NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-95

A Facility for High-Intensity Neutron Irradiations Using Thick-Target Sources at the Argonne Fast-Neutron Generator

by

Donald L. Smith and James W. Meadows

May 1986

ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.

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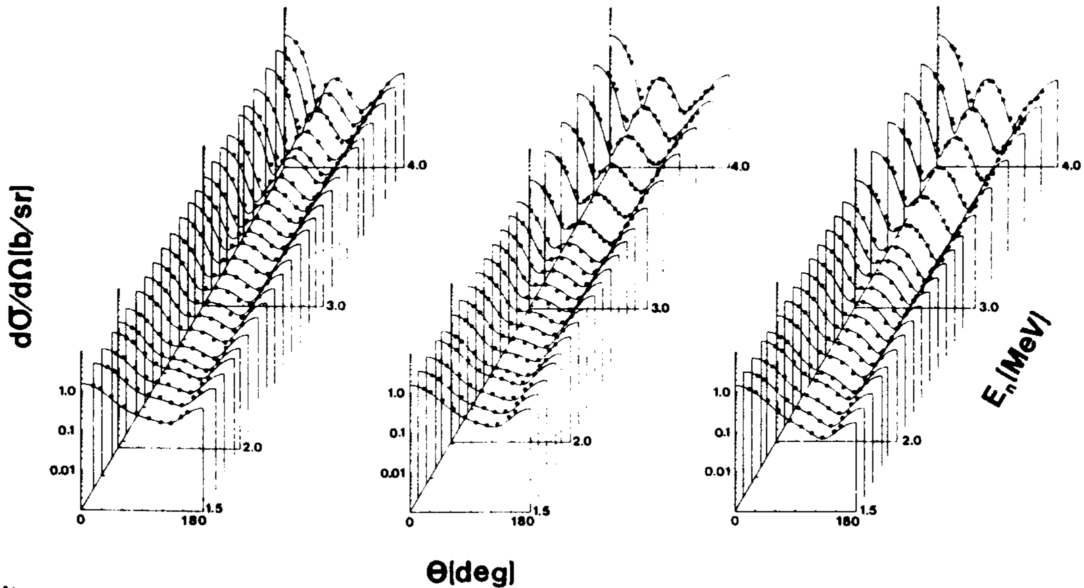

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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under Contract W-31-109-Eng-38

Radiation doses normalized to 1 microampere of 7 MeV deuteron beam current on a thick Be metal target:

Rad meter used	Distance*	Angle**	Meas Dose
FNG separable ball (neutrons)	12 inches	0 deg	804 Rem/h
	16 inches	0 deg	357 Rem/h
	16 inches	0 deg	424 Rem/h
	29 inches	135 deg	25.3 Rem/h
	29 inches	135 deg	21.4 Rem/h
	56 inches	45 deg	11.8 Rem/h
	56 inches	45 deg	11.4 Rem/h
HP separable ball (neutrons)	20 inches	0 deg	294 Rem/h
	29 inches	135 deg	23.5 Rem/h
	See note#		13.9 Rem/h
	See note#		13.6 Rem/h
	12 inches	0 deg	674 Rem/h
	12 inches	0 deg	675 Rem/h
	12 inches	0 deg	693 Rem/h
Victoreen meter (gammas)	40 inches	135 deg	0.5 R/h
	12 inches	0 deg	28.6 R/h

* Measured distance from the target, which is a point source.
** Angle measured relative to incident deuterons.
\# Measured as Position No. 1 as defined in report ANL/NDM-95.

ANL/NDM-95

A FACILITY FOR HIGH-INTENSITY NEUTRON IRRADIATIONS USING THICK-TARGET SOURCES AT THE ARGONNE FAST-NEUTRON GENERATOR*

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May 1986

E

NUCLEAR INSTRUMENTATION. Neutron irradiation facility. Shielding. Thick-target neutron production. Neutron monitors. Neutron spectrum characteristics.

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by

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ABSTRACT

A shielded neutron-irradiation cavity has been designed and constructed for use in high-intensity-neutron-irradiation experiments at the Argonne National Laboratory Fast-Neutron Generator facility. A target assembly which can withstand the maximum practical beam-power levels of the Fast-Neutron Generator has been developed for use in thick-target-source applications. Measurements of neutron-intensity levels inside the cavity and outside the shielded enclosure have been performed for radiological protection purposes. Two relative neutron monitors have been installed and tested. One is based on a boron-triflouride counter while the second employs neutron fission of natural uranium. A versatile apparatus for performing precision sample irradiations and quantitative fast-neutron fluence measurements with a fission-ionization-chamber detector close to the thick-target assembly has been installed and tested. Three different ionization-chamber filler gases have been investigated to see how well they perform in the high-intensity neutron environment encountered in this facility. Time-of-flight measurements were performed with a fission chamber, employing both U-235 and U-238 enriched uranium deposits. It was found that in the region of the cavity near the target, where samples are normally irradiated, the portion of the specturm above 1 MeV is dominated by direct neutrons from the source. The contribution from neutrons which have been scattered by the shielding surrounding the cavity is relatively small.

*This work supported by the U.S. Department of Energy.

I. INTRODUCTION

It is well known that proton and deuteron bombardment of thick, light-element targets can yield very intense fast-neutron fields (e.g., Refs. 1-6). For a number of years we have employed such neutron sources, predominantly deuterons on beryllium, for a variety of qualitative measurements at the Argonne National Laboratory Fast-Neutron Generator (FNG) facility (Ref. 7). A common application in our laboratory is neutron activation of samples to levels high enough to permit detector calibration by coincidence measurements, or by activity measurements under good geometry (small solid angle) conditions where certain corrections, such as those for sum-coincidence effects, are minimal (Ref. 8).

Intense thick-target neutron sources are also employed in our laboratory for neutron-total-cross-section measurements (e.g., Ref. 9) and for neutron-activation cross-section validation studies (e.g., Refs. 10-13). It has been suggested by Smith (Ref. 14), and demonstrated by Woelfe et al. (Ref. 15), that more detailed neutron-activation-cross-section information can be deduced by unfolding the results of irradiation measurements performed in sets of diverse thick-target neutron fields. Consequently, there is a continuing motivation for using these sources in nuclear-data research, and thus for better characterizing the neutron fields which various thick-target reactions produce.

A practical problem which we have encountered in using these sources is that they are so prolific that they present potential biological hazards when used in conjunction with conventional target arrangements in our laboratory. They must therefore be dealt with by methods not routinely required for the more-conventional monoenergetic neutron sources (Ref. 7). In the past we have adhered to requisite radiation safety standards by keeping the duration of our irradiations quite short, or by using extensive temporary shielding in experiments where longer exposures were necessary (Ref. 13). We have learned from experience that hydrogenous shielding of at least 1 m thickness around the target is required in the target area of our laboratory in order to meet radiation-protection requirements during extended periods of irradiation. The amount of effort required to assemble a temporary shielding arrangement which meets safety requirements, while providing an irradiation cavity of adequate size, is prodigious and ought not to be undertaken very often!

Consequently, we made the decision to dedicate one beam line at the FNG to thick-target experiments, and there to construct a permanent shielded-cavity, high-intensity irradiation facility. Included in this upgrade program was the design of a new thick-target assembly capable of sustaining the maximum likely beam-power levels at the FNG (approximately 400 watts), the installation and testing of reliable relative neutron-intensity monitors, and the installation and testing of a precise but versatile apparatus for irradiating activation samples and for performing quantitative fast-neutron fluence measurements.

The present report is dedicated to the documentation of this new facility. The various components of the facility are described in Chapter II. Chapter III presents results of several tests which have been conducted to characterize the performance of the facility. Finally, some of the intended near-term and longer-term applications for this facility are discussed in Chapter IV.

II. FACILITY COMPONENTS

The principal components of this facility are: i) a shielded enclosure, ii) The target assembly, iii) A boron-triflouride-counter monitor, iv) a fixed, natural-uranium fission-counter monitor, and v) a versatile apparatus for sample irradiation and precise neutron-fluence measurement (involving a fission detector) in the vicinity of the target. Each of these elements are discussed in a separate section of this chapter.

A. Shielded irradiation cavity

Experience suggested that four basic requirements had to be met in the design of a cavity facility:

i) The source had to be shielded by at least 1 m of hydrogenous shielding material on all sides, and preferably with more in the forward direction since the neutron yield is predominantly forward-peaked for thick-target reactions (e.g., Ref. 16).

ii) The cavity had to be large enough to contain the target assembly and sample-irradiation apparatus, to permit convenient working space for experimenters, and to minimize the return of neutrons scattered from the cavity walls (relative to the direct neutrons from the target) to the region near the target where sample irradiations are normally conducted. A clearance of about 1 m in all directions from the target seemed to be adequate and feasible in this regard.

iii) Ease of access to the cavity by laboratory personnel was considered to be a necessity, not only for convenience but also to permit prompt removal of irradiated samples with relatively short-half-life activities. Although such a design was more demanding of shielding material than some possible alternatives, it was decided that a baffled access passageway would best satisfy our requirements.

iv) Provision had to be made for obtaining an external neutron beam at zero degrees, primarily for neutron-spectrum measurements by the time-of-flight (TOF) method. It was decided that this requirement could be met by providing a cylindrical access port at zero degrees, into which a variety of collimators or plugs could be inserted as needed.

The shielding arrangement indicated in Fig. 1 is composed largely of concrete blocks of various sizes, as available in the laboratory. The concrete floor of the laboratory is at ground level, so in this direction earth is the predominant shielding material. The cavity itself is lined on all sides (ceiling and floor included) with polyethelene blocks to a thickness of about 20 cm. To these are attached a layer of cadmium metal sheet of about 0.05-cm thickness, and finally a layer of 2-cm-thick plywood to provide a convenient working surface with which to line the cavity. In the vicinity of the beam-line and zero-degree collimator ports, various other hydrogenous shielding materials were used because of the odd sizes and shapes required to fill the available empty spaces in order to minimize "streaming" of the neutrons through voids. The cavity is shielded to a thickness exceeding 1 m in all directions. In the roof, and in those sections of the wall near the zero-degree collimator port, the shielding approaches 1.5 m. The interior dimensions of the cavity do provide about 1 m of clearance in all directions from the target, in accordance with the design goal. The personnel access passageway, shown schematically in Fig. 1, permits easy entry and exit from the cavity with little loss of overall shielding effectiveness.

Most of the required beam-line components (e.g., electromagnetic optical elements, beam-defining slits and vacuum systems) are situated outside the blockhouse for convenient serviceability. However, electrical power, water and air service (for target cooling) and illumination are conveniently provided inside the cavity region. A fan is also permanently mounted in the access passageway to insure adequate ventilation inside the cavity while personnel are working there on equipment.

The access port at zero degrees is 7 cm in diameter. A variety of collimator units and solid plugs available in our laboratory can be inserted into this port, as required to either seal the cavity or to provide the means to produce a well-defined collimated external neutron beam. The beam-line port serves only to permit entry of the accelerator beam tube into the cavity, and it is not as precisely fabricated or aligned as is the zero-degree access port.

Fig. 2 offers several photographic views of the exterior of the facility, while Fig. 3 provides various photographic views of the cavity interior.

B. Thick-target assembly

The FNG accelerator is designed to deliver approximately 50 microamps of proton or deuteron beam at 8 MeV on target, i.e., approximately 400 watts of beam power (Ref. 17). This power level has been achieved but is rarely employed in practice. A more typical upper-level operating condition is 20 microamps of beam at 7 MeV, i.e., 140 watts of beam power. The target we have developed is intended to be able to dissipate as much as 400 watts of beam power over an extended period of usage. To achieve this, the target is cooled both by water and an air jet.

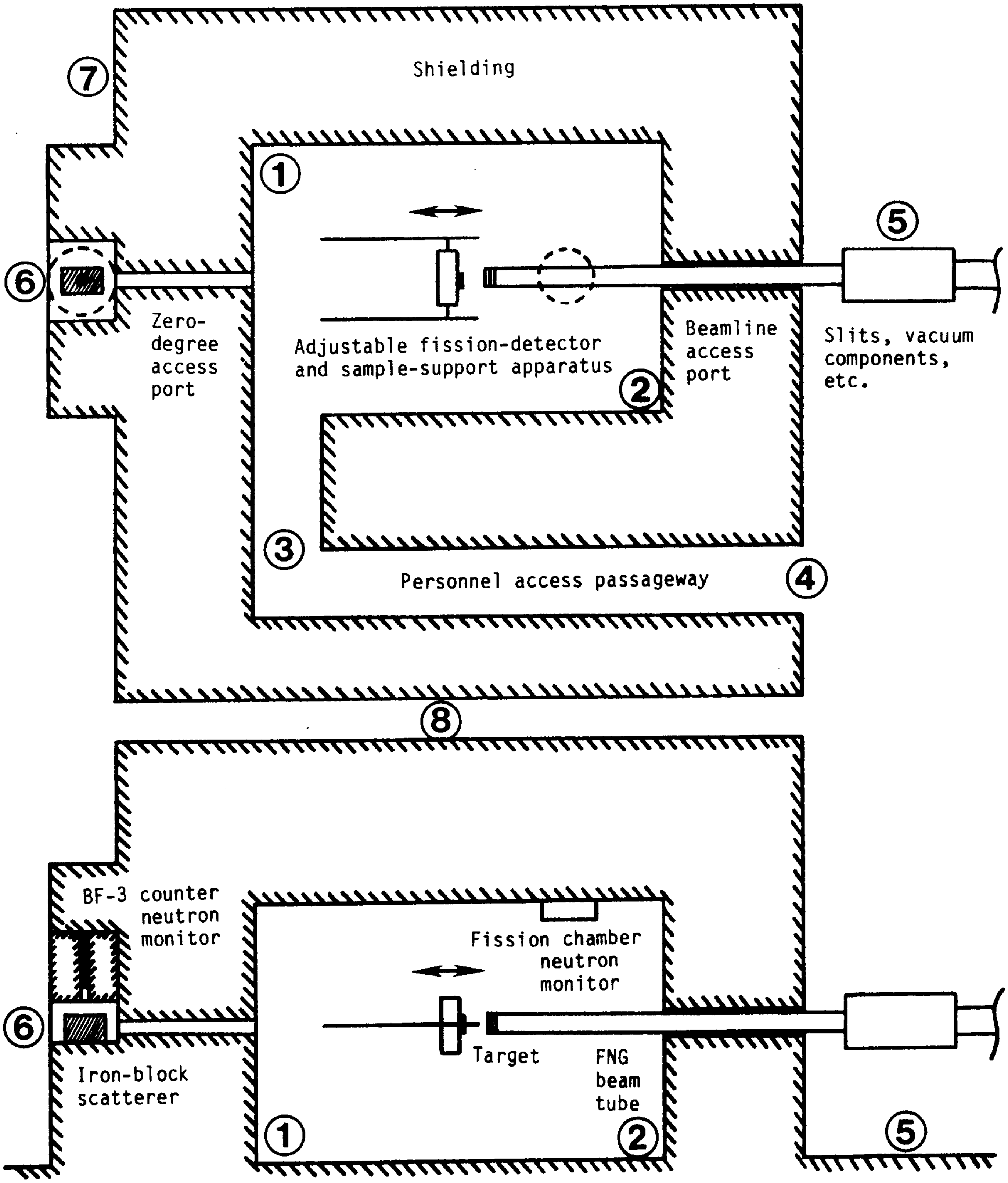
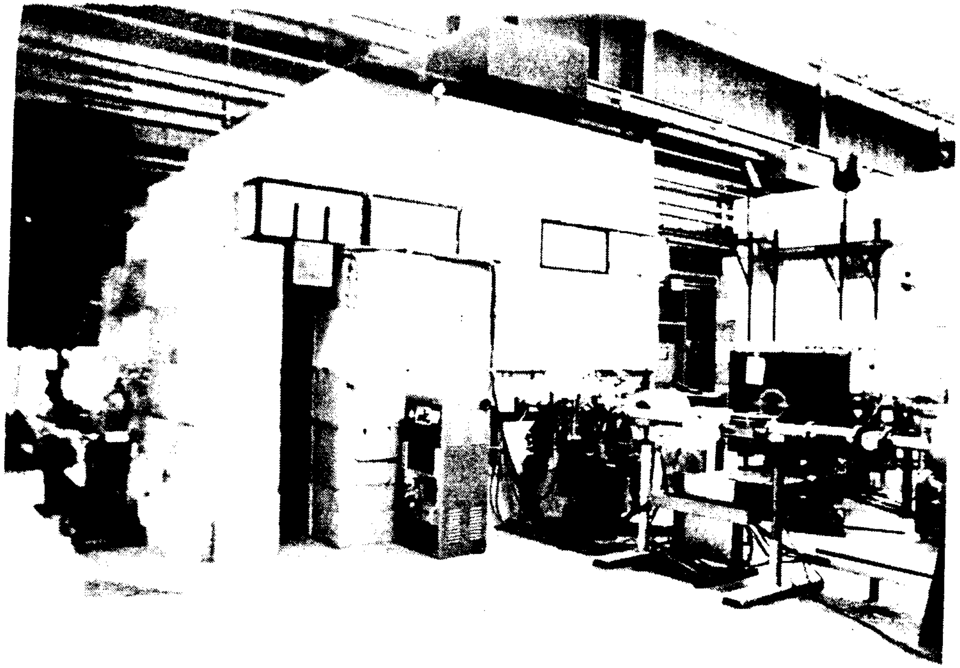
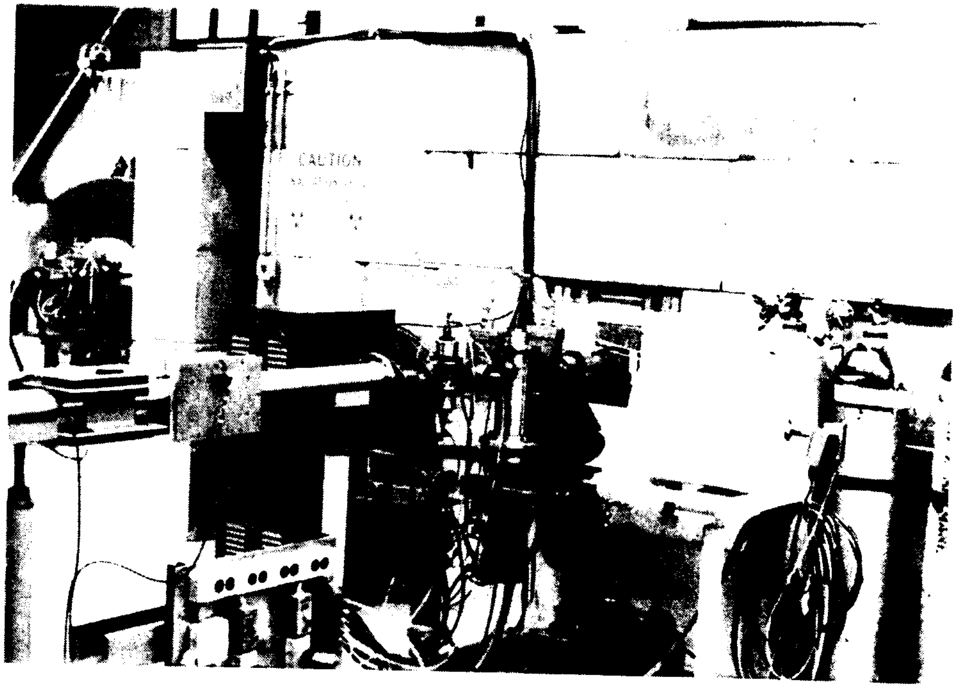


Figure 1: Schematic diagram showing major components of the high-intensity neutron-irradiation facility (not to scale). Top (above) and side (below) views are provided. Positions of neutron intensity measurements performed with a neutron Rem meter (see Section III.A and Table 1) are indicated by circled numerals. Position No. 8 is on the blockhouse roof.



(A)



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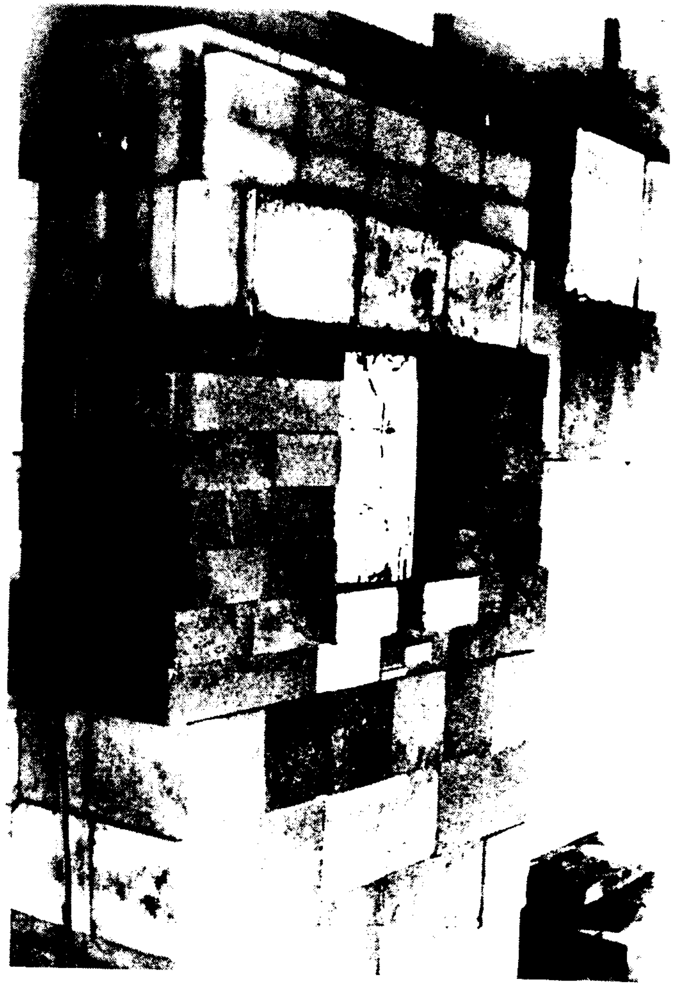
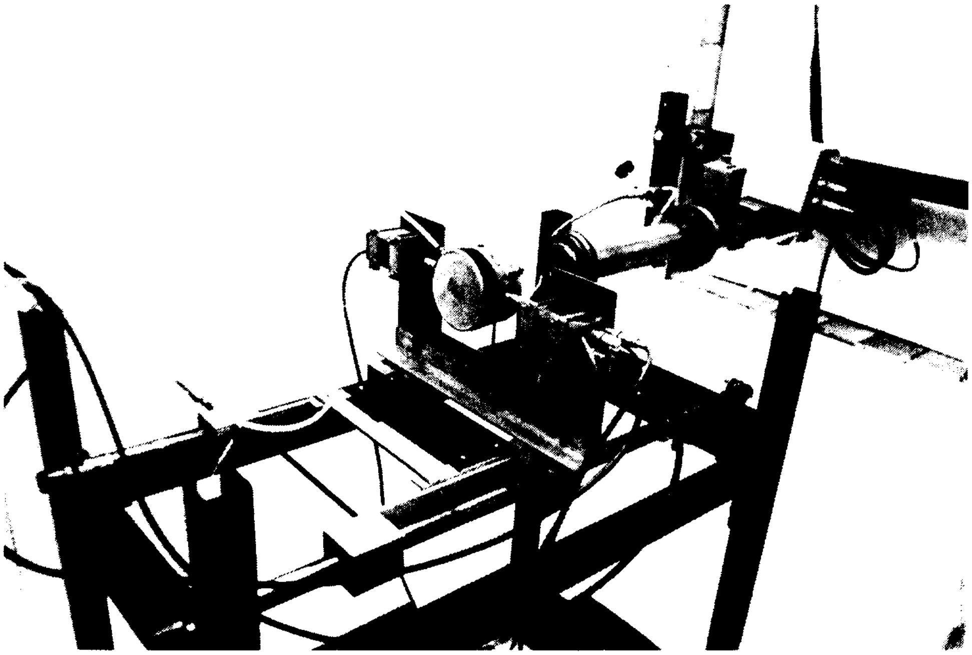
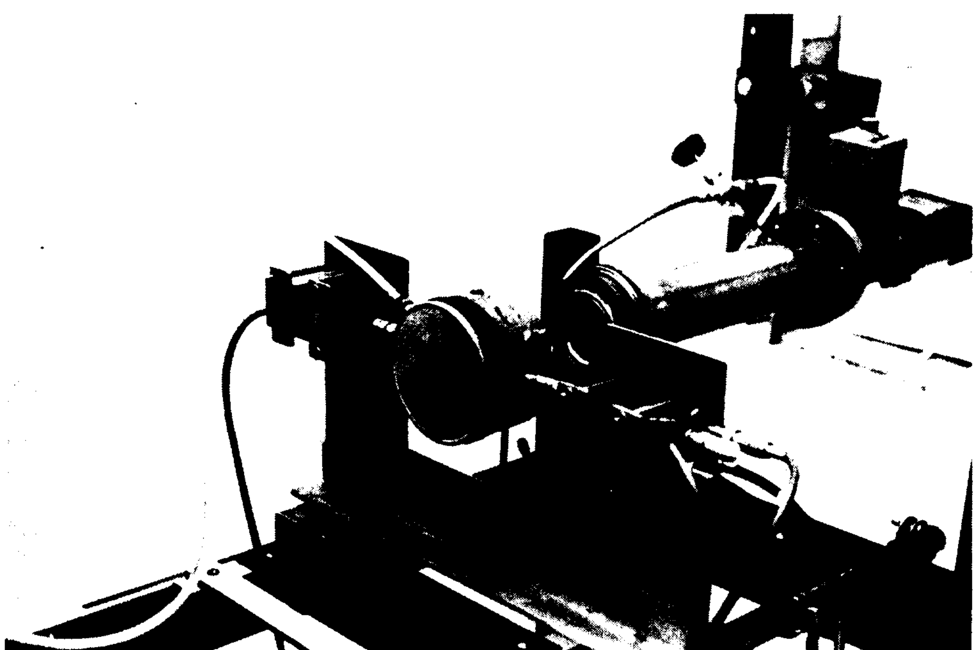


(C)

Figure 2: Various exterior views of the high-intensity neutron-irradiation facility - (A) overview, (B) view of beam-line entrance port and (C) view of zero-degree collimator port.



(A)

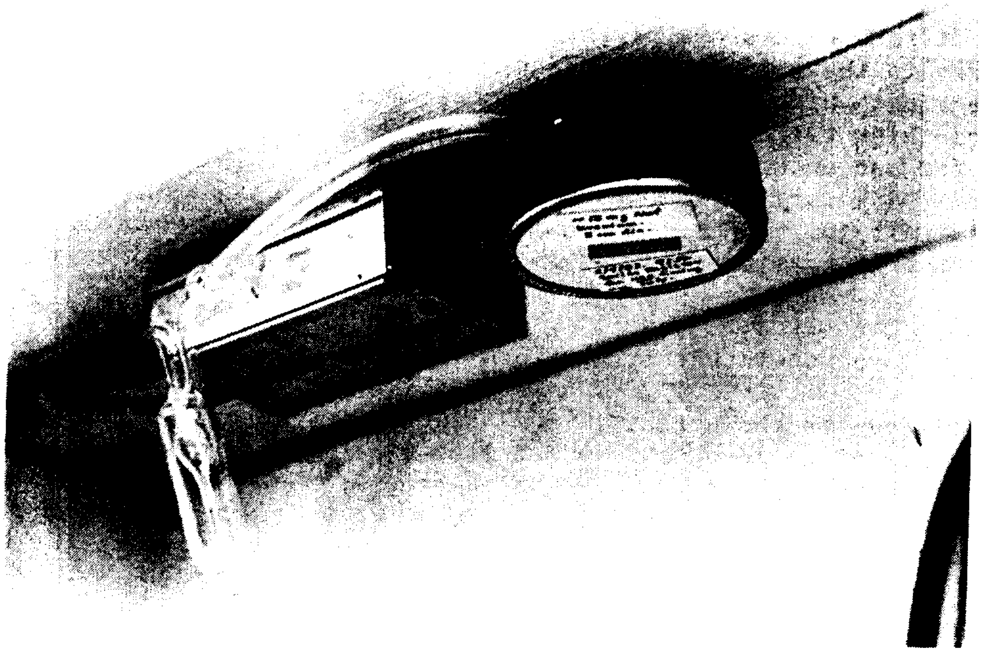


(B)

Figure 3: Various interior views of the high-intensity neutron-irradiation facility - (A) detector support stand, (B) target and detector in normal irradiation position, (C) bare target assembly and (D) natural uranium fission detector monitor (attached to ceiling of the cavity).

Figure 3: (continued)

(C)



(D)

The target design must satisfy a second criterion which tends to conflict with its capacity to dissipate heat, namely, it must possess a relatively low mass to minimize the neutron-multiple-scattering effects which can have an important influence on precise cross-section measurements. Since neutron yields from thick-target reactions tend to be strongly-peaked in the forward direction (e.g., Ref. 16), the main effort on target-mass reduction is focused on the vicinity of the beam spot. An earlier thick-target design (Fig. 1 of Ref. 13) which has been used in this laboratory with reasonable success has been found to involve scattering corrections amounting to only about 2-3% for most threshold-reaction processess (Ref. 13).

The present target design does not differ radically from the design of the earlier target described in the preceding paragraph, but there are some improvements which make it more convenient to use-especially from the point of view of being able to easily replace the target elements. In the present design, the target and the beam-defining aperture are both water-cooled. Furthermore, the target and aperture are both insulated electrically from the accelerator beam tube, and from each other, so that the target current and the aperture-plate current can be independently monitored.

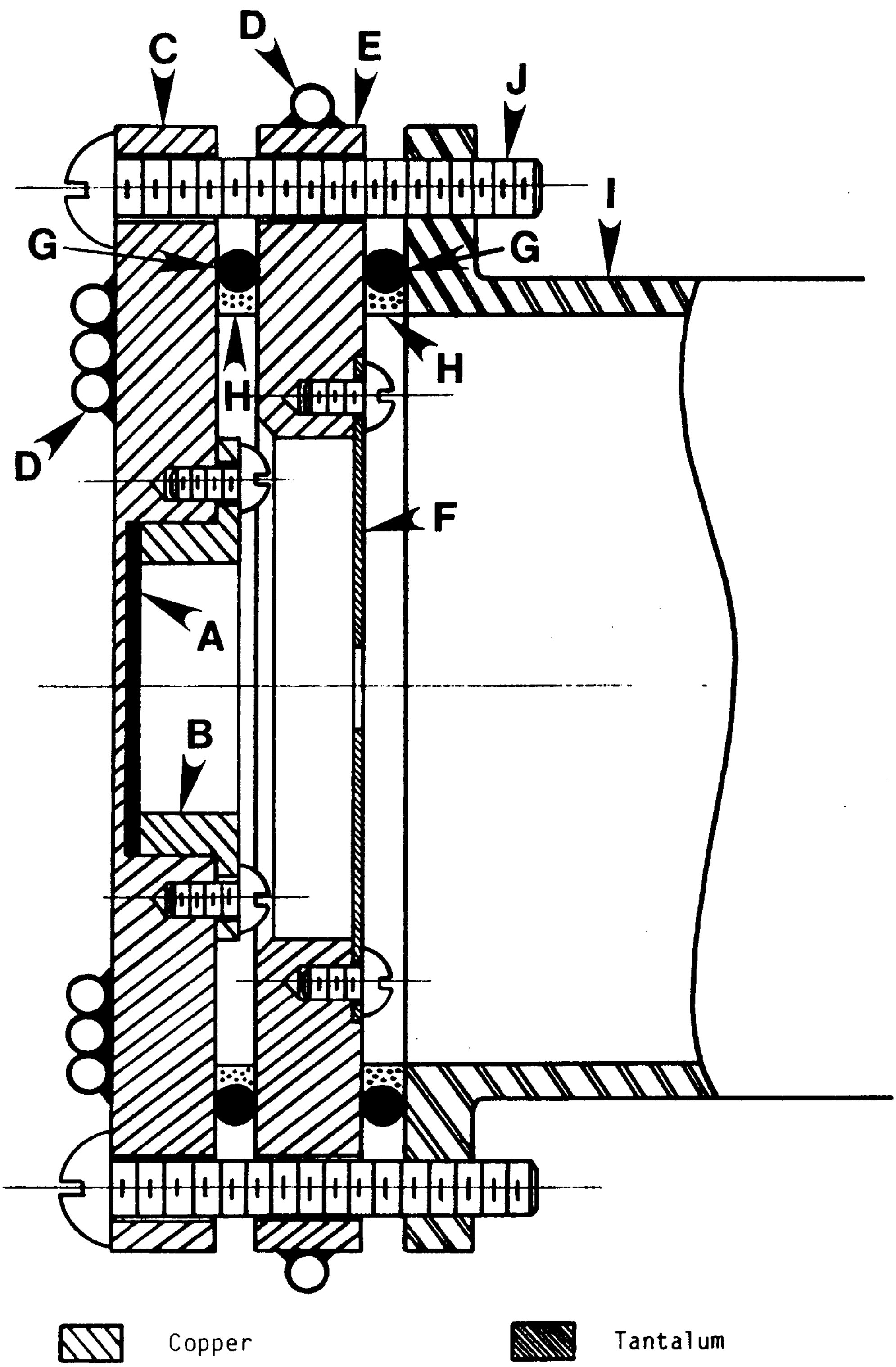
The present target assembly is shown schematically in Fig. 4. It is fabricated mainly of copper because of the superior heat-conductive properties of this element. The beam-defining aperture plate is made of 0.05-cm-thick tantalum. There is no need in principle for this aperture plate to be kept cool, however, the copper aperture flange on which it is mounted is water-cooled to prevent thermal damage to the O-ring seals in the event that the full beam should impinge upon the unit. As indicated above, most of the beam power is deposited in the region where the target mass is purposefully-low (the beam-spot position). For this reason, an external air jet is directed toward this spot to aid in heat dissipation.

Two different versions of this target have been fabricated. They differ only in the thickness of the target element and that of the copper backing against which the target element is clamped. One version employs a 0.150-cm-thick target element and a 0.150-cm-thick copper backing. It is intended for use under high beam-power conditions. A second version employs a 0.075-cm-thick target element and a 0.075-cm-thick copper backing. This lower-mass unit is intended for use where neutron-multiple-scattering corrections have to be miminized, at the expense of lowering the beam current.

C. Relative neutron-intensity monitors

Experience has shown that in most neutron-irradiation experiments with thick-target sources it is essential to be able to reliably monitor neutron output from the source during the measurements. Relative neutron-dose monitoring from exposure to exposure is required in order to be able to normalize results obtained from measurements where data for unknown processes and for standards are acquired from distinct exposures. Although

Figure 4: Schematic drawing of the thick-target assembly used in the high-intensity neutron-irradiation facility. Components: A) Target element. B) Target clamp. C) Target body. D) Water-cooling tubing (attached with solder). E) Aperture flange. F) Aperture plate. G) O-ring gasket. H) O-ring gasket spacer. I) FNG accelerator flight tube. J) Nylon screw. Components are shown at twice full size.



the need for such neutron monitoring can in principle be avoided in activation experiments by using composite samples (e.g., sandwiches, chemical compounds or mixed powders) in which both unknown and standard activities are produced simultaneously, it is not always convenient or desirable to do so in practice. Another reason why it is desirable to continuously monitor the neutron output from the source is that this provides a sensitive measure of the stability of the target and the constancy of the neutron spectrum. Deterioration of the thick-target element (e.g., due to to thermal effects, radiation damage or build up of contaminants on the surface of the target) can seriously alter the spectrum and thus invalidate the measurements. However, these undesirable effects are readily sensed during a measurement by changes in the neutron yield per unit of incident beam charge on the target.

In fixed-geometry situations a standard boron-triflouride detector provides a very useful neutron monitor for such purposes. In a typical "long-counter" type configuration this detector offers good efficiency, a high degree of stability, moderate sensitivity to changes in the neutron environment and insensitivity to radiation other than neutrons. It was obvious a priori that the neutron intensity in the present arrangement would be too great under normal conditions to permit the use of an ordinary long counter inside the irradiation cavity itself. In fact, the intensity of the direct neutrons emanating from the zero-degree access port turns out to also be too great for a long counter to handle. Pulse-pileup and detector-deadtime effects prevent use of such an instrument as a reliable relative monitor in routine experiments. Therefore, it was decided to construct a detector arrangement that would measure indirect-neutron yield. This arrangement would nevertheless have to be quite responsive to the nature of the direct neutron output from the target. This has been achieved by placing a conventional boron-triflouride long counter off the zero-degree beam line, outside the shielded cavity but close to the zero-degree access port. This counter then detects mainly those neutrons which are scattered from a solid iron block (5 cm x 8 cm x 15 cm) that intercepts the direct neutron beam which emanates from the zero-degree port (through an inserted collimator). The physical arrangement of this detector is shown in Figs. 1 and 2. The electronics circuitry is very conventional, with a scaler used to record counts above a selected linear-signal pulse-height cutoff level.

It was decided to have a second relative neutron monitor which would be mounted inside the irradiation cavity in a permanent position that is out of the way of all other experimental apparatus placed near the target itself. This monitor needed to be very stable and to possess a much lower efficiency than the long-counter arrangement described in the preceding paragraph. It also had to be quite insensitive to radiation other than neutrons. This need has been met by a simple parallel-plate ionization chamber which contains a natural-uranium deposit of about 12 mg in mass as the active element and methane at atmospheric pressure as the filler gas. This detector is attached to the ceiling of the irradiation cavity at a distance of about 90 cm from the target in the backward hemisphere (at about 106 degrees relative to the beam line). In this position the detector is relatively insensitive to variations in the details of the experimental components which are placed in the vicinity of the target, since these are normally situated near zero degrees and thus do not obstruct the view of the natural-uranium fission-chamber monitor. The arrangement is shown in Figs. 1 and 3. Again, the circuitry used is very conventional. Those fission events above the alpha-particle, gas recoil and (n,C.P.) events cutoff are recorded with a scaler (C.P. = charged particle).

D. Sample-irradiation and absolute neutron-fluence measurement apparatus

The principal intended application for this high-intensity neutron-irradiation facility is the measurement of integral neutron-activation cross sections for various thick-target neutron fields. For a number of years we have performed activation measurements in this laboratory using an experimental procedure in which a sample is attached to a low-mass fission chamber and the entire assembly is placed at zero degrees near the target (e.g., Fig. 1 of Ref. 13). The fission detector of this assembly provides quantitative information on the neutron fluence in the vicinity of the target where such irradiations are performed. Various types of fissionable deposits are routinely used. We sought to continue to employ this proven method in experiments using the present facility. The distance from the target to the sample/fission-detector assembly must be varied often. Thus, we have installed an adjustable low-mass support assembly to facilitate this task. Using this device it is possible to readily transport the sample/fission-detector arrangement from a position of direct contact with the target to one as far away as 40 cm without departing from the beam line. This apparatus is shown in Figs. 1 and 3.

We had learned from earlier measurements (Ref. 13) that difficulties arise when using a fission ionization chamber in the high-neutron-intensity environment encountered close to a thick-target source. The resulting large pulse rate, due not only to legitimate fissions but also to recoiling gas atoms (particularly hydrogen) and to (n,C.P.) reactions on the fission chamber structure, leads to pulse-pileup effects which can produce spectrum distortions and event losses. In earlier measurements we avoided this problem to a large extent by keeping the beam current on target at modest levels, and by not placing the fission detector too close to the target (Ref. 13). However, this is not a very satisfactory solution because it places some inconvenient restrictions on employing the maximum available intensity from these sources for investigating very-low-cross-section or long-half-life activation processes. Consequently, we have investigated other possibilities for coping with this pulse-rate problem during the course of setting up the electronics apparatus to be used for activation measurements in the high-intensity neutron environment of this facility. The two approaches we have pursued in tandem are: 1) use of fission-chamber filler gases other than methane (which has a high hydrogen content and thus is prone to many energetic recoils), and ii) implementation of electronics circuitry which is designed to process signals of relatively short duration at high count rates when compared to more conventional signal processing methods. A schematic diagram of the circuitry implemented in this apparatus appears in Fig. 5. The principles involved here have been described by Budtz-Joergensen and Knitter (Ref. 18). Details of our investigation are presented in Chapter III. It suffices to say here that these methods have enabled us to greatly expand our capacity to make accurate neutron fluence measurements with a fission counter in the vicinity of the target when the neutron intensity is very high.

III. FACILITY PERFORMANCE

In this chapter we discuss the results of a variety of tests which were conducted during the commissioning phase of this facility. The results of these investigations are generally applicable to a variety of experiments planned for this facility, and are thus justifiably-documented in this report. The major emphasis in these tests has been on the effectiveness of the shielding and on the performance of the neutron detectors. The performance of the new thick-target assembly can only be judged in terms of its ability to function stabily under relatively-elevated beam conditions over an extended period of time. It is too early to pass final judgement on this unit, however it did hold up very well during the course of the present measurements.

A. Effectiveness of the shielding

As indicated in Chapter I, the principal motivation for constructing the blockhouse facility was to insure that thick-target neutron irradiations could be performed on a routine basis without jeopardizing the safety of personnel in the FNG laboratory. Consequently, the first series of tests performed on this facility involved measurements of radiation levels at various locations near the facility and around the FNG laboratory in general. These measurements were performed using an Eberline Portable Neutron Rem Counter (Model PNR-4, Ref. 19).

Of greatest concern was the neutron radiation level in the vicinity of the FNG accelerator console, since various individuals in the laboratory routinely spend a lot of time in this area. With a 10 microamp beam of 7-MeV deuterons on a thick beryllium metal target element (the zero-degree yield of this reaction is known to be of the order of 3(+9)* neutrons/microcoulomb/sr according to Ref. 2), the neutron radiation level at the console was barely measurable (much less than 1 mRem/h). Furthermore, when the beryllium target element was replaced with a tantalum target element (which has a greatly-reduced neutron yield compared with beryllium) the Rem-counter reading remained essentially unchanged. This indicates that whatever neutron radiation is produced in the FNG laboratory by the operation

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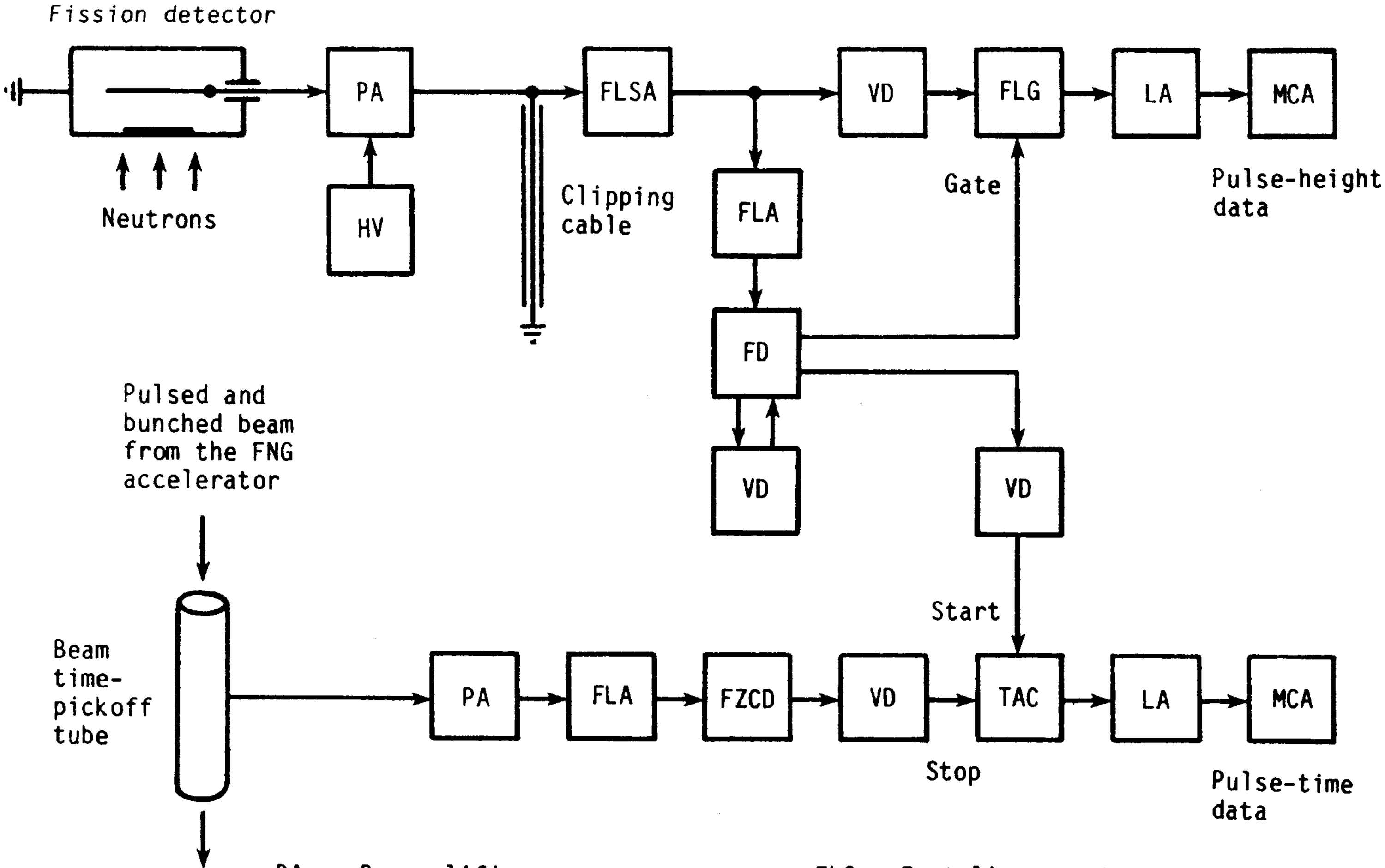
*3(+9) implies 3×10^9.



PA:	Preamplifier
HV:	High-voltage supply
FLSA:	Fast linear shaping amplifier
FLA:	Fast linear amplifier
FD:	Fast discriminator
VD:	Variable delay
FLG:	Fast linear gate
LA:	Linear Amplifier
TAC:	Time-to-amplitude converter
MCA:	Multi-channel pulse-height analyzer
FZCD:	Fast zero-crossing discriminator

Figure 5: Electronic circuitry used in processing fission events from an ionization detector which is placed in a high-intensity neutron environment.

of this facility comes mainly from sources along the beam line outside of the cavity and indeed is not directly related to the thick-target facility. Essentially the source of this radiation is stray deuterons on accelerator flight-tube components, not leakage from the cavity which contains the thick-target itself. This result proves that the blockhouse meets its primary requirement to serve as a biological radiation shield.

A number of other measurements of neutron-radiation levels were made in the vicinity of this facility. These measurements were performed with the aid of a remote TV monitor in order to avoid exposure to the high radiation levels present in certain locations. The particular locations where data were acquired are indicated in Fig. 1 by circled numerals, and the corresponding values are listed in Table 1, normalized to a beam of 1 microamp of 7-MeV deuterons on a thick beryllium target element.

From the results of Table 1 it is evident that the only locations outside of the blockhouse which experience neutron radiation levels of any serious concern are those near the beam line (especially in the vicinity of the slits), near the entrance of the passageway into the shielded cavity and near the zero-degree access port when it is not plugged. Undoubtedly, there is some streaming of neutrons through the beamline port but no measurements were made there. Inside the blockhouse the radiation levels are clearly lethal under normal operating conditions, and access to this area during run times is to be avoided without exception.

Although the target assembly becomes somewhat beta and gamma-ray active during normal usage, and one should not tarry for long very close to the target after an extended irradiation period, there appear to be no problems associated with changing samples (since that normally takes less than a minute). Left overnight with the beam off, the target activity is observed to decay to quite low levels. We have not attempted to quantify these observations, however as a routine practice we carry a beta-gamma survey meter into the irradiation cavity between runs and qualitatively ascertain the radiation levels present at the target.

B. Relative neutron-intensity monitors

All of the following tests of the relative neutron monitors were conducted with a 7-MeV deuteron beam. Targets of beryllium metal and tantalum metal were used as described below.

In preliminary tests using the boron-triflouride counter neutron monitor it was observed that the counts measured per unit beam charge on target decreased steadily as the beam current, and thus the detector count rate, increased. This effect was attributed to detector deadtime so several carefully-controlled measurements were conducted in order to determine this deadtime experimentally. What were measured were the counts per unit charge vs. count rate. A straight line was fitted by

Table 1: Measured neutron-radiation levels at various locations near the high-intensity neutron-irradiation facility*

Location	Neutron radiation level (mRem/h/microamp)	Comments
1	11500 +- 600	1.3 m from Be target
2	9500 +- 600	1 m from Be target
3	650 +- 70	laboratory floor level
4	25 +- 3	laboratory floor level
5	11 +- 1**	1 m from beam slits
6a***	500 +- 17	open collimator, no iron block scatterer present
6b***	17 +- 1	open collimator with iron block scatterer in position
6c***	< 1	plugged collimator
7	< 1	laboratory floor level
8	< 1	no direct view of external beam line

* Measurements performed with a 7-MeV deuteron beam incident upon a thick beryllium metal target.

** This value can vary considerably depending upon beam alignment, focusing conditions and slit settings.

*** Rem counter is situated directly on the beam line and next to the shield wall at the zero-degree access port.

least squares to these data, yielding the value 3.58 microsec for the deadtime. Given this deadtime, the observed pulse losses amounted to less than 3% under the highest count-rate conditions we encountered during the present tests with this setup. Data from the boron-triflouride counter neutron monitor must therefore be corrected for this small but non-negligible deadtime in routine applications. In our investigations we found that the data were very consistent provided that this correction was applied.

The yield at the boron-triflouride counter neutron monitor is attributed to three general origins: i) neutrons produced outside the blockhouse, ii) neutrons produced inside the blockhouse which manage to penetrate the shielding, and iii) neutrons which pass through the collimator hole in the zero-degree port before reaching the detector. It was observed that component (i) was small but quite variable. Components (ii) and (iii) are proportional to the total neutron output of the target and are therefore both satisfactory for general monitoring purposes. Component (iii) is most sensitive to details of neutron production from the target. Enhancement of component (iii) relative to the other two is thus desirable. This is the purpose for using an iron-block scatterer, as discussed in Section II.C.

Our first endeavor was to measure component (i) above to insure that it was indeed relatively small, and to establish some range for its variability under normal conditions. A tantalum target element was employed in this investigation. Then, neutron production was predominantly external to the blockhouse. A number of runs were made with various deuteron-beam conditions. The average count rate of neutrons observed by the boron-triflouride neutron detector was 2.8 (-2) counts/microcoulomb (+- 50%). The indicated uncertainty is the standard deviation of the accumulated set of measured values for this parameter. The range of actual values observed was 1 (-2) to 6 (-2) counts/microcoulomb. In the present investigation it was ultimately determined that the yield from component (i) never exceeded 1% of the total when a beryllium target was used, as discussed below. Thus, the performance of the boron-triflouride neutron monitor is not particularly sensitive to normal variations in the beam focusing and alignment conditions, and their effects can be neglected in practice. For a neutron-producing target (beryllium in the present situation), the total yield in this detector does depend critically upon the choice of collimator used, and also to some extent on the orientation of the particular collimator since our available collimators are tapered and also are not quite azimuthally symmetric. Detailed measurements were performed for two collimators which differed substantially in bore size. The count rates for the collimator with the larger bore were in the range 8.3 to 8.5 counts/microcoulomb while those for the collimator with the smaller bore were in the range 3.0 to 4.0 counts/microcoulomb. When any particular collimator was plugged, the count rates were < 0.3 counts/microcoulomb.

Yield enhancements produced by the use of an iron-block scatterer amount to a factor of 22 to 23 for the collimator with the larger bore and to a factor of 8 to 12 for the collimator with the smaller bore.

These enhancement factors were observed to be rather insensitive to the exact position of the iron block scatterer. Component (iii) is clearly dominant in each instance. We have chosen to routinely use the collimator with the larger bore since then more than 95% of the measured yield is produced by target neutrons which have scattered from the iron block into the boron-triflouride detector. Although a small deadtime correction has to be routinely applied for this configuration, this can be done quite accurately in practice.

The natural-uranium deposit used in the second neutron monitor of this facility is relatively thick so it was necessary to determine whether a reasonable separation between the low-pulse-height events and the fission events could be obtained. With this detector mounted as described in Section II.C, and as shown in Figs. 1 and 3, the spectra shown in Fig. 6 were obtained. The separation between the fissions and the low-pulse-height events is excellent which implies that the uniformity of the natural-uranium deposit is exceptionally good. Furthermore, these measurements confirmed that the efficiency of this detector arrangement is adequate for the intended monitoring purposes, namely about 2.9 (-2) fission counts/microcoulomb (above the low-pulse-height event cutoff).

In order to serve as useful monitors, the boron-triflouride and natural uranium detectors described above must be acceptably stable and exhibit count rates which are proportional to neutron output from the target. To examine this issue, we carried out a large number of runs under varying conditions, i.e., with a wide range of beam-current levels and many different positions for the close-in fission detector along the beam line near the target. Yields from both monitors were normalized to integrated beam charge for each run. We performed measurements both with and without target water cooling since we knew from experience that water-cooled targets are prone to leakage of charge due to ions present in the flowing cooling water. In fact, in the present investigation we observed that when the target was water-cooled a steady "zero-level" current of < 0.1 microamp was present. All data from measurements of accumulated beam charge on target were corrected for this effect. In order to examine the intrinsic reproducibility of relative neutron-fluence measurements made with the boron-triflouride and natural uranium fission monitors used in this facility, we first performed a series of measurements with carefully-controlled, fixed geometric conditions and no target water cooling. The normalized yield of the boron-triflouride monitor was found to vary with a standard deviation of $< 1\%$ with respect to the average. For the natural uranium monitor, the corresponding observed variation was $< 2\%$. These variations are generally consistent with the statistical uncertainties associated with these particular measurements. It was thus indirectly concluded that the neutron output from the thick beryllium target used in these tests is quite stable over a reasonable period of time. A considerable body of data was then accumulated for a wide range of experimental conditions which might be encountered during the course of normal operation of this facility. The target was water-cooled and the geometric conditions were varied

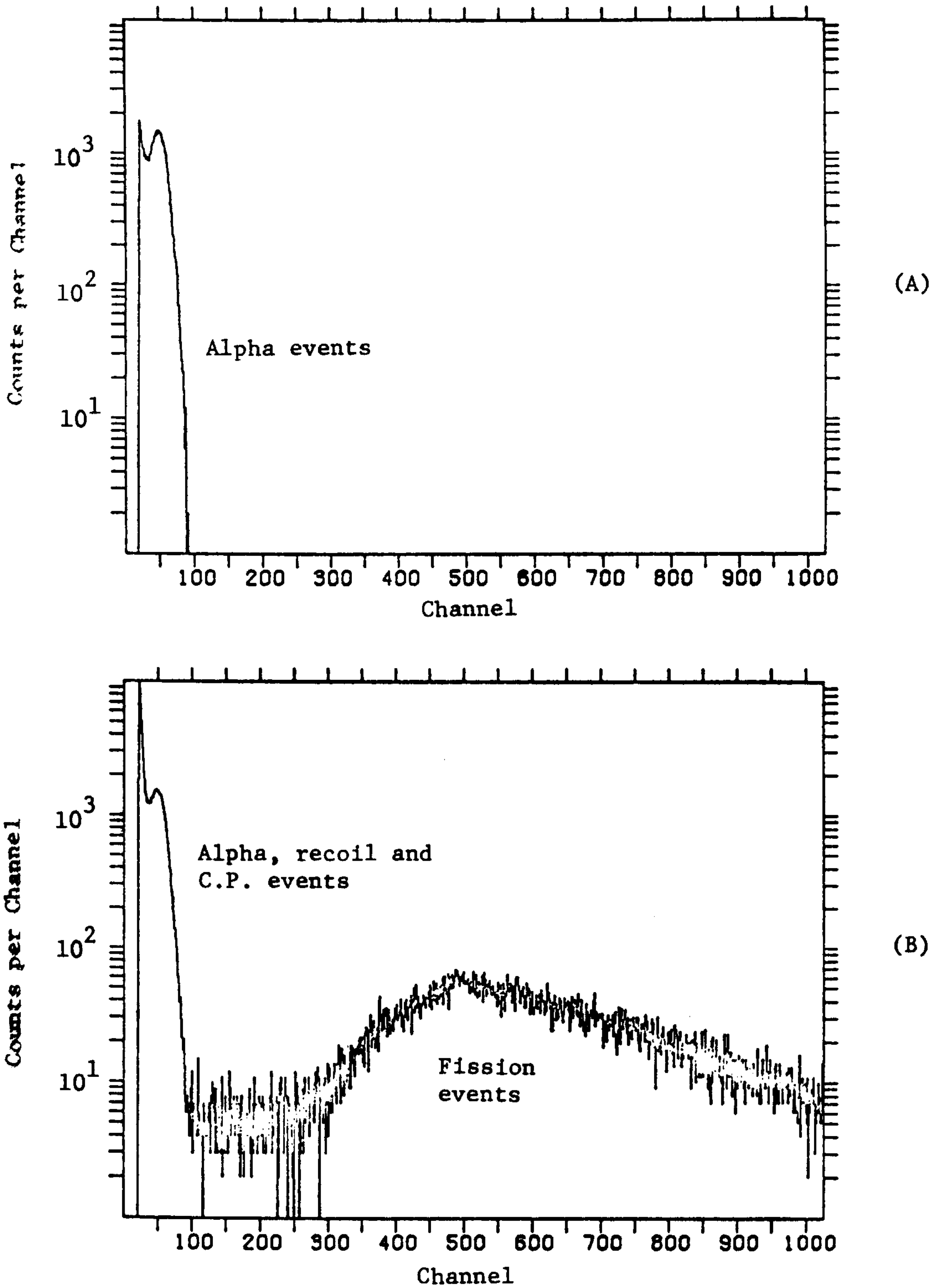


Figure 6: Pulse-height spectra recorded with the natural uranium fission-detector monitor - (A) no neutrons present, alpha-particle events only and (B) Be-9(d,n)B-10 neutron field, spectrum contains alpha, recoil, C.P, and fission events.

substantially by moving the fission detector used to monitor neutron fluence near the target over a wide range of allowed positions along the beam line. The observed variations in the monitor-detector normalized yields became noticeably larger than was the case for measurements under tightly-controlled fixed conditions. For the boron-triflouride monitor the standard deviation with respect to the average was <4% while for the natural uranium monitor it was < 5%. These variations were considerably in excess of the statistical uncertainties. There seems to be no obvious correlation between these observed variations and the beam-current levels, an effect which one might expect to be present if the leakage-current correction described above were improperly determined. In fact, the ratio of the two monitor detectors (a beam-current independent quantity) was observed to vary about the average with a standard deviation of about 4%, indicating that there were other effects besides leakage current which apparently can contribute noticeably to variation in normalized monitor count rates. We did not investigate in detail the extent to which these variations might be traced to geometric factors. It is clear, however, that to insure monitoring of relative neutron fluence to accuracies of a few percent from run to run it is necessary to examine the reproducibility of the yield rates under fixed conditions and then to determine experimentally any corrections which might be required to compensate for altered experimental conditions, e.g., a change in geometric configurations within the irradiation cavity.

C. Sample-irradiation and absolute neutron-fluence measurement apparatus

The performance of the fission detector to be used under high-count-rate conditions is of fundamental concern in the present investigation. The electronics setup used is as shown in Fig. 5, and three different filler gases (at atmospheric pressure) are considered: i) 99.9+% pure methane, ii) argon (95%) + carbon dioxide (5%) and iii) argon (90%) + methane (10%)-commonly known as "P10". Two different uranium deposits were used in the measurements. The first was fabricated from depleted uranium (nearly 100% U-238) and contains approximately 5 (+18) atoms. The second is fabricated from U-235 enriched material. The isotopic content of this deposit was approximately as follows: U-235 (93%), U-238 (6%) and the rest U-234 and U-236. The total atom content of this deposit is about 2.6 (+18). The measurements performed with this system fall into two broad categories: i) investigation of the detector pulse-height spectrum under various conditions and ii) time-of-flight spectrum measurements at various distances from the neutron source. The details of these measurements, and the information acquired from performing them, are topics of discussion in the present section and in Section III.D.

First we consider the pulse-height spectrum investigation. For this, the fission detector was placed quite close to the target assembly (the uranium deposit was 5.7 cm from the beam-spot position). The U-238 deposit was placed in the chamber and spectra were recorded under various deuteron-beam intensity conditions (in the range 0.9 to 7.9 microamps) for each of the filler gases indicated in the preceding paragraph. The electronics circuitry was checked for linearity-and the spectrum zero level was established-with the aid of a pulser. The system was found to be adequately linear over the range of recorded pulse height. It was noticed that the intrinsic pulse amplitudes varied significantly with the choice of filler gas, with methane providing the greatest-amplitude signals. For these measurements, the gain of the electronics circuitry was adjusted to compensate for these amplitude differences so that spectra recorded with different filler gases could be more readily compared. With such adjustments made, the spectra recorded with the various gases all had essentially the same shape. A representative member of this set of recorded spectra is shown in Fig. 7. As is typical for detectors of this type, some of the fission events are masked by the low-level pulses attributed to electronic noise, alpha-particle events, neutron-induced recoils and charged particle (C.P.) events. In order to estimate the total fission-event yield for each spectrum, we assumed a constant extrapolation to zero pulse-height for these "masked" fission pulses, as shown in Fig. 7 with dashed lines. These extrapolated fission events amounted to about 4% of the total for each of the measured spectra. The fission-event total for each spectrum was corrected for the corresponding deadtime of the multi-channel analyzer used to record the spectrum. These deadtime corrections were indeed essentially proportional to the deuteron beam current (and thus the neutron yield from the target) and they were observed to be in the range 0.3 to 3.0%. The corrected fission-event data for this detector were then normalized by dividing by monitor-count values-including the corrected current-integrator readings, the corrected boron-triflouride readings and the natural-uranium detector counts. Several conclusions can be drawn from the results of this analysis. The most stable parameter observed in this investigation was the ratio of the U-238 fission detector counts to the boron-triflouride detector monitor counts. It was found to vary with a standard deviation about the average of approximately 1%, in spite of the wide range of deuteron beam currents employed and the interchange of three distinct chamber filler gases. This variation is consistent with statistical uncertainties. Intrinsic stability is qualitatively evident from the fact that all the recorded spectra had the same shape in spite of substantial variations in the neutron-field intensity. From this we conclude that the fission detector used to monitor neutron fluence close to the target under high-count-rate conditions is capable of providing reliable performance, and is not particularly sensitive to count-rate variations for any of the filler gases investigated. This is probably the most important result of the present experiment. It offers confidence that the high-intensity neutron irradiation facility can be conveniently used for the purposes for which it is intended. Ratios involving the current integrator and natural-uranium fission detector were found to be not as stable as was the case for the boron-triflouride monitor. For the current integrator, the standard deviation around the average for all the data of the present set was about 4%. Since no changes were made in the geometry, it is clear that current leakage through the water-cooling system can be problematic if a high degree of reproducibility is required.

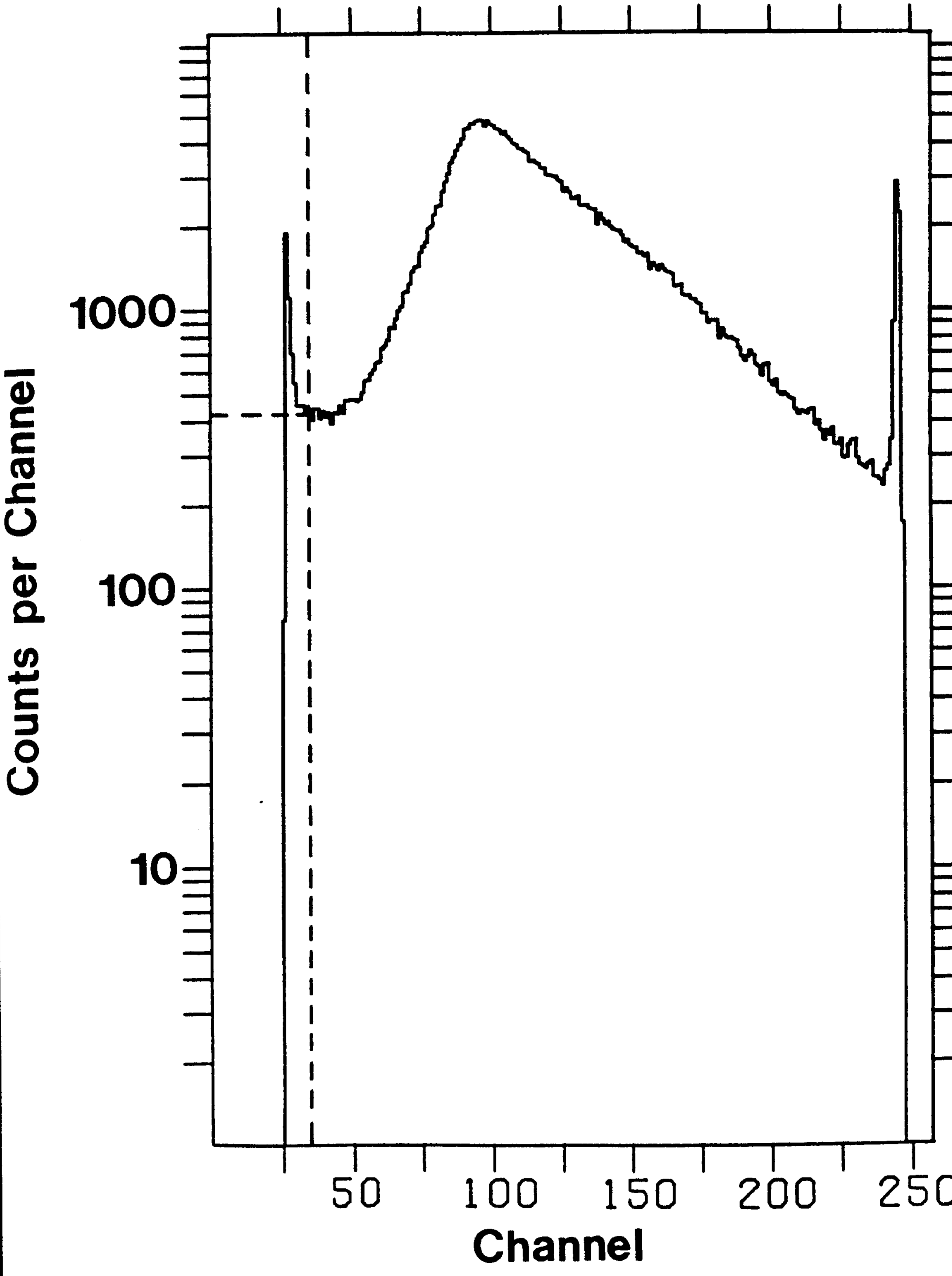


Figure 7: A pulse-height spectrum recorded with the fission detector which is used as a neutron-fluence measurement device in activation sample irradiations. A U-238 deposit and an argon-carbon dioxide mixture as the filler gas were used in this measurement, as described in Section III.C. Dashed lines indicate how the fissions extrapolation correction is determined.

However, this is not a fundamental limitation because leakage effects can be reduced by the use of other coolants, e.g., freon, or by lengthening the section of tubing which connects the aperture flange and target. This point was not examined further. The standard deviation about the average for the ratios involving the natural-uranium monitor was about 3%, a result which is somewhat in excess of the statistical uncertainties in the data. The origin of such variations in excess of statistics is not clear, but the matter was pursued no further. We conclude that investigation of the stability of neutron fluence monitors is a matter which ought to be pursued routinely in all experiments involving this facility. It is not adequate to rely on the results of the present investigation, though they can be considered characteristic of what is to be anticipated in routine practice.

D. Neutron-spectrum measurements near the target

Time-of-flight (TOF) measurements were performed with both the U-238 and U-235 deposits, using the electronics circuitry indicated in Fig. 5. The purpose of this investigation was to obtain quantitative information about the fission events produced by neutrons scattered back to the detector from the walls of the cavity. It is reasonable to assume a priori that the fission yield from direct target neutrons would vary roughly as the inverse square of the distance from the target to the uranium deposit while the fission yield from wall return neutrons-which for convenience we denote here as "albedo" neutrons-would vary much more slowly with distance of the fission detector from the target. For this reason, we performed measurements at roughly equal invervals in the square of the distance from the neutron source. The TOF spectra were recorded over a time range of approximately 500 nanoseconds since the beam-pulse frequency was 2 MHz. The resolution of the beam pulse from the FNG accelerator was of the order of 2 nanoseconds. The time scale calibration was measured with a commercial time calibrator and was determined to be 2.564 nanoseconds per channel for the setup of the present investigation. A pulse-height bias level was set well above the pulses from the various non-fission events to insure that only fissions were represented in the TOF spectra. From the spectra recorded at distances close to the target, it was concluded that the overall time resolution for the measured spectra was $<$ 5 nanoseconds FWHM. Although the measurement and data analysis techniques were almost identical for the U-235 and U-238 deposits, the characteristics of the spectra were quite different owing to the radically different fission cross sections for these two reactions. Consequently, we will describe the results from these two investigations separately.

TOF spectra recorded for the U-238 deposit are shown in Fig. 8. It is clear that the fission yield from albedo neutrons is very small relative to that from direct neutrons, even for substantial distances from the target to the detector. The U-238 fission process is relatively insensitive to neutrons with energies below 1 MeV, so the albedo component of the spectrum represents only relatively-energetic neutrons returning from the walls to the detector. It is quite interesting to note that these events tend to fall into a reasonably well defined "peak" located below the prompt-event peak. The average separation of these peaks is about 76 nanoseconds. Since the walls of the chamber are lined with

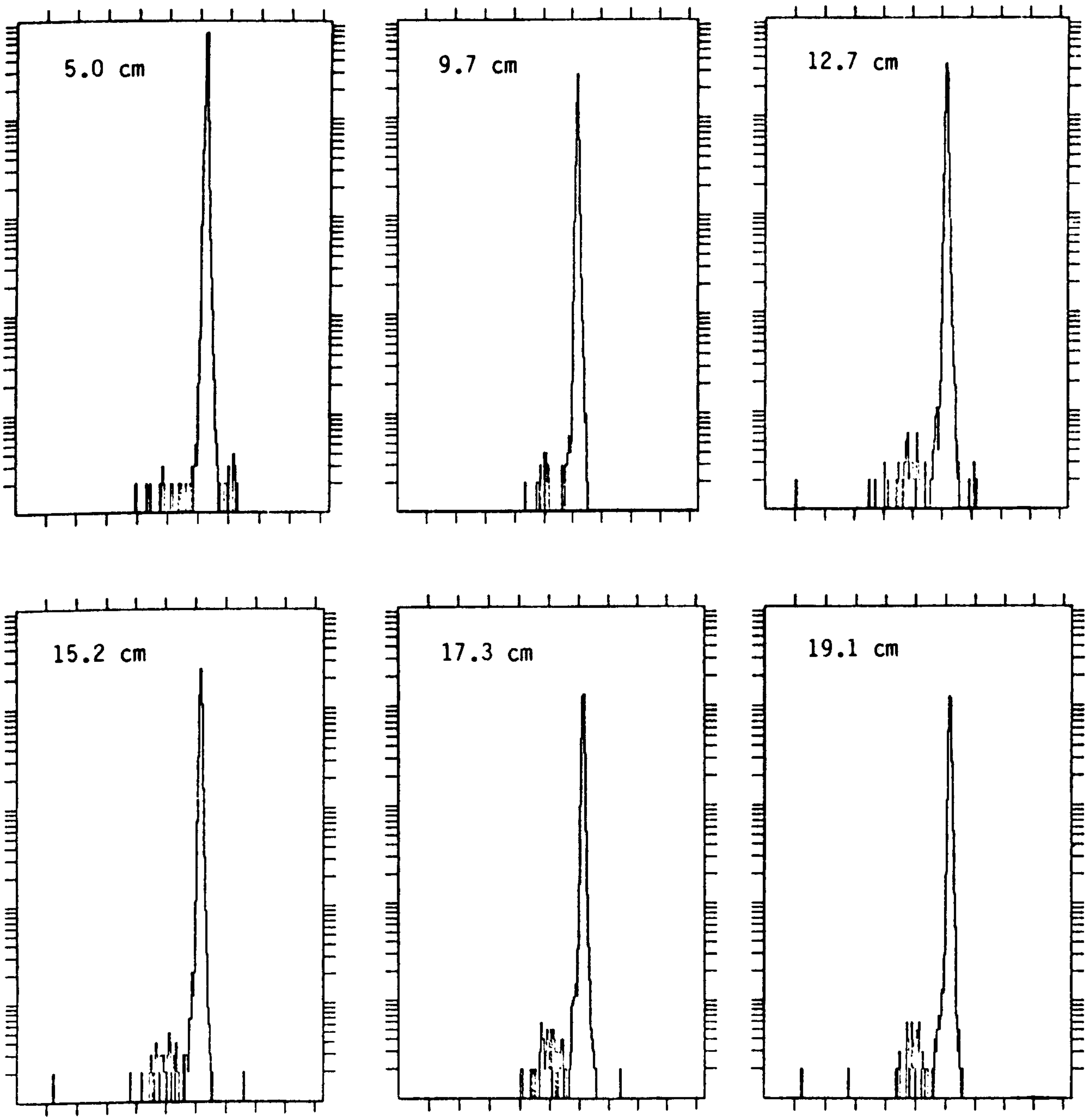
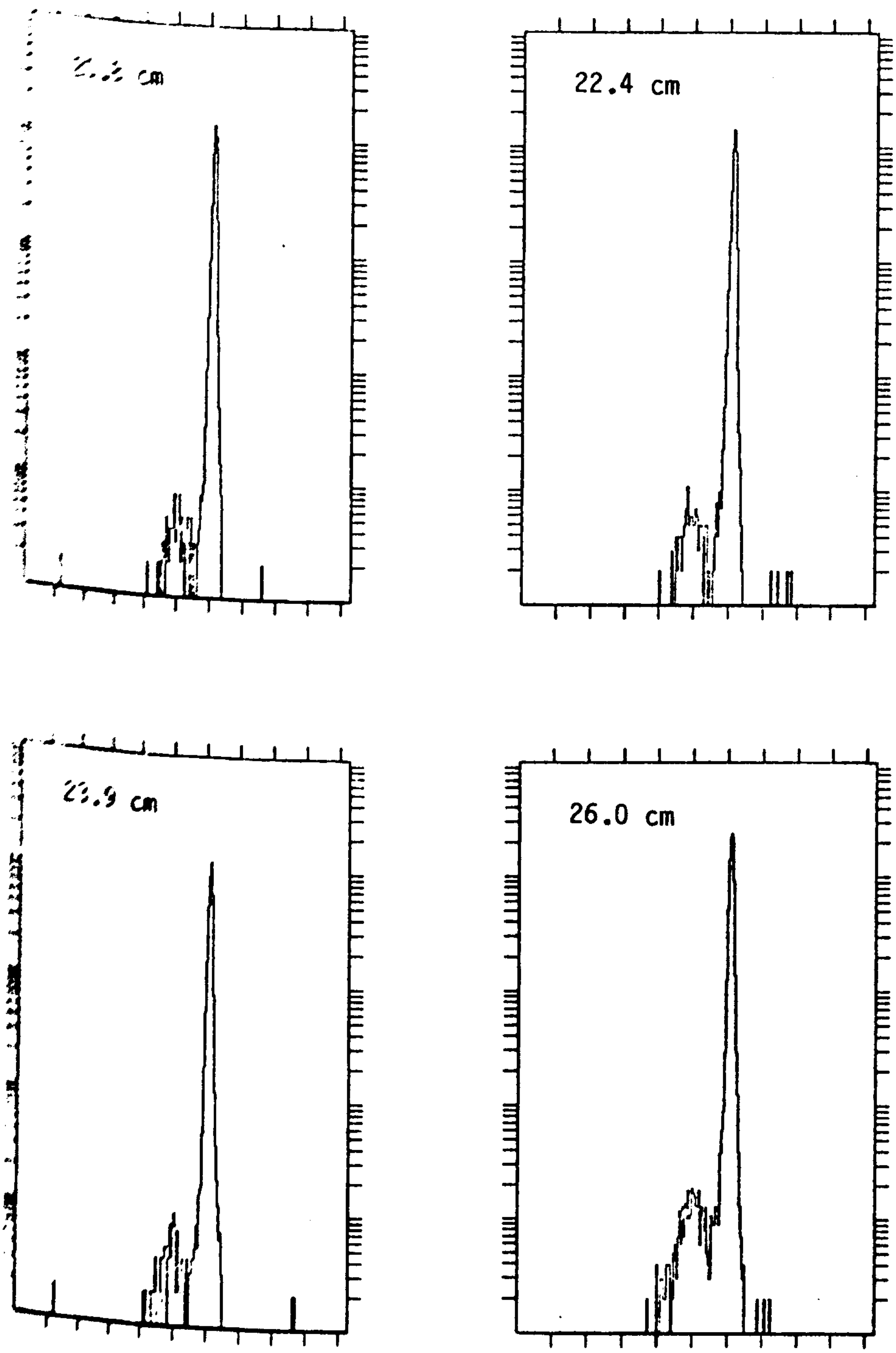


Figure 8: Time-of-flight spectra measured with a fission chamber which contained a depleted uranium (U-238) deposit. Absolute distances of the uranium deposit from the neutron source are indicated. Axes are unlabelled, but each abscissa division corresponds to 25 channels while the logarithmic ordinate scales are set to unity at the lower borders. The time calibration for these spectra is 2.564 nanoseconds per channel.

Figure 8: (continued)



polyethelene blocks, and since neutrons cannot backscatter from hydrogen, we assume that the energetic albedo neutrons are predominantly those which have elastically scattered once from carbon. The average energy of the direct target neutrons (weighted by target fluence and the U-238 fission cross section) is about 4.3 MeV, at least in the forward direction where most of the neutrons are emitted (Ref. 16). Very roughly, the average energy of these neutrons would be reduced to about 3.1 MeV by backscattering from carbon (A = 12). Considering that the distance from the walls to the neutron source is about 1 meter, we find that a time separation of the order of that observed (76 nanoseconds) is indeed reasonable for neutrons of these indicated average energies. Ratios of albedo-neutron to direct-neutron yields were computed from the spectral information represented in Fig. 8. Uncertainties in these ratios are due primarily to counting statistics for the albedo component. These errors are in the range 5.2 - 14.0%. The results are listed in Table 2 and plotted in Fig. 9. Since these results do seem to vary more or less linearly with the square of the distance, a straight line was fitted to the data by a weighted least-squares method. The parameters of this line are given in Fig. 9. Inverse-square dependence breaks down at close distances, so this explains the non-zero intercept of the fitted line.

TOF spectra recorded for the U-235 enriched deposit are shown in Fig. 10. These spectra are markedly different from those in Fig. 8. The yield from the albedo neutrons is much greater here because of the high sensitivity of the U-235 fission reaction to low-energy neutrons. In fact, the albedo component is apparently rather uncorrelated in time with the direct neutron burst. This indicates that these neutrons have generally undergone numerous collisions before reaching the detector, and thus for the most part are of quite low energy. The detector was not shielded with a low-energy neutron absorber such as cadmium so it would indeed be responsive to nearly-thermalized neutrons present in the cavity. Ratios of albedo-neutron to direct-neutron fission yield were computed from the spectral information represented in Fig. 10. For this analysis, the albedo spectra were assumed to be flat so that an extrapolation under the direct peak could be performed. The results are listed in Table 2 and plotted in Fig. 11. Once again there appears to be a quite linear relationship between this ratio and the square of the distance from the neutron source to the detector. The small non-zero intercept again is most likely indicative of a breakdown from linearity at close distances. The errors in the measured ratios were in the range of 1.1-1.6 %, and they are due entirely to counting statistics. A straight line was fitted to these data by a weighted least-squares method. The parameters of this line are given in Fig. 11.

From this investigation we have learned that a monitor with a strong response to low-energy neutrons is not a particularly favorable one to use in the cavity environment for monitoring of the direct-neutron fluence, though at positions quite close to the target (a few centimeters), the correction for albedo neutrons is not too large (a few percent). Likewise, one needs to be quite careful when performing activation measurements

Table 2: Ratios of fission events produced by albedo neutrons to those produced by neutrons direct from the beryllium target

D[a] (cm)	D^2 (cm^2)	U-235[b] Ratio	U-235[b] Error (%)[d]	U-238[c] Ratio	U-238[c] Error (%)[d]
5.0	25.0	4.08(-2)	1.1	4.97(-4)	10.5
9.7	94.09	0.131	1.3	9.48(-4)	14.0
12.7	161.29	0.223	1.4	1.31(-3)	9.7
15.2	231.04	0.310	1.4	1.77(-3)	10.1
17.3	299.29	0.408	1.5	2.53(-3)	10.5
19.1	364.81	0.485	1.6	2.82(-3)	10.2
20.8	432.64	0.580	1.6	3.20(-3)	9.0
22.4	501.76	0.673	1.5	3.74(-3)	8.1
23.9	571.21	0.776	1.5	3.95(-3)	8.4
26.0	676.0	0.888	1.6	4.73(-3)	5.2

[a]Distance from the neutron source to the uranium deposit.

[b]Uranium deposit enriched to 93% U-235.

[c]Depleted uranium.

[d]Statistical errors.

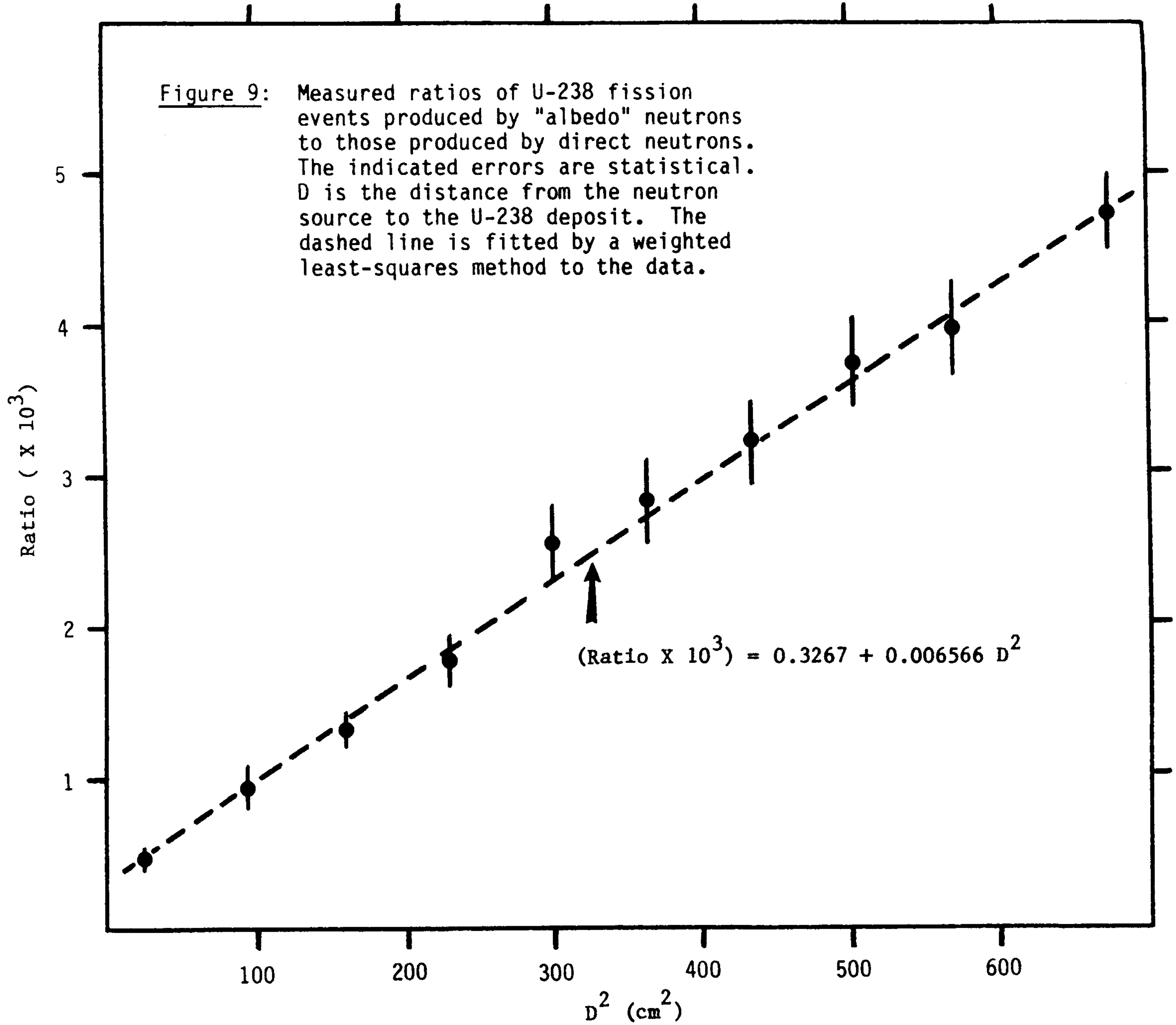


Figure 9: Measured ratios of U-238 fission events produced by "albedo" neutrons to those produced by direct neutrons. The indicated errors are statistical. D is the distance from the neutron source to the U-238 deposit. The dashed line is fitted by a weighted least-squares method to the data.

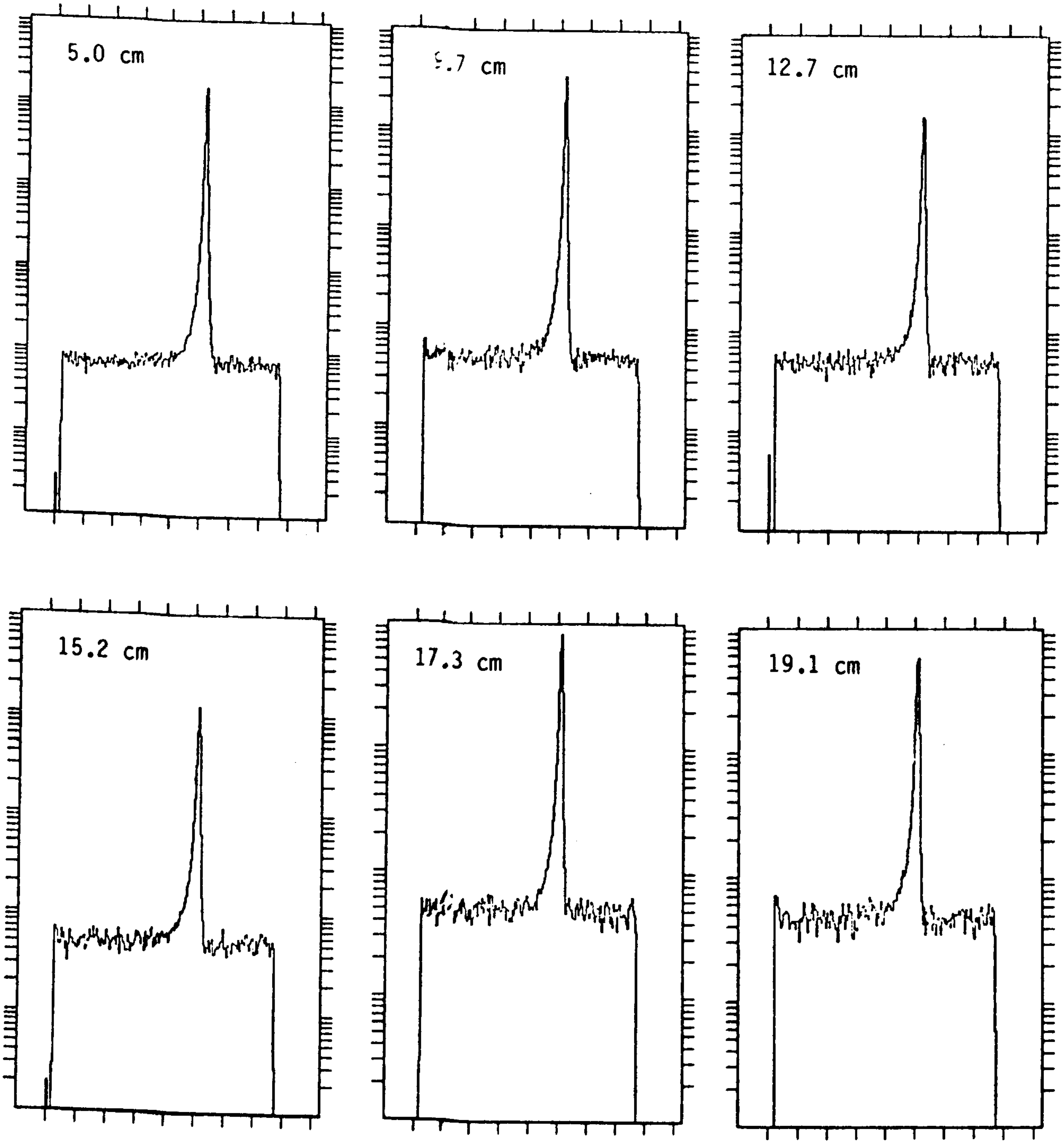
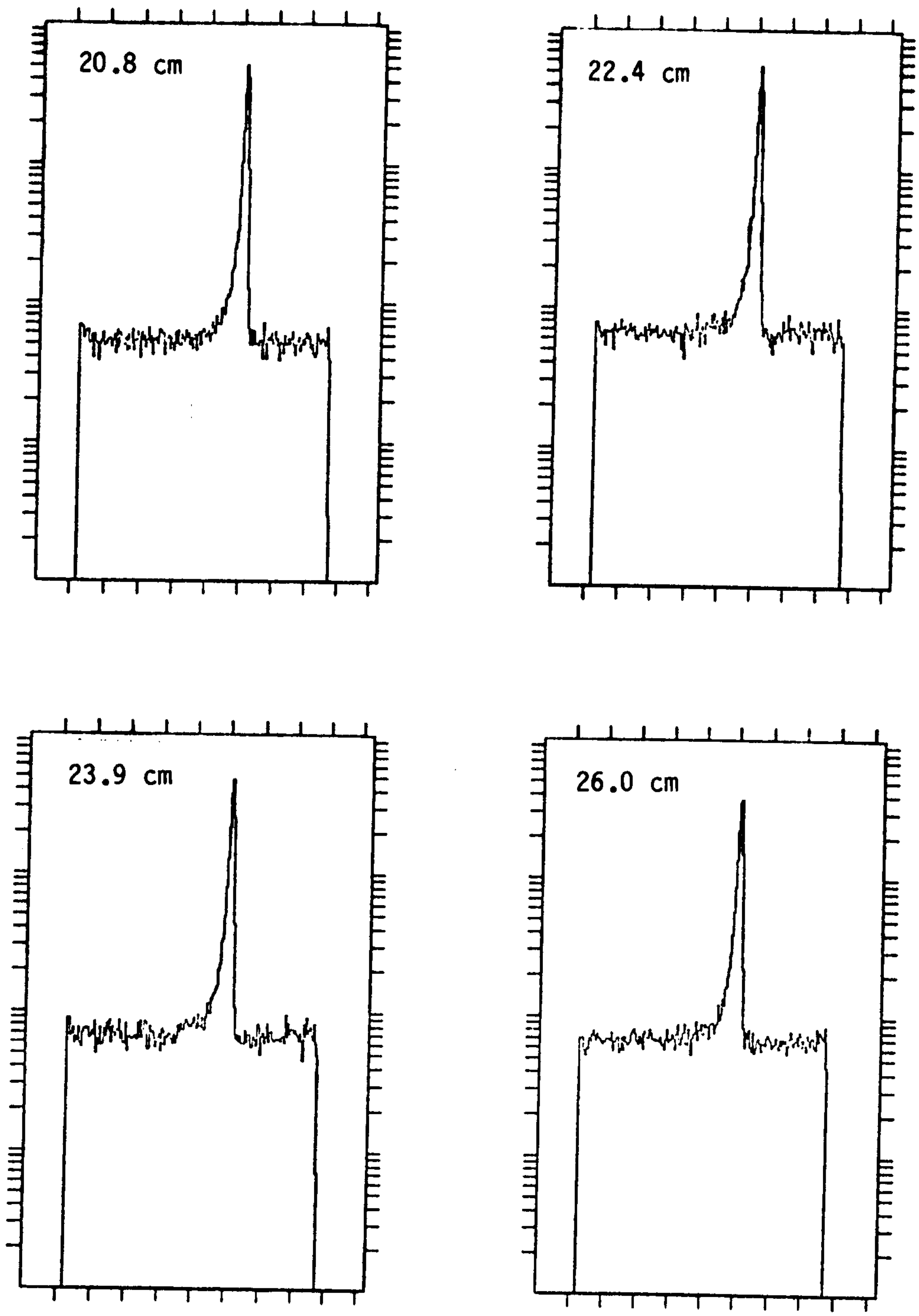


Figure 10: Time-of-flight spectra measured with a fission chamber which contained a U-235 enriched (93%) uranium deposit. Absolute distances of the uranium deposit from the neutron source are indicated. Axes are unlabelled, but each abscissa division corresponds to 25 channels while the logarithmic ordinate scales are set to unity at the lower borders. The time calibration for these spectra is 2.564 nanoseconds per channel.

Figure 10: (continued)



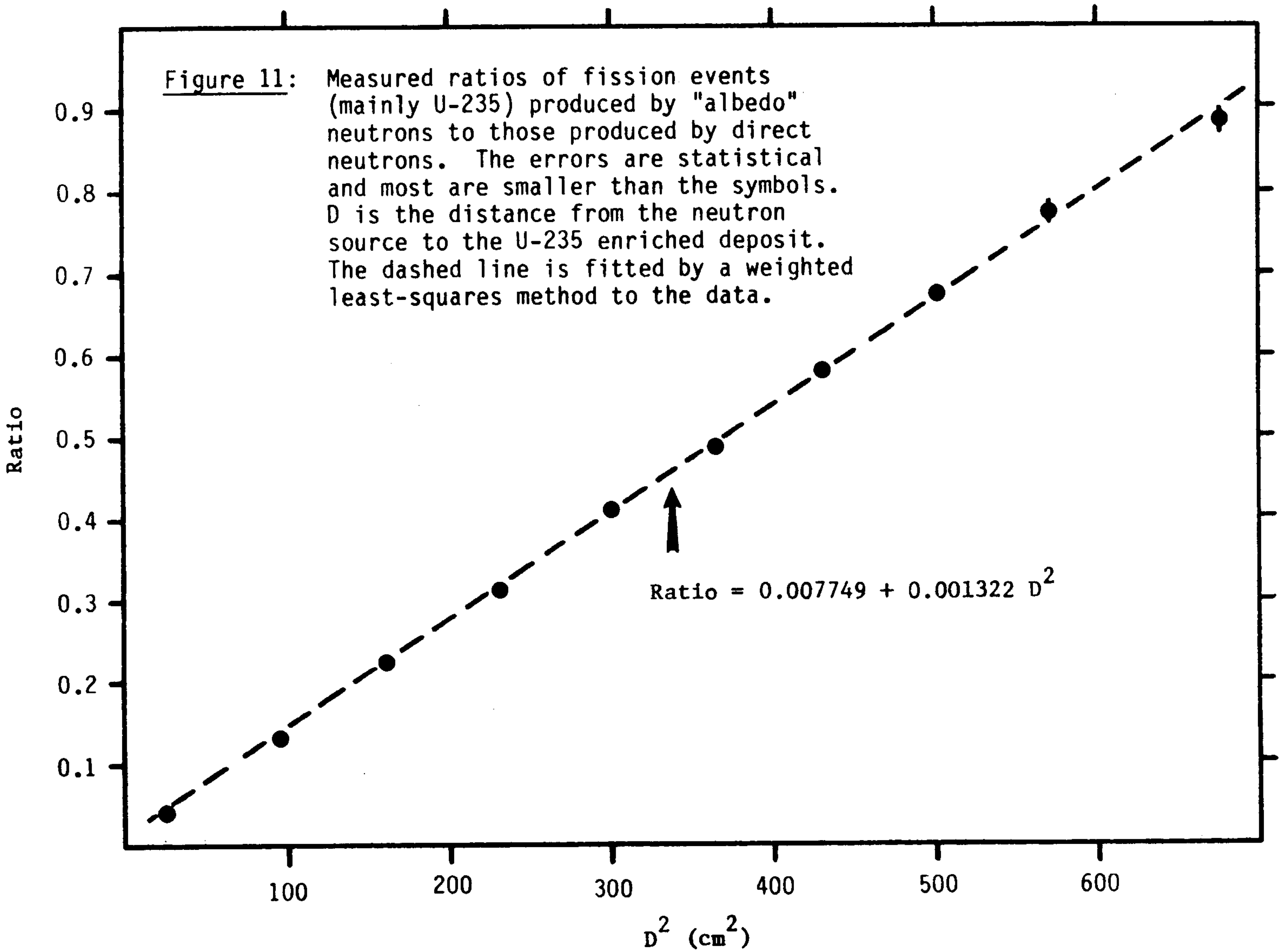


Figure 11: Measured ratios of fission events (mainly U-235) produced by "albedo" neutrons to those produced by direct neutrons. The errors are statistical and most are smaller than the symbols. D is the distance from the neutron source to the U-235 enriched deposit. The dashed line is fitted by a weighted least-squares method to the data.

if a strong low-energy neutron response is expected (e.g., most neutron capture processes). Certainly one can minimize the correction for albedo neutrons by choosing a fluence monitor with a response similar to that of the unknown reaction. If a considerable response to low energy neutrons is anticipated, then ratio measurements of activation to monitor yield must be performed at several distances in order to experimentally determine the necessary correction for albedo neutrons.

IV. APPLICATIONS

The availability of a convenient facility for high-intensity irradiations with neutrons produced by proton or deuteron bombardment of thick light-element targets opens up a number of possible areas for nuclear-data research in our laboratory.

As indicated in preceding chapters of this report, our main interest is in the specific area of activation reactions. For reactions which can be studied by the conventional monoenergetic method, it is generally the preferred approach. However, selected integral measurements in suitable accelerator-neutron spectra could prove to be very useful in resolving major discrepancies, or in indicating needs for new differential measurements. In some situations, differential measurements may not be practical for reactions which have small cross sections, such as one might expect for (n,C.P.) reactions on high-Z targets, or for reactions which lead to long-half-life products. Then, irradiations in intense thick-target fields, especially when used in conjunction with sensitive detection methods such as high-efficiency gamma-ray detectors, beta detectors or accelerator mass spectrometry, offer the potential for providing data in situations where no other method will suffice. Such data, in conjunction with nuclear model calculations, could prove very useful in determining whether these processes are significant in certain applications, e.g., fusion energy, or whether they can be ignored. It is our intent to explore this avenue of research on a gradual basis in order to determine whether the approach is useful in practice. We are proceeding cautiously because there are a number of important technical details which must be addressed very carefully in order to insure that reliable quantitative results are obtained.

A method for unfolding the integral cross-section data from measurements in diverse neutron fields, in order to produce differential information, has been described in Ref. 14. This approach is complex, but it offers the potential for accessing the difficult energy range from 8-14 MeV. At the FNG facility, with the Be-9(d,n)B-10 thick-target reaction, we can access only the lower-energy portion of this difficult range (Refs. 16 and 20). However, there are other neutron-producing reactions with larger Q values which could be used to access higher energies. We intend to test this method first at lower energies using the Be-9(d,n)B-10 reaction, and then examine the possibilities available to us at higher energies through the use of other neutron-source reactions.

Contemporary knowledge of the neutron-emission spectra from these thick-target reactions is fragmentary in the energy range of concern for the FNG facility. The applications mentioned above all rely on good quantitative knowledge of these details, so a great deal of work will have to be done to characterize these spectra. This can be achieved conveniently using the zero-degree access port of the present facility. Measurements of spectra for various promising reactions will form an important part of the applications program for this facility.

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