simulation was run before the thickness optimization was complete.

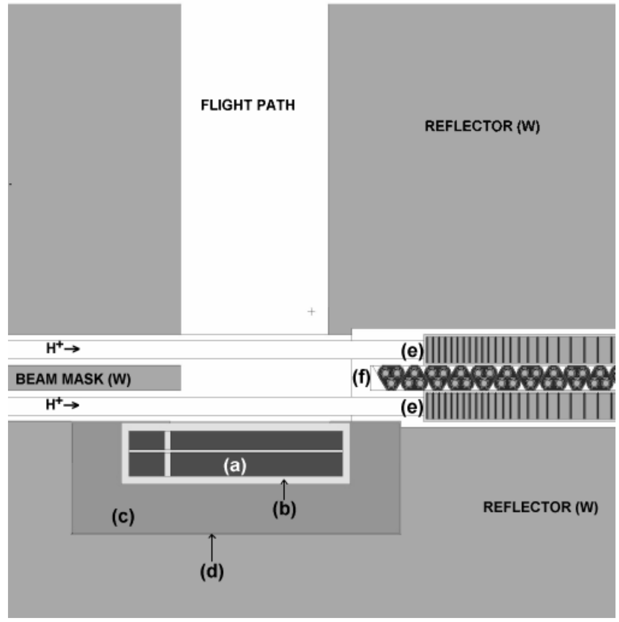

Fig. 1. Cross-section of target station geometry for LPSS moderator study. The liquid moderator itself (a) is contained in an aluminum tank (b), in turn surrounded by beryllium pre-moderator (c) and cadmium decoupler (d). The proton beam approaches from left and strikes D_2O-cooled tungsten target blocks (e) surrounding HEU fuel bundles (f). Scale of drawing is such that the horizontal extent represents about 0.5 m.

II. METHOD

Simulations were carried out using the Monte-Carlo code MCNPX[5] 2.4.f with full transport of protons, neutrons, photons, pions, and muons. An 800-MeV proton source was defined to represent the divided beam impinging on the two tungsten targets. Cross-sections and neutron $S(\alpha,\beta)$ data, where available, were taken from the standard libraries supplied with the code. Since the MTS fuel can produce delayed neutrons, the TOTNU card was present.

We defined neutron point-detector (F5) tallies located on the flight-path centerline, approximately 30 m from the exposed surface of the moderator. All time-dependent tallies were used in conjunction with a custom TALLYX subroutine that subtracted from the raw tally contents the neutron time-of-flight from the exposed surface of the moderator. This surface could be defined for TALLYX on the FU card in the problem input.

The tallies measured the flux binned by time and energy, $\phi(E,t)\Delta E\Delta t$, under the assumptions that (a) neutrons instantly reach the detector position after leaking from the moderator (see TALLYX description above), and that (b) all neutrons are generated by a proton pulse of zero duration at t = 0 on the target. The tallies were defined with narrow bins ΔE about several particular energies E corresponding to neutron wavelengths of interest—e.g. 0.5Å, 1Å, 2Å 4Å. Although the assumptions (a) and (b) are obviously unphysical, the resulting pulse shapes can be used in further calculations if warranted to determine pulse shapes for flight paths of arbitrary length and proton pulses of arbitrary duration.

The weight-window generator was found to be particularly advantageous for variance reduction with the time-dependent tallies.

Subsequent manipulation and curve-fitting of tally data were carried out with the aid of MatLab and MS Excel.

III. RESULTS AND ANALYSIS

Dividing the tally results by the bin widths ΔE and Δt approximates the differential flux with respect to E and t, φ(E,t). This is the form in which the results are reported here, in units of n cm^{-2} s^{-2} mA^{-1} eV^{-1}. Data for a 9.2-cm thick water moderator are plotted in Figs. 2-5. Data for the 5.2-cm thick liquid hydrogen moderator with 1:1 *ortho:para* ratio are plotted in Figs. 6-9. Error bars are present on all data.

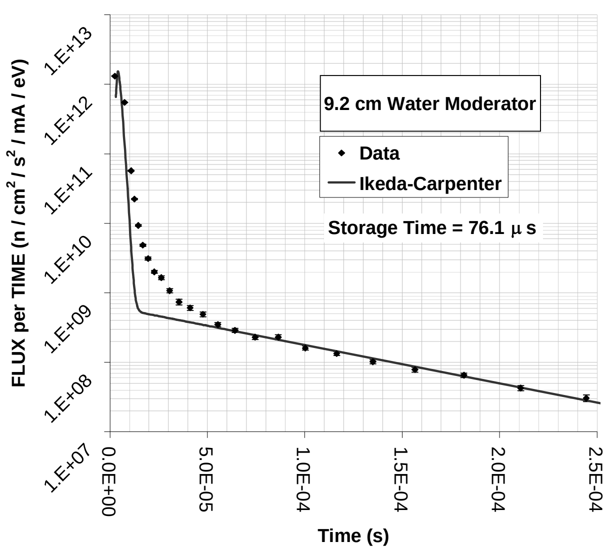

Fig. 2. Flight-path differential neutron flux φ(E,t) at λ = 0.5 Å, for a water moderator.

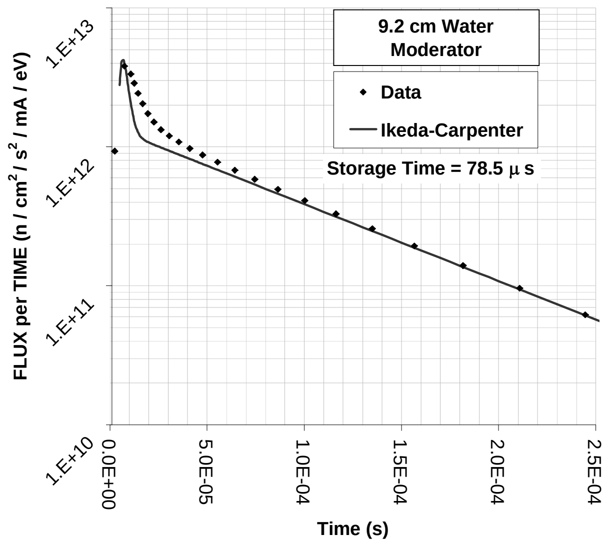

Fig. 3. Flight-path differential neutron flux φ(E,t) at λ = 1 Å, for a water moderator.

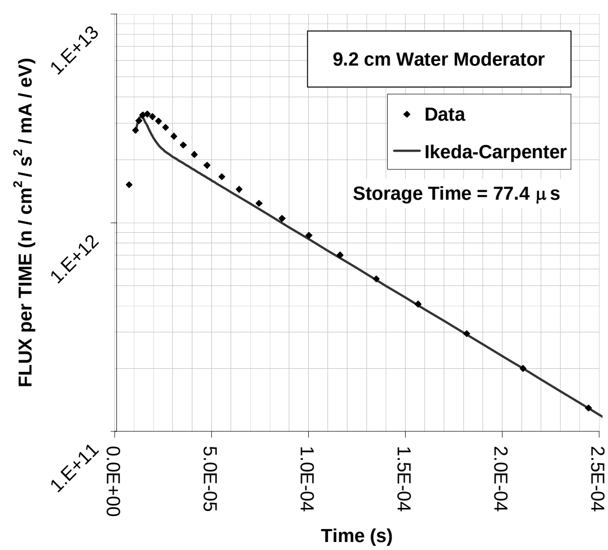

Fig. 4. Flight-path differential neutron flux φ(E,t) at λ = 2 Å, for a water moderator.

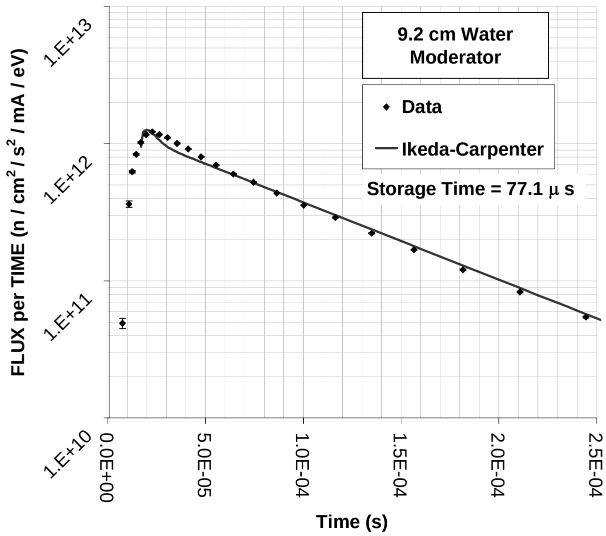

Fig. 5. Flight-path differential neutron flux ϕ(E,t) at λ = 4 Å, for a water moderator.

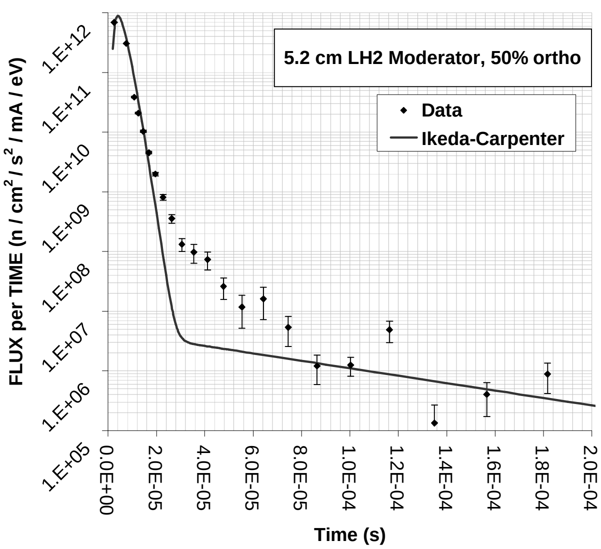

Fig. 6. Flight-path differential neutron flux ϕ(E,t) at λ = 0.5 Å, for a liquid hydrogen moderator.

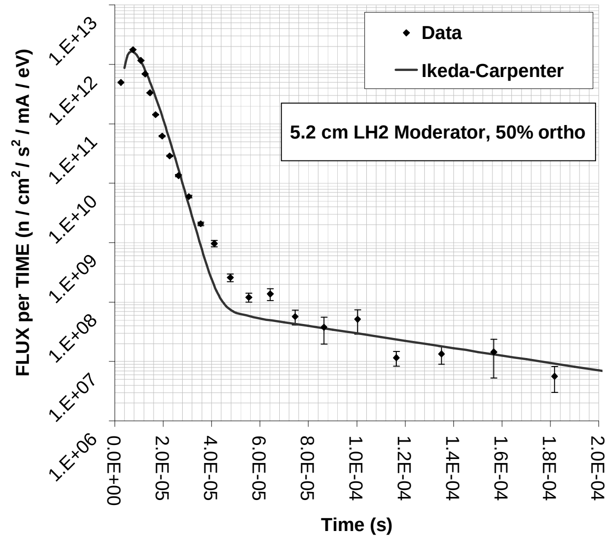

Fig. 7. Flight-path differential neutron flux ϕ(E,t) at λ = 1Å, for a liquid hydrogen moderator.

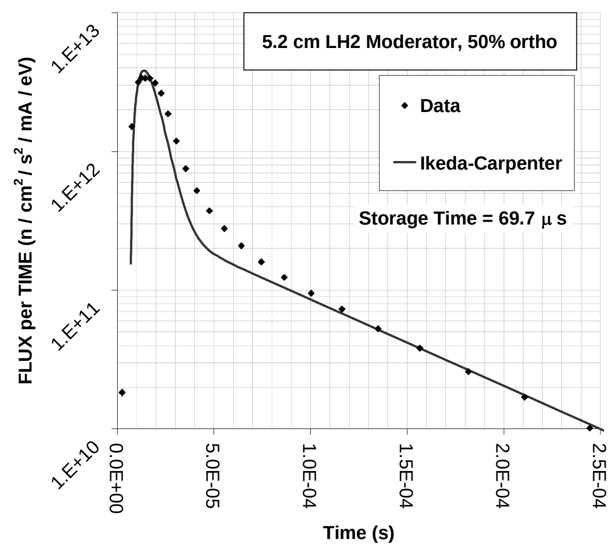

Fig. 8. Flight-path differential neutron flux ϕ(E,t) at λ = 2Å, for a liquid hydrogen moderator.

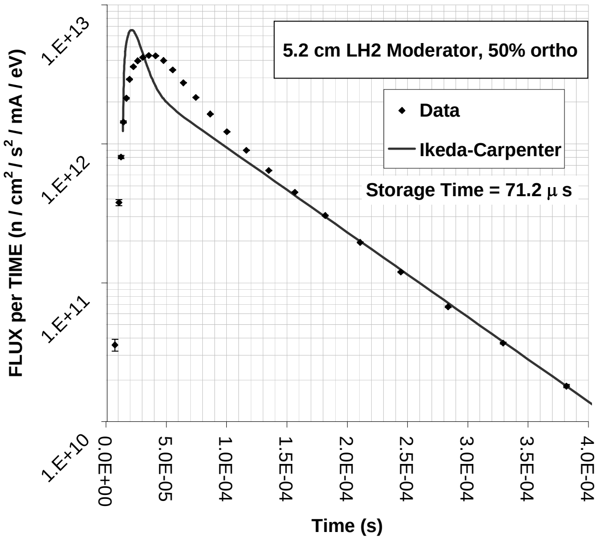

Fig. 9. Flight-path differential neutron flux $\phi(E,t)$ at λ = 4Å, for a liquid hydrogen moderator.

We made efforts to explain the pulse shapes observed via the Ikeda-Carpenter (I-C) model,[6] which describes the pulse shape as the coupled result of two processes, slowing-down and "storage." Neutrons of predominantly high energy take some time, characterized by a time constant τ_{sd}, to lose energy by scattering in the moderator. Low-energy neutrons diffuse throughout the moderator (and are hence "stored" in it) over a generally longer time scale $\tau_{storage}$ before leaking out. The I-C model assumes a homogenous, non-absorbing, hydrogenous moderator containing a homogenous volume neutron source.

The explicit form of the I-C function $f(v,t)$ is as follows:

$$f(v,t) = \frac{\alpha(t\alpha)^2 \exp(-t\alpha)}{2} + A\exp(-t\beta) - A\exp\left[-t\alpha\left(1+(\alpha-\beta)t+\frac{\alpha(\alpha-\beta)^2 t^2}{2\beta}\right)\right] \quad (1)$$

where α is the inverse of the slowing-down time constant,

$$\alpha = \frac{1}{\tau_{sd}} = \Sigma_s(v)\cdot v \quad (2)$$

β is the inverse of the storage time constant $\tau_{storage}$; and A is as follows:

$$A = R\frac{\alpha^3\beta}{(\alpha-\beta)^3} \quad (3)$$

In Eq. 2, $\Sigma_s(v)$ is the macroscopic scattering cross-section of the moderator material at a particular neutron velocity. In Eq. 3, R is a scaling parameter.

To fit Eq. 1 to data, the first step is to determine β. Since storage dominates at long elapsed time, $\tau_{storage}$ can be found by fitting a least-squares exponential decay curve to the $\phi(E,t)$ data after about 100 μs has elapsed. This was done for the data in Figs. 2-7 and the storage times thus calculated are printed on the graphs. In two situations we felt the data were statistically too poor to warrant reporting the value, but the fitting process remained the same.

The next step is to calculate α. The microscopic scattering cross-sections $\sigma_s(v)$ at energies corresponding to the wavelengths in Figs. 2-7 were interpolated from cross-section plots made in MCNPX, and then $\Sigma_s(v)$ was calculated (Eq. 4). In Eq. 4, N_A is Avogadro's number, ρ is the mass density of the moderator material, M is its molecular weight, and n is the number of nuclei per molecule. Table 1 reports the values of $\sigma_s(v)$ and α that were used.

$$\Sigma_s(v) = \frac{\sigma_s(v)\cdot\rho\cdot N_A\cdot n}{M} \quad (4)$$

At this point, R remains the last undetermined parameter in Eq. 1 and was fit by eye to the data to the extent possible. A slight negative time offset (less than 20 μs) was also found to be helpful in fitting. The I-C functions are plotted alongside the data in Figs. 2-7.

TABLE I. Cross-sections And α For Ikeda-Carpenter Functions

	LH2, 50% *ortho*		Water	
λ	σ_s (b)	α $\times 10^5$ (s^{-1})	σ_s (b)	α $\times 10^5$ (s^{-1})
0.5 Å	21.4	13.6	15.58	7.17
1 Å	23.9	7.60	17.35	4.00
2 Å	32.4	5.06	23.1	2.71
4 Å	55.0	4.24	38.7	2.30

IV. CONCLUSIONS

In these MCNPX models of moderators for NxGENS, neutron storage dominates the observed pulse shape after an elapsed time on the order of 100 μs. In problems where the tally uncertainty is low, a simple exponential decay fits this region of the pulse shape very well. The storage time constant is about 77 μs for the 9.2 cm water moderator and about 70 μs for the 5.2 cm liquid hydrogen moderator, and does not noticeably depend on neutron energy. The shorter time constant for hydrogen may be attributable to the thinner moderator and its lower atom density. Neutrons delayed predominantly by storage do not contribute much to total yield at the higher neutron energies. For instance, in Fig. 7 (1Å neutrons from the hydrogen moderator), the storage-dominated portion of the IC function is more than four decades below the slowing-down peak.

The slowing-down portion of the IC functions show considerable disparity with the data. Better fits seem to be associated with the higher energies / shorter wavelengths, a trend that is particularly apparent in Figs. 6-9. The largest systematic difference between data and the IC functions occurs around 30 μs with water and 50 μs with hydrogen, when the IC function undershoots the data considerably. This could result from (a) inaccuracy or miscalculation of α from the scattering cross-sections, although the fits seem passable at low energies, e.g. Fig. 7; or (b) influence of the materials surrounding the moderator and flight path. Examples of the latter cause might be delayed fission neutrons from the MTS fuel or the diffusion of neutrons into the moderator from the tungsten surroundings. We believe that additional simulations without the TOTNU card would provide a useful comparison with regard to delayed fission contributions.

A fuller understanding of the time structure of neutron pulses from the NxGENS moderator-target system will be valuable to the design of flight paths, choppers, and instruments, and will lead to more accurate instrument performance estimates. It is hoped that the method and results discussed in this study are a useful springboard for in-depth studies that may follow.

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