SLAC-PUB-447
July 1968
(ACC)

EMERGENCY DETERMINATION OF DOSE EQUIVALENT IN HIGH ENERGY ACCELERATOR ACCIDENTS*

Theodore M. Jenkins and Richard C. McCall
Stanford Linear Accelerator Center
Stanford University, Stanford, California

In working with high energy accelerators, the possibility exists of personnel being inside the shielding when the beam is on. Elaborate precautions are taken to guard against this eventuality, e.g., locks, interlocks, audible and visual alarms, search procedures, etc. In spite of this, nearly every large accelerator has had cases when all these devices failed and serious radiation doses were avoided only by good fortune. It appears that a proper radiation protection program should include plans to handle such an incident. These plans should include methods for making a rough estimate of the dose as soon as possible after the accident and a more accurate study at a later date.

The assessment of dose in an accelerator accident is usually difficult. The irradiation is usually very non-uniform and may come from a variety of particles, i.e., photons, neutrons, etc. The more accurate determination of the individual dose will usually have to be made by reproducing the accident conditions as accurately as possible and making exhaustive measurements of the spatial and energy distribution of the radiation. This is too time consuming to satisfy the immediate demands for rough dose estimate to assess the severity of the accidents, guide medical treatment, and allay the fears of the victims. In this article we will discuss the rough dose estimates.

---

*Work supported by U. A. Atomic Energy Commission.
Submitted to Physics in Medicine and Biology

At SLAC all personnel working in and around the accelerator are required to wear the usual film badge and also a thermoluminescent LiF dosimeter mounted on a wallet card. Both of these share some of the usual problems of dosimeters in that they measure the dose to the dosimeter rather than to the body and are easily separable from the person supposed to be wearing them. The film badge also has limited dynamic range and requires several hours at best to obtain results. To overcome these difficulties, a biological dosimeter was indicated.

Several workers[1] had previously used activation of the human body in criticality accidents. Several recent papers discuss the activation of the body in high energy accelerator exposure[2-4]. These papers were concerned with proton accelerators, however; and it was decided to explore the possibilities with electron accelerators.

Some preliminary measurements were made using one-quart phantoms. These phantoms were made up by placing in a one-quart polyethylene bottle

364.	g	Brown Sugar
100	g	Urea
5.7	g	KCl
5.5	g	$Na_2S_2O_3$
0.24	g	$FeSO_4$

and enough water to fill the bottle. A piece of bone was also added. This recipe for "Instant People" approximates the chemical composition of the human body. These phantoms were used to determine the major radioisotopes produced and to study the effect of varying the primary energy of the electron beam.

In the final experiment, an Alderson phantom* was used. This is a man-sized phantom containing a human skeleton and with the tissue represented by the "Instant People" solution above. The phantom was studied in the Hanford shadow counter[5]

*Alderson Research Labs, Inc., Long Island City, New York.

(Fig. 1). The authors are indebted to H. E. Palmer for the loan of the Alderson phantom and the shadow counter and his assistance in making the measurements.

Activation is to be expected from both photons and high energy nuclear particles, mostly neutrons. In all the discussion that follows, we assume the irradiation is such that the radiation producing activation and the radiation producing the dose to the subject are in some kind of equilibrium. In some cases, e.g., a subject standing at 90° to an object being hit by a collimated photon beam, the absorbed dose might be very high and activation minimal, since there would be few photons with sufficiently high energy.

Previous measurements with a 1.5 GeV electron beam striking a target had indicated a photon to neutron dose equivalent ratio of between 5 and 100, except in the extreme forward direction where it may exceed 1000.[6] This implies a photon to neutron flux ratio of similar magnitude. It would be expected then that photon induced reactions would dominate. Since the body is mostly oxygen and carbon (65% and 18% by weight respectively), it was expected that reactions of these elements would be most likely. Some reactions with carbon and oxygen are listed in Table 1.[7] All daughter products are positron emitters with no gamma-rays with the exception of ^{7}Be which emits a 0.477 MeV gamma-ray following electron capture. Identification of the isotopes therefore must be made on the basis of half-life measurements using the 0.511 MeV annihilation gamma-rays. Since there will be some neutron thermalization in the body, it was also expected to see some 15-hour ^{24}Na activity.

For convenience the irradiations were performed at the Stanford Mark III electron accelerator. The radiation source chosen was a collimator about 15 feet upstream of the irradiation point (Fig. 2). The phantoms were irradiated at approximately 10° off the beam axis. The "Instant People" phantoms were irradiated at

beam height and the Alderson phantom stood with the beam at about hip height. The "Instant People" phantoms were irradiated at primary electron energies ranging from 300 MeV to 1 GeV. No significant differences were seen in the activation products at these energies. Typical gamma-ray spectra at varying times after irradiation are shown in Figs. 3 and 4. A decay curve is shown in Fig. 5. It can be seen that for a least several hours after the irradiation, the decay curve shows a 20.4 minute half-life indicative of virtually all ^{11}C. Some survey instrument measurements immediately after the exposure showed an approximately 2-minute half-life indicating ^{15}O. No evidence of ^{13}N could be found. This would indicate that the cross section for ^{16}O $(\gamma, p\ 2n)$ ^{13}N reaction shown in Table 1 is wrong. Bishop, et al.[8] investigated the photon activation of oxygen up to 150 MeV and state that the production of ^{13}N is small relative to ^{11}C. The correction of indicated activity for decay becomes quite simple then, since only a single half-life is observed after the first few minutes. It does become quite important to know the time of exposure, however, since the 20.4-minute half-life is rather short.

Based on the experiment above, an exposure was made on the Alderson phantom. For the man-sized phantom the irradiation is very non-uniform as would probably be the case for a real exposure of a person. The phantom covered the range from about 8 to 11 degrees with the beam axis in the horizontal plane and considerably greater than that in the vertical plane. In addition the hole in the 12" concrete wall was not quite large enough and provided some shielding of the extremities. The exposure was made at 995 MeV primary electron energy. An ion chamber placed near the left hip acted as a monitor and the exposure was continued until the chamber indicated an exposure of about 1000 R. The beam was on for 2 minutes at 60 pps and 8×10^{10} electron/pulse. It was estimated that about half of the beam was lost in the collimator. Dose distributions were made on and in the phantom

with 29 ^{7}LiF (Harshaw TLD 700) thermoluminescent dosimeters (TLD) for photons and the dosimeters read on a ConRad reader. Rough neutron spectra were measured using activation of bare and moderated In foils, Al discs and carbon scintillators. These detectors determine the neutron flux in the ranges, thermal, 20 keV-6 MeV, greater than 3 MeV and greater than 20 MeV, respectively. These detectors and their use have been described in detail in other reports.[9-11] Neutron spectra using these 4 detectors, were taken at three points, shown in Fig. 2 as A, B, and C. Al discs were taped at other positions on the phantom. Assuming the spectra at the three points measured (A, B, and C) do not change too much, then the Al discs may be used to assign neutron dose to the phantom without the need for the other three neutron detectors. It is expected that some of these activation detectors will be disturbed by competing photon induced reactions resulting in the same daughter activity. This should be more true for the ^{11}C detectors than for the Al discs, based on other measurements by the authors. All of the doses calculated by these detectors should be considered as upper limits for the neutron component.

The results of the TLD measurements are shown in Fig. 6. It can be seen that the dose varied by a factor of 7.6 over the body. The results of the neutron spectral measurements made at points A, B, and C, are shown in Table 2. The spectra are not too constant since the two high energy components are depressed considerably at the position behind the hip and above the head. The doses, however, amount to only a few percent of the photon doses so this is probably not too important. The Al discs are still of some value and the results are shown in Fig. 7. Again, the doses (and fluxes) are much less than those of the photons.

As was the case with the "Instant People" phantoms, an approximate 2-minute half-life was observed immediately after irradiation and a 20.4-minute half-life for several hours thereafter. Decay data shown by the 0.511 MeV gamma-ray measurements are shown in Fig. 8. Gamma-ray spectra at various times after

irradiation are shown in Fig. 9. The 1.37 MeV and 2.76 MeV gamma-rays of ^{24}Na show clearly in the later spectra. The phantom was measured at intervals in the shadow counter and also with a 3" × 3" NaI scintillator placed in the lap of the phantom with the phantom in a sitting position. This is a geometry which is reasonably independent of the location of the activity within the body and one that could be used at any laboratory as an emergency technique.

The interpretation of the dose to the phantom is difficult because of the non-uniform radiation field. From the cross sections given in Table 1 and the abundance of carbon and oxygen in the Standard Man[12], one can estimate that roughly 1/4 of the ^{11}C activity came from the oxygen in the body and 3/4 from the carbon. Both of these elements are distributed fairly uniformly through the body. It should be noted that in a human, the activity would be distributed somewhat more uniformly than in our phantom because of blood circulation. It would appear that the only reasonable method of attack would be to evaluate the dose on a gram-rad basis, i.e., the integral absorbed dose. In order to estimate this, we separated the body into eleven segments (head, upper and lower trunk, upper and lower arms and upper and lower legs). The average exposure dose to each portion was estimated from Fig. 6 and multiplied by the weight of that segment. All of these values were added to obtain the integral absorbed dose. The result of this exercise was 1.4×10^7 gram-rads. The neutron dose was neglected in the calculation. The result of the measurements in the shadow counter indicated an activity of 860 μCi of ^{11}C at the end of the irradiation.

Corrected to the time of the irradiation a 3" × 3" NaI crystal placed in the lap gave 7.8×10^5 counts per minute in the 0.511 MeV peak. Background was 300 counts/minute. For detection of an exposure, one can construct the plots shown in Fig. 10. For convenience the curves are labeled in terms of a total body dose in a standard man, e.g., 1.4×10^7 gram-rad ÷ 70,000 grams = 200 rads whole body dose. It can

be seen that even small doses can be detected for some time after the exposure. For example, a 1 rad dose will double background for more than an hour after the exposure. Use of a whole body counter would, of course, allow detection of even smaller doses or alternatively, after longer decay times, since it is easy to detect quantitites as small as 0.01 μCi. One can use then a figure of 1.4×10^7 gram-rad ÷ 860 μCi = 1.6×10^4 gram-rad per μCi of ^{11}C produced. This is, of course, strictly valid only for a two-minute exposure at a uniform rate. In any real incident it would be necessary to consider the circumstances in the light of the usual radioactive buildup and decay laws. The greatest error possible is the spread between the cases where all the radiation comes in a burst at the beginning and end of the exposure period. In our two-minute exposure, this spread is only 5%; in a ten-minute exposure it would be 29%. The assumption of uniform exposure rate will give an intermediate value within these limits. The error will probably be small since prolonged exposures are unlikely in an accelerator due to the sophisticated warning devices used.

It appears that this is a practical method of estimating the integral absorbed dose. It is very difficult to determine the accuracy of the method. If a whole body counter is used to determine the ^{11}C content of the subject, the dominant error is probably our determination of the phantom's integral absorbed dose. This is true in spite of the fact that we used a total of 48 detectors to measure the dose to the phantom, and illustrates the difficulty to be expected in a real accident where the subject would have, at most, two dosimeters and be moving around. It would appear, however, that the results should be valid within about ±25%. If the 3" × 3" NaI crystal in the lap position were used, the error could be much larger due to localized distribution of the ^{11}C activity. Wilson[13] has used a similar geometry for quick analysis in criticality accidents. From his results it would appear that a dose localized to a point would at worst cause an error of a factor of two; this would

exclude the case where all the activity is in the feet. In general, the accuracy should be much better than that since a part of the activity will always circulate through the body. A survey of the body with the crystal should show whether the activity is concentrated at a point or not. Usually people attempt to determine the absorbed dose rather than the integral absorbed dose. However, absorbed dose is not a very useful concept in cases where the dose is extremely non-uniform. In our particular case, we were 15 feet from the source and the dose varied over at least the range 63 to 480 rads--about a factor of eight. In such a case it would probably not be too unreasonable to divide his gram-rad dose by his weight and assign an absorbed dose value, i.e., 1.4×10^7 gram-rad $\div$ 70,000 gram = 200 rads as above. In cases where the non-uniformity is much greater as can easily happen in an accelerator accident, such a procedure would be meaningless.

It should be noted that the additional dose to the body from the decay of the ^{11}C and from ejected neutrons and protons in the formation of the ^{11}C can be calculated and are found to be negligible compared to that due to the directly produced ionizing particles as measured here.

After waiting for a sufficient time, it was possible to determine the ^{24}Na content of the body as 180 μCi corrected to time of exposure. Parker and Newton[1] report values indicating that a dose of 0.5 rads of fission spectrum neutrons would produce this quantity of ^{24}Na. We would expect a similar number in our case, since the major part of the neutron dose was produced by giant resonance neutrons with energies similar to a fission spectrum. From our spectral measurements, we find that the total neutron dose was of the order of 6-7 times the dose indicated by the Al discs. The neutron dose then to the phantom was of the order of 3-4 rems. Use of a Quality Factor in the range 6 to 8 would be quite reasonable and would give results in reasonable agreement with the number above. It would appear that

measurement of ^{24}Na can also be a useful tool, but it would usually require a whole body counter.

It is obviously important to know as accurately as possible both the time of the irradiation and its duration. Operators of accelerators should have emergency instructions to follow in the event they discover someone has been in the accelerator housing during a beam run. These instructions should include immediate entry in the log book of as many details of the incident as possible, both to provide the above information and to facilitate the investigation and reconstruction of the accident which may be necessary.

REFERENCES

1. Parker, H. M. and C. E. Newton, "Accidental Radiation Excursion at Y-12 Plant," Final Report Y-1234 (1958), in Personnel Dosimetry for Radiation Accidents, 567, International Atomic Energy Agency, Vienna (1965).
2. Legeay, G., L. Court, L. Prat, L. Jeanmaire, M. L. Daburon, H. DeKerviler, and P. Tardy-Joubert, "Dosimetrie des Protons de Haut Energie par Mesure de Beryllium-7 Forme dans les Tissus," in Personnel Dosimetry for Radiation Accidents, p. 507, International Atomic Energy Agency, Vienna (1965).
3. Kamochkov, M. M., "Estimation of the Dose From Accidental Irradiation by a Large Amount of High Energy Particles," CERN TRANS-66-5, Original JINR Report P-2008 (1965).
4. Barbier, M., A. Hutton, and A. Pasinetti, "Radioactivity Induced in Tissue by 600 MeV Protons," CERN 66-34 (1966).
5. Palmer, H. E. and W. C. Roesch, "A Shadow Shield Whole-Body Counter," Health Physics, vol. 11, 1213-1219 (1965).
6. Jenkins, T. M., Richard C. McCall and Gary J. Warren, Radiation Protection Problems at the Stanford Two-Mile Linear Accelerator, Proceedings of the USAEC First Symposium on Accelerator Radiation Dosimetry and Experience, CONF 651109 (1965).
7. DeStaebler, H., "Photon Induced Residual Activity," TN-63-92 (1963).
8. Bishop, G. R., B. Brossetete, and J. C. Risset, "Etude de L'Electrodesintegration de L'Oxygen 16, Journal de Physique et le Radium 23, 31 (1962).
9. McCaslin, J. B., "A High-Energy Neutron-Flux Detector," Health Physics, vol. 2, 399-407 (1960).
10. Ringle, John Clayton, A Technique for Measuring Neutron Spectra in the Range 2.5 to 30 MeV Using Threshold Detectors (thesis), UCRL 10732 (1963).

11. Stephens, Lloyd D. and Alan R. Smith, Fast Neutron Surveys Using Indium-Foil Activation, UCRL-8418 (1958).

12. Radiological Health Handbook, PB121784R, U. S. Dept. of Health, Education and Welfare, (1960).

13. Wilson, R. H., "A Method for Immediate Detection of High Level Neutron Exposure by Measurement of ^{24}Na in Humans," HW-73891, Rev. (1962).

TABLE 1

Nuclide	Reaction	Daughter	Half-life	Cross Section $\int \sigma dk$ (MeV-mb)
^{16}O	(γ, n)	^{15}O	2.1 min.	150
^{16}O	$(\gamma, p\ 2n)$	^{13}N	10 min.	1.5
^{16}O	$(\gamma, 2p\ 3n)$	^{11}C	20.5 min.	~ 13.
^{16}O	$(\gamma, 4p\ 5n)$	^{7}Be	53 days	~ 0.6
^{12}C	(γ, n)	^{11}C	20.5 min.	~ 45.
^{12}C	$(\gamma, 2p\ 3n)$	^{7}Be	53 days	~ 2.2

TABLE 2

NEUTRON FLUXES AND DOSES NEAR THE MAN-PHANTOM

Positron	Fluxes (n/cm^2 - sec)				Dose (mrem)			
	Thermal	20 keV-20 MeV	>3 MeV	>20 MeV	Thermal	20 keV-20 MeV	>3 MeV	>20 MeV
Beside Left Knee	5.5×10^5	4.0×10^5	4.2×10^5	5.7×10^3	70	1.7×10^3	1.7×10^3	48
Behind, Waist Level	6.7×10^5	5.8×10^5	9.5×10^4	1.8×10^3	83	2.4×10^3	400	15
Head Height, Behind, Near Wall	7.6×10^5	6.9×10^5	7.6×10^4	2.4×10^3	95	2.8×10^3	320	20

Thermal fluxes measured with bare In foils.

20 keV - 20 MeV fluxes measured with moderated In foils.

> 3 MeV fluxes measured with Al discs.

>20 MeV fluxes measured with carbon scintillators.

FIGURE CAPTIONS

1. Shadow Shield Whole Body Counter. Detector is an 8" diameter NaI (TI) crystal.
2. Bunker Area of MK III Accelerator Where Phantom was Irradiated. Narrow room and close proximity to concrete walls are similar to most SLAC accelerator areas.
3. Spectrum from Small Sample (Instant People) irradiated for 2 minutes at 800 MeV with about 1×10^{12} e^-/sec striking collimator. Curve A taken about 20 minutes after irradiation when 2-minute ^{15}O has decayed away. Curve B 22 minutes after Curve A. Curve C 42 minutes after Curve A. The integral counts under the 0.511 MeV peak show an unequivocal 20.4-minute slope corresponding to ^{11}C.
4. Spectrum from Instant People Sample (Fig. 3) taken 15 1/2 hours after irradiation, showing only 1.37 MeV peak of ^{24}Na.
5. Decay of 0.511 MeV Annihilation Peak in Small Samples showing slope of 20.4-minute ^{11}C.
6. Photon Dose Distribution in the Phantom as Measured with Small TLD Capsules. All measurements are in RADS.
7. Neutron Fluxes, and Dose Equivalent in Rems, as Measured on the Phantom with 4" diameter by 1" thick aluminum discs.
8. Decay of 0.511 MeV Activity in Phantom as Measured by 3"× 3" NaI (TI) Crystal in Lap Position.
9. Shadow Shield Counts of Phantom at Different Times After Irradiation showing both ^{11}C annihilation peak and ^{24}Na peaks. Curve A--127 minutes after irradiation. Curve B--12.5 hours after irradiation. Curve C--26 hours after irradiation.
10. Count Rate from a 3"× 3" NaI (TI) Crystal in the Lap Position at various times after irradiation for different exposures. Exposures are for a whole body dose.

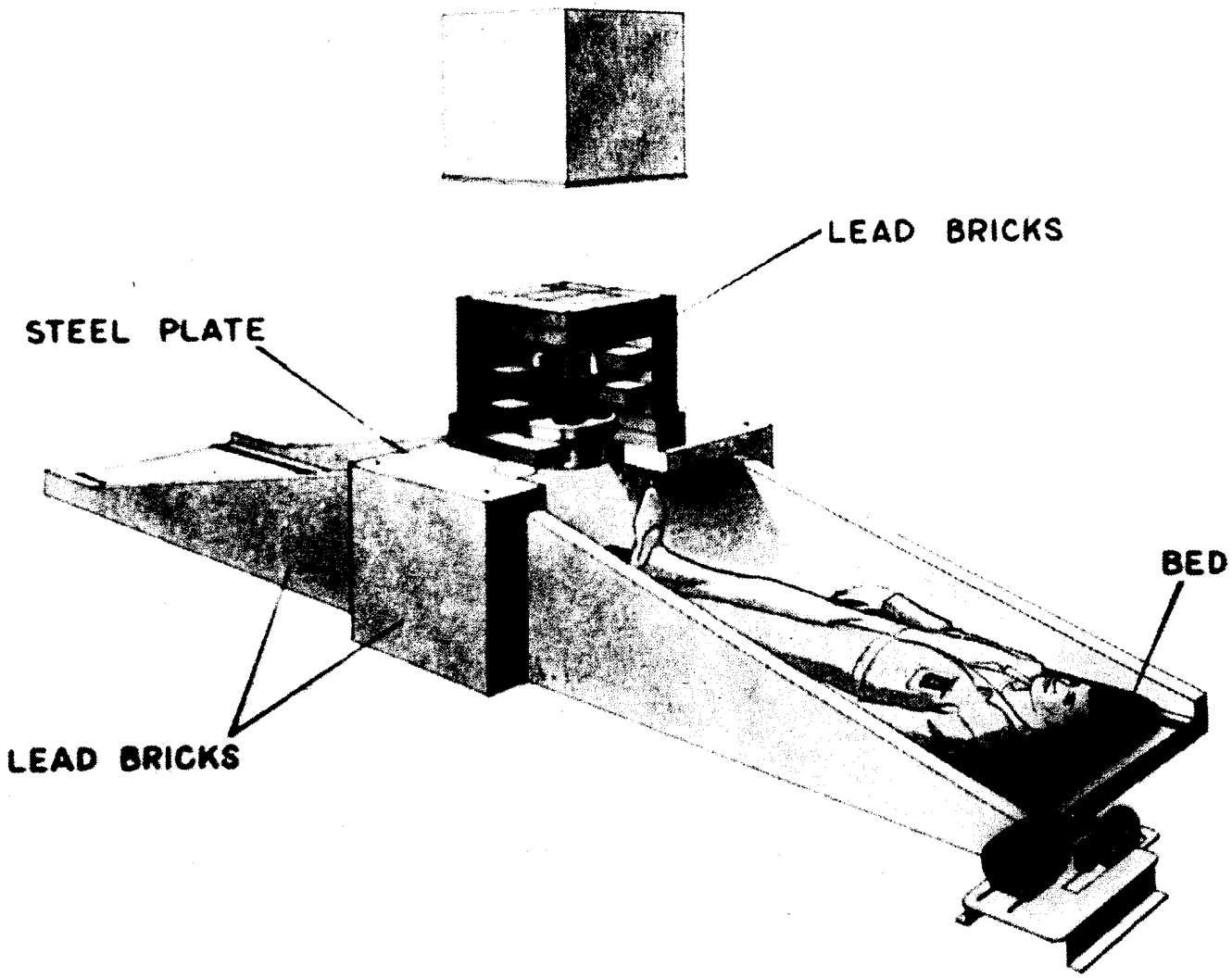

Fig. 1

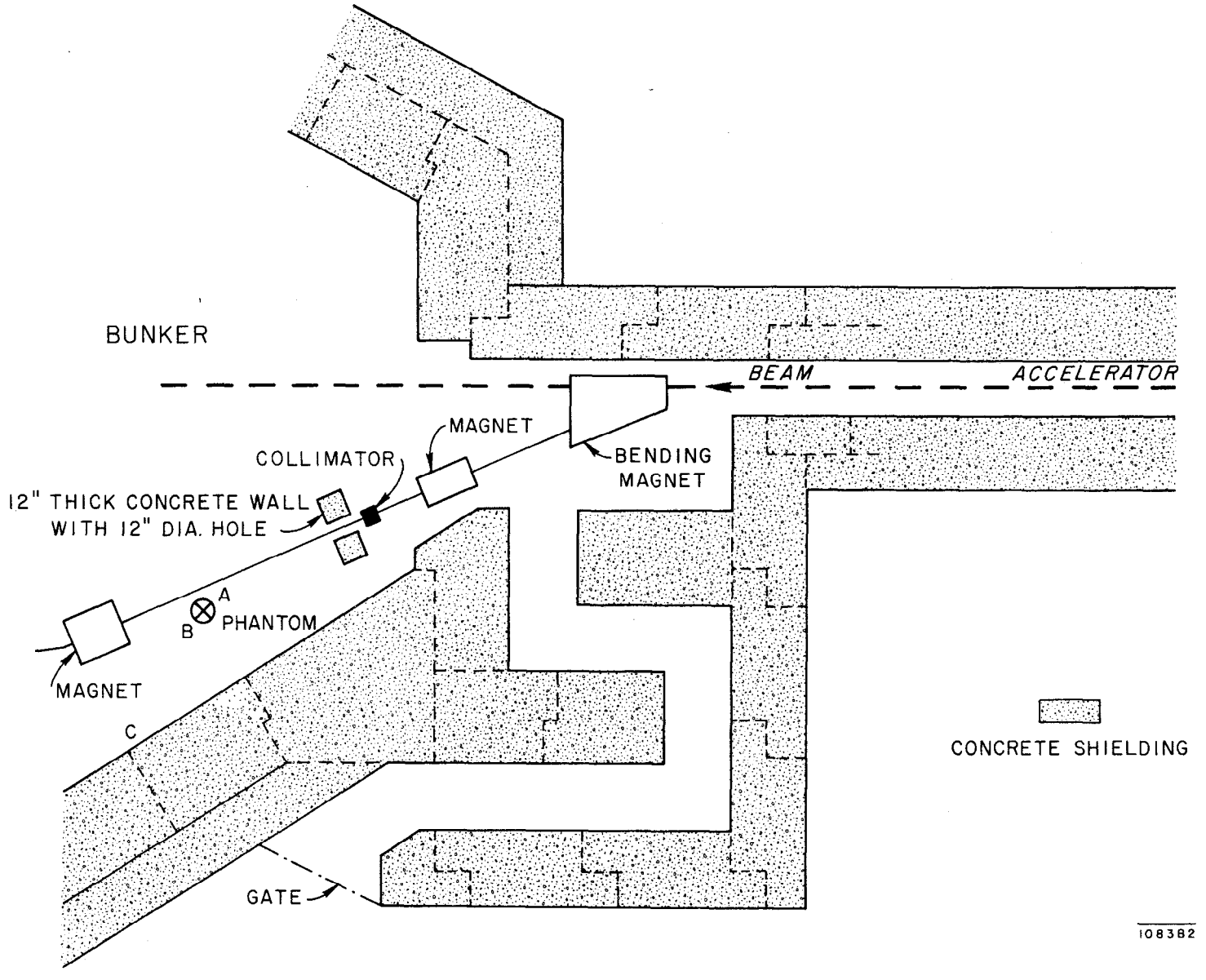
BUNKER
BEAM
ACCELERATOR
MAGNET
COLLIMATOR
BENDING MAGNET
12" THICK CONCRETE WALL WITH 12" DIA. HOLE
A
B
PHANTOM
MAGNET
C
GATE
CONCRETE SHIELDING
108382

Fig. 2

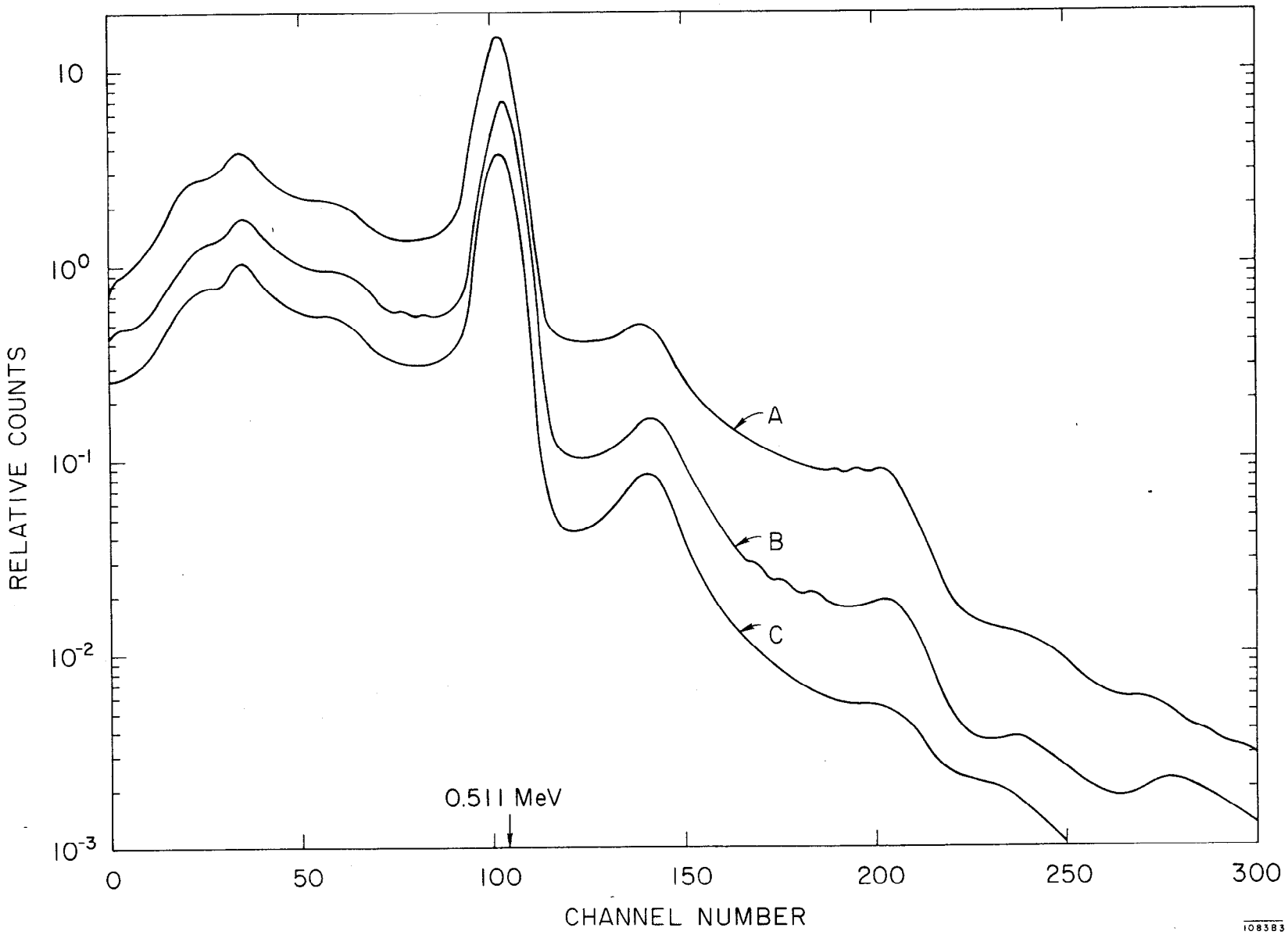
RELATIVE COUNTS
10
10^0
10^{-1}
10^{-2}
10^{-3}
0
50
100
150
200
250
300
CHANNEL NUMBER
0.511 MeV
A
B
C
108383

Fig. 3

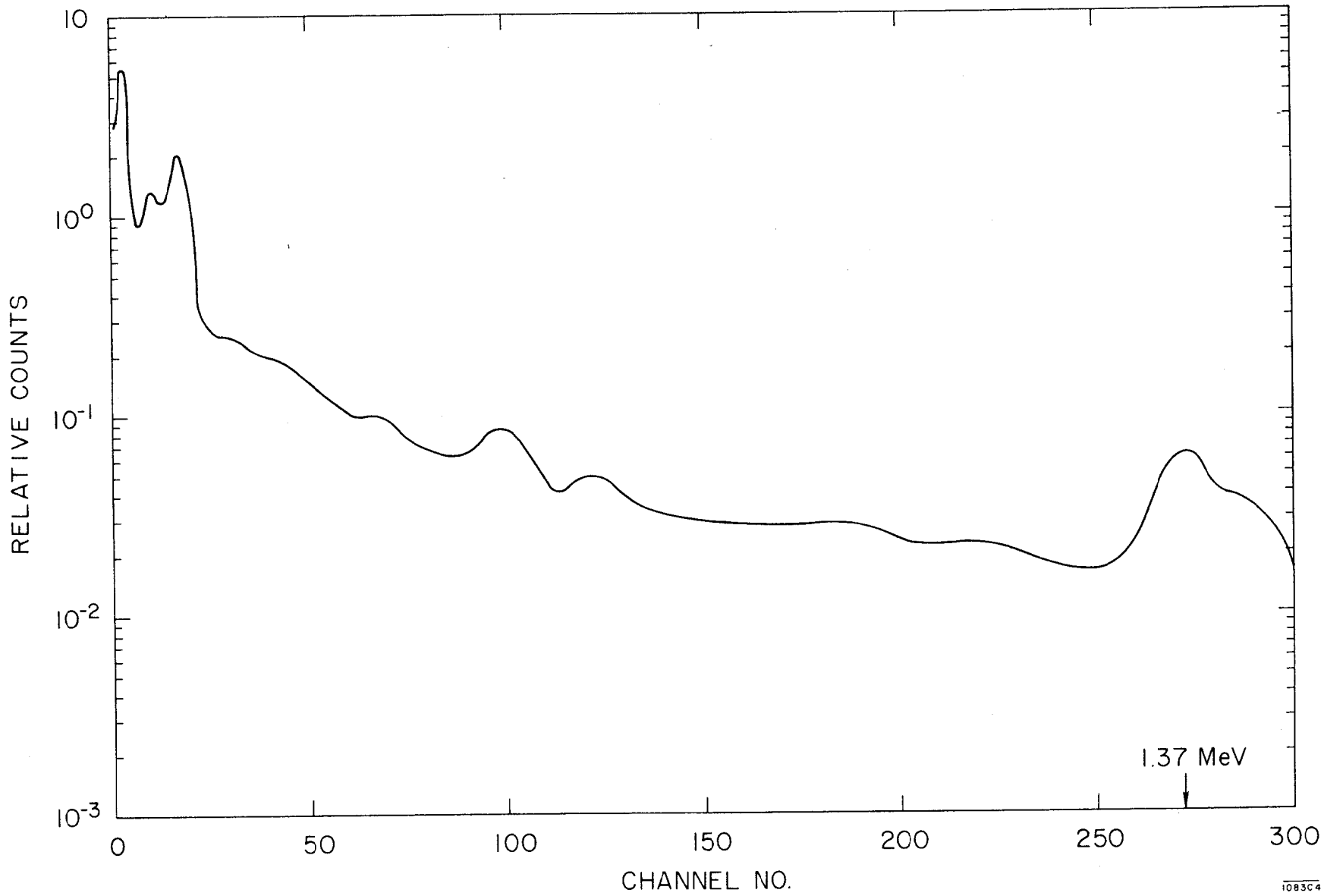
10
10^0
10^{-1}
10^{-2}
10^{-3}
RELATIVE COUNTS
0
50
100
150
200
250
300
CHANNEL NO.
1.37 MeV
1083C4

Fig. 4

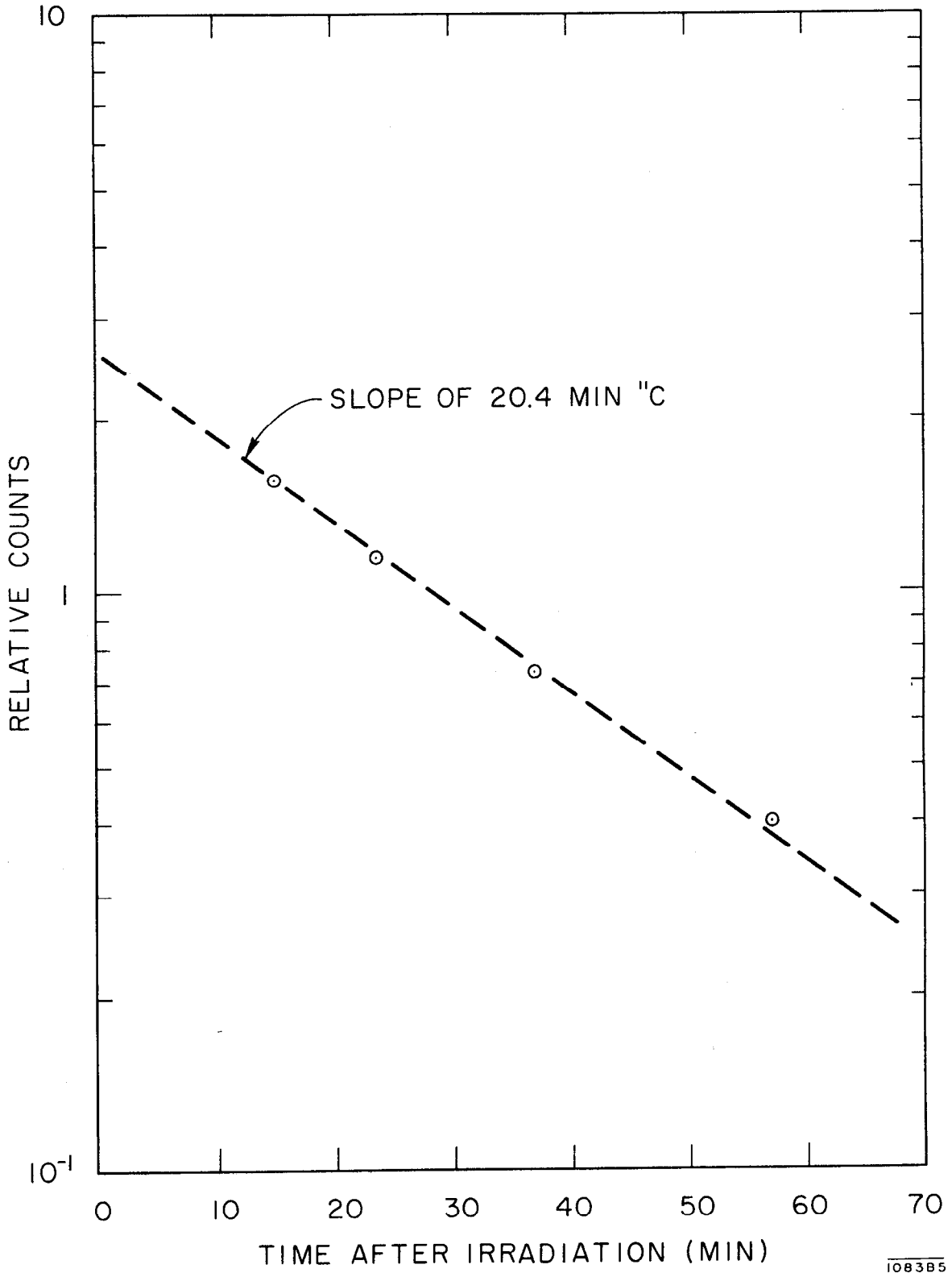
10
1
10^{-1}
RELATIVE COUNTS
SLOPE OF 20.4 MIN ^{11}C
0
10
20
30
40
50
60
70
TIME AFTER IRRADIATION (MIN)
1083B5

Fig. 5

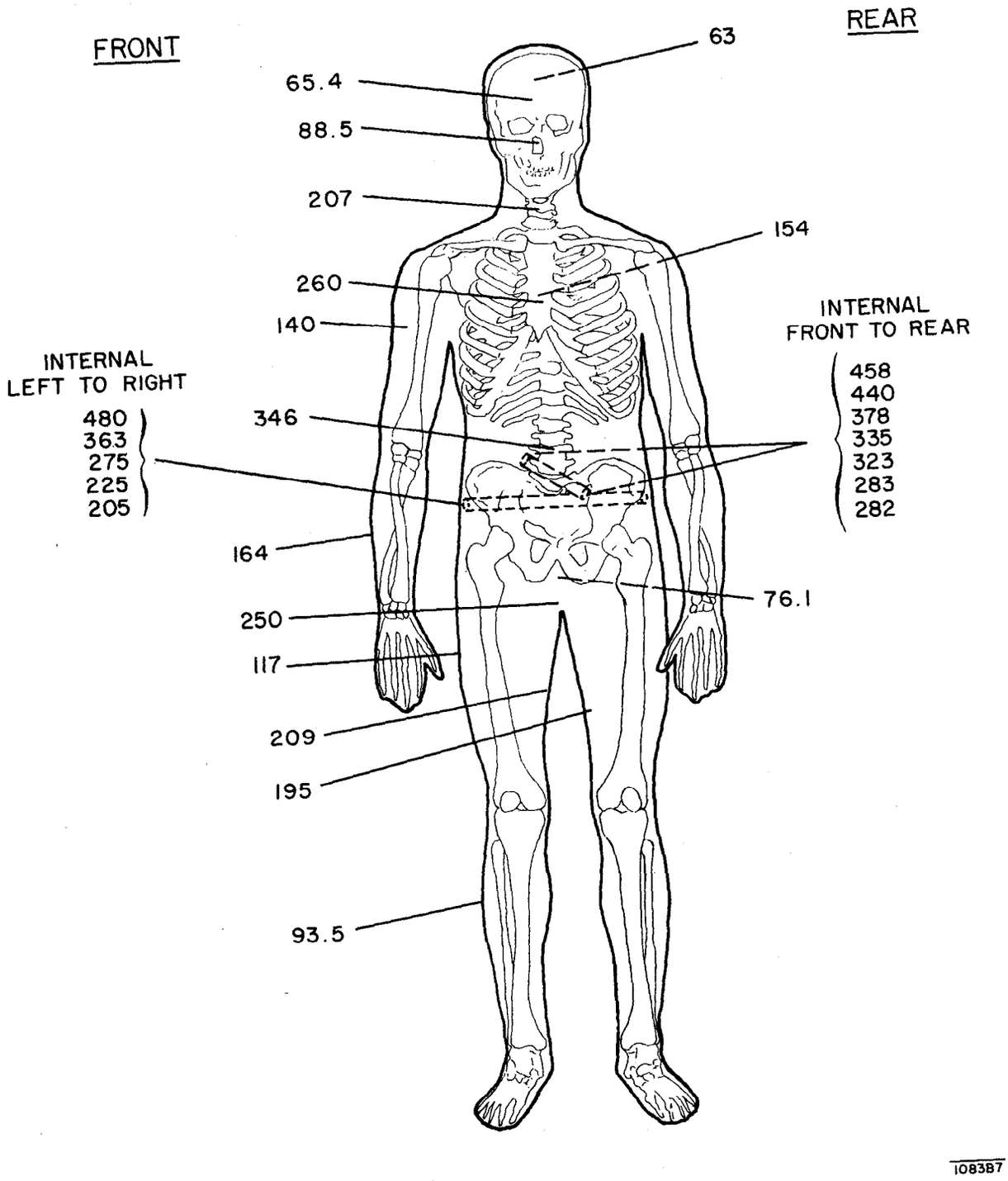
FRONT
REAR
63
65.4
88.5
207
154
260
140
INTERNAL
FRONT TO REAR
458
440
378
335
323
283
282
INTERNAL
LEFT TO RIGHT
480
363
275
225
205
346
164
76.1
250
117
209
195
93.5
1083B7

Fig. 6

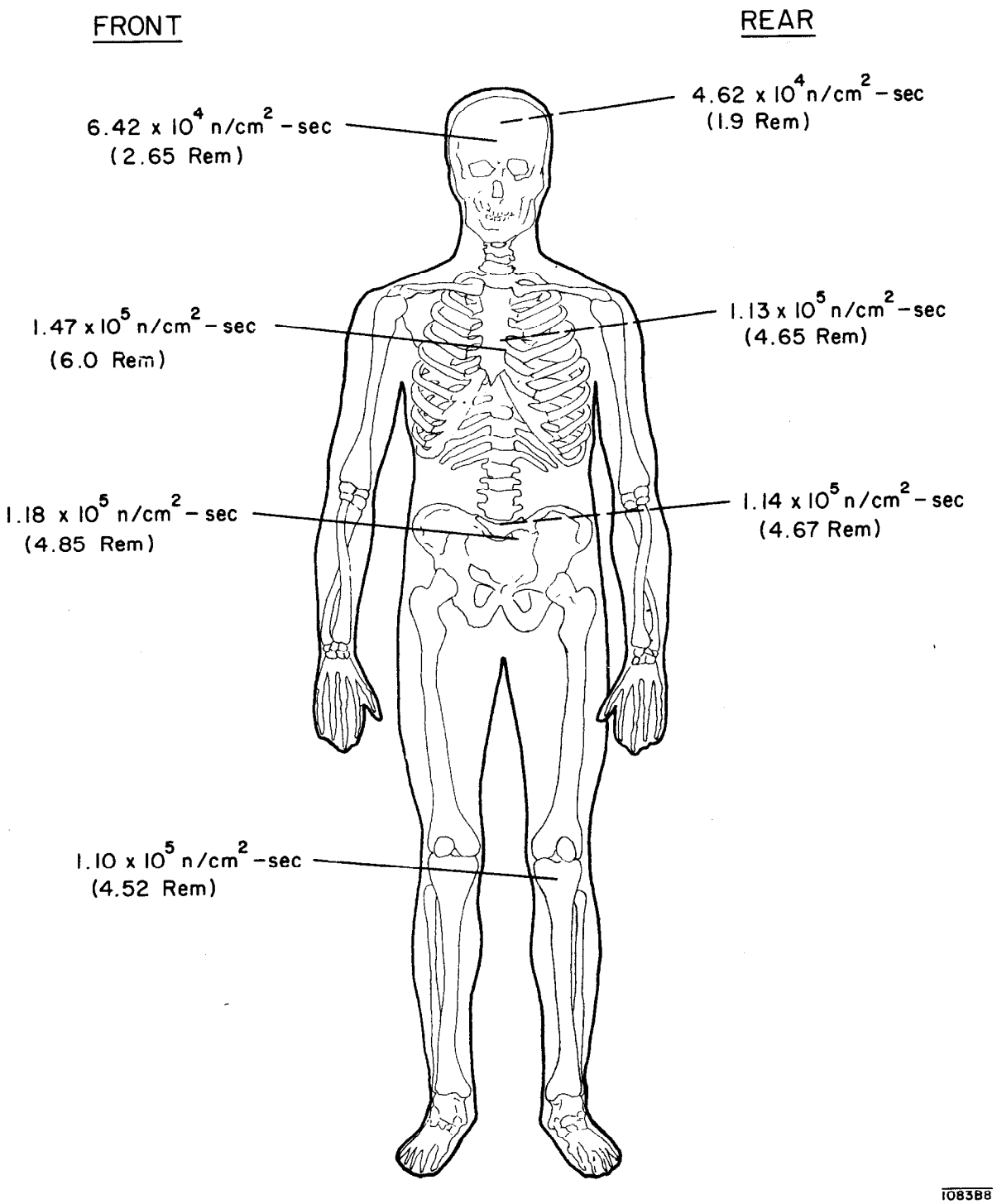
FRONT
REAR
6.42 x 10^4 n/cm^2 - sec
(2.65 Rem)
4.62 x 10^4 n/cm^2 - sec
(1.9 Rem)
1.47 x 10^5 n/cm^2 - sec
(6.0 Rem)
1.13 x 10^5 n/cm^2 - sec
(4.65 Rem)
1.18 x 10^5 n/cm^2 - sec
(4.85 Rem)
1.14 x 10^5 n/cm^2 - sec
(4.67 Rem)
1.10 x 10^5 n/cm^2 - sec
(4.52 Rem)
1083B8

Fig. 7

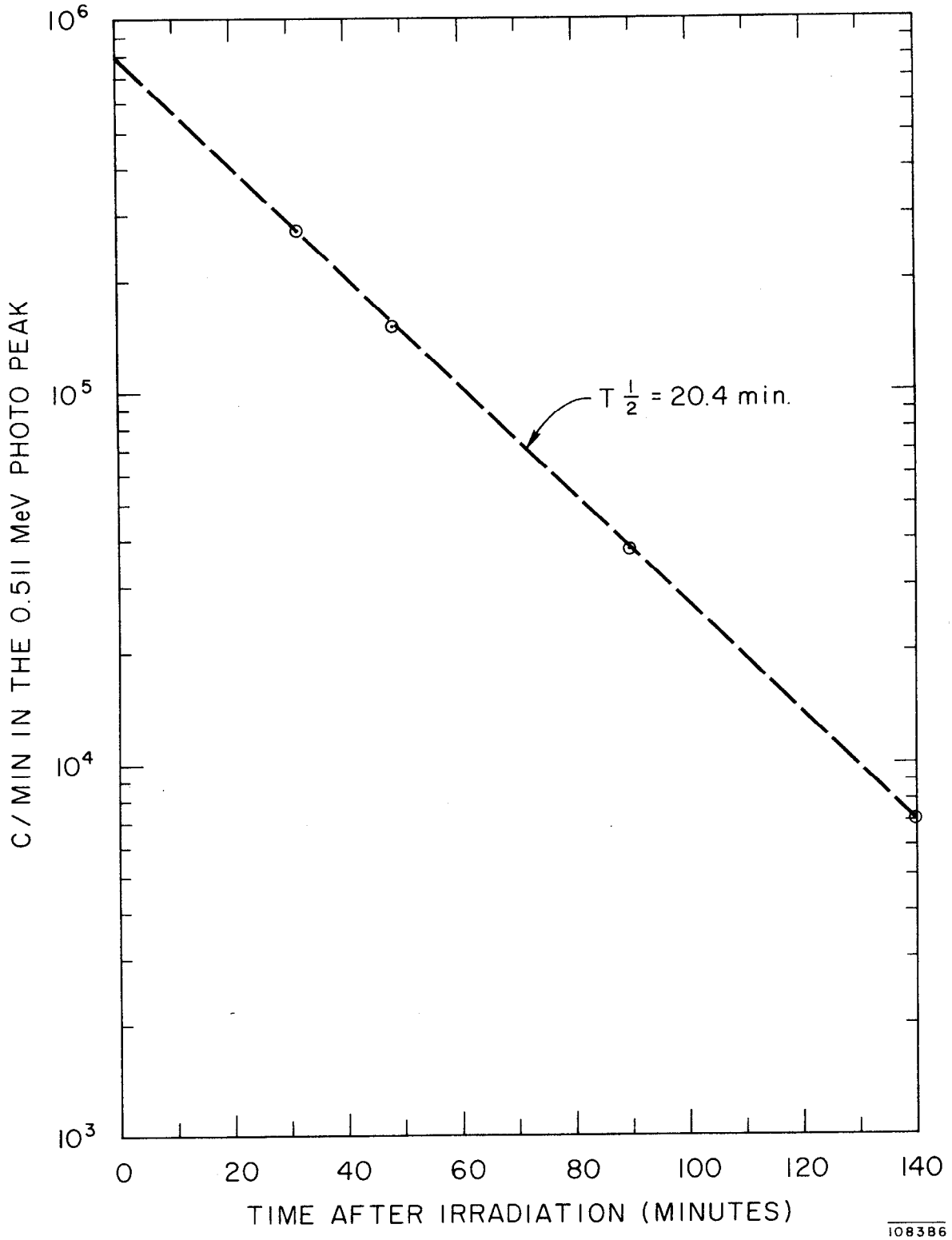
10^6
10^5
10^4
10^3
C/MIN IN THE 0.511 MeV PHOTO PEAK
$T\frac{1}{2}$ = 20.4 min.
0
20
40
60
80
100
120
140
TIME AFTER IRRADIATION (MINUTES)
1083B6

Fig. 8

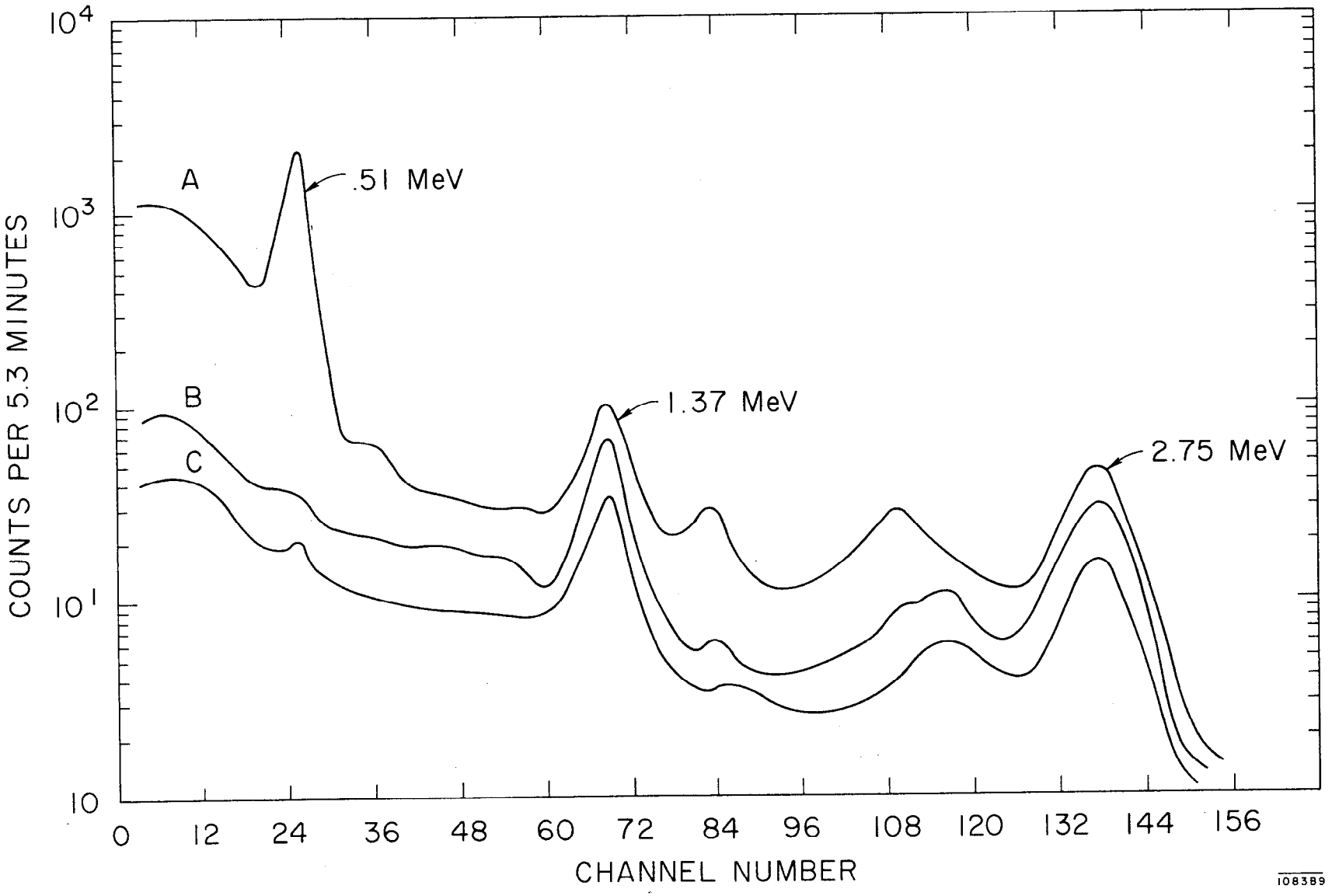
COUNTS PER 5.3 MINUTES
10^4
10^3
10^2
10^1
10
A
B
C
.51 MeV
1.37 MeV
2.75 MeV
0
12
24
36
48
60
72
84
96
108
120
132
144
156
CHANNEL NUMBER
108389

Fig. 9

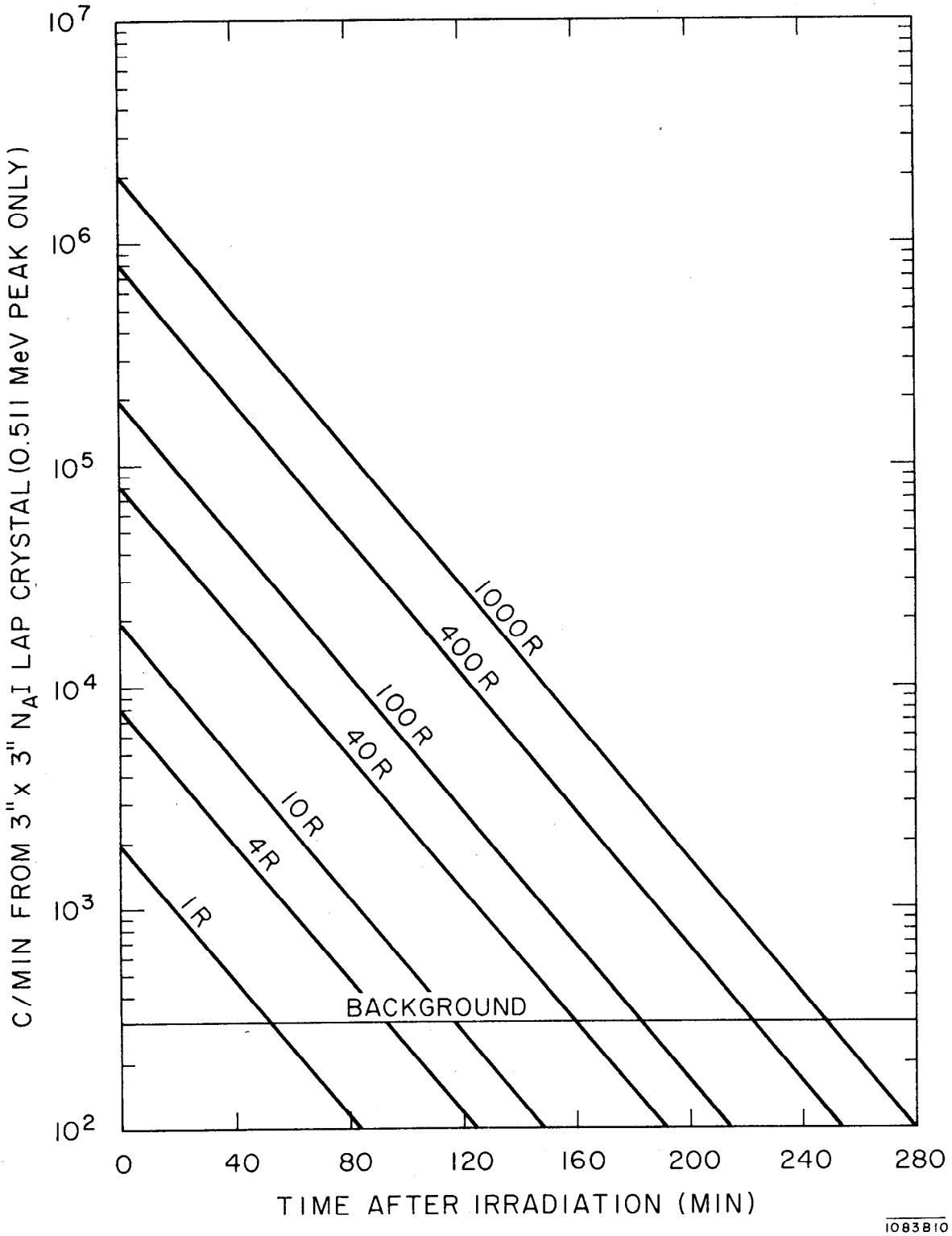
C/MIN FROM 3" x 3" NaI LAP CRYSTAL (0.511 MeV PEAK ONLY)
10^7
10^6
10^5
10^4
10^3
10^2
1000R
400R
100R
40R
10R
4R
1R
BACKGROUND
0
40
80
120
160
200
240
280
TIME AFTER IRRADIATION (MIN)
1083B10

Fig. 10