Summary of Results from the ZING-P' Pulsed Neutron Source

J.M. Carpenter and IPNS Program Staff*

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

---

* The number of people who have made important contribution to this work is so large that it is impractical to include a complete list of authors' names.

Summary of Results from the ZING-P' Pulsed Neutron Source

J.M.Carpenter and IPNS Program Staff

Our goals in operating ZING-P' were to test further the applications of pulsed spallation neutron sources in scattering studies and to develop information needed for design of IPNS. Starting with low intensity operation, with 0.5×10^{12} proton/pulse at 1 Hz, while sharing the injector linac with ZGS, we reached in the end 1.8×10^{12} proton/pulse at 30 Hz in a dedicated mode with reliability of about 90%. (See above summary of ZING-P' Operation.)

Scientists of the Argonne scientific divisions developed and operated five scattering instruments and one general physics experiment. An extensive series of measurements of target, moderator, reflector and cooling system performance were carried out, and the source was used as a test-bed for neutron detector tests by Argonne and Rutherford Lab groups.

The table summarizes source measurements and tests of applications of pulsed spallation neutron sources that we have carried out.

Source Measurements

Total power in W and U targets

Local power density in U target

$\gamma + n$ dose rates in neutron beams

Total nuclear heating in liquid hydrogen moderator

Nuclear heating power densities in polyethylene, Be and Pb

Nuclear heating in boron and Cd-shielded boron decoupler materials

Absolute neutron beam intensities for W and U targets

Delayed-neutron fraction

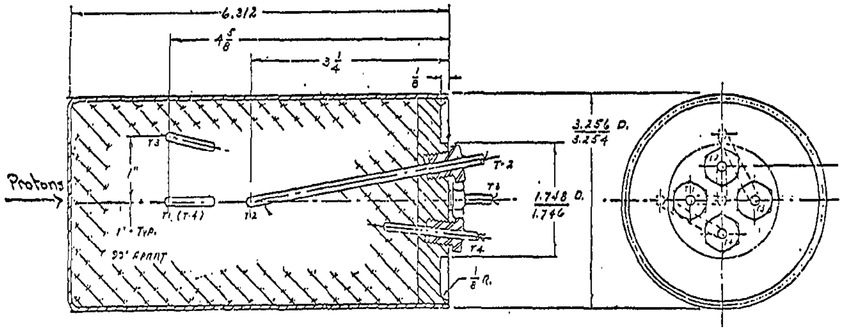
Neutron spectra for liquid hydrogen and polyethylene moderators

Neutron pulse widths vs wavelength for liquid hydrogen and polyethylene moderators

In the following we give some of the results of these measurements.

Uranium Target

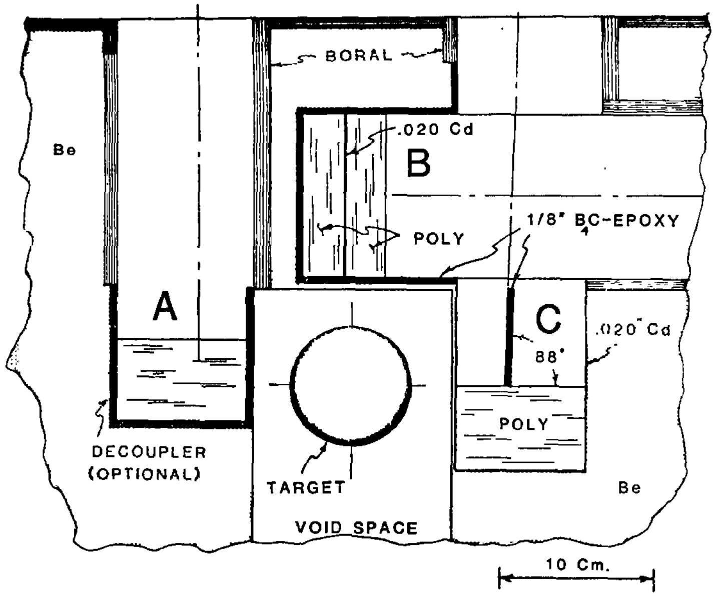
The Uranium target is shown below. The material was depleted Uranium (0.2% ^{235}U), with Zerconium cladding applied in a Hot Isostatic Pressure (diffusion) bonding process. Four stainless steel-clad, MgO-insulated Cu-constantan thermocouples were let into ELOXed holes in the Uranium.



The ZING-P' Uranium Target

(Dimensions in inches)

The target and moderator arrangement of ZING-P' are shown in the figure below:



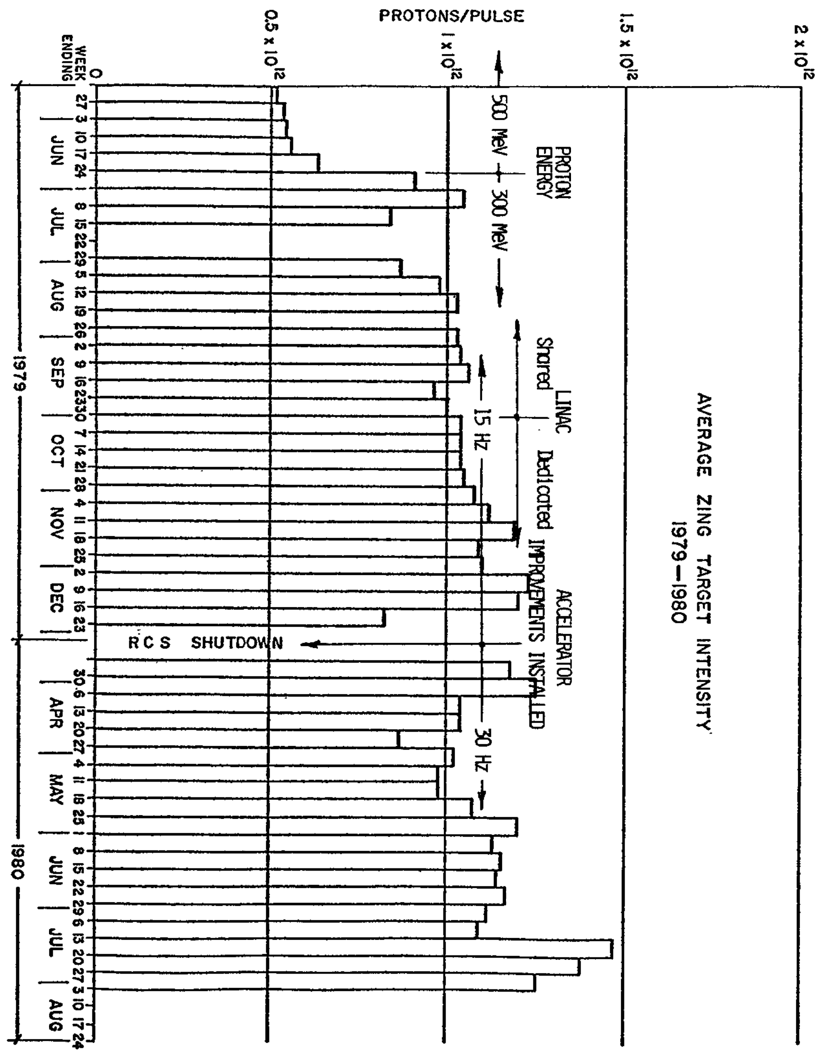
The ZING-P' target-moderator configuration.

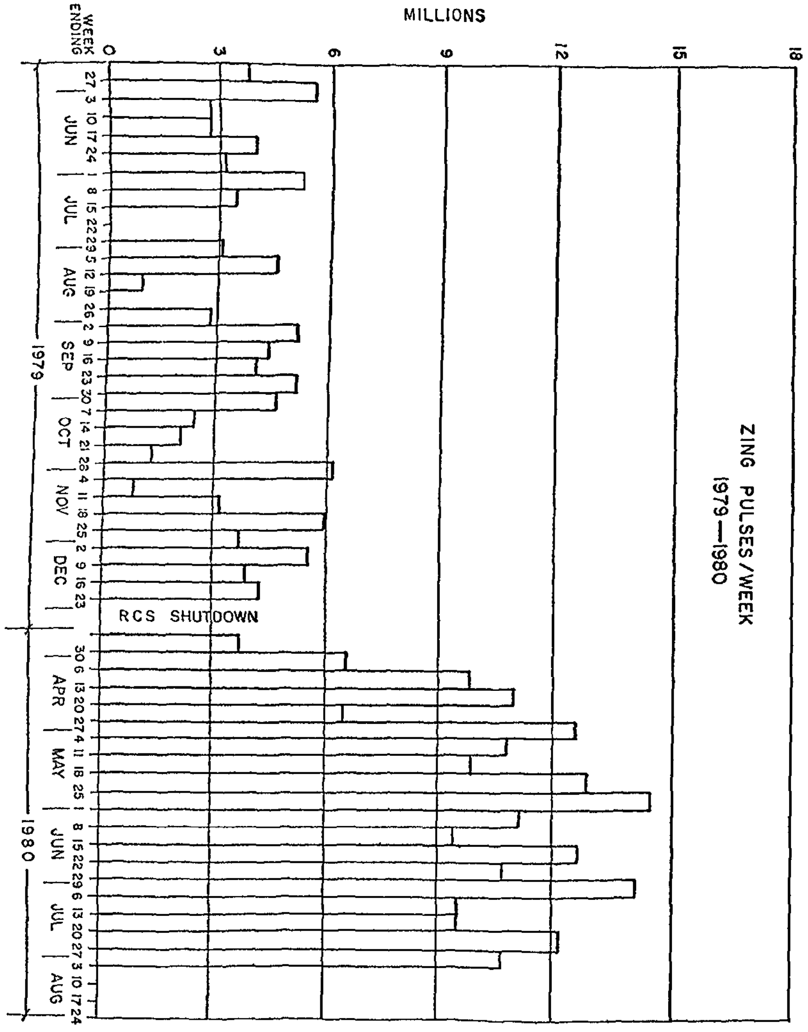
The data acquisition system was a Nuclear Data ND6600 computer-based multichannel analyzer system, using eight time of flight ADC's providing 4K channels for each of 4 inputs. Input/output devices were a magnetic tape, paper tape, line printer and a removable disk, and one CRT terminal. Signals were transmitted using optically-decoupled cables to minimize noise pickup.

ZING-P' Operating Record

From the time of turnon, ZING-P' and the RCS were continuously improved. Starting in December 1977, delivering about .5 x 10^{12} protons per pulse at 1 Hz (.08 μA) to a W target, we reached week-long averages of 1.5 x 10^{12} protons per pulse, at 30 Hz (7.2 μA) on a U target. On a 24 hour basis we reached 7.6 μA, and for a few minutes, a current of 9.6 μA at 30 Hz (nearly 2 x 10^{12} protons/pulse). The U target increased the neutron beam intensities by about x2 over the intensities for the W target. During the first part of the history, the machine delivered 500 MeV protons. In the later part, we lowered the energy to 300 MeV to minimize the effects of lossy extraction while the intensity reached its highest levels. Extraction system improvements will enable 500 MeV operation at the higher intensities when IPNS-I is turned on.

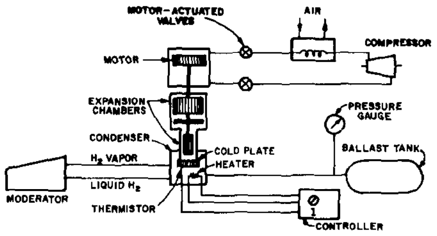
The following figures summarize the recent operating history.





Liquid Hydrogen Moderator

Cold neutrons for the first stage of an ultracold neutron experiment were produced by a liquid hydrogen moderator installed in place of the original polyethylene moderator for beam V-2 at ZING-P'. The liquid hydrogen moderator and the refrigeration system shown schematically in the figure operated essentially **trouble free since its installation.**



The ZING-P' Liquid Hydrogen Moderator System

The moderator, which had a volume of 368 cm^3 was connected through recirculating tubes to the condenser. Liquid H_2 flows to the condenser under natural circulation. Hydrogen was condensed by a cold plate chilled by cold helium provided by a Displex refrigerators were operated in parallel (only one is shown in Fig.2). The refrigerators operated steadily at constant power.

The moderator was connected through an open gas line to a 0.29 m^3 ballast tank. Temperature was controlled by a controller which sensed the temperature of a thermistor in the condenser. The H_2 system was charged when the system was warm to a pressure of 37 psia. This ensured that when the moderator was cold, it was filled with liquid when the controlled temperature was the same as the temperature of liquid hydrogen at a pressure of 16 psia. This small overpressure relative to atmosphere was maintained to prevent inward leakage of condensable gases (air).

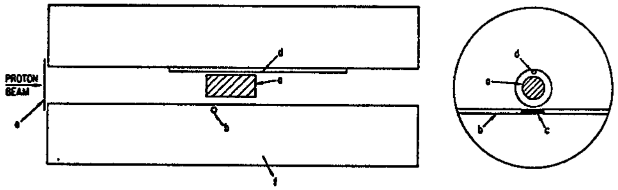
The moderator was of somewhat irregular shape to fit the geometric constraints of the ZING-P'reflector, shield and beam pipes. The 3° slope of the top plate provided that vapor bubbles flow readily to the vapor oulet. The insulating vacuum space contained several layers of aluminized glass-fiber paper as radiation shielding. The moderator container was supported by ceramic standoffs from the vacuum enclosure.

Radiation Effects Facility Mockup

The proton beam from RCS was directed through the normal target position of ZING-P' (the ZING-P' target was removed) to a shielded location downstream, for test of a mockup of the fast neutron Radiation Effects Facility.

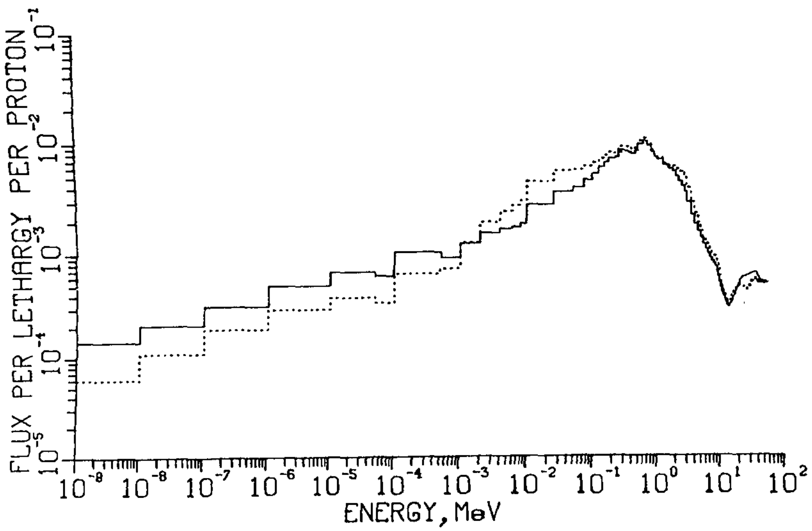
Neutron spectra, fluxes and flux gradients were measured in a mock-up at ZING-P' using 478 MeV protons bombarding solid targets of tantalum and depleted uranium. The targets were surrounded by a thick lead neutron reflector. Neutron spectra were determined from multifoil activation by spectrum unfolding using the STAYSL computer code. The materials and geometry of the mock-up were selected so that neutron production and transport could be easily calculated theoretically by the HETC and VIM computer codes.

A simplified chematic of the target system and dosimetry positions is shown in the Figure. The targets were watercooled solid cylinders of Ta or Zircaloy clad ^{238}U. Each target was irradiated separately while centrally located in a Pb cask, which provided 25 cm of neutron reflector. The integrated proton beam current and profile was measured by activation of Al foils at the entrance to the Pb cask. The neutron spectra for each target was determined by 28 neutron reactions. The neutron spectrum from the ^{238}U target is shown in the Figure. The neutron flux distributions were measured along and perpendicular to the targets by 11 neutron reactions.



Schematic of the radiation effects target-reflector mock-up: a Ta or ^{238}U target, b. perpendicular neutron dosimetry position, c. primary neutron dosimetry position, d. parallel neutron dosimetry position, e. Al foil for p^+ dosimetry, f. Pb reflector.

The exact geometric and material arrangement of each target system was modeled for computer calculation of the neutron spectra, fluxes and flux gradients. The measured proton beam profile was used as input to each calculation. The figure compares the measured and calculated neutron spectra for the ^{238}U target system. The calculations are in good agreement with the experimental results. In the mock-up configuration, the ^{238}U target produces 50% more neutrons that the Ta target. The neutron spectrum is affected by the reflector material. The (n,xn) reactions in the Pb reflector also increase the neutron flux.



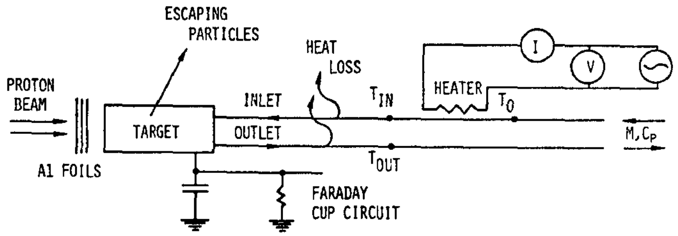
Spallation neutron spectra for the ^{238}U target. The solid line is calculated and the dotted line is experimental.

Source Measurements

Total Power Measurements in W and U Targets

The total power deposited in these targets was measured using the arrangement described in the diagram. The energy deposited is the net of energy carried in by protons, energy released by nuclear reactions, the separation energy of particles produced, and the kinetic energy of escaping particles. Proton beam intensities were monitored by the $^{27}Al(p,x)^{22}Na$ reaction.

ARRANGEMENTS FOR MEASURING TOTAL POWER IN ZING-P' TARGETS



The results are tabulated below.

Total Power in Zing-P' Targets

Target (Proton Energy)	Total Power/Beam Power
U (300 MeV)	1.5
U (500 MeV)	1.5
W (500 MeV)	.94

The results are about 30% higher than were predicted by our HETC and VIM codes.

Local Power Density in the U Target

Four thermocouples were embedded in the ZING-P' U target. The power density at each thermocouple location was determined from obervations of the rate of temperature change when the proton beam was instantaneously turned off after steady operation. Then, the power density at point $\underline{r}$ is, quite rigorously

$$p(\underline{r}) = -\rho C \left(\left.\frac{dT(\underline{r})}{dt}\right|_{t=o^{+}} - \left.\frac{dT(\underline{r})}{dt}\right|_{t=o^{-}} \right)$$

The lag in response of the thermocouples (about 2 seconds) produces the major uncertainty in our results, since this makes it difficult to determine the initial rate of temperature change. We have made "best-fit" corrections to the data, to account for this effect. The proton beam profile was determined from a Teflon-foil autoradiograph. The results are summarized below, and compared with predictions of HETC and VIM codes.

Measured Power Densities

Thermocouple	Position (r,z),cm	Power Density $w/cm^3\mu A$	Thermocouple Lag time, sec
TC1	0.0, 4.1	3.75-6.46	1.75-2.85
TC2	0.0, 7.6	.049-.074	1.8-2.5
TC3	2.5, 4.1	.79-1.33	2.5-4.0
TC4	2.5, 4.1	1.00-1.17	.95-1.1

These results are subject to random error due to the thermocouple lag correction procedure, which gives rise to the large range of results. The results are still tentative as we continue our efforts to refine them.

Computed Power Densities, $w/cm^3\mu A$

FWHM of Proton Beam	TC1	TC2	TC3 & 4
1.95	7.5 ± .2	.17 ± .02	.41 ± .02
2.25	6.4 ± .2	.17 ± .02	.60 ± .02
2.30	5.7 ± .2	.16 ± .02	.63 ± .02

The measurements are uncertain ± 20% since they are based on Faraday-cup measurement of the proton intensity. The calculations contain about ± 10% error from HETC. These errors both appear in the results as scale factors. The HETC-VIM results have not been connected here to give the observed total power -- this factor is 1.30, to give the observed ratio actual power/beam power = 1.5.

Gamma Ray and Neutron Dose Rates in the Neutron Beams

The total dose rate due to gamma rays and neutrons from the U target was determined using thermoluminescent detectors, in beam H-2 of ZING-P', 18 meters from the source viewing the entire moderator. We found the following results:

Proton Energy	Dose Rate mrad/hr-μA	Dose Rate x (Distance)^2 rad-m^2/hr-μA
300 MeV	62.	20.
500 MeV	230.	74.5

The proton beam intensity was determined using the target Faraday cup circuit, thus the results are uncertain by ± 20%.

Total Nuclear Heating in the Liquid Hydrogen Moderator

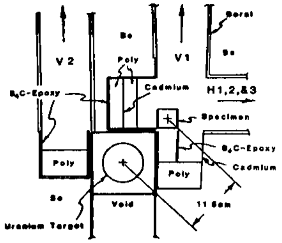
Energy deposited by neutrons, gamma rays and other particles produces heat which must be removed from moderators. We have measured the heat deposited in the 368 cm^3 liquid hydrogen moderator by using it as a gas thermometer to observe the rate of pressure increase when the refrigerator is turned off. The proton beam intensity was monitored using the target Faraday cup circuit, therefore results are uncertain by ± 20%. The target was Uranium and the proton energy 300 MeV. The result is

$$P = 100 \text{ mW}/\mu\text{A} \quad .$$

No decoupling material surrounded the moderator, and a 5 cm thick Be reflector-filter topped the moderator.

Nuclear Heating of Moderator and Reflector Materials

Neutron and gamma ray induced heating have been measured in a position 11.5 cm from the Uranium target as shown below. The proton energy was 300 MeV.



The ZING-P' target-moderator configuration for moderator-reflector measurements. The distance from target center-line to the center of the specimen used for heating measurements was 11.5 cm, as roughtly depicted above.

A thermocouple was used to determine the rate of temperature rise in a well-insulated specimen, and the power density inferred from the relation

$$p = \rho C\left(\left.\frac{dT}{dt}\right|_{t=o^+} - \left.\frac{dT}{dt}\right|_{t=o^-}\right)$$

which applies after startup of the proton beam at time o.

The results are summarized below and are in reasonable agreement with first-principles estimates

Material	Power Density
CH_2	1.2 $mW/cm^3\mu A$
Be	.3 $mW/cm^3\mu A$
Pb	1.7 $mW/cm^3\mu A$

The proton beam was monitored by the installed target Faraday cup circuit, and the results are therefore subject to about ±20% error. The power densities are expected to scale according to the neutron production rate in the target.

Decoupler Heating

Decoupler materials (Cd, Boron, etc.) needed to prevent long-lived thermal neutrons in the reflector from broadening the pulses from the moderator, are heated by neutron capture processes. This heating is difficult to estimate analytically, yet may require provision for cooling. We have measured the power deposited in decouplers of Boron-fiber-aluminum composite materials at ZING-P', in a position adjacent to the fact of the polyethylene horizontal beam moderator. The proton energy was 300 MeV, and the target was U. An insulated specimen of the composite material with area density $.68 \times 10^{21}$ B^{10}/cm^2 backed with 5 cm Be (to simulate reflector material) was instrumented with a thermocouple and the rate of temperature change upon change of proton beam power was determined. The results give area power densities:

composite only: .74 $mw/cm^2\mu a$ (±10%)
with .5mm Cd shielding: .32 $mw/cm^2\mu a$ (±10%)

The heat capacity per unit area for the boron composite was assumed to be .0355 cal/°C-cm^2. The horizontal beam moderator was $5 \times 10 \times 10$ cm^3 slab of polyethylene, poisoned by .5mm Cd 2.5 cm below the surface.

The result is in reasonable agreement with first-principle estimates.

Absolute Neutron Beam Currents

Epithermal neutron beam currents were measured using Au foil resonance activation, with the ZING-P' Uranium target and for 315 and 489 MeV protons. The proton beam intensity was monitored using the $^{27}Al(n,x)$ ^{22}Na reaction. The results are tabulated below, with the results of HETC-VIM calculations. We computed for two cases, assuming theoretical Be density for the reflector, and assuming 75% density (closer to the truth, since the stacking of the Be blocks in the reflector left considerable voids.

Beam Currents Measured by Gold Foil Activation at ZING-P'
(Units of n/ster-μA-s)
Ep = 489 MeV

Moderator	Experimental	Calculated (100% Be)	Calculated (75% Be)
A: liq. H_2 (no filter)	3.02×10^{10}	3.78×10^{10}(3.18)	3.00×10^{10}(2.52)*±.65
		$\alpha = .043$	$\alpha = .068$
B: Polyethylene		1.94×10^{10}	2.01×10^{10} ± .7
		$\alpha = .048$	$\alpha = .052$
C: Polyethylene	2.38×10^{10}	2.89×10^{10}(2.43)*	2.61×10^{10}(2.20)*±.65

Ep = 315 MeV

Moderator	Experimental	Calculated
A: liq. H2 (no filter)	1.17×10^{10}	$1.39 \times 10^{10} \pm .04(1.18)$*
B: Polyethylene	0.88×10^{10}	$0.68 \times 10^{10} \pm .02$
C. Polyethylene	1.00×10^{10}	$1.12 \times 10^{10} \pm 0.4(0.93)$*

*Corrected for area viewed by the beam tube, as though intensity were uniformly distributed across the moderator surface.

The results of experiment and calculation correlate quite well, the calculations with 100% and 75% Be densities seem to bracket the measurements.

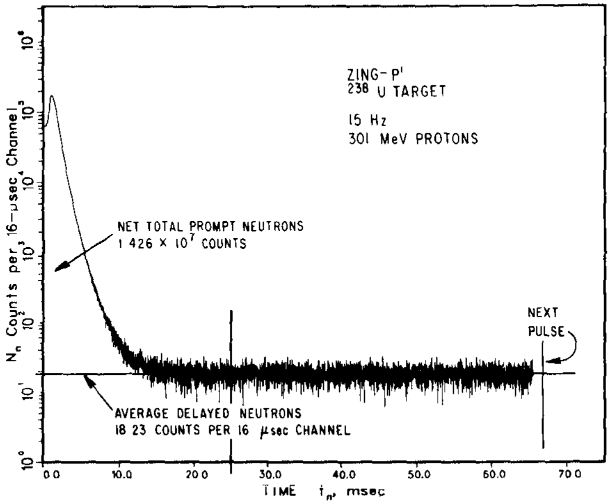
Measurements of The Delayed-Neutron Fraction in The Uranium Target

When fissionable material (^{238}U, ^{232}Th, etc.) is used as target in a pulsed spallation neutron source, delayed neutrons are produced from certain "precursor" fission fragments which decay by neutron emission following one or more steps of beta decay. Energetic photons emitted from beta-decaying products of fission and spallation processes can also induce delayed neutrons through (γ, n) reactions in materials such as ^{9}Be and ^{2}D which may be close to the primary source. The delay half-lives range from fractions of a second to 1 min for precursor fission fragments, and from a few seconds up to several days, with 98% less than 1 min for fission product gamma rays interacting with ^{9}Be. When the interpulse time is short by comparison with these delay times, delayed neutrons constitute a nearly steady source (unless there exist yet-undiscovered, shorter-lived precursors) of neutrons between source pulses.

We made two measurements, in beam V-2 of ZING-P', with the U target in place. For the "SIGNAL" run, the detector was open to the beam from the moderator, and surrounded by B_4C and ^{10}B shielding. For the "BACKGROUND" run, the detector was surrounded by the same shielding, but closed to the beam by 10 cm of ^{10}B shielding. A 1-mm-thick Corning 7740 boron glass filter plate (6.4×10^{20} B/cm^2) was placed in the beam to diminish the counting rate due to long-wavelength neutrons from the prompt pulse, which would obscure the delayed neutrons at long times. The detector was a low-efficiency BF_3 beam monitor detector. The moderator was a 10 x 10 x 5-cm^3 slab of polyethylene at 300 K decoupled by 4×10^{21} ^{10}B/cm^2. The assembly was surrounded by beryllium reflector material. The proton energy was 301. MeV.

The figure shows the net counting rate as a function of time. The delayed neutron fraction β is taken as the ratio of the number of counts in the "prompt" peak (which reflects the wavelength distribution of neutrons) and the total number of counts in the constant part of the distribution. The result is

$$\beta = .0053$$



This fraction is not expected to be a strong function of proton energy. At this level, delayed-neutron background will not be a problem in most slow neutron experiments using neutron beams derived from a ^{238}U target.

Studies of a Grooved Moderator

A grooved moderator was placed in Beam V-1 (Moderator C) of ZING-P'. The moderator was of polyethylene, $\rho = .915$ gm/cm^3, overall 10 x 10 x 5 cm, with 1-cm wide x 2-cm deep grooves placed 1 cm apart on the viewed surface. The moderator was reflected by Be, decoupled by .020" Cd, and was unpoisoned. We measured the intensity vs. wavelength, normalized against that in an unaffected beam from moderator B in beam H-1. We also measured the time structure of the pulses using a time-focussed crystal spectrometer with a Germanium (220) crystal (d = 2.0003 A) and Bragg angle of 168.9°. Comparisons of normalized spectra and pulse width were made between the grooved moderator and the previously-installed, flat, 10 x 10 x 5 cm unpoisoned CH_2 moderator (its condition is described elsewhere in this summary). The moderators were not cooled, and the temperature of the moderators was not measured, but near ambient (300.C).

The figures below compare the time distributions measured for the grooved moderator and the flat moderator at $\lambda = 1.991$ A.

We find that the pulse from the grooved moderator starts at the same time as that from the flat moderator, but rises more slowly, and for $\lambda = 4.02$ A, peaks at a time roughly equal to the flight time across the groove depth. The exponential decay time (1/e) of the longest-lived mode is 50.8 μs for the flat moderator and 41.7 μs for the grooved moderator (average for three wavelengths). The grooved moderator pulse decays more rapidly, but rises more slowly, thus is broader, but more symmetric than the flat moderator pulse. The figure shows the pulse FWHM vs E for the two moderators.

Comparisons of the spectra indicate that the grooved moderator produces higher beam currents. The table below indicates ratios of spectral intensities for various energy ranges; adjustment has been made for detector efficiency.

Comparison of Intensities for Grooved and Flat Moderators

	Intensity (grooved/flat)
I_{Th}	1.10
$EI(E)_{1ev}$	1.24
I_{Total} (E<1.ev)	1.13

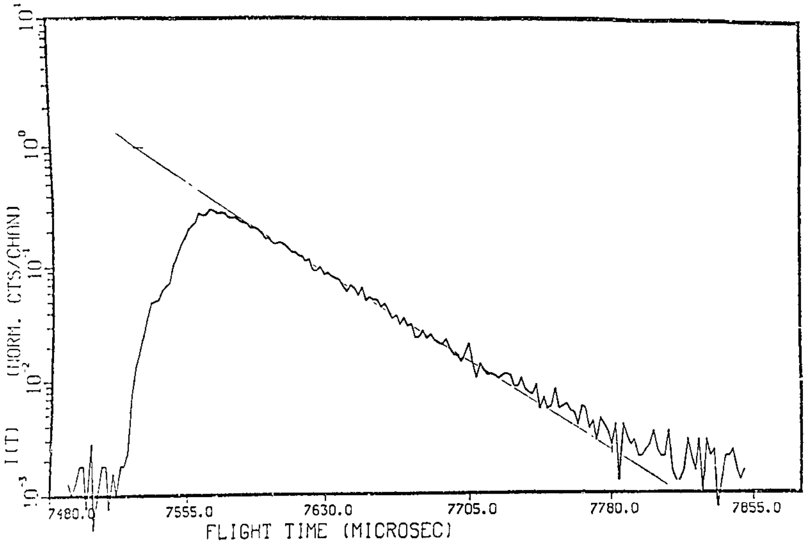
The moderating ratios were

$$I_{Th}/EI(E)_{1ev} = \begin{cases} 4.46 \text{ (Grooved)} \\ 4.75 \text{ (Flat)} \end{cases}$$

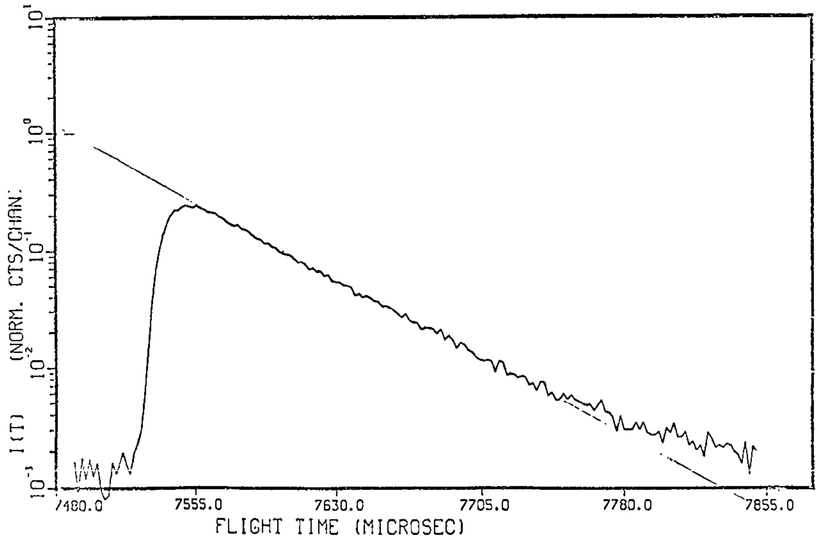
The spectral temperatures were also determined:

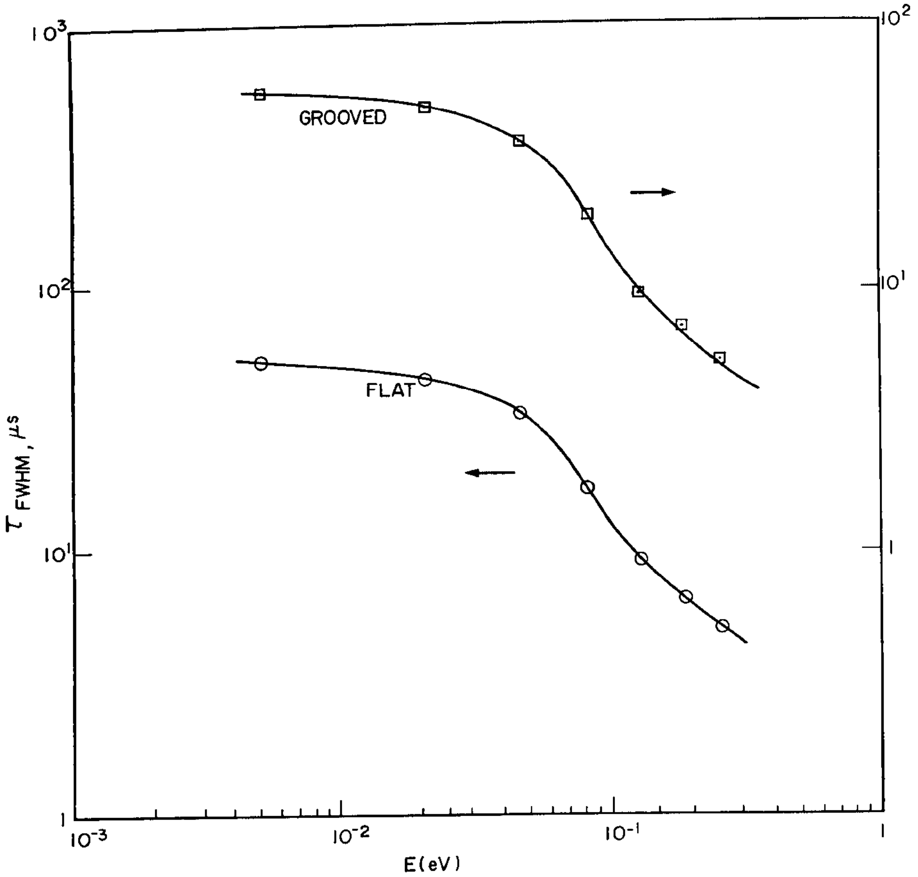
$$E_T = \begin{cases} 33.4 \text{ meV (388 K) (Grooved)} \\ 36.9 \text{ meV (428 K) (Flat)} \end{cases}$$

GROOVED MODERATOR RAW PULSE WIDTH DATA



FLAT MODERATOR RAW PULSE WIDTH DATA





Summary

We found that the grooved moderator produces higher neutron beam currents, a broader, more-symmetric pulse, and lower spectral temperature than the flat moderator. This indicates useful possibilities for improving moderator performance, but also shows the need for further experimental and theoretical study.

Examination of an Irradiated Polyethylene Moderator

The CH_2 moderator of Beam V-1 of ZING-P' (Moderator C of the diagram) has been removed and examined. The moderator had been in place from the start of ZING-P' until 10 June 1980, and endured a fluence of about 1.5×10^{18} n/cm^2, most of it since March 1980, during irradiation of the U target with 300 MeV protons, and was surrounded by Be and decoupled by Cd. The moderator was not cooled, and we do not know the temperatures reached.

Physical Appearance

The moderator was completely balck in appearance. An oily substance had collected on the surface, which crystallized after about 1 month. A crack had appeared on one edge.

Density

The density of the original material was .915 gm/cm^3. After irradiation, the density was .97 gm/cm^3.

Radioactivity

A sample of the polyethylene material was subjected to γ-ray spectral analysis, about 2 months after removal from ZING-P'. Radionuclide concentrations were found to be

^{7}Be: 4.1 μCi/gm CH_2
^{65}Zn: 2.8 nCi/gm CH_2

The Zinc presumably was an activated impurity. The ^{7}Be was presumably created by fast neutron (and perhaps proton) spallation of Carbon. It must be concluded that Tritium at a level of around .2 μCi/gm CH_2 is also present, (although it would not have been observed in the γ spectrum) since it would be created by mechanisms similar to those producing ^{7}Be.

Carbon-Hydrogen Analysis

Six samples of irradiated material were examined. The average H/C ratio was found to be 1.784 H/C. H and C constituted an average 97.3 w% of the total mass. The remainder is presumably Oxygen, which was not determined in our tests. The unirradiated material had an H/C ratio of 2.08 H/C. (Errors are approximately .5%.) The oily material had an H/C ratio of 1.54 H/C, while H and C constituted 46% of the mass, but it was not chemically identified.

The proton densities computed for the unirradiated and irradiated materials are thus

$$n_H = \begin{cases} .0736 \text{ protons/cm}^3 \text{ (irradiated)} \\ \\ .0814 \text{ protons/cm}^3 \text{ (unirradiated)} \end{cases}$$

These results indicate that room-temperature, organic moderators sustain substantial damage in spallation neutron sources. However, their performance, up to the level of damage we observed, did not significantly deteriorate.