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# SNS Moderator Performance Predictions

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## ABSTRACT

Predictions are given for the neutronic performance of the SNS based on neutron transport calculations and experimental work at existing low power pulsed spallation sources.

SNS MODERATOR PERFORMANCE PREDICTIONS

## INTRODUCTION

In this paper we present the predicted neutronic performance of the SNS target-moderator-reflector system. This information has been previously given in a series of internal papers to the SNS Science Planning Group [1,2] and in working papers of the Target Reflector and Moderator Design Team, TRAM [3-8].

## MODERATOR DESIGN

The object of the target-moderator-reflector design optimisation is the production of a wide variety of beams with appropriate spectral and resolution characteristics matched to the envisaged instrument suite. This has been achieved using four independent moderators in wing geometry, two above and two below the target, Figure 1. To facilitate heat removal and to minimise radiation damage the moderator materials are fluids. The four moderators are a 4.5cm thick liquid methane moderator at 95K poisoned with gadolinium at a depth of 2.25cm; a 4.5cm thick ambient water moderator asymmetrically poisoned with gadolinium to give 1.5cm and 3.0cm effective thicknesses; an 8cm thick supercritcal hydrogen moderator at 25K; and a 4.5cm thick ambient water moderator poisoned with gadolinium at a depth of 2.25cm. Important aspects of the physical design of the moderators are summarised in Table I. Further details may be found in references [9,10].

In its initial configuration SNS has

- seven beams viewing the high intensity, high resolution liquid methane ($CH_4$) moderator, which is optimised for pulse structure;

- three beams viewing a very high intensity face (A) and three beams viewing a high intensity, high resolution face (AP) of an ambient moderator;

- three beams of long wavelength neutrons from the liquid hydrogen ($H_2$) moderator, which is optimised for intensity;

- and the remaining two beams viewing an intermediate resolution ambient moderator (D).

The predicted beam currents and pulse widths for these moderators at full SNS intensity are given in Figures 2 and 3.

## INTENSITY

The intensity predictions are based on calculations with the Monte Carlo code TIMOC [4,5,7,11-13], experiments in the low current target station at Los Alamos [14-16] and experience at Argonne [17-19]. These neutronic data are normalised to the fast neutron production appropriate to the SNS plated uranium target assembly by assuming the value of 24.7 fast neutrons per proton calculated by Atchison [20].

The spectral distributions of Figure 2 may be described by a maxwellian region

$$\phi_{max}(E) = J \frac{E}{T^2} \exp\{-E/T\}$$

a slowing down epithermal region

$$\phi_{epi}(E) = \frac{\phi_o}{E^A}$$

joined together by an empirical switch function $\Delta(E)$

$$\phi(E) = \phi_{max}(E) + \Delta(E)\phi_{epi}(E)$$

In these equations J is the integrated maxwellian intensity, T is the effective temperature of the maxwellian in energy units, $\phi_o$ is the differential flux at 1eV and A is a leakage parameter. A suitable joining function for the ambient and methane moderators is

$$\Delta(E) = [1 + \exp\{\frac{W_1}{\sqrt{E}} - W_2\}]^{-1}$$

This function is somewhat empirical and less signifance ought to be attached to the values of $W_1$ and $W_2$ than to the parameters describing the maxwellian and slowing down region. The switch energy

$$E_s = \left(\frac{W_1}{W_2}\right)^2$$

does give an indication of the lower limit of the slowing down region for that moderator. The switch function for the hydrogen moderator is more difficult. Mildner has suggested [21] that a more complex switch function is required for low temperature moderators. In his description $\Delta(E)$ is multiplied by a second switch function giving

$$\Delta'(E) = \Delta(E)\left[1 + W_3 \left\{1 + \exp\left\{W_4 - \frac{W_5}{\sqrt{E}}\right\}\right\}^{-1}\right]$$

Experience at Argonne indicates that two different maxwellian distributions are required to describe their low temperature moderator data [22]. Since the SNS hydrogen moderator is intended primarily for the production of long wavelength neutrons, it is sufficient for our purpose to parameterise only the maxwellian part of the spectrum.

The predicted parameters for the SNS with 200μA of 800MeV protons on target are given in Table II. Values for other proton energies may be calculated by scaling fast neutron production by ($E_p$ - 120), where the proton energy $E_p$ is in MeV [23].

TIME STRUCTURE

The time structure of the pulse of neutrons emanating from the moderators is of prime importance. We attempt to preserve the intrinsically sharp proton burst (0.4μs) by using thin hydrogeneous moderators, heterogeneously poisoned by gadolinium and decoupled from the reflector by boron. The methane moderator is cooled to 95K further modifying the time structure by delaying the onset of thermalisation to energies less than 50meV.

Figure 3 gives the full width at 50% height, $\Delta t_{50}$, for the SNS moderators. These predictions are again based on Monte Carlo calculations [4,6-8,11-13] and experiments at Los Alamos and Argonne [14-19].

In addition to the full width at half maximum, the pulse shape is of critical importance for many experiments. In the slowing down region the pulse shape is well described by [24].

$$\phi_{epi}(t) = (\Sigma_s vt)^2 \exp\{-\Sigma vt\}$$

where $\Sigma_s$ is the macroscopic cross-section and v the neutron velocity. In the maxwellian region, the pulse shape is dominated by a long-time exponential tail [25].

$$\phi_{max}(t) \sim \exp\{-t/\tau\}$$

where

$$\tau^{-1} = \alpha_o + DB^2 - CB^4$$

In this equation $\alpha_o$ is the absorption probability, D the diffusion coefficient, C the diffusion cooling constant and $B^2$ the geometric buckling. Values for the long time decay constant $\tau$ have been predicted for the SNS ambient moderators [8] and are given in Table II.

A detailed computational study of the SNS liquid methane moderator [7], benchmarked against measurements at IPNS [19], predicts the time profiles illustrated in Figures 4 and 5. The resultant lineshape may be described as the convolution of a gaussian with two decaying exponentials, weighted by a switch function R.

$$\phi(t) = G(\sigma,t) * [R \exp\{-t/\tau'\} + (1-R) \exp\{-t/\tau\}]$$

In this equation $\tau$ is the decay constant given in Table II and the wavelength dependence of the parameters $\tau'$ and $\sigma$ is

$$\tau' = 2.5\ \lambda$$

$$\sigma = 1.5\ \lambda$$

when $\tau'$ and $\sigma$ are in μs and $\lambda$ in Å.

The switch function R may be modelled as

$$R = 0.5 \left[1 + \mathrm{erf}\left(C(1/\lambda_o - 1/\lambda)\right)\right]$$

where $\lambda_o$ is 1.45Å and C = 3.4Å.

We have compared calculated pulse shapes for a decoupled liquid hydrogen moderator with measurements at IPNS [18]. The long time decay constant for such a moderator with SNS dimensions is given by

$$\tau = 25\ \lambda \qquad \text{for } 1 < \lambda < 6\text{Å}$$

$$= 150\ \mu s \qquad \text{for } \lambda > 6\text{Å}$$

Again $\tau$ is measured in $\mu s$ and $\lambda$ in Å.

A simpler model of a single decay mode convoluted with a gaussian whose width varies as

$$\sigma = 3.7\ \lambda$$

was found to give a reasonable description of the pulse in the range of interest.

OVERALL PERFORMANCE

The $4\pi$-equivalent flux,

$$\phi^{4\pi} = \frac{4\pi\phi}{Af\Delta t_{50}}$$

where $\phi$ is the time averaged flux (Figure 2), A the moderator area, f the frequency of the source and $\Delta t_{50}$ the FWHM of the pulse (Figure 3), is often used to compare pulsed and steady state neutron sources. This function is given in Figure 6 for SNS and a comparison made with ILL high flux reactor in Grenoble. Although indicative of the overall performance, this function does not take into account details of instrumentation or source utilisation. The comparison of one type of source with another is fraught with difficulty [26]. No single number or merit function exists and in the end theonly real comparison must lie in the quality of papers published from each source!

## ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the work of the Target Moderator Design Team at Rutherford Appleton Laboratory and colleagues at Los Alamos and Argonne. Particular thanks are due to George Stirling, Michael Johnson, David Picton, Bill David, Alan Carne, Rob Robinson, Gary Russel and Jack Carpenter.

TABLE I

| MODERATOR | Front Ambient | | Liquid Methane | | Liquid Hydrogen | Rear Ambient |
|---|---|---|---|---|---|---|
| Mnemonic | AP | A | $CH_4$ | | $H_2$ | D |
| Material | $H_2O$ | | $CH_4$ (4 atm) | | p-$H_2$ (15 atm) | $H_2O$ |
| Temperature (K) | 316 | | 95 | | 25 | 316 |
| Position | Top Front | | Bottom Front | | Bottom Rear | Top Rear |
| Height (cm) | 12 | | 11.5* | | 12* | 12 |
| Width (cm) | 12 | | 12* | | 11* | 12 |
| Thickness (cm) | 4.5 | | 4.5* | | 8* | 4.5 |
| Poison | 0.05 mm Gd | | 0.05 mm Gd | | -- | 0.05 mm Gd |
| Poison Depth (cm) | 1.5 | 3.0 | 2.25 | 2.25 | -- | 2.25 |
| Beam Lines (Angle to Moderator Normal) | N7(0)<br>N8(14)<br>N9(27) | S1(14)<br>S2(1)<br>S3(12) | N1(14)<br>N2(1)<br>N3(12) | S6(13)<br>S7(0)<br>S8(14)$^+$<br>S8(14)$^+$<br>S9(27) | N4(13)<br>N5(0)<br>N6(13) | S4(13)<br>S5(0) |
| Decoupler | Boron$^x$ | | Boron$^x$ | | None | Boron$^x$ |
| Void Liner | Boron$^x$ | Boron$^x$ | Boron$^x$ | Boron$^x$ | Boron$^x$/Cd | Boron$^x$ |

Notes:

* Maximum dimension. Moderator containment is a pressure vessel whose faces have radii of 25 cm.

\+ S8 beam line is multiplexed with two guides.

x 1/e transmission of boron layer at 3.6 eV.

TABLE II

| | AP | A | D | $CH_4$ | $H_2$ |
|---|---|---|---|---|---|
| J ($n/sr.100cm^2.s$) | $1.7\ 10^{13}$ | $3.0\ 10^{13}$ | $1.5\ 10^{13}$ | $1.1\ 10^{13}$ | $1.7\ 10^{13}$ |
| $\phi_o$ ($n/eV.sr.100cm^2.s$) | $7.2\ 10^{12}$ | $7.2\ 10^{12}$ | $4.2\ 10^{12}$ | $6.0\ 10^{12}$ | $6.5\ 10^{12}$ |
| $J/\phi$ | 2.4 | 4.2 | 3.5 | 1.8 | 2.6 |
| T (meV) | 33.9 | 33.1 | 33.6 | 11 | 2.8 |
| A | 0.9 | 0.9 | 0.9 | 0.9 | -- |
| $W_1$ ($meV^{\frac{1}{2}}$) | 90 | 125 | 114 | 54 | -- |
| $W_2$ | 8.9 | 10.6 | 9.8 | 6.7 | -- |
| $E_s$ (meV) | 100 | 140 | 135 | 65 | -- |
| $\tau$ ($\mu s$) | 20 | 30 | 26 | 32 | $25\lambda$ |

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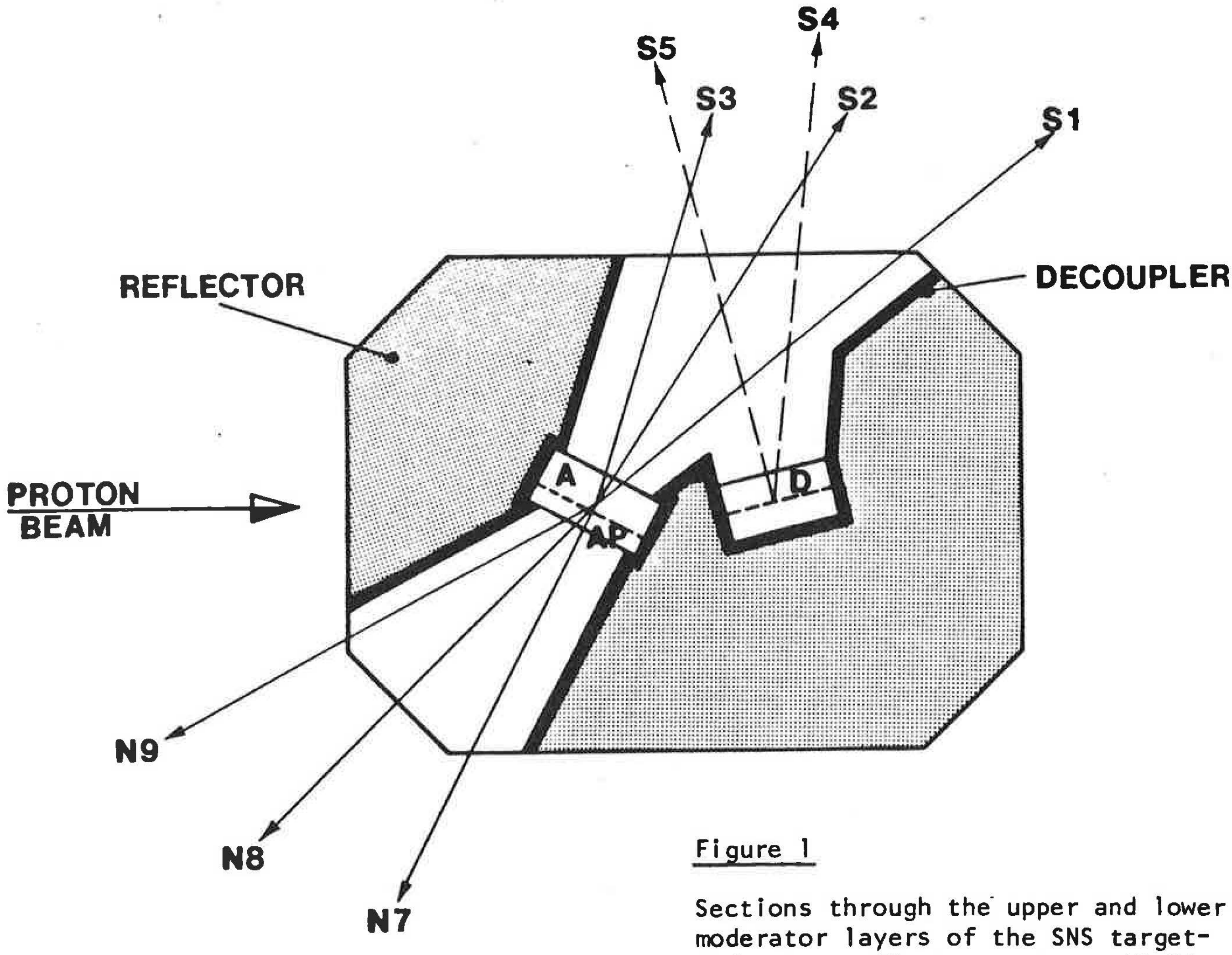


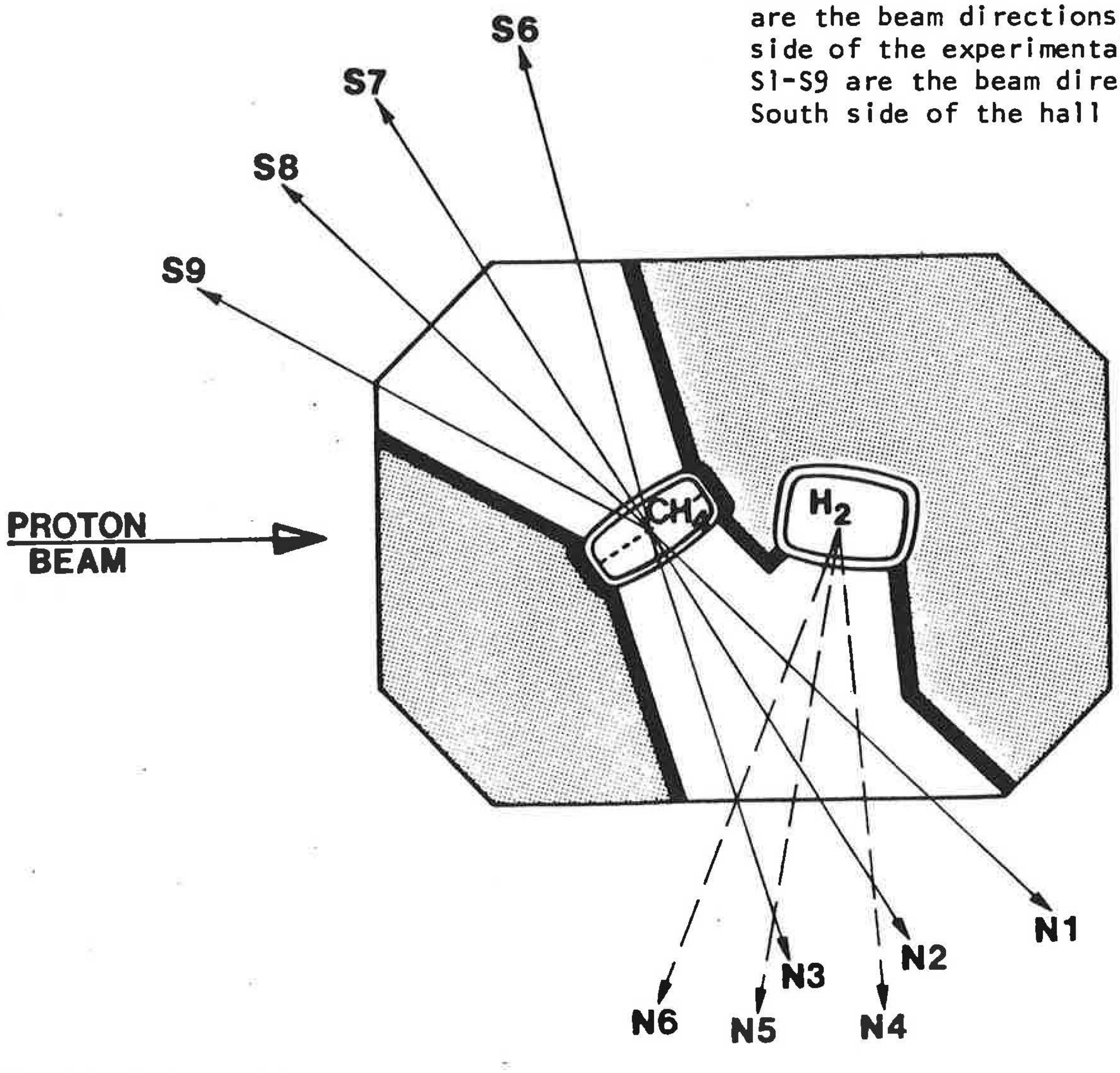


Figure 1

Sections through the upper and lower moderator layers of the SNS target-moderator-reflector system. N1-N9 are the beam directions on the North side of the experimental hall and S1-S9 are the beam directions on the South side of the hall

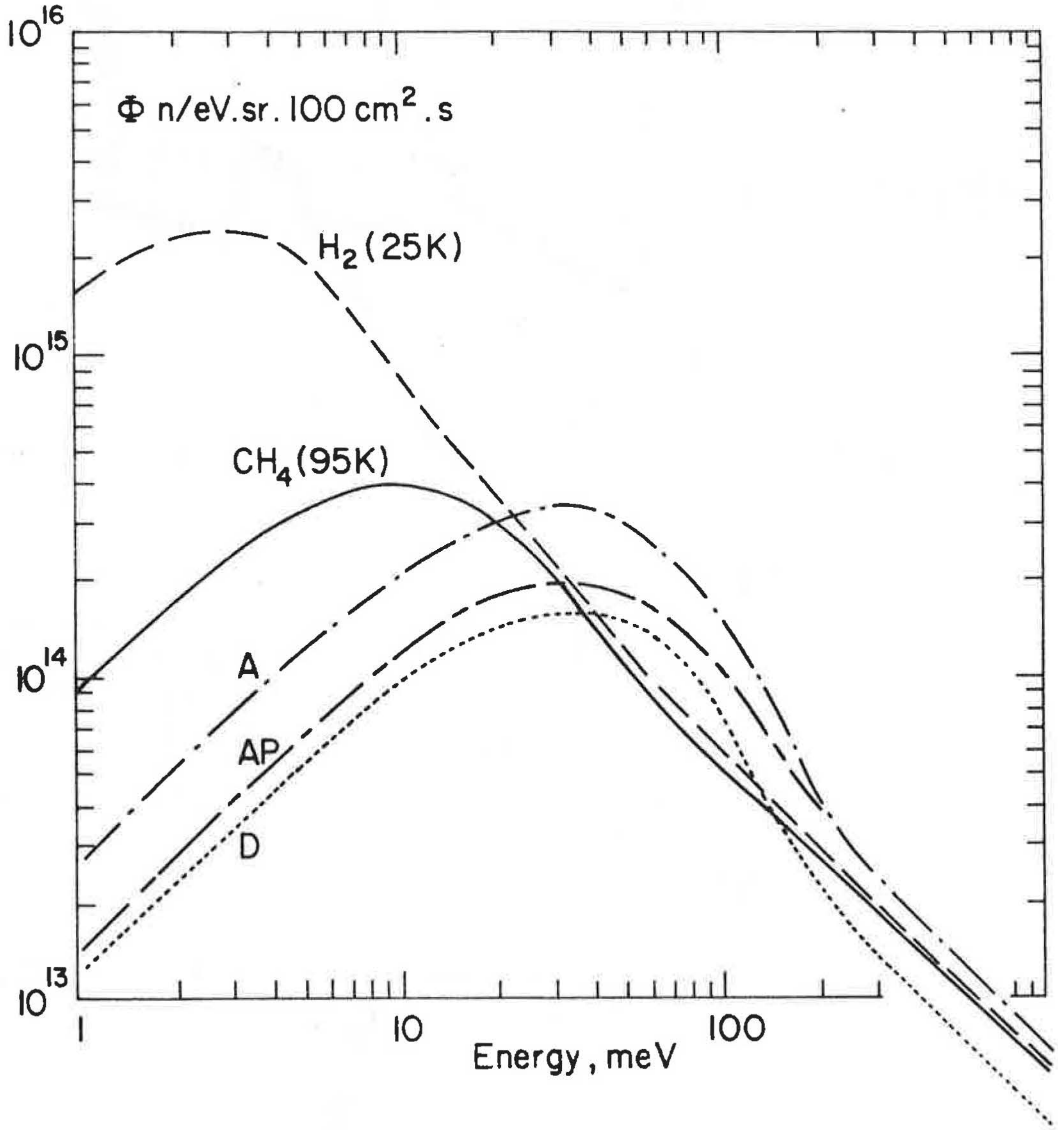


Figure 2 The predicted spectral distribution from the six faces of the four SNS moderators. The $CH_4$ moderator has two identical faces. Physical details of the moderators are given in Table I and the parameterisation of the spectral functions are given in Table II.

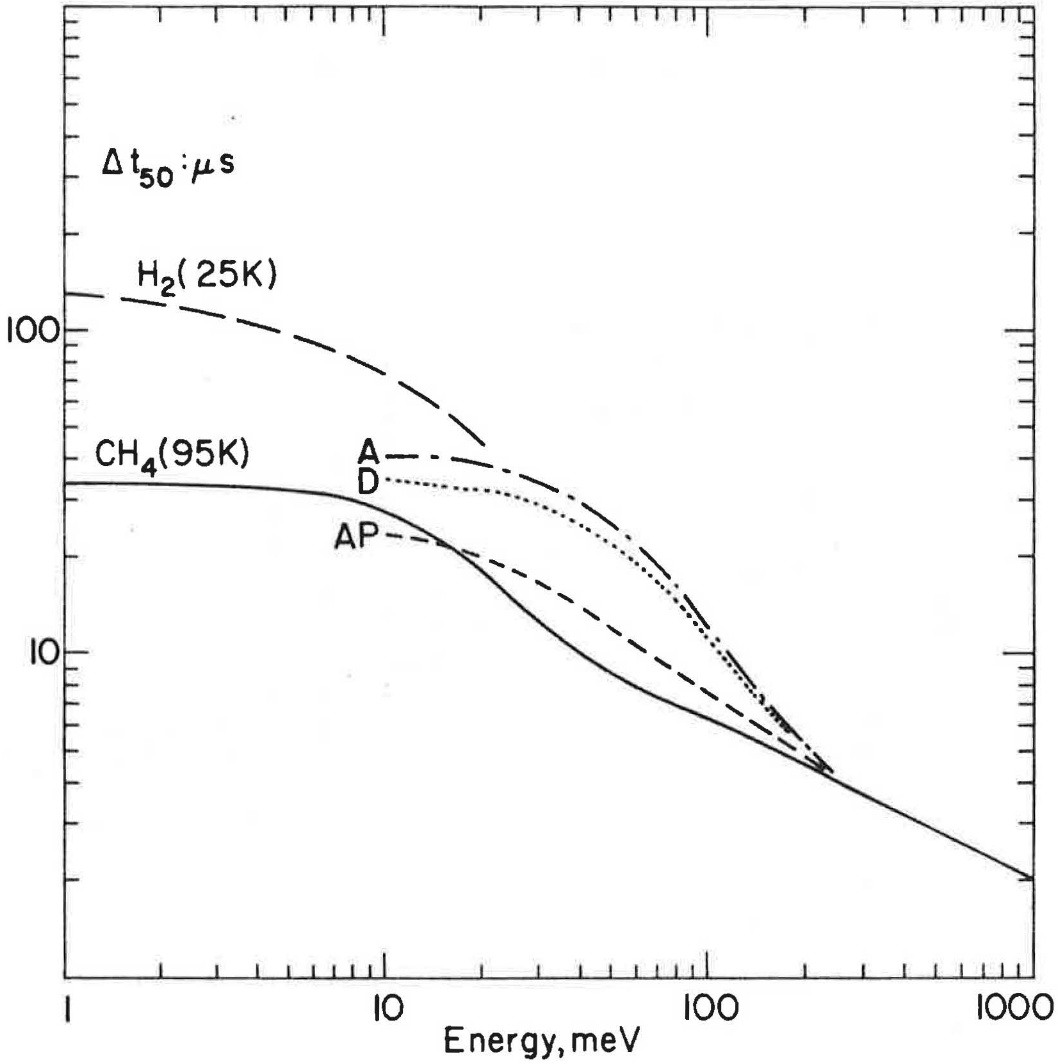


Figure 3 The predicted FWHM of the six faces of the SNS moderators as a function of energy.

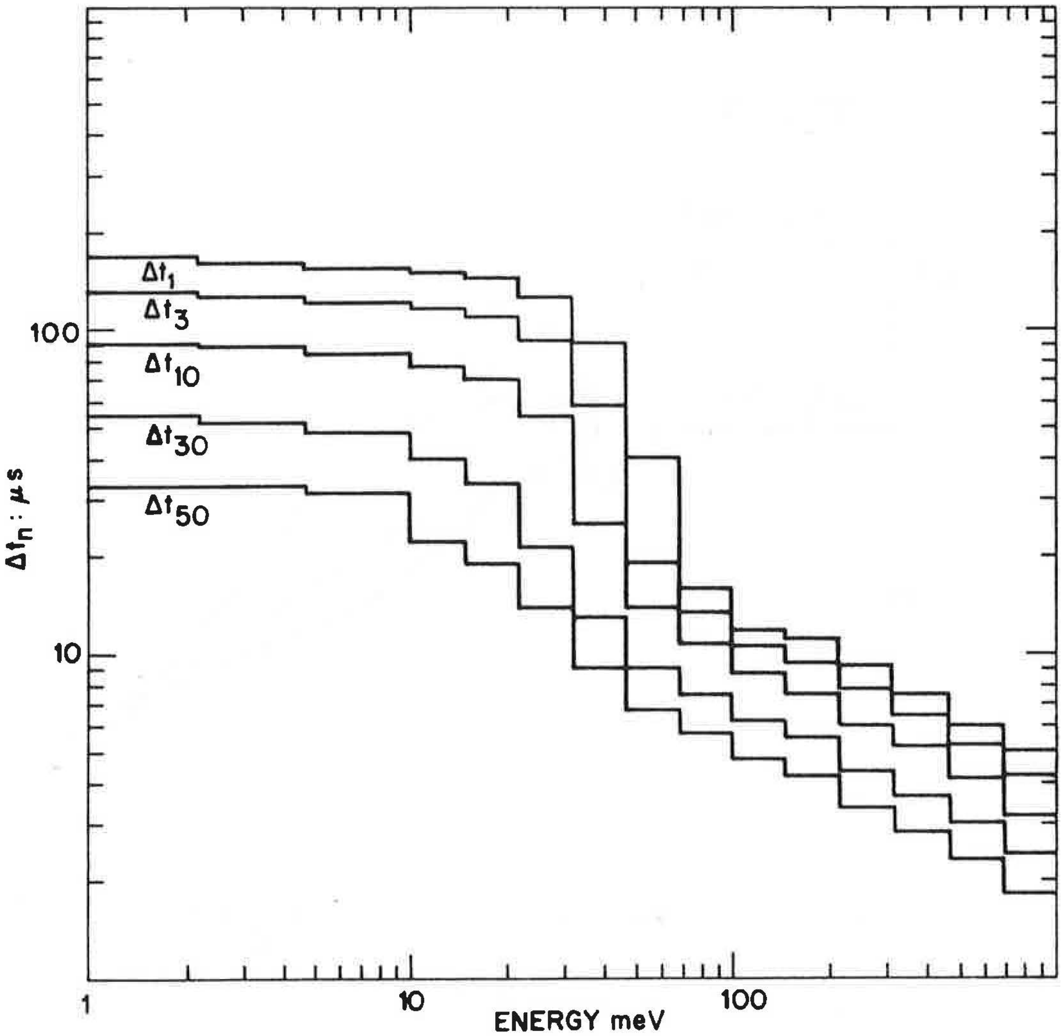


Figure 4 The calculated behaviour of the pulse widths at n % height, $\Delta t_n$, for the poisoned SNS liquid methane moderator as a function of energy.

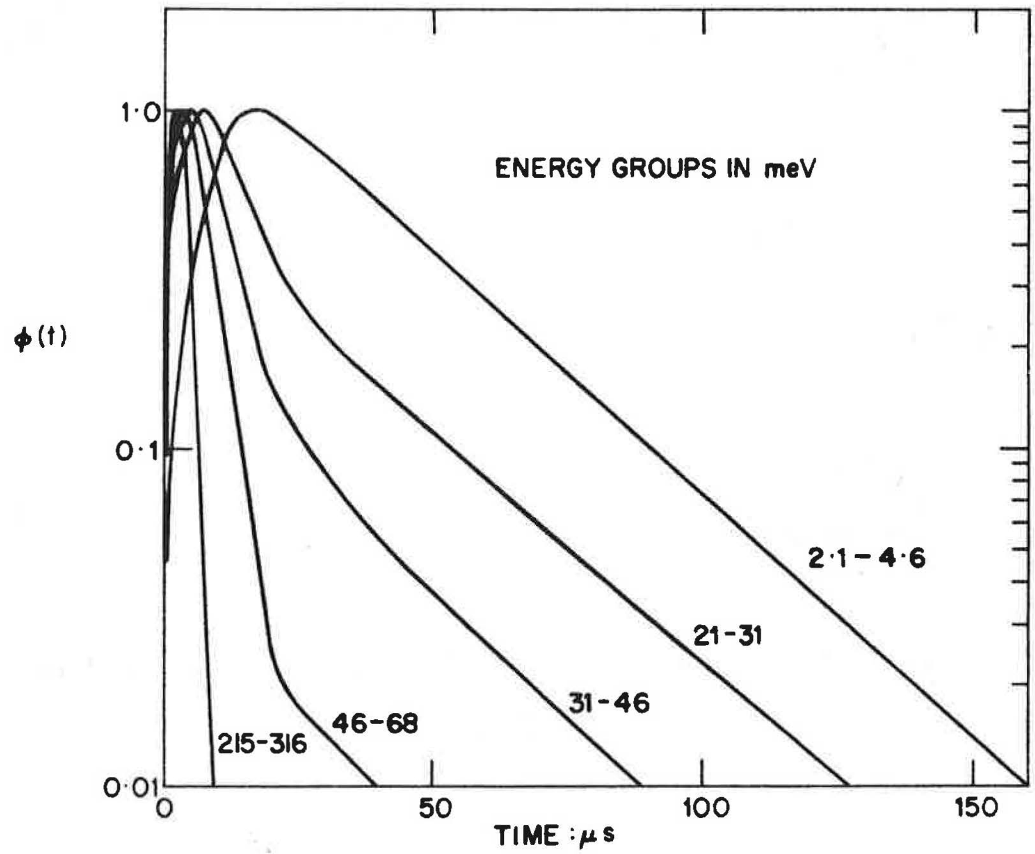


Figure 5 The calculated pulse shape of the poisoned SNS liquid methane moderator for several energy groups.

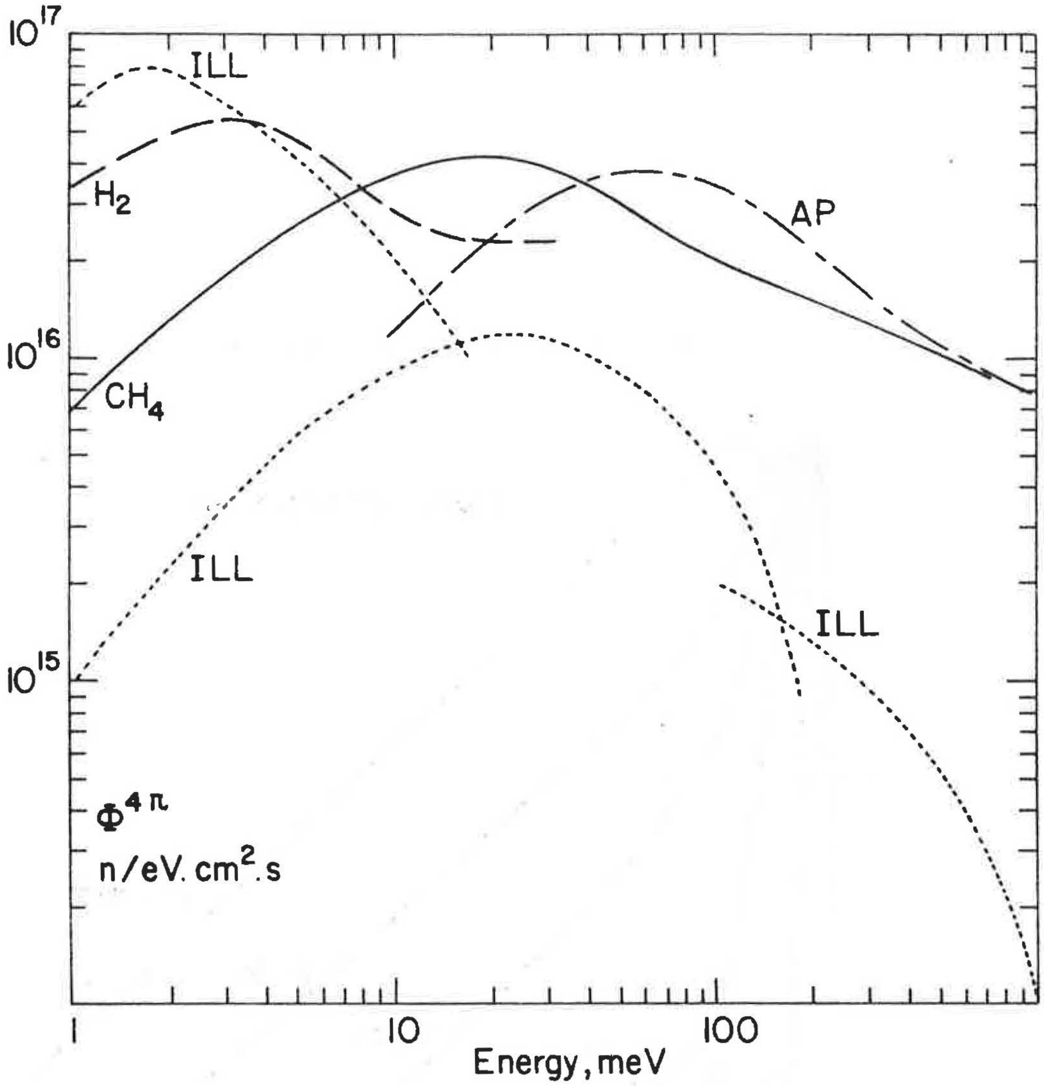


Figure 6 The predicted $4\pi$ equivalent flux for SNS based on Figures 2 and 3 compared with the flux of the three moderators at the ILL high flux reactor in Grenoble.