BNWL-531-2
UC-41

PACIFIC NORTHWEST LABORATORY

SECOND QUARTERLY ACTIVITY REPORT TO THE NASA, AMES RESEARCH CENTER

October 1, 1967 Through January 1, 1968

INDUCED RADIONUCLIDES IN ASTRONAUTS

by

R. W. Perkins

January 12, 1968

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECOND QUARTERLY ACTIVITY REPORT TO THE
NASA, AMES RESEARCH CENTER
OCTOBER 1, 1967 THROUGH JANUARY 1, 1968
INDUCED RADIONUCLIDES IN ASTRONAUTS

R. W. Perkins

INTRODUCTION

The first quarterly report on the above subject, BNWL-531-1 covered the need for the study, its objectives, and some of the initial calculations and experimental work. Work during the past quarter has been in two main areas. One area is that of the direct experimental measurement of induced radioactivity in tissue and tissue equivalent solutions as a function of proton bombarding energy. The initial experiments using the Harvard University Cyclotron have been very fruitful, providing dose to induced activity factors as a function of depth for a few specific geometries. Continuation of these experiments and extention to several geometries can provide the necessary data for estimates of irradiation dose to astronauts from induced radionuclides. The second area involves the measurement of induced radionuclides in high flying Air Force pilots and is providing a basis for testing the relationships derived in the accelerator bombardment experiments.

IRRADIATION OF TISSUE EQUIVALENT MATERIALS

Tissue equivalent solutions which contained H, O, C, N, Na, K, Cl, Rb, and Cu near the concentrations present in a standard man were prepared by using the chelating agent, ethylenediaminetetraacetic acid, to hold the elements in solution. The weights of the compounds used in preparing the solution, along with their reported trace elements, are listed in Table I. The tissue equivalent solution, T.E.S., was contained in a lucite target box, Figure 1, which was in the form of a six-inch cube. This cube was divided by 1/16-inch lucite spacers into three compartments each of which were six-inch by six-inch by about two-inches thick. The following four experiments were run at the Harvard Cyclotron using this target box with 900 mls of the prepared tissue equivalent solutions in each of the three compartments.

For these experiments the 160 MeV proton beam was degraded by a polyethylene absorber(1) to 125 MeV and then defined by a brass collimator to a two-inch diameter. In the first experiment the beam was then allowed to strike the center of the target box - T.E.S. assembly directly. It passed through the first two compartments, A and B, and was stopped completely in the third compartment, C. Two LiF, thermoluminescent dosimeters were placed on the target box, one at the center-rear of the box, and another in the center of compartment B at the side of the box. This experiment was designed to measure the radioactivity induced by 125 MeV proton reactions and secondary fast and thermal neutrons in tissue equivalent solutions.

In the second experiment the arrangement was identical to experiment one except that five inches of paraffin were placed on all sides of the target box except the bombarding face. A comparison of the neutron induced activity in this T.E.S. with that obtained from run one will permit an estimation of the neutron loss from the target assembly.

In experiment three, the 125 MeV proton beam was degraded with 0.75 inch thick (2-S) aluminum to 98 MeV. This aluminum absorber was placed directly against the face of the target holder which the proton beam entered. This experiment was designed to determine the effect of a lower energy proton beam on the induced activity and to determine its effect on neutron induced reactions in the solutions from the secondary neutrons produced in the absorber.

In the last experiment, the proton beam was again degraded to 98 MeV but with a polyethylene absorber. In these last two experiments the beam was stopped in compartment B, and compartment C radioactivity is entirely from secondary neutron reaction. The beam energies at various points within the assembly are listed in Table II. This series of experiments was designed to measure primary proton and secondary neutron induced activity in tissue media of known elemental concentration and changes in radionuclide production rate as the proton beam was degraded through a tissue equivalent material.. The radionuclide analysis for this set of experiments is underway and will be reported in subsequent reports.

IRRADIATION OF TISSUE MATERIAL

For this study a six-inch cubical target box was also used. Homogeneous tissue material was obtained by triple grinding of beef muscle. The tissue was formed into six 15/16 inch thick sections (designated A, B, C, D, E, F) and these were separated by 1/16 inch thick lucite plates to form the six-inch cube. Aliquots of this tissue were analyzed for trace element composition by neutron activation. The trace elements listed in Table III are being measured but to date only the Na concentrations have been determined. Two LiF, thermoluminescent dosimeters were placed on the six-inch by six-inch cube, one in the center of the 15/16-inch side of section C and one in the center of six-inch end face of section F. This was proton irradiated at the Harvard Cyclotron with the beam entering normal to the six-inch by six-inch face of section A. In these experiments, the 160 MeV proton beam was attenuated with polyethylene absorbers to 125 MeV and then collimated to a two-inch diameter cross section which was centered on the tissue section. In the first experiment no additional absorbers were used but in the second experiment a 0.75-inch thick 2-S aluminum absorber was placed against the face of section A.

The proton beam homogeneity was analyzed by irridating a two-inch circularly grooved aluminum target holder (see Figure 2) containing a standard reference material in the grooves. Analysis of the activity induced in each of the concentric rings provided an estimate of the beam inhomogeneity within its two-inch diameter.

MEASUREMENT OF THE COSMIC RAY NEUTRON FLUX IN PILOTS AT 60,000 to 63,000 FEET

In a flight in an Air Force plane at 60,000 to 63,000 ft., sodium fluoride monitors were placed at various locations on the pilot and in the fuselage of the aircraft. ~~Also~~ an aluminum monitor was located in the fuselage of the aircraft. The sodium fluoride was to serve as a flux monitor for the thermal neutrons; the reaction $^{23}\text{Na}\ (n,\gamma)\ ^{24}\text{Na}$ is indicative of the thermal neutron flux. The aluminum monitor was to serve as a measure of fast neutrons and is based on the reaction $^{27}\text{Al}\ (n,\alpha)\ ^{24}\text{Na}$. The observed neutron fluxes from these monitors are tabulated in Table IV. Flux monitors were placed on the thigh and the ankle of both pilot and navigator. It is evident from these results that the neutron flux at the surface of the pilot was some three-fold higher than that on the navigator. Also, the neutron flux at the thigh was about two-fold higher than that at the ankle. The neutron flux in the center of the fuselage was somewhat higher than that on the ankle position of the navigator. Also included in Table IV is the observed average neutron flux which we have previously observed in pilots at these altitudes. It is apparent that even the highest neutron flux, observed on the surface of the pilot's thigh was some three-fold lower than the average neutron flux in the body of pilots flying at these altitudes. These data point out the importance of using an integral flux in the body rather than that measured at a pilot on the surface of an individual. The fast neutron flux in the center of the fuselage as measured by the $^{27}\text{Al}\ (n,\alpha)\ ^{24}\text{Na}$ reaction was about half the thermal neutron flux measured at this same location. Further experiments with threshold monitors of this type are required to carefully define the neutron flux to which an individual is exposed.

RESULTS AND DISCUSSION

The experimental relationship between radionuclide production and radiation dose to astronauts should be defined over the energy range encountered in the Van Allen belt, galactic, and solar radiation fields. Although our experimental data as well as that in the literature is as yet rather meager, some striking observations can be made. In Table V , production rates in muscle tissue of ^{7}Be from 98 MeV and 125 MeV proton irradiations and the ^{24}Na from secondary thermal neutrons are compared to the production rates observed in primates with 700 MeV(2) and 2300 MeV(2) proton irradiations. The ^{7}Be production rate remains constant prior to significant energy degradation and is in the region of 0.8×10^{-10} d/m/proton/cm^{2} while the ^{24}Na production rate drops about an order of magnitude from 2300 to 98 MeV. Figures 3 and 4 demonstrate the ^{7}Be and ^{24}Na production for 125 MeV and 98 MeV protons as a function of depth through a muscle tissue media. The ^{7}Be concentration remains fairly constant with depth until the proton energy drops below the threshold for ^{7}Be formation. A small increase in ^{7}Be production with depth was noted in both the 98 and 125 MeV proton bombardments just prior to the threshold drop. This is due to the increasing cross section for ^{7}Be from ^{12}C which peaks between 36 and 47 MeV.(3) A compilation of the surface dose to induced activity conversion factors in the tissue sections is given in Table VI. The dose is given as a surface dose and ignors the effect of nuclear reaction secondaries.(4) A relationship, such as that given in Table VI, in d/m/rads could be used to estimate the dose to an astronaut from cosmic radiation. Although these dose conversion factors must at this time be regarded as preliminary since they ignore all secondary reactions and some other factors. Although measurements of ^{22}Na on the samples are not yet complete it appears to follow the ^{7}Be pattern illustrated in Figures 3 and 4 and must therefore be produced in a proton reaction. If it were due to fast neutrons, the value obtained at 125 MeV should not be below detectable limits since the average (crow flight) distance traveled in a H_2O media by a fission neutron before reaching thermal energies is 5.7 cm(7) and after reaching thermal energy is 2.76 cm.(7) Further analysis of the experimental data is needed to verify this. The ^{24}Na histograms in both Figures 3 and 4 show an increase in ^{24}Na in the second one-inch section which is probably due to the greater thermalization media plus lower neutron loss in the inner tissue section. On superpositioning of Figures 3 and 4 the neutron loss from the sections is evident. Further studies determining the scatter and loss from the sides are necessary before the loss can be calculated.

PLANNED WORK

Due to the consistency of ^{7}Be concentrations from 100 to 2300 MeV and the large difference in ^{24}Na values over the same energy region, the production rates of ^{24}Na at 700 and 2300 MeV should be confirmed. Additional measurements in the energy range of 200 to 500 MeV and below 100 MeV are also needed to define the ^{24}Na production rate as a function of bombarding energy. In order to determine the extent of fast neutron reactions in the human body, arrangements have been made to acquire bioassay samples from humans which are being bombarded in medical research programs to a dose of 0.1 rads by fast neutrons. Additional samples are being obtained from humans which are receiving a therapeutic bombardment of about 12,000 rads of approximately 100 MeV protons.

Measurements of bioassay samples from high altitude pilots who have a few hundred hours at 60,000 ft., will continue with an attempt to measure not only ^{24}Na but also the accumulated ^{7}Be.

TABLE I

CHEMICAL COMPOUNDS IN PREPARING THE TISSUE EQUIVALENT SOLUTION

			Trace Elements, %							
Element	Compound	Grams	Pb	Fe	PO_4	SO_4	Cl	K	Na	Br
C,H,O,N	$C_{10}H_{16}N_2O_8$	5845	0.0005	0.002						
H,O	H_2O	7381								
H,O,N	NH_4OH *	2970	0.00005	0.00001	0.00004	0.001	0.00005			
O,N,Na	$NaNO_3$	153.4	0.0005	0.0003	0.0005	0.003	0.001	0.0020		
K, Cl	KCl	53.4		0.003	0.005	0.001			0.005	0.01
Rb, Cl	RbCl	0.338								
Cu,Cl	$CuCl_2 \cdot 2H_2O$	0.0536		0.005		0.002				

* NH_3 assay 28 to 30%, Specific Gravity, 0.90.

TABLE II

PROTON BEAM ENERGIES ENTERING THE VARIOUS SECTIONS OF THE TISSUE EQUIVALENT SOLUTION ASSEMBLY

			Energy, MeV				
Beam Entrance Energy, MeV	Aluminum Absorber	Experiment	Face of Target Assembly	Face of Solution A	Face of Solution B	Face of Solution C	Rear of Solution C
125	None	1	125 ± 2	123 ± 2	88 ± 4	42 ± 6	0
125	None	2	125 ± 2	123 ± 2	88 ± 4	42 ± 6	0
125	0.75 in.	3	100 ± 3	97 ± 3	59 ± 5	0	0
98	None	4	98 ± 2	95 ± 2	56 ± 5	0	0

TABLE III

INDUCED RADIOACTIVITY IN MUSCLE TISSUE FROM THERMAL NEUTRON IRRADIATION

	Aliquot P.P.M.				
	#1	#2	#3	#4	Average
gms	1.212	1.477	1.298	1.136	
Elements					
Na	411	468	519	494	473
Bn					
Co					
Zn					
Fe					
Rb					
Sc					
Hg					
Cr					
P					

TABLE IV

THERMAL AND FAST NEUTRON FLUX MEASUREMENT FROM EXPOSED FLUX MONITORS AT 60,000 TO 63,000 FEET

Monitor Composition	Monitor Weight (grams)	Location of Monitors	^{24}Na Atoms Produced [Atoms-(gram Na)$^{-1}$·min^{-1}]	Neutron Flux n· cm^{-2} · min^{-1}	Reaction
NaF	35	Fuselage Center (under wings)	7	50	(n,γ)
NaF	35	Pilot Thigh	2.5	180	(n,γ)
NaF	35	Navigator Thigh	.8	58	(n,γ)
NaF	35	Pilot Ankle	1.5	108	(n,γ)
NaF	35	Navigator Ankle	.5	36	(n,γ)
Al	76	Fuselage Center (under wings)	5.38	26*	(n,α)
Na		Whole Body	6.9**	480**	(n,γ)

* Fast neutron Reaction (n,α) σ = 120 mb.

** Whole Body ^{24}Na per gram of Na based on bioassay samples from Pilots.(1)

(1) R.W. Perkins, Quarterly Activity Report to the NASA, Ames Research Center, Moffett Field, Calif., July 1, 1967 through October 1, 1967, Induced Radionuclides in Astronauts, BNWL-531-1 (October 8, 1967).

TABLE V

INDUCED RADIOACTIVITY IN BEEF MUSCLE TISSUE AND LUCITE WAFERS FROM PROTON IRRADIATION

Proton Energy (MeV)	Total Protons	Bombardment Time, Min.	Sample Weight kg.	Sample Depth, in.	Section	d/m/Proton/cm^2 +			
						Tissue			Lucite
						^{7}Be x 10^{10}	^{24}Na x 10^{10}	^{22}Nax10^{10}	^{7}Be x 10^{10}
125	1.2 x 10^{13}	45.10	0.632	0.938	A	0.88	0.1		
			0.035	0.062	a				0.25
			0.548	0.938	B	0.81	0.12		
			0.040	0.062	b				0.22
			0.515	0.938	C	0.93	0.084		
			0.033	0.062	c				0.37
			0.536	0.938	D	0.70	0.051		
			0.036	0.062	d				0.14
			0.571	0.938	E	0.068	0.028		
				0.062	e				$<$0.0001
			0.582	0.938	F	$<$0.0001	0.012	$<$0.0001	
98 +++	1.2 x 10^{13}++	48.08	0.508	0.938	A	0.77	0.059		
				0.062	a				
			0.541	0.938	B	0.87	0.082		
				0.062	b				
			0.685	0.938	C	0.20	0.048		
				0.062	c				
			0.478	0.938	D	0.0009	0.027		
				0.062	d				$<$0.0001
			0.538	0.938	E	$<$0.0001	0.017	$<$0.0001	
				0.062	e				$<$0.0001
			0.612	0.938	F	$<$0.0001	0.0082	$<$0.0001	
700*			2.39	Primate		0.5	0.5		
2300*			3.07	Primate		0.9	1.0		

\+ The values are all relative to a homogeneous proton beam over a two inch diameter area at the face of a 6 inch cubic target. All radionuclide concentration values have been corrected to the end of the bombardment period.

++ The beam current at the face of the tissue is about 2 to 3 percent less than this figure due to the nuclear reaction which occurred in the aluminum absorber.

+++ The 98 Mev proton beam was obtained by degrading 125 Mev incident beam using a .75 aluminum absorber.

* Reference 2 calculated by using a target area of 310 cm^2 on the 700 MeV Primate and 350 cm^2 on the 2300 MeV Primate.

TABLE VI

SURFACE DOSE CONVERSION FACTOR AND THE ASSOCIATED INDUCED ACTIVITY AT SELECTED PROTON ENERGIES

Proton Energy MeV	Energy Loss MeV/gm/cm^2	Dose Conversion Factor Rads/Proton/cm^2	d/m/Rad *	
			^{7}Be	^{24}Na
32	17.787	2.85×10^{-7}		
60	10.761	1.72×10^{-7}		
100	7.2733	1.17×10^{-7}	0.65×10^{-3}	0.50×10^{-4}
125	6.1783	0.99×10^{-7}	0.89×10^{-3}	1.04×10^{-4}
200	4.4803	0.72×10^{-7}		
500	2.7318	0.44×10^{-7}		
700 +	2.4127	0.39×10^{-7}	1.1×10^{-3}	1.1×10^{-3}
2300 +	2.014	0.32×10^{-7}	3×10^{-3}	3×10^{-3}

* In the first inch of tissue material, or to a depth where degradation is negligable.

\+ Reference 5, 6.

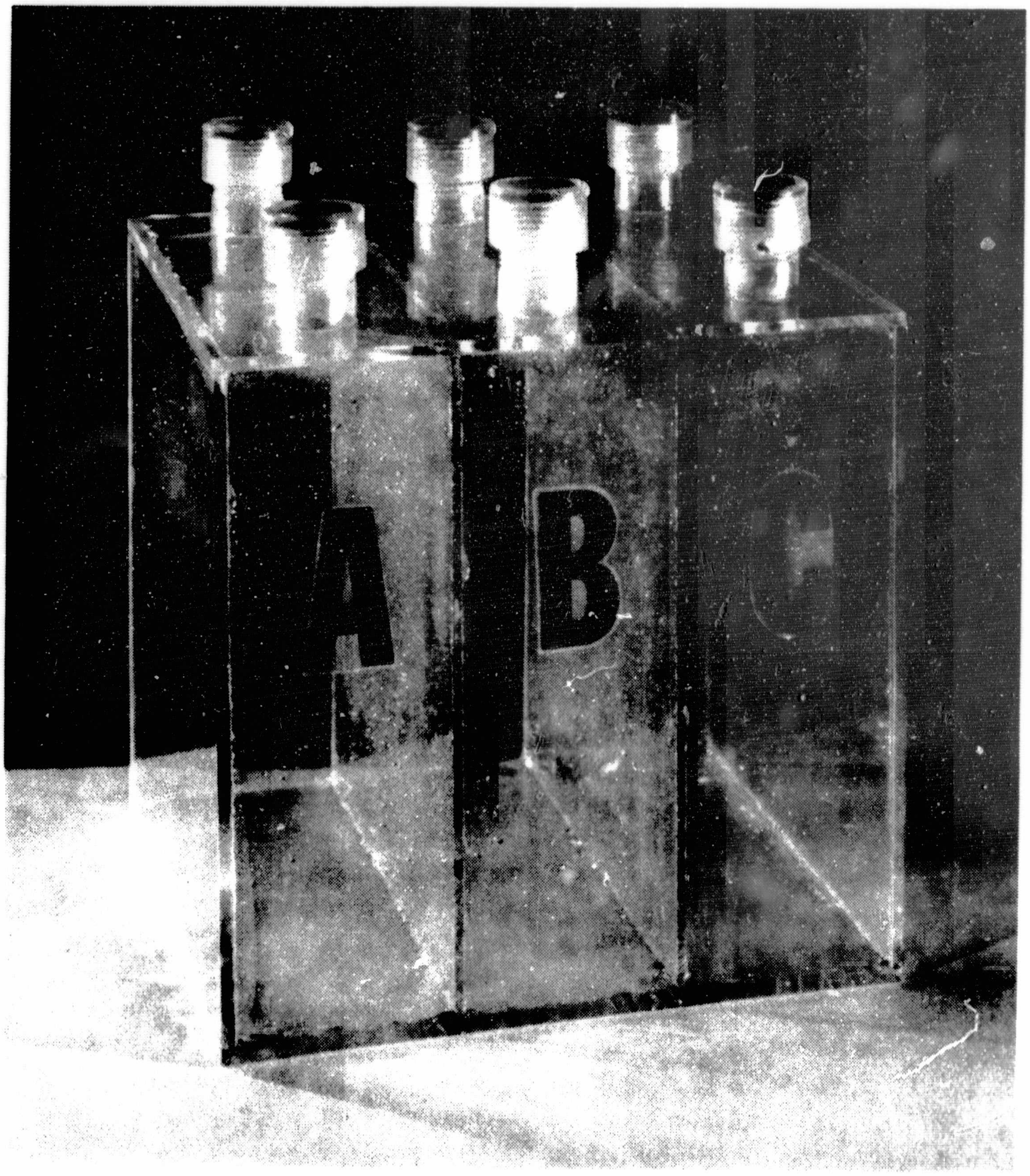

FIGURE 1
A Three Compartment Proton Irradiation Assembly for Tissue Equivalent Solutions

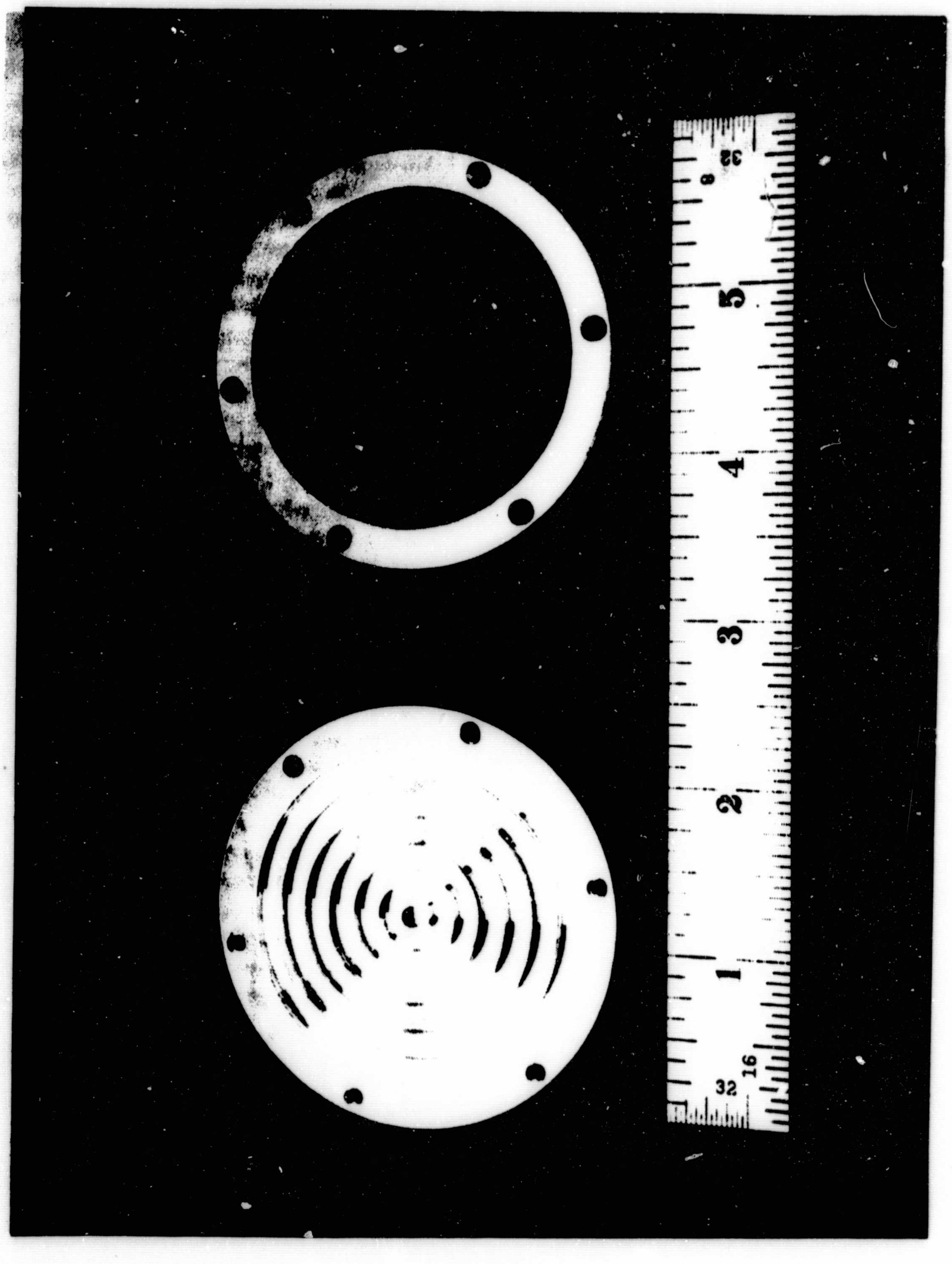

FIGURE 2
A Grooved Proton Irradiation Assembly for Powder Targets

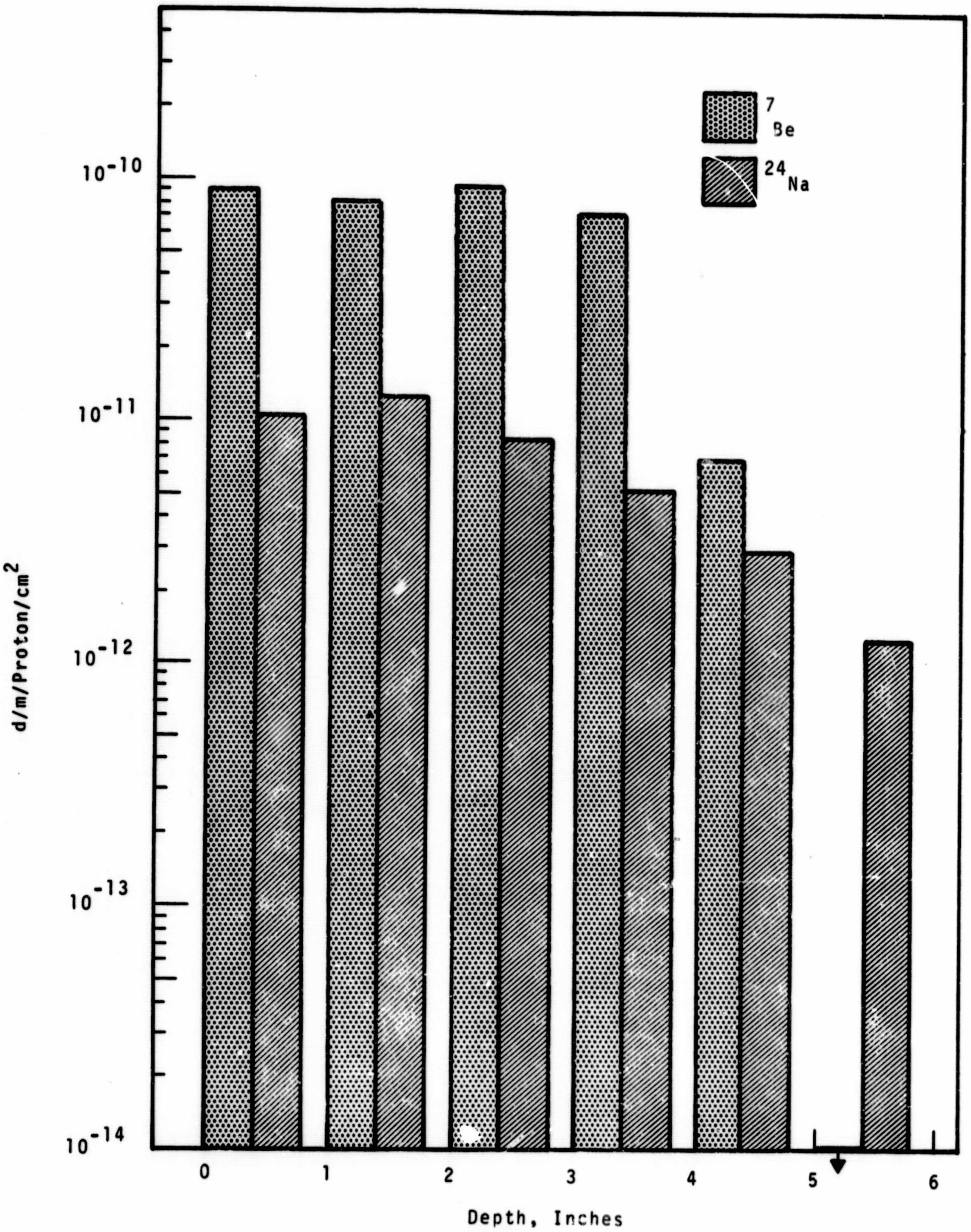

FIGURE 3
^{7}Be and ^{24}Na Production by 125 MeV Protons as a Function of Depth in Tissue

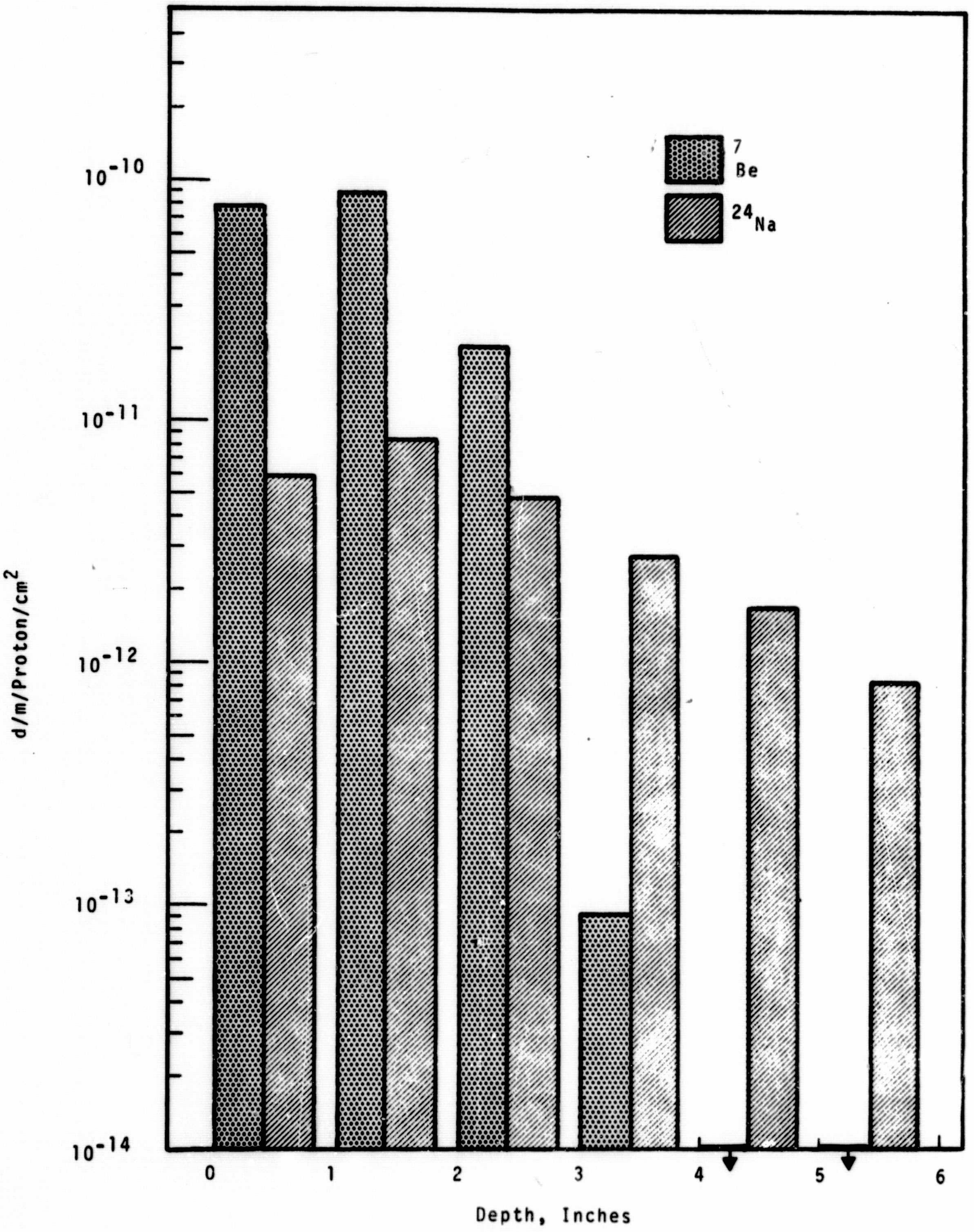

FIGURE 4
^{7}Be and ^{24}Na Production by 98 MeV Protons as a Function of Depth in Tissue

REFERENCES

1. A. Koehler (Private Communications).

2. R. E. Benson, R. G. Thomas, and L. T. Odland, Health Physics 13, 1123 (1967).

3. I. R. Williams and C. B. Fulmer, Phys. Rev. 154, 1005 (1967)

4. J. E. Turner, C. D. Zerby, R. L. Woodyard, H. A. Wright, W. E. Kenniy, W. S. Synder and J. Neufeld, Health Physics 10, 783 (1964).

5. Martin Berger and Stephen Seltzer, NASA-SP-3036.

6. Joseph F. Janni, AFWL-TR 65-150.

7. Gerhart Friedlander, Joseph W. Kennedy, and Julian M. Miller, "Nuclear and Radiochemistry", 2nd Edition, John Wiley, 1964.