C.W. Malick

BNWL-SA-1921

NASA BNW-167

CR 73251
Available to The Public

COSMIC RAY INDUCED RADIOACTIVITY IN ASTRONAUTS AS A MEASURE OF RADIATION DOSE (a)

GPO PRICE $ ________

CSFTI PRICE(S) $ ________

Hard copy (HC) ___

Microfiche (MF) ___

ff 653 July 65

R. L. Brodzinski
N. A. Wogman
R. W. Perkins

Battelle Memorial Institute
Pacific Northwest Laboratory
Richland, Washington

September 1, 1968

FACILITY FORM 602

N68-34400 (ACCESSION NUMBER)	(THRU)
15 (PAGES)	1 (CODE)
73251 (NASA CR OR TMX OR AD NUMBER)	04 (CATEGORY)

SEP 1968
RECEIVED
NASA STI FACILITY
INPUT BRANCH

(a) This paper is based on work supported by the National Aeronautics and Space Administration - Biotechnical Division of Ames Research Center - under Contract AT(45-1)-1830 between the United States Atomic Energy Commission and Battelle-Northwest.

COSMIC RAY INDUCED RADIOACTIVITY IN ASTRONAUTS AS A MEASURE OF RADIATION DOSE

R. L. Brodzinski
N. A. Wogman
R. W. Perkins

September 1, 1968

INFORMATION CONCERNING USE OF THIS REPORT

PATENT STATUS

This document copy, since it is transmitted in advance of patent clearance, is made available in confidence solely for use in performance of work under contracts with the U. S. Atomic Energy Commission. This document is not to be published nor its contents otherwise disseminated or used for purposes other than specified above before patent approval for such release or use has been secured, upon request, from the Chief, Chicago Patent Group, U. S. Atomic Energy Commission. 9800 So. Cass Ave., Argonne, Illinois.

PRELIMINARY REPORT

This report contains information of a preliminary nature prepared in the course of work under Atomic Energy Commission Contract AT(45-1)-1830. This information is subject to correction or modification upon the collection and evaluation of additional data.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

ABSTRACT

The activity-dose energy relationships for ^{7}Be, ^{13}N, ^{22}Na *and* ^{24}Na *activities induced in muscle tissue by proton bombardment have been measured through the energy range up to 580 MeV. The relationship between radiation dose and induced activity for any given proton bombarding energy is defined. The determination of the radiation dose received by an astronaut from cosmic radiation of unknown energy by measuring the concentrations of the radioactive isotopes induced in his body is discussed.*

During space flights astronauts are exposed to cosmic radiation which does biological damage to, and produces radioactive isotopes in, the body. Cosmic radiation consists of galactic cosmic radiation and Van Allen Belt radiation, which are quite predictable, and solar flare radiation, which is relatively unpredictable. The radiation dose received from galactic cosmic radiation is not high enough to be considered a health hazard by itself (< 100 mrad/24 hrs)(1). The dose received from Van Allen radiation (> 200 rad/hr)(1) can be calculated. The partial dose from protons can be rather accurately calculated, however, the assessment of tissue dosage for the electron flux of the Van Allen Belt is possible only by approximation methods (even using only the primary and secondary electron interactions). In addition, the mass shielding of the spacecraft produces bremsstrahlung radiation up to 8 MeV which easily penetrates the vehicle and further complicates the total dose appraisal.

The dose from a large solar flare, which can develop in minutes and emit high energy particles for periods of 36 to 48 hours, could be quite substantial. Indeed, there have been several solar flares observed which produce a particle flux high enough to be lethal to an unshielded astronaut in space(2). Even within the confines of a typical spacecraft , the radiation dose received from the energetic primary particles of such a flare and the secondary neutrons produced within the hull of the spacecraft, would be considerably above the presently accepted tolerance levels(3). The trapped and solar flare particles have steep negative flux/energy gradients, consequently depth-dose distributions depend sensitively on shielding. Biswas(4) has shown that the number of particles other than protons in a solar flare constitute a minor fraction of the total flux (from a maximum of 10% at average energies of 50 MeV/nucleon to less than 1% at energies of 100 MeV/nucleon). Schaefer(1) discusses a proton to alpha particle ratio of 1:1 which has been observed at very low energies (a few MeV), however, these low energy alpha particles will not strike the astronaut and thus will not impart any primary radiation dose to him. For this reason these initial studies have been restricted to proton irradiations.

The normal method for estimating the radiation exposure to astronauts involves the use of nuclear emulsion film dosimeters and thermoluminescent dosimeters which are worn on the body and ionization chambers which are placed at specific locations within the spacecraft. These dosimeters limit the dose measurement to specific points on the astronaut's body or specific capsule locations, and have a very limited sensitivity to variation in particle type and energy. Thus, as yet, no completely satisfactory method exists for accurately measuring the radiation dose received by an individual in the multiparticle, multienergy space environment, although this information is of vital importance for the safety of future astronauts(1).

Experience in nuclear criticality accidents (5,6,7) where individuals were exposed to a high energy particle flux, has shown the most certain index of radiation dose was the induced activity in their bodies. A similar approach to estimating the radiation dose received by an astronaut following exposure to solar flare particles appears to be practical and would have the advantage of providing a direct measure of the total effect of the bombarding particles as recorded by radionuclide production throughout the body.

Experiments have been performed by Benson, et al.(8) in which the radionuclides ^{7}Be and ^{24}Na were measured in primates (Macaca mulata) following exposure to proton beams of various energies. In their work the ^{7}Be and ^{24}Na activities were measured in the sacrificed monkeys following exposure. Analysis of these data indicates that these radionuclides would be measurable in a man by whole body counting following an irradiation with five to ten rads of high-energy protons. Graffman and Jung (9) have reported measurements of the induced ^{11}C (20.5 m half-life) activity in the blood from patients undergoing therapeutic irradiation with high-energy protons. They suggest the possibility of using a blood ^{11}C analysis as a measure of radiation dose from high energy protons. Häller and Jung (10) have made calculations of the amounts of radionuclides produced by 150 MeV protons in targets of the same elemental composition as the human brain and the whole human body using known or estimated spallation cross sections. Numerous investigators have calculated the radiation dose to muscle tissue in specific geometries by protons of various energies. However, most reports on the activity induced by, or radiation dose from, a broad spectrum of high energy protons have been theoretical with no animal or human exposure data, and very little experimental work to help assess astronaut exposure status.

This communication describes a technique whereby the radiation dose received by an astronaut could be determined for a given geometry of spacecraft and astronaut from a measurement of the radionuclides produced in his body.

Theoretical

The use of induced radionuclides in the body as a measure of proton radiation dose has several advantages over film badge dosimeters: 1) the activity is indicative of the whole body exposure rather than a single point(s) on the body; 2) the radionuclides are induced by the spectrum of particles which are doing the radiation damage, and the radionuclide production reflects the spectrum changes in different parts of the body rather than depending only on the incident radiation, and 3) the induced activities provide a sensitive measurement of radiation dose over an extensive energy range of incident radiation.

In Table 1, the calculated amounts of the various radionuclides which would be produced in the body of the astronaut by a two day exposure to normal galactic radiation are summarized. The three most abundant species which are of half life sufficiently long to serve as a monitor after returning to earth from a space flight are ^{24}Na ($t_{1/2}$= 15.0 h), ^{7}Be ($t_{1/2}$= 53 d) and ^{22}Na ($t_{1/2}$= 2.60 y). The radionuclides ^{11}C ($t_{1/2}$= 20.5 m) and ^{13}N ($t_{1/2}$= 9.96 m) would serve as the most sensitive activities for in-flight monitoring. The ^{42}K ($t_{1/2}$= 12.4 h, $E\gamma$ = 1.524 MeV) radionuclide although produced in relatively large quantities would be difficult to measure due to the similar energy of its gamma radiation to that of the natural ^{40}K (2.8×10^5 dis/min/70 kg man, $E\gamma$=1.460) in the body.

If the bombarding energy of the cosmic particles were monochromatic and precisely known, then an activity-dose-energy relationship for any one of the above listed isotopes would yield the radiation dose received by the astronaut. However, since cosmic ray spectra (solar flare spectra) are neither monochromatic nor precisely known, an "effective" proton bombarding energy must be obtained for use in the activity-dose-energy relationships. This "effective" proton energy can be determined from the measurement of two or more of the induced activities. The ratio of any two of the induced activities changes with energy, and this ratio provides the necessary information for determining the "effective" bombarding energy which can then be used in the determination of radiation dose.

Experimental Procedure

The targets used to simulate the thoracic region of the body of an astronaut in this work were made of beef muscle tissue which was triply ground to help insure homogeneity. Samples were pressed into one inch thick circular sections eleven inches in diameter, stacked together to any desired target depth for the irradiations, and frozen. They were separated by thin films of saran to permit easy separation of the target after the radiation exposure.

Targets were exposed to proton beams generated by the Harvard University and the Space Radiation Effects Laboratory Cyclotrons. The two inch diameter beams were incident normally in the center of the face of cylindrical targets which were either twelve or eighteen inches thick. The beam energies were obtained by degrading the maximum energy cyclotron beam at Harvard with polystyrene absorbers. The SREL cyclotron nominally generates two energies, and a third was obtained by the use of a copper absorber. The beam currents were measured by a proportional counter and by the induced activity in aluminum and lucite discs. Primary proton energies of 580, 430, 320, 125, 86 and 50 MeV were used with a total of 10^{13} to 10^{14} protons incident at each energy. The tissue targets were frozen at dry ice temperatures prior to irradiation, irradiated for periods of twenty minutes to two hours with no additional cooling and returned to dry ice temperatures immediately after irradiation. No thawing of the target was observed during the irradiation. The targets were separated into their one inch thick sections shortly after each irradiation at the SREL cyclotron, and the positron annihilation radiation was determined by coincidence counting techniques using five inch diameter by four inch thick sodium iodide, thallium activated, scintillation detectors. A preliminary bombardment of a muscle tissue sample at 320 Mev showed the positron activity to follow the half life of ^{13}N for over twelve half lives. This indicates that the contribution to the positron activity induced in muscle tissue by proton irradiation at this energy from ^{11}C, or any other positron emitter, to be negligible compared to the ^{13}N activity.

All targets were returned to the laboratory at Richland, Washington after irradiation for analysis of the induced radionuclides ^{7}Be, ^{22}Na and ^{24}Na. The targets were separated into their one inch thick sections, and a six inch diameter center portion of each section was removed. This center section was sealed in a one inch deep by six inch diameter Petri dish and counted in a multidimensional, sodium iodide, gamma-ray spectrometer. Aliquots were taken from the outer portion of each section and counted to determine the radial distribution of the radionuclides.

Because of the very small amounts of radioactivity in many of the samples multidimensional gamma-ray spectrometers were used for all of the measurements. These counting systems are composed of two large sodium iodide, thallium activated, scintillation crystals between which the sample is positioned for counting. The crystals are operated simultaneously in both the coincidence and singles modes and in anticoincidence with an annular sodium iodide or plastic phosphor detector.

These entire crystal assemblies are shielded with a minimum of four inches of lead in all directions. The single and coincidence events are stored in 4096 channel multiparameter analyzer memories. These systems are designed for maximum efficiency with minimum background and Compton interference(11,12,13).

Experimental Results and Discussion

The most abundant radionuclides produced in the tissue samples, which have half-lives in a convenient range for analysis, are ^{7}Be, ^{22}Na and ^{24}Na. The radionuclide ^{13}N is the most abundant short-lived radionuclide, and although it could provide a very sensitive estimate of in-flight exposure its short half life would usually result in its decay before ground based measurements could be made on returning astronauts. The production rates of these radionuclides were determined from the irradiation time and beam current using the appropriate buildup and decay equations. Beryllium-7 and sodium-22 were shown to be predominantly proton produced species as no measurable activity could be observed beyond the proton range in the muscle tissue, while ^{24}Na was shown to be produced primarily by (thermal) neutrons. This latter fact was evident from the radial distribution of ^{24}Na in the tissue sections. It was also evident on comparing the ^{24}Na activities in two different tissue targets, one of which was irradiated directly with 125 MeV protons and the other which had the primary beam totally absorbed in a 2.4 inch aluminum absorber placed directly in front of the target. The mode of production of the ^{13}N activity is as yet uncertain.

The observed activities of ^{7}Be, ^{13}N, ^{22}Na and ^{24}Na per incident proton vs. proton energy are shown in Figure 1. These relationships are unshielded tissue targets which were 11 inches in diameter by 12 inches thick. A plot of activity per unit of whole body dose vs. proton energy, which is based on Fig. 1, is shown in Figure 2. In these two figures the total activity in 11 inch diameter by 12 inch thick tissue samples was used. This volume would simulate the thoracic region of an astronaut. The solid curves in Figures 1 and 2 represent our experimental data and the dashed curves are based on the theoretical calculations of Jung (14). Similar theoretical calculations for the production of ^{22}Na have not been made. These experimental relationships alone provide the necessary information for determining radiation exposure and dose from observed activity where the energy spectrum of the incident protons is known. However, where the energy spectrum is unknown the ratios of the various induced radionuclides can provide an "effective" energy of the incident protons. The various ratios of the isotopes ^{7}Be, ^{13}N, ^{22}Na and ^{24}Na as a function of incident proton energy are shown in Fig. 3. It is immediately evident that these curves of isotope ratios are energy dependent and that the isotope ratios in muscle tissue samples define the energy of the primary proton beam. In an actual situation the measurement of the ratios of these radionculides in an astronaut who had been exposed to direct cosmic radiation in space, by means of whole body counting, bioassay analysis, etc., could serve to define an effective proton bombarding energy. Once this effective proton bombarding energy was established, reference to any of the activity per unit dose vs. proton energy curves would provide the dose received by the astronaut.

This method provides an extremely sensitive measure of radiation dose to an astronaut. By use of the anticoincidence shielded counters at our Laboratory, it would be possible to determine as little as 1 rad of 125 MeV protons by whole body counting of ^{7}Be and ^{24}Na. Radiation doses of less than 0.001 rad could be detected from whole body measurements of ^{24}Na alone; however, precise dose estimates would not be possible. Once the complete activity-dose-energy relationships are established for ^{13}N production, precise measurement of doses of less than 0.001 rad will be possible.

Since a unidirectional proton beam from an accelerator has been used to simulate the fairly isotropic cosmic radiation and ground beef muscle tissue has been used to simulate an unshielded astronaut, changes must be made to define the activity-dose-energy and the isotope ratio-energy relationships for actual space conditions. Such relationships can undoubtedly best be determined experimentally although the trend of any changes can be predicted.

First consider the changes involved by shielding an astronaut in a space capsule. How does the dose received from a unidirectional proton beam compare to the unshielded dose from the same beam? The dose from the primary radiation is reduced since the low energy component of the spectrum is stopped by the absorber and the high energy component is degraded to a lower energy. This would not be the case if all the particles had sufficient energy to penetrate both the hull of the spacecraft and the astronaut; however, typical solar flare spectra do not fall in this category. The dose from the secondary radiation will probably not change appreciably, and although this secondary dose now becomes more significant relative to the primary dose, the net effect is still a large decrease in the total radiation dose. The effect on the ratio of isotopes will be more pronounced for the low energy region with very little if any effect at the higher energies. For the charged particle produced radionuclides little or no modifications would be expected under any shielding conditions. A few properly planned experiments would allow the changes in the radionuclide production and ratio as a function of shielding and geometry to be established. This could provide relationships of the type presented here for any arbitrary geometry and shielding.

An additional consideration in actual space exposures is the degree of isotropy of the radiation. The exact changes which will occur in going to the isotropic cosmic radiation from the unidirectional radiation field of the laboratory are uncertain; however, the calculations of Wright, et al.(15) indicate that the whole body dose will go down by a significant amount for a given incident radiation.

Once sufficient data have been collected to draw the activity-dose-energy curves for a given geometry and shielding, the dose received by an astronaut in a spacecraft can be determined by means of whole body counting or bioassay analysis on his return to earth or perhaps during flight. The ratio of two or more of the induced activities serves to define an effective proton bombarding energy from the isotope ratio-energy curves. This effective energy and one of the radionuclide concentrations are then used to determine the radiation dose from the appropriate activity-dose-energy curve.

As the size of spacecraft and the payload capacity of launch vehicles increase, similar dose measurements could be performed routinely in flight. In this situation the ^{13}N activity would be a prime choice due to its very high specific activity following solar flare proton bombardment. Coincidence measurements of the positron annihilation radiation associated with ^{13}N decay would be a relatively simple matter, and perhaps the astronaut could merely insert an arm or leg in a small counting system for the measurement. Similarly a fairly small counter assembly could be designed for on-board use which would measure this or perhaps other induced radionuclides in a bioassay (urine) specimen.

In summary, the relationship between radiation dose and induced activity in tissue has been established for unshielded tissue samples of a size comparable to the thoracic region of a man. The measurement of the ratios of the observed radionuclides defines the energy of the incident proton beam. If these relationships were established for typical shielding conditions of an astronaut it should be possible to determine the dose received by an astronaut from cosmic radiation of unknown energy by measuring the radioactive isotopes induced in his body.

References and Notes

1. H. J. Schaefer, *Health Physics* 13, 327 (1967).
2. A. J. Beck, E. Divita and S. L. Russak, *Am. Rocket Soc. J.* 32, 1668 (1962).
3. Recommendations of the international commission on radiological protection, *Pergamon Press*, London (1960).
4. S. Biswas, *J. Geophys. Res.* 71, 4071 (1966).
5. Dosimetry investigation of the recuplex criticality accident, *Health Physics* 9, 757 (1963).
6. R. W. Perkins and L. J. Kirby, Radiological chemistry associated with the Hanford criticality of April 7, 1962, USAEC rpt. HW-76823 (1962).
7. Accidental radiation excursion at the Y-12 plant, Y-1234 (1958).
8. R. E. Benson, R. G. Thomas and L. T. Odland, *Health Physics* 13, 1123 (1967).
9. S. Graffman and B. Jung, Radioactivity of human blood as a measure of integral dose from high energy protons, AF 61(052)-740 SR-4 (1964).
10. I. B. Häller and B. Jung, Radionuclides produced in man by high energy protons, AF 61(052)-740 SR-1 (1963).
11. R. W. Perkins and D. E. Robertson, Selective and sensitive analysis of activation products by multidimensional gamma-ray spectrometry. Proceedings, 1965 international conference: *Modern trends in activation analysis*, College Station, Texas (1965).
12. R. W. Perkins, *Nucl. Instr. Methods* 33, 71 (1965).
13. N. A. Wogman, D. E. Robertson and R. W. Perkins, *Nucl. Instr. Methods* 50, 1 (1967).
14. B. Jung, Radionuclide production and effects of nuclear reactions on dose from 193 MeV protons stopped in tissue, AF 61(052)-740 SR-2 (1964).
15. H. A. Wright, V. E. Anderson, J. E. Turner, J. Neufeld and W. S. Snyder, Calculation of radiation dose due to high-energy protons and neutrons. To be published.

16. We thank Dr. A. Koehler at the Harvard University Cyclotron and George Burtner and his staff at the Space Radiation Effects Laboratory Cyclotron for making the irradiations.

17. This paper is based on work supported by the National Aeronautics and Space Administration - Biotechnical Division of Ames Research Center- under Contract AT(45-1)-1830 between the United States Atomic Energy Commission and Battelle-Northwest.

TABLE I
Estimated Radionuclide Concentration in an Astronaut After a Two Day Actual Flight

Radionuclide	Half-Life	Activity dpm*	Mode of Production
^{7}Be	53 d	190	Spallation of ^{16}O, ^{12}C and ^{14}N, $\bar{\sigma}$ = 10 mb.
^{11}C	20.5 min	20,000	Spallation of ^{12}C, ^{14}N and ^{16}O
^{13}N	9.96 min	$>10^{6}$	Spallation of ^{14}Na and ^{16}O
^{22}Na	2.58 yr	0.3	Spallation of ^{23}Na, ^{40}Ca and ^{31}P
^{24}Na	15.0 hr	2,300	Neutron Activation of ^{23}Na
^{28}Al	2.3 min	3,000	Spallation of ^{31}P
^{28}Mg	21.3 hr	5	Spallation of ^{31}P, ^{40}Ca and ^{32}S
^{31}Si	2.6 hr	2,300	Spallation of ^{31}P, ^{34}S and ^{40}Ca
^{38}S	2.9 hr	3	Spallation of $^{42\ \text{to}\ 48}$Ca and ^{41}K
^{38}Cl	37 min	440	Neutron Activation of ^{37}Cl
^{39}Cl	55 min	2	Spallation of $^{42\ \text{to}\ 48}$Ca and ^{41}K
^{41}Ar	110 min	20	Spallation of ^{41}K
^{42}K	12.4 hr	300	Neutron Activation of ^{41}K
^{43}K	22 hr	2	Spallation of ^{44}Ca
^{43}Sc	3.9 hr	2	Spallation of ^{44}Ca
^{44}Sc	4.0 hr	2	Spallation of ^{44}Ca
^{49}Ca	8.8 min	150	Neutron Activation of ^{48}Ca
^{56}Mn	2.58 min	5	Neutron Activation of ^{55}Mn
^{64}Cu	12.9 hr	30	Neutron Activation of ^{63}Cu
^{86}Rb	18.7 d	0.7	Neutron Activation of ^{85}Rb

* dpm > 0.2, γ Active

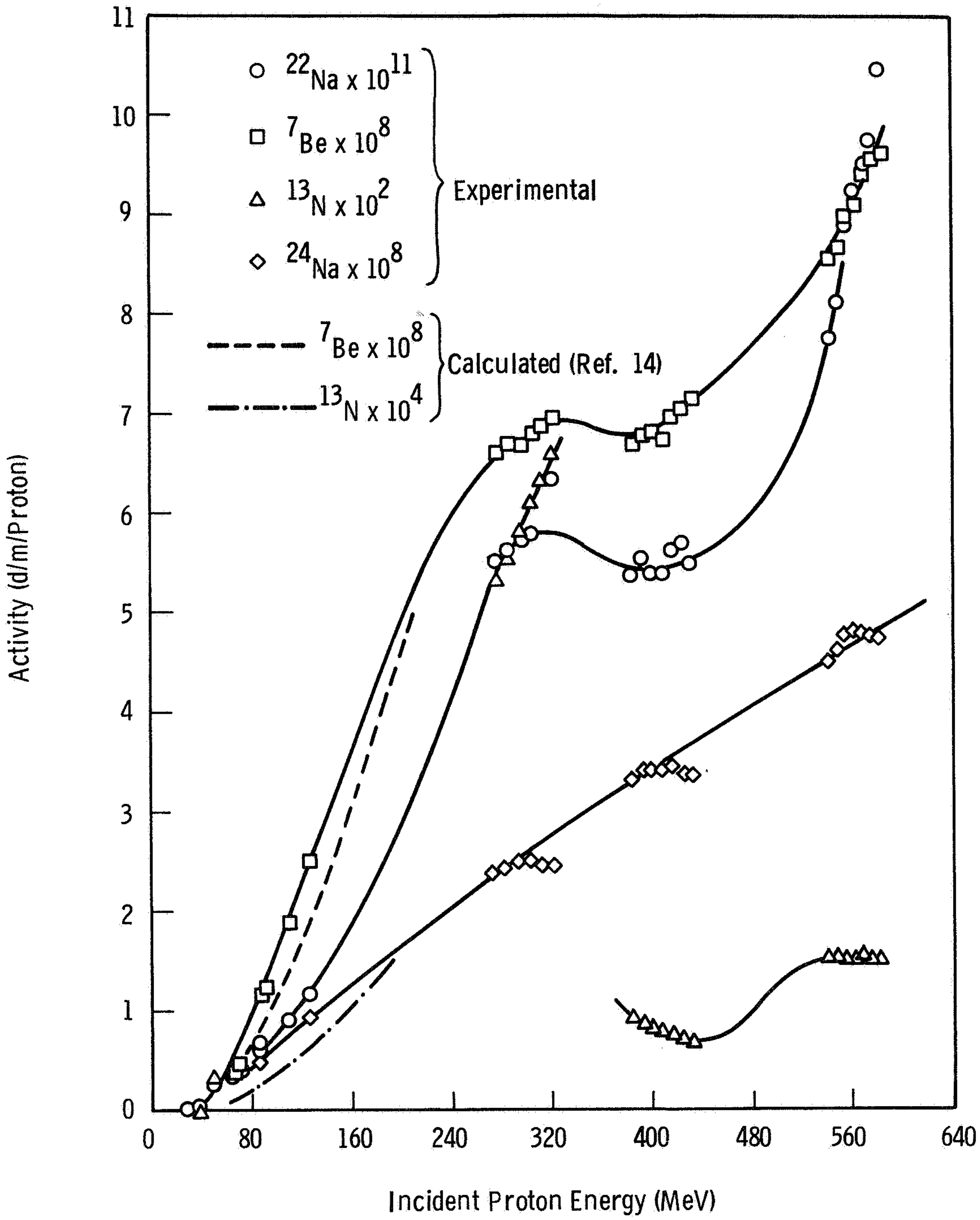

FIGURE 1
^{7}Be, ^{13}N, ^{22}Na, and ^{24}Na Activity Induced in a Beef Muscle Tissue Sample Eleven Inches in Diameter by Twelve Inches Thick as a Function of Proton Bombarding Energy

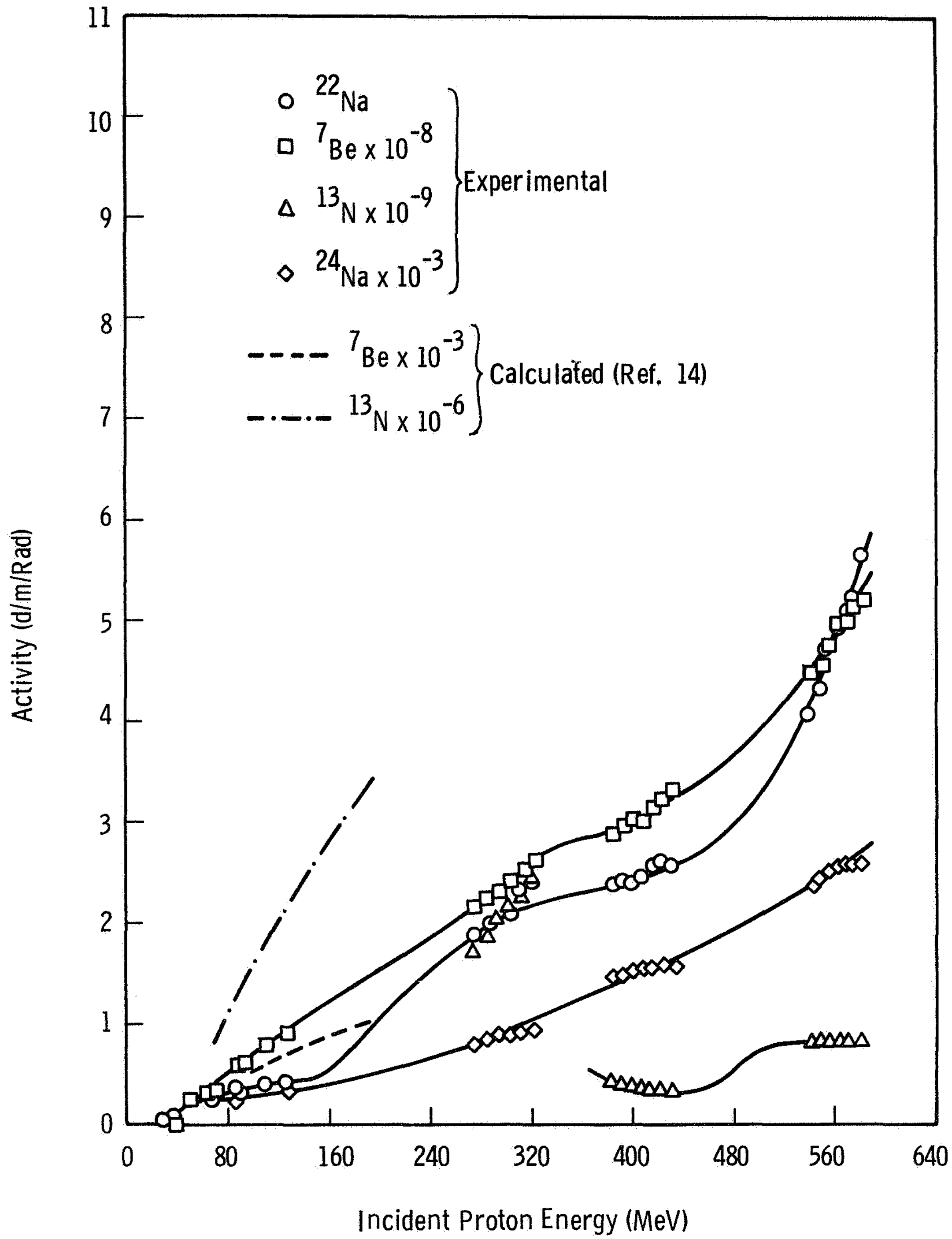

FIGURE 2

^{7}Be, ^{13}N, ^{22}Na, and ^{24}Na Activity Induced in a Beef Muscle Tissue Sample Eleven Inches in Diameter by Twelve Inches Thick as a Function of Proton Bombarding Energy. Dose Based on 70 kg. Standard Man

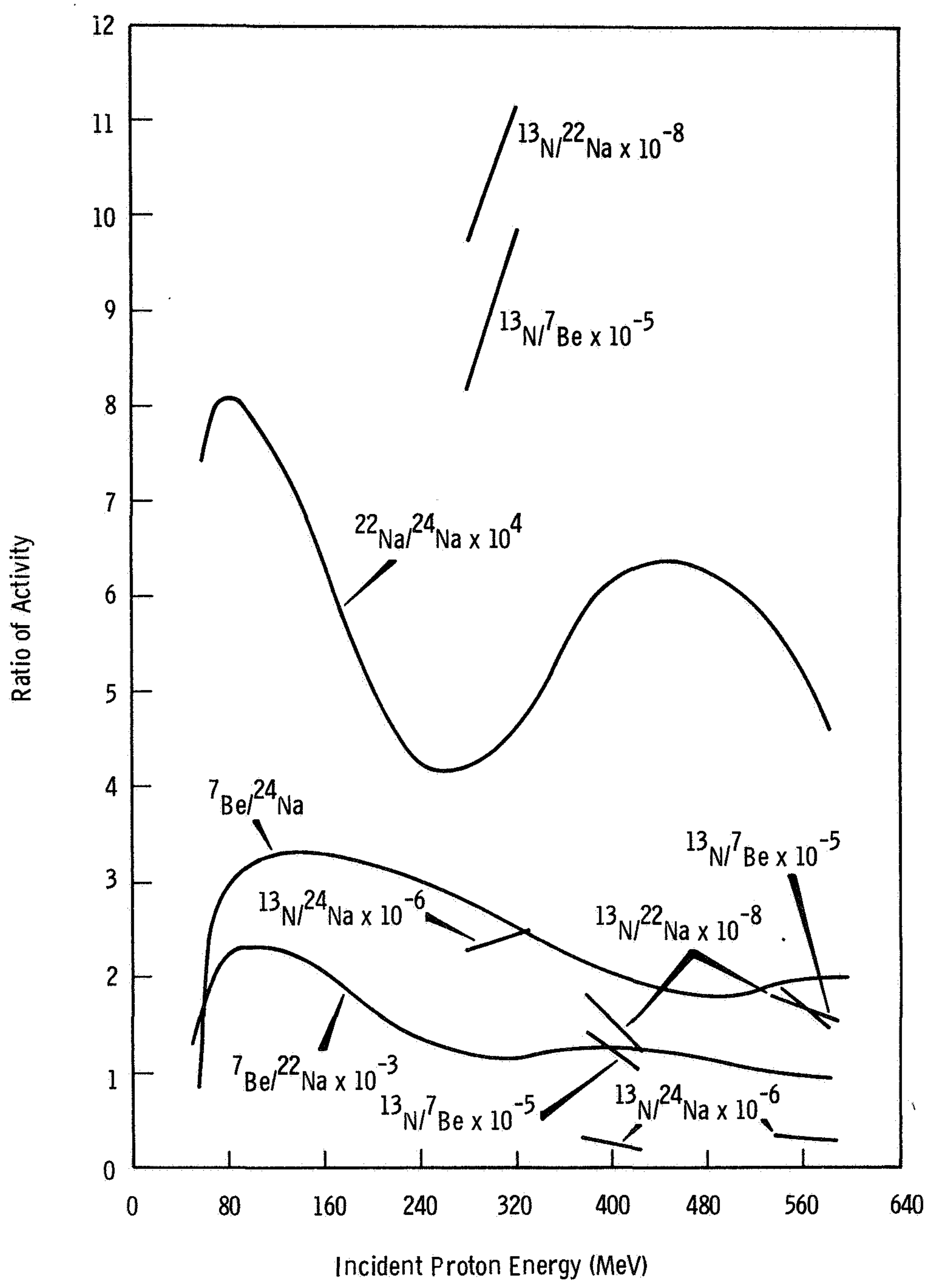

FIGURE 3
Ratios of Various Activities Induced in a Beef Muscle Tissue Sample Eleven Inches in Diameter by Twelve Inches Thick as a Function of Proton Bombarding Energy