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A. J. Miller and H. W. Patterson

June 1971

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MEASUREMENT OF INDUCED ACTIVITY TO ESTIMATE PERSONNEL RADIATION EXPOSURES RECEIVED FROM ACCELERATOR BEAMS

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June 1971

ABSTRACT

A method has been developed at the Lawrence Radiation Laboratory in Berkeley to estimate the dose received by an individual accidentally exposed to an accelerator particle beam. The dose estimate is based on measurement of the gross induced activities, primarily ^{11}C, resulting from nuclear interactions of the particle beam with the body tissues of the exposed individual.

The activities are measured with a portable NaI crystal γ-ray scintillation detector. To achieve maximum sensitivity and counting statistics, the activity measurements are made in the LRL Health Physics Group's Low-Background Counting Enclosure very soon after exposure.

Doses have been estimated by exposing two tissue-equivalent phantoms, one simulating an arm and the other simulating a torso, to particle beams (protons, π^+ mesons, and neutrons) of various energies. Results indicate that independent of the part of the body exposed, the beam size, or the beam energy from 50 MeV to $\approx$ 6 GeV, the actual dose can be estimated within a factor of 2. Under favorable conditions the lower limit of sensitivity in estimating the dose is less than 1 rem.

INTRODUCTION

Early in 1969 we noted that ~150 nCi of ^{59}Fe could be detected in an individual by using a 3- × 3-in. portable NaI crystal γ-ray scintillation detector in the LRL Health Physics Group's Low-Background Counting Enclosure.[1] The method of examination consisted of placing the NaI crystal at the midsection of the individual and noting the net counting rate (background subtracted) of the γ rays.

Based upon the observation that this detector system could measure very low levels of radioactivity in an individual, we felt that the same technique could be applied to measure the induced radioactivities resulting from an accidental exposure to an accelerator-produced particle beam. The activity induced[2] within the body tissues from nuclear interactions is primarily ^{11}C with a 20.4-min half-life, ^{13}N with a 9.96-min half-life, and ^{15}O with a 123-sec half-life.

To determine the sensitivity of this technique we constructed two tissue-equivalent phantoms. A 5-gallon polyethylene bottle (29 cm diam and 40 cm high) simulating the torso of a man and a 500 ml polyethylene bottle (10 cm diam and 18 cm high) simulating the arm were filled with a tissue-equivalent fluid.[3] Each phantom was exposed to various energy particle beams (50 MeV to 6 GeV) of protons, positive pions, and neutrons. After being irradiated, the phantoms were returned to our Low-Background Counting Enclosure where the gross induced radioactivity was measured.

With each phantom exposure a polyethylene or polystyrene disc of known thickness was also exposed. Subsequent counting of the ^{11}C activity in the disc provided a monitor from which the particle fluence of the beam was calculated. Knowing the following additional information, (1) particle composition, (2) energy, (3) irradiated area, (4) time duration of the exposure, and (5) decay time after the exposure, we calculated the absorbed dose and the dose equivalence for each phantom irradiation. By combining the dose equivalence and absorbed dose values with the respective phantom activity data, we were able to establish sensitivity of detection values for the different beams employed in this study.

PARTICLE BEAMS

Table I summarizes the pertinent information concerning each particle beam used in our study. The types and energies of the beams reflect those most commonly found and potentially the most hazardous at this laboratory. Of the particle beams used for the phantom irradiations, only one consisted primarily of secondary particles: ~ 75% neutrons and ~ 12.5% p^+ and π^+ respectively. The remaining irradiations were of different energy primary proton beams from the LRL Bevatron and from the 184-in., and 88-in. cyclotrons.

With the exception of the secondary particle beams, the "Beam Area" for each phantom exposure was obtained by simultaneously exposing a 4- × 5-in. Polaroid film packet, type 55, with the polyethylene or polystyrene disc, and the phantom. The Beam Areas quoted for the secondary particles were obtained from information supplied by the experimenters actually using the beam.

BEAM MONITOR

A convenient means of determining the total number of charged particles and/or neutrons with energies greater than ~ 20 MeV is to use the carbon-11 technique.[4,5] Carbon-11, a positron emitter with E_{max} = 0.98 MeV and a half-life of 20.4 min can be produced from ^{12}C by (p, pn), (n, 2n) reactions, and by other charged particles.

Following the irradiation of a polyethylene or polystyrene disc, the annihilation γ rays (0.51 MeV) were counted with an 8-in. -diam × 4-in. -thick NaI crystal γ-ray scintillation detector. Subsequent analysis of the counting data yields the integral number of beam particles in the exposure. Combining the "Beam Integral" data of Table I with the respective "Beam Area" gives the particle fluence (particles/cm^2 greater than 20 MeV) of the exposure.

PHANTOM IRRADIATION AND COUNTING

For each exposure a phantom was centered in the desired beam line. Phantom orientation was such that the focused or collimated particle beam traversed the phantom's narrow axis. In addition, care was taken to ensure that any particle traversing the phantom had first to pass through the monitoring disc. Exposure time depended upon the expected particle fluence and typically ranged from ~ 1 sec in a 6-GeV primary proton beam to ~ 1 min in a secondary particle beam of 1.5 BeV/c π^+ and p^+.

Table I. Physical properties of particle beams studied.

Particle beam	Particle energy	Beam integral particles	Beam area
Protons	50 MeV	1.5×10^{11} protons	6.41 cm^2
Protons	730 MeV	4.9×10^{9} protons	8.83 cm^2
Positive pions	1.37 GeV		6.45 cm^2
Protons	800 MeV	1.49×10^{8} particles	6.45 cm^2
Neutrons	400 MeV		81.3 cm^2
Positive pions	1.37 GeV		6.45 cm^2
Protons	800 MeV	4.23×10^{8} particles	6.45 cm^2
Neutrons	400 MeV		81.3 cm^2
Positive pions	1.37 GeV		6.45 cm^2
Protons	800 MeV	1.87×10^{8} particles	6.45 cm^2
Neutrons	400 MeV		81.3 cm^2
Positive pions	1.37 GeV	7.83×10^{7} particles	6.46 cm^2
Neutrons	400 MeV		81.3 cm^2
Protons	5 GeV	1.37×10^{11} protons	7.5 cm^2
Protons	5 GeV	2.06×10^{11} protons	6 cm^2
Protons	6 GeV	1.53×10^{10} protons	7.07 cm^2

The nuclear interactions of the particle beams with the tissue-like phantoms produced numerous radioactive nuclides. Several of the possible proton and neutron activation reactions in tissue are shown in Table II, alone with the decay modes of the radioactive product nuclei and the calculated reaction threshold energy. Of the radionuclides produced, only $^{11}_{6}C$ has a half-life such that its activity can be detected some 30 to 60 min following an radiation exposure.

Following irradiation, the phantom's gross radioactivity was measured in our Low-Background Counting Enclosure with the 3- × 3-in. NaI crystal γ-ray scintillation detector.[6] Basically this instrument is a transistorized count-rate meter designed by Goldsworthy,[7] but slightly modified for our use. The detector is a thallium activated sodium iodide crystal 3 inches in diameter and 3 inches in thickness. The crystal and phototube assembly are housed in a stainless steel canister of 1/16 in. thickness. Because of the canister thickness, and the copper can housing the crystal, it is estimated that all β particles of energy less than 2.75 MeV are excluded from the crystal. In addition the instrument has been adjusted to have a γ-ray energy threshold of ~ 100 keV. With these energy level thresholds, the instrument measures a background of 15 to 18 counts/sec in our Low-Background Counting Enclosure.

For counting, the irradiated phantoms were placed in direct contact with the detector assembly. The induced activities in the phantom, as indicated by the rate meter, were measured and recorded for periods up to ~ 2 hr after exposure. Figures 1 and 2 show graphically the data for 730-MeV protons and 1.5-BeV/c positive pions and protons respectively. Both graphs show that by 30 min after the exposure, the predominant activity is ^{11}C with the 20.4-min half-life.

DOSE AND DOSE SENSITIVITY DETERMINATIONS

The dose equivalent and absorbed dose values given in Tables III and IV—with the exception of the 50-MeV proton data—come from Figs. 3a, b, c and 4a, b, c respectively. Data for these graphs were obtained from the calculations by Alsmiller et al.,[8,9] at Oak Ridge National Laboratory. The 50-MeV proton values are given by Thomas[10] of the Lawrence Radiation Laboratory. Dose equivalent and absorbed dose for each exposure were calculated by combining the measured particle fluence for that exposure with the appropriate values from the tables.

Table II. Possible tissue activation reactions decay modes and reaction threshold energies.

Reaction	Calculated reaction threshold energy (MeV)
$^{12}_{6}C(p,pn)^{11}_{6}C \xrightarrow[20.3\ min]{\beta^+ 0.98\ MeV} {}^{11}_{5}B$	~ 20.3
$^{12}_{6}C(n,2n)^{11}_{6}C \xrightarrow[20.3\ min]{\beta^+ 0.98\ MeV} {}^{11}_{5}B$	
$^{16}_{8}O(n,d2n)^{13}_{7}N \xrightarrow[9.96\ min]{\beta^+ 1.2\ MeV} {}^{13}_{6}C$	~ 26.6
$^{16}_{8}O(n,p3n)^{13}_{7}N \xrightarrow[9.96\ min]{\beta^+ 1.2\ MeV} {}^{13}_{6}C$	
$^{14}_{7}N(n,2n)^{13}_{7}N \xrightarrow[9.96\ min]{\beta^+ 1.2\ MeV} {}^{13}_{6}C$	~ 11.3
$^{14}_{7}N(p,pn)^{13}_{7}N \xrightarrow[9.96\ min]{\beta^+ 1.2\ MeV} {}^{13}_{6}C$	
$^{16}_{8}O(p,\alpha)^{13}_{7}N \xrightarrow[9.96\ min]{\beta^+ 1.2\ MeV} {}^{13}_{6}C$	~ 5.5
$^{16}_{8}O(n,2n)^{15}_{8}O \xrightarrow[123\ sec]{\beta^+ 1.74\ MeV} {}^{15}_{7}N$	~ 16.7
$^{16}_{8}O(p,pn)^{15}_{8}O \xrightarrow[123\ sec]{\beta^+ 1.74\ MeV} {}^{15}_{7}N$	

Table III. Dose equivalent values for π^+, p^+, and neutrons at different energies and depths in tissue.

Particle	Energy	Tissue depth	Dose equivalent
p^+	50 MeV	2 cm	5.0×10^{-7} rem/p^+/cm^2
p^+	730 MeV	8 cm	1.35×10^{-7} rem/p^+/cm^2
p^+	5 BeV	8 cm	1.7×10^{-7} rem/p^+/cm^2
p^+	5 BeV	25 cm	2.1×10^{-7} rem/p^+/cm^2
p^+	6 BeV	8 cm	1.7×10^{-7} rem/p^+/cm^2
Neutrons	400 MeV	8 cm	4.6×10^{-8} rem/n/cm^2
Neutrons	400 MeV	25 cm	6.3×10^{-8} rem/p^+/cm^2
p^+	830 MeV	8 cm	1.4×10^{-7} rem/p^+/cm^2
p^+	830 MeV	25 cm	1.55×10^{-7} rem/p^+/cm^2
π^+	1.37 BeV	8 cm	1.85×10^{-7} rem/π^+/cm^2
π^+	1.37 BeV	25 cm	1.85×10^{-7} rem/π^+/cm^2

Table IV. Absorbed dose values for π^+, p^+, and neutrons at different energies and depths in tissue.

Particle	Energy	Tissue depth	Absorbed dose
p^+	50 MeV	2 cm	4×10^{-7} rad/(p)/cm^2)
p^+	730 MeV	8 cm	6.7×10^{-8} rad/(p)/cm^2)
p^+	5 BeV	8 cm	8.45×10^{-8} rad/(p/cm^2)
p^+	5 BeV	25 cm	1.1×10^{-7} rad/(p)/cm^2)
p^+	6 BeV	8 cm	8.7×10^{-8} rad/(p)/cm^2)
p^+	6 BeV	25 cm	1.16×10^{-7} rad/(p)/cm^2)
Neutrons	400 MeV	8 cm	1.6×10^{-8} rad/(p)/cm^2)
Neutrons	400 MeV	25 cm	2.2×10^{-8} rad/(p)/cm^2)
p^+	830 MeV	8 cm	6.9×10^{-8} rad/(p)/cm^2)
p^+	830 MeV	25 cm	7.2×10^{-8} rad/(p)/cm^2)
π^+	1.37 BeV	8 cm	7.3×10^{-8} rad/(p)/cm^2)
π^+	1.37 BeV	25 cm	8.1×10^{-8} rad/(p)/cm^2)

The dose sensitivity for detection of a given exposure is then the ratio of the measured phantom activity at a known time after exposure, e.g., 30 minutes, to the total dose. Table V lists the total absorbed dose, dose equivalence, and dose sensitivity values for each phantom exposure. The sensitivities are quoted for 30 min following the exposures. The 30-min time interval was selected because we believe this is a reasonable time between an accidental exposure and a measurement of the induced activities.

RESULTS

Graphical representation of the dose equivalent sensitivity values for each beam measurement is given in Fig. 5. With but one exception, all of the sensitivity values are grouped within a factor of ~ 2 of each other. Figure 6 shows the same type of data but for absorbed dose.

The dose equivalent and absorbed dose sensitivity values for 50-MeV protons are noticeably lower than those for the other particle beams. This is explained by the fact that 50-MeV protons have a total range of only ~ 2.5 cm in tissue, and after a penetration of 1 cm have fallen in energy below the production threshold (20 MeV) for $^{11}_{6}C$. The higher-energy particles pass completely through the phantoms with sufficient energy to produce $^{11}_{6}C$ along their entire path. The cross section for $^{11}_{6}C$ production favors the 50-MeV protons by a factor of ~3; therefore, the total $^{11}_{6}C$ produced per 50-MeV proton entering and stopping in the arm phantom is about one-third that for a higher-energy (~ 1-GeV) proton. Applying the above argument to our 50-MeV proton data yields a new dose equivalent sensitivity value that would be in excellent agreement with the other higher-energy values. The absorbed dose sensitivity for 50-MeV protons remains in poor agreement with the high-energy data even after the factor-of-3 correction has been applied. The cause of this is that the quality factor is nearly 1 for protons in the energy range 10 to 100 MeV,[9] thus the dose equivalent and absorbed dose have nearly the same numerical value.

CONCLUSIONS

Our studies indicate that the technique of counting the induced radioactivity in tissue following an accidental particle beam exposure is a valid means for rapidly estimating the dose equivalent. We have shown that, within a factor of ~ 2, the dose equivalent can be estimated for particle beams of energy 730 MeV to 6 GeV. Further, this estimate

Table V. Phantom exposure and dose sensitivity summary.

Phantom	Particle	Energy	Total dose to phantom (rads)	Total dose to phantom (rems)	Dose sensitivity at 30 min after exposure (c/sec/25 rads)	Dose sensitivity at 30 min after exposure (c/sec/25 rems)
Arm	p^+	50 MeV	9040	1.13×10^4	40.7 ± 6.4	32.5 ± 5.7
Arm	p^+	730 MeV	34.1	68	4.36 ± 20.9	218.8 ± 14.8
Arm	π^+	1.37 BeV	0.434	1.04	363 ± 19	152 ± 12
	p^+	830 MeV				
	Neutron	400 MeV				
Torso	π^+	1.37 BeV	1.59	3.63	784 ± 28	343.5 ± 19
	p^+	830 MeV				
	Neutron	400 MeV				
Torso	π^+	1.37 BeV	0.565	1.29	708.6 ± 26.6	310 ± 17.6
	p^+	830 MeV				
	Neutron	400 MeV				
Torso	π^+	1.37 BeV	0.389	0.606	449 ± 21	288 ± 17
	Neutron	400 MeV				
Arm	p^+	5 BeV	1654	3100	167.8 ± 12.9	90 ± 9.5
Torso	p^+	5 BeV	3777	7200	207 ± 14.4	110 ± 10.5
Arm	p^+	6 BeV	187	303	226 ± 15.0	140 ± 11.8

requires no knowledge of the beam composition, its size, or whether the torso or limb is irradiated. If, as is usually the case, certain beam and exposure information is known, then the dose equivalent estimate can be made more accurately. The important requirements of the technique are: (1) examination (measurement of the induced activity) of the irradiated individual as soon as possible (within ~ 30 min) after the exposure occurrence and (2) measurement of the induced activity which must be made in a very low- and constant-background area.

Although our studies did not include particle beams in the energy range 200 to 700 MeV, we feel that the dose equivalent sensitivity values for exposures in this range would be similar to those for particle 730 MeV and greater. Our reasoning derives from the fact that protons of energy > 200 MeV have a range, in tissue, that is greater than ~ 30 cm—the approximate thickness of a man. For particle beams in the 20- to 200-MeV range, a knowledge of the beam energy and exposure conditions is essential for a reliable estimate.

It is important to stress that this dose-estimating technique does not, in any way, preclude a carefully performed beam survey and dose estimate when an accidental beam exposure occurs or is suspected. The technique is intended to do only the following: (1) determine whether an exposure occurred, (2) if an exposure occurred, within a factor of 2, establish what the dose was, and (3) supply preliminary information concerning the course of action to be taken if the exposure occurred.

Based on these conclusions, we have developed the following procedure to be followed in an actual or suspected case of accelerator radiation accident.

In the event that an individual may have been exposed to accelerator radiation, the following procedure should be followed.

1. Call at least one of the Health Physics personnel on your emergency list and inform him of the occurrence. The list should be familiar to all accelerator operators and crew members.

2. Call the Medical Department and inform them of the occurrence.

3. Bring the individual to Building 72, Room 129, and wait outside the room for the Health Physicist to arrive and make the measurement.

4. Try to verify the circumstances of the accident; e.g., did it actually occur, at what time, where, how, and how long did the exposure last?

5. If the exposure involved failure of an interlock, take steps to prevent another exposure.

6. Record the operating parameters of the accelerator.

The Health Physicist will assist in this procedure and in addition will collect and process the individual's film badge and other dosimeters.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1. Activity of arm phantom vs time after exposure to 730-MeV proton beam.

Fig. 2. Activity of torso phantom vs time after exposure to secondary particle beam of 1.5-BeV/c π^+ and p^+ and 400-MeV neutrons.

Fig. 3a. Dose equivalent for protons at ~ 8 cm and ~ 25 cm depth in tissue—monoenergetic normally incident protons.

Fig. 3b. Dose equivalent for π^+'s at ~ 8 cm and ~ 25 cm depth in tissue—monoenergetic normally incident positive pions.

Fig. 3c. Dose equivalent for neutrons at ~ 8 cm and ~ 25 cm depth in tissue—monoenergetic normally incident neutron.

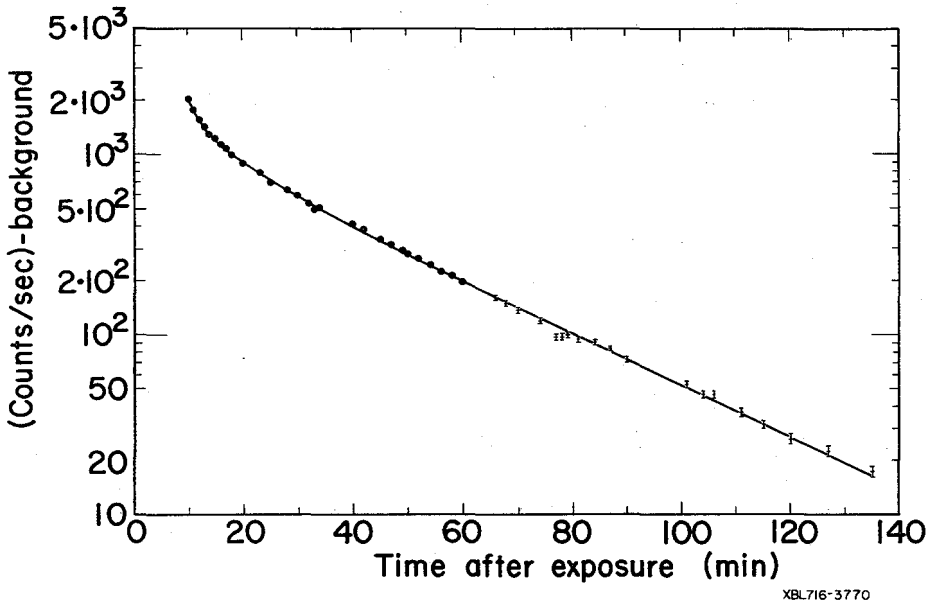
Fig. 4a. Absorbed dose for protons at ~ 8 cm and ~ 25 cm depth in tissue—monoenergetic normally incident protons.

Fig. 4b. Absorbed dose for π^+'s at ~ 8 cm and ~ 25 cm depth in tissue—monoenergetic normally incident π^+'s.

Fig. 4c. Absorbed dose for neutrons at ~ 5 cm and ~ 25 cm depth in tissue—monoenergetic normally incident neutrons.

Fig. 5. Graphical representation of dose equivalent sensitivity values.

Fig. 6. Graphical representation of absorbed dose sensitivity values.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2·10³
10³
5·10²
2·10²
10²
50
20
10
(Counts/sec)-background
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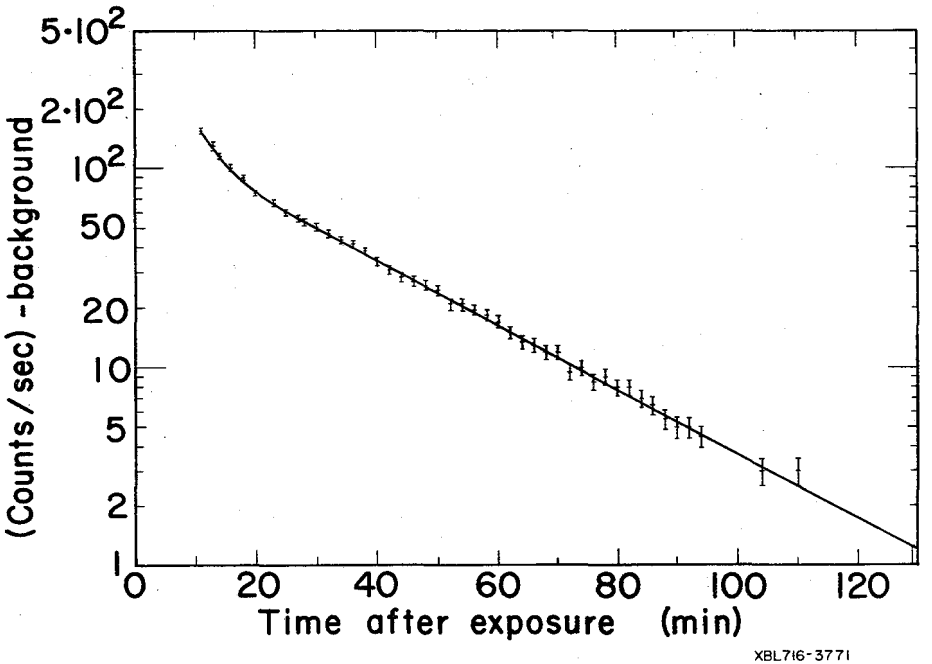
20
40
60
80
100
120
140
Time after exposure (min)
XBL716-3770

Fig. 1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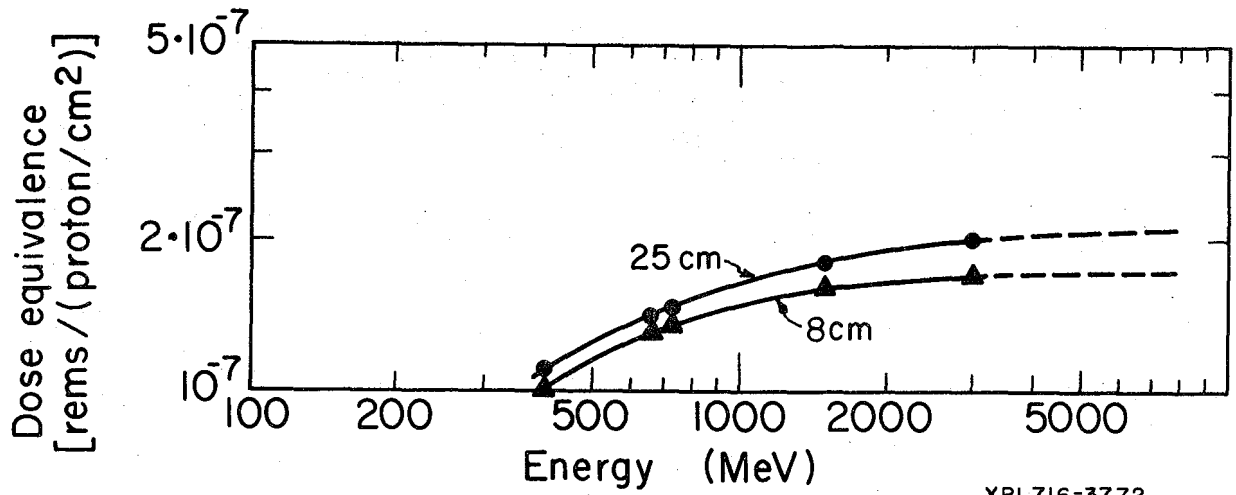
100
120
Time after exposure (min)
XBL716-3771

Fig. 2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10⁻⁷
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200
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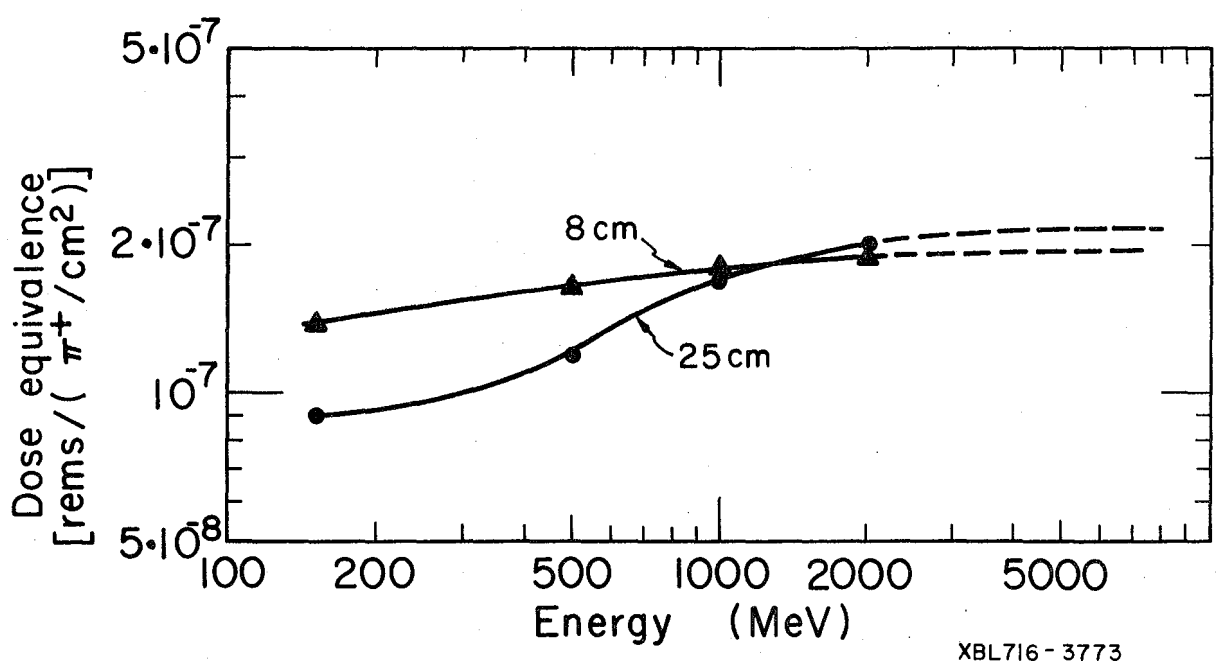
2000
5000
Energy (MeV)
XBL716-3772

Fig. 3a


5·10⁻⁷
2·10⁻⁷
10⁻⁷
5·10⁻⁸
Dose equivalence
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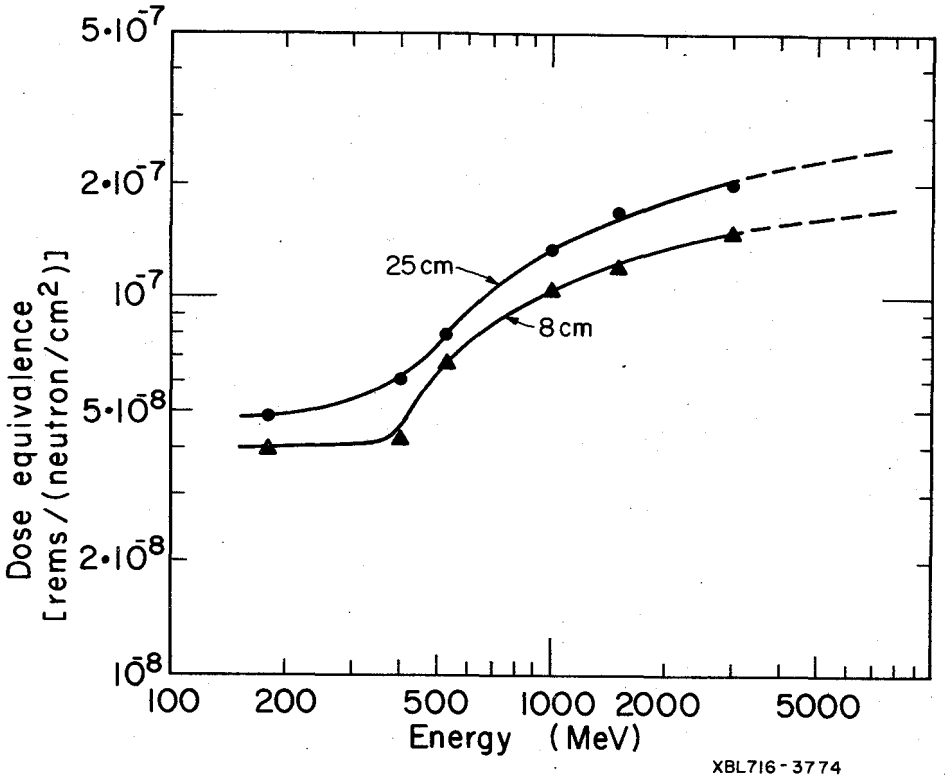
25 cm
100
200
500
1000
2000
5000
Energy (MeV)
XBL716-3773

Fig. 3b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2·10⁻⁷
10⁻⁷
5·10⁻⁸
2·10⁻⁸
10⁻⁸
Dose equivalence
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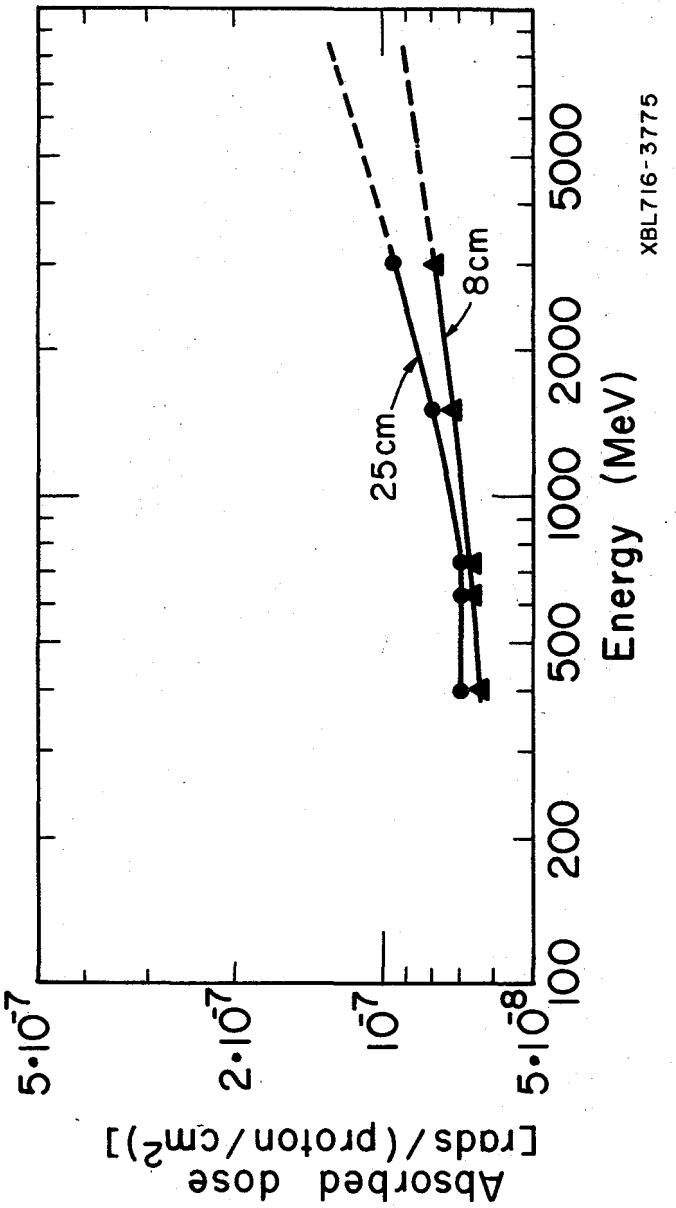
8 cm
100
200
500
1000
2000
5000
Energy (MeV)
XBL716-3774

Fig. 3c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10⁻⁷
5·10⁻⁸
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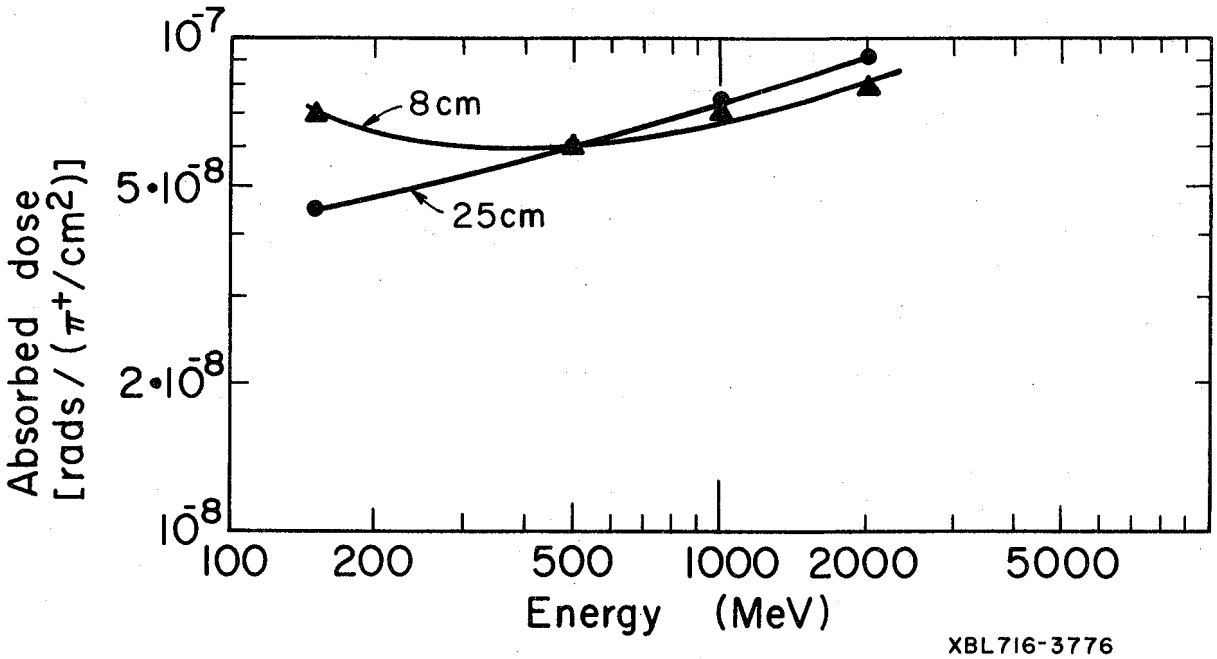
Energy (MeV)
XBL716-3775

Fig. 4a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10^{-8}
Absorbed dose
[rads / (π^+/cm^2)]
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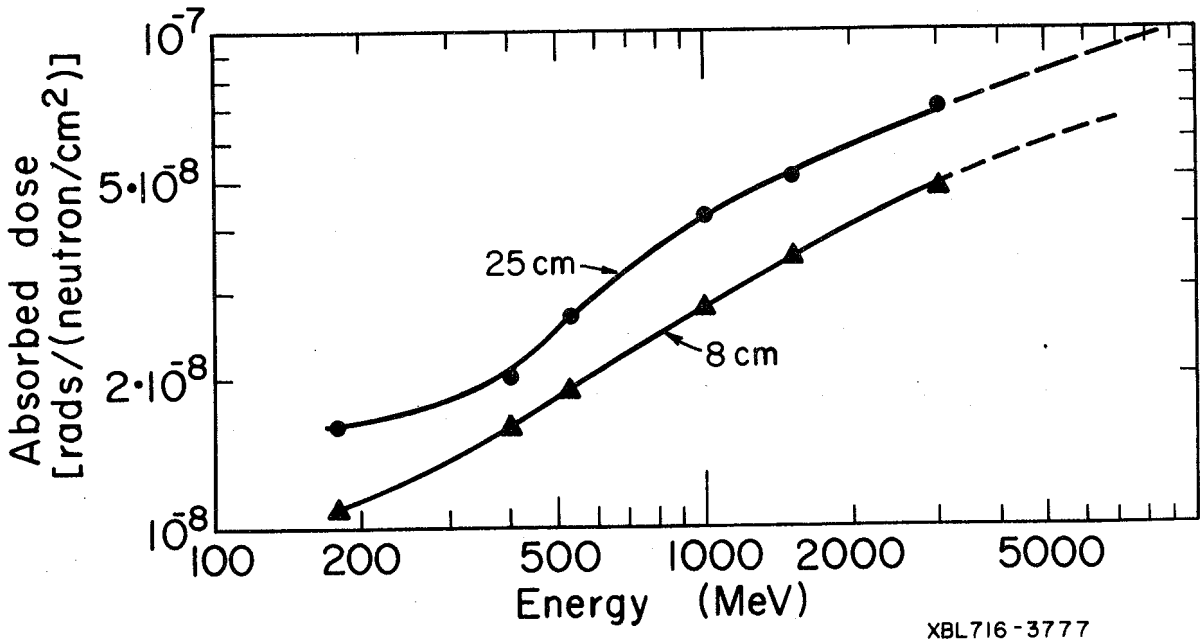
100
200
500
1000
2000
5000
Energy (MeV)
XBL716-3776

Fig. 4b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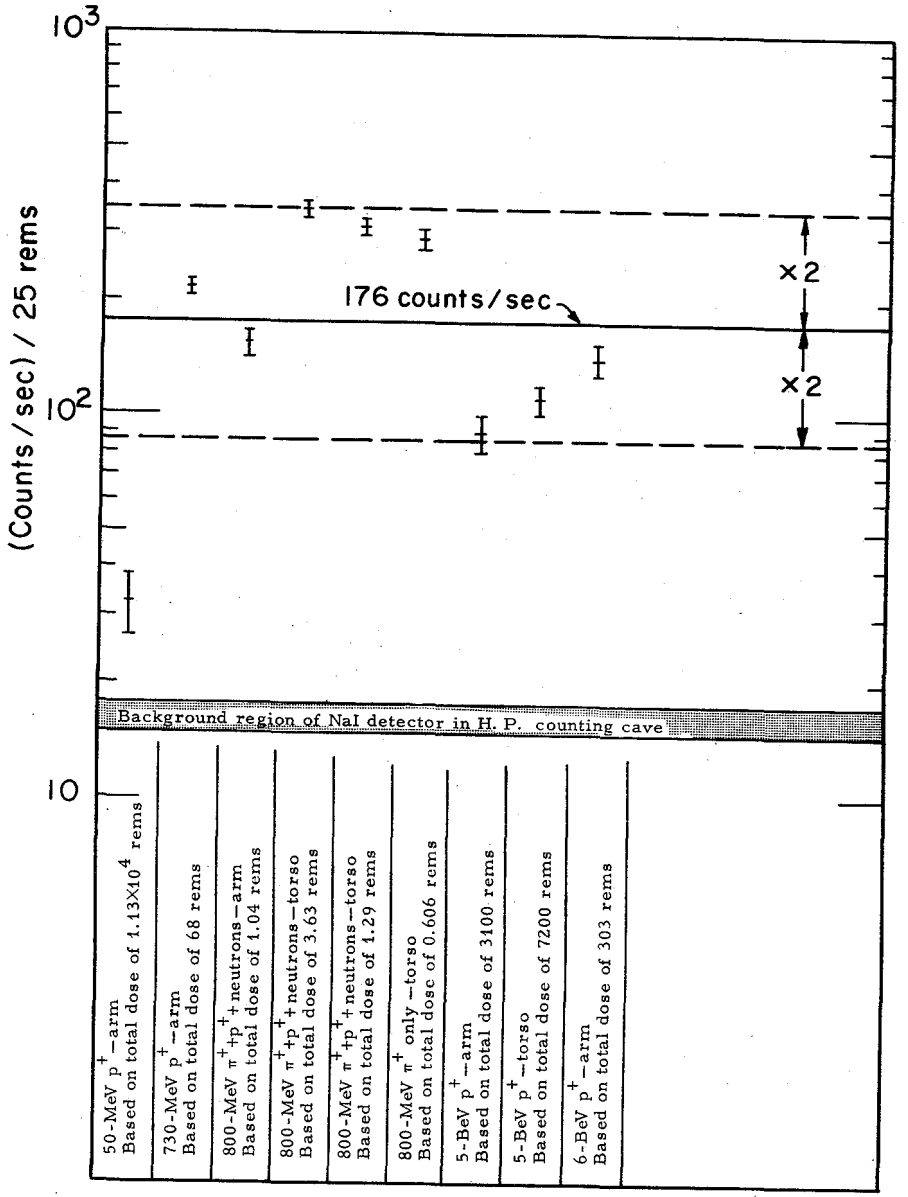
10^{-8}
Absorbed dose
[rads/(neutron/cm^2)]
25 cm
8 cm
100
200
500
1000
2000
5000
Energy (MeV)
XBL716-3777

Fig. 4c



XBL716-3769

Fig. 5

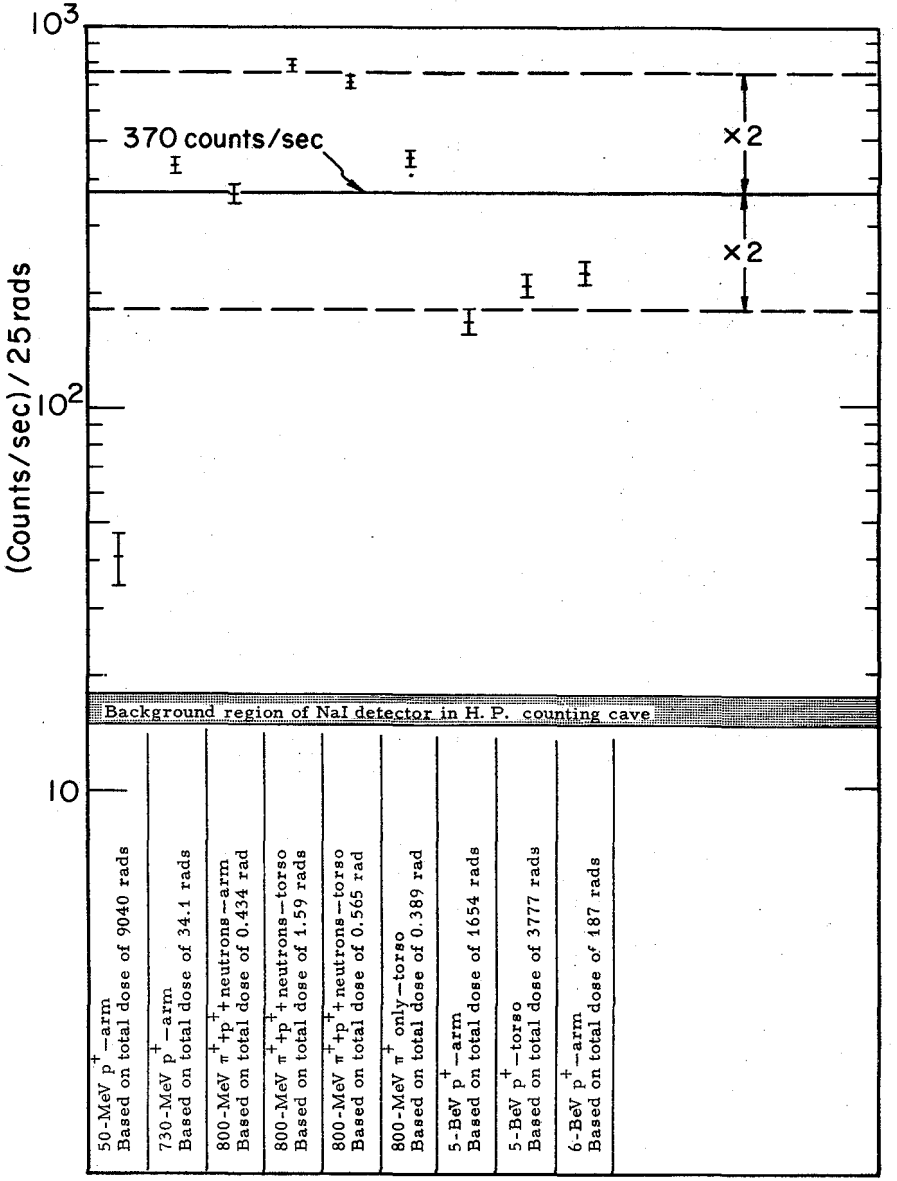


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Fig. 6