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THE MEASUREMENT OF RADIATION EXPOSURE OF ASTRONAUTS BY RADIOCHEMICAL TECHNIQUES

R. L. Brodzinski

Battelle Memorial Institute
Richland, Washington

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QUARTERLY RESEARCH REPORT TO THE NASA MANNED SPACECRAFT CENTER

THE MEASUREMENT OF RADIATION EXPOSURE OF ASTRONAUTS BY RADIOCHEMICAL TECHNIQUES

October 5, 1970 Through January 3, 1971

by

R. L. Brodzinski

January 15, 1971

Battelle Memorial Institute
Pacific Northwest Laboratories
Richland, Washington 99352

TABLE OF CONTENTS

BNWL-1183 7

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Gamma-ray analyses of the neutron activated fecal samples from the Apollo 12 and 13 missions have been completed, and the data are being evaluated.

Samples of the exposed Apollo 12 solar wind composition (SWC) foil and blank foils have been obtained for analysis of the ^{210}Po (^{210}Pb, ^{222}Rn) content. It is expected that the determination of the ^{210}Po content of these foils will yield the concentration of radon atoms incident on the foil while exposed to the lunar atmosphere, and this indirectly will permit an estimate of the average uranium concentration of the lunar surface.

Proposals to measure the cosmic-ray intensity and energy spectra inside and outside of late Apollo and Project Skylab spacecraft by exposing and subsequently analyzing pure metal foils, and to measure the elemental mass balance in Project Skylab astronauts by instrumental neutron activation analysis of the intake and excreta, are summarized.

The abstract of a paper entitled, "The Measurement of Radiation Exposure of Astronauts by Radiochemical Techniques," and the text of a paper entitled "Calcium, Potassium, and Iron Loss by Apollo VII, VIII, IX, X, and XI Astronauts" are included as appendices.

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TASK - DETERMINATION OF THE RADIONUCLIDE CONTENT OF FECES AND URINE FROM ASTRONAUTS ENGAGED IN SPACE FLIGHT

A paper has been prepared for oral presentation on March 1, 1971 at the National Symposium on Natural and Manmade Radiations in Space. The paper, entitled, "The Measurement of Radiation Exposure of Astronauts by Radiochemical Techniques," is based on the measurements of the cosmogenic radionuclides in the feces and urine of the Apollo 7 through 13 astronauts. The abstract of this paper is reproduced in Appendix A of this report. The entire manuscript, which will be published in the proceedings of the symposium, will be incorporated in a later report.

TASK - NEUTRON ACTIVATION ANALYSIS OF FECES AND URINE FROM ASTRONAUTS ENGAGED IN SPACE FLIGHT

Gamma-ray analyses of the neutron activated fecal samples from the Apollo 12 and 13 astronauts have been completed, and the data are presently being reduced. The elemental concentrations of these samples will be given in a later report.

Recent discussions with NASA personnel have developed the possibility of obtaining representative samples of all foodstuffs used on the Apollo missions for neutron activation analysis in order to determine the intake values for those elemental concentrations measured in the feces. Only a few intake values have thus far been obtained, and these have been furnished by NASA[1]. Based on these values a manuscript entitled, "Calcium, Potassium, and Iron Loss by Apollo VII, VIII, IX, X, and XI Astronauts" has been prepared for submission to the journal Aerospace Medicine and is reproduced in its entirety in Appendix B of this report.

TASK - SEARCH FOR LUNAR ATMOSPHERE

Project Apollo has been designed to [illegible] the earth's moon. One basic feature is that [illegible] apparently composed of only the solar wind [illegible] emanations from the natural decay chains [illegible]. In order to characterize the composition of the [illegible] the moon, aluminum foils (SWC foils) have been [illegible] by the Apollo 11 and 12 crews and subsequently [illegible] on the solar wind particles which have [illegible]

The radon atoms present in the lunar [illegible] thermal velocities with ballistic trajectories [illegible] embed themselves in the exposed SWC foil. These [illegible] be transformed to ^{210}Po through [illegible] radon fluence incident on the foil and [illegible] in the lunar atmosphere can be calculated from a [illegible] concentration of any of the daughter species at a known time [illegible]. Appropriate assumptions regarding lunar surface porosity and [illegible] diffusion coefficients will allow the average lunar surface uranium concentration to be estimated since uranium is the ultimate parent of the radon gas.

Three samples of SWC foil have been obtained for analysis of ^{210}Po (one of the radon daughters). Two of these are blank foils of the same material as the exposed SWC foil. A ^{210}Po activity of $(2.9-6.6)\cdot 10^{-4}$ d/m/cm^2 was observed in the first of these. This is comparable to the expected ^{210}Po activity of $(3-20)\cdot 10^{-4}$ d/m/cm^2 from radon decay in the exposed Apollo 12 SWC foil. The second foil, G30-11, and the Apollo 12 SWC foil exposed to the lunar atmosphere, G 17-7-6-7, have not yet been analyzed.

PROPOSED RESEARCH

A three-part proposal for future research has been prepared and will be forthcoming as a separate document. The essence of the first part was presented in an earlier report.[2] Parts two and three are summarized below.

COSMIC-RAY ENERGY SPECTRA AND INTENSITY

High-energy cosmic particles impinging on a spacecraft cause some radiation damage to the vehicle and its contents, and may result in a substantial radiation dose to the occupants. These cosmic particles come from three major sources: the trapped or Van Allen radiation, solar flares, and galactic radiation. In order to accurately evaluate the damage caused by these particles it is necessary to define the energy spectrum and intensity of the composite radiation. The galactic portion of the spectrum is fairly constant with time and reasonably well defined. The Van Allen and solar portions, however, vary considerably with time and location depending on solar activity and relative proximity to the magnetically trapped radiation belts. For this reason, the radiation damage to the vehicle and the radiation dose to the astronauts will be different for each space mission.

The cosmic radiation dose is a primary concern and is carefully monitored by various dosimetry techniques during each space flight. These standard dosimetry techniques have one major drawback, for determining the dose delivered by cosmic particles, however, in that they show reduced response characteristics to different particle energies. A 100 MeV proton stopped in the body of an astronaut will deliver twice the radiation dose of a 50 MeV proton stopped in his body, but most standard dosimetry techniques can barely distinguish them from one another. If the number of particles of each energy incident on an astronaut is known, the radiation dose he receives can be precisely calculated.

Another application of the measured cosmic spectrum and intensity inside the spacecraft is for the determination of the radiation shielding effectiveness of the hull and contents. By comparison to the spectrum and intensity outside the spacecraft, the particle attenuation and absorption in the vehicle as a function of energy can be determined. A determination of the magnitude of secondary particle production including neutrons can also be obtained from the same comparison.

Finally, a knowledge of the particle spectrum and intensity would be particularly helpful in several basic space science programs which are dependent on cosmic-ray activation, such as the analysis of lunar samples, meteorites, and recovered space "junk". These basic knowledge programs will be most benefited by a separation of the various components of cosmic radiation into their respective particle spectra.

It is possible to determine the charged particle (proton) flux and energy spectrum from a few MeV through thousands of MeV simultaneously with the thermal and epithermal neutron flux from measurements of the quantities of the various radionuclides produced in exposed metal foils by spallation and capture reactions. Different spallation products are produced with different probabilities (cross sections) as a function of energy (excitation functions) of the incident particle and have different minimum reaction energies (thresholds). From measurements of the quantities of radionuclides produced in pure metal foils which have been exposed to cosmic particles both inside and outside spacecraft, and the application of well known

excitation functions, the incident cosmic spectrum can be characterized with rather good accuracy.

In the proposed work Battelle-Northwest will arrange through appropriate NASA personnel to install thin sheets of pure metal foils in the spacecraft. These foils can be located in unobtrusive places so that they do not interfere with any other aspects of the mission. For example, the standard passive dosimetry cannisters could be fabricated from a lamination of the thin foils. The feasibility of this approach has already been discussed with responsible NASA representatives and appears reasonable. If possible, arrangements will be made to expose similar foils outside the spacecraft by incorporating them with manually or remotely deployed devices. Foils ranging in thickness from one thousandth to ten thousandths of an inch from a prospective list of metals including aluminum, iron, titanium, cobalt, scandium, and possibly copper and tantalum would be employed.

On return to earth the short-lived induced radionuclides in the individual foils will be measured with the multidimensional gamma-ray spectrometer proposed earlier[2]. If possible, these measurements will be made onboard the recovery vessel since a minimum radioisotope decay would insure maximum accuracy. Very long counts for precise determination of the long-lived induced radioactivities will be made later at the Battelle-Northwest laboratories.

From the measured quantities of induced radionuclides in each pure metal foil and the known excitation functions for production of each radionuclide, the cosmic-ray energy spectrum and intensity incident on that foil will be determined. Since each radionuclide concentration will only be representative of an exposure period corresponding to effective saturation for that nuclide, different radionuclides will be representative of different portions of the mission, and temporal variations in the spectrum and flux of cosmic particles will also be determined. Induced radioisotopes with half-lives long compared to the duration of the mission will, of course, integrate the average spectrum and flux throughout the exposed period. By use of scandium and cobalt foils the thermal and epithermal neutron flux will be determined. These two metals appear to be best suited for this purpose because of their neutron capture and subsequent decay characteristics. Commonly used gold foils will be rather useless for neutron monitoring due to the relatively short half-life of the product radionuclide compared to the duration of Project Skylab missions. Once the cosmic-ray energy spectra and intensities incident on each of the several foil packets have been determined, the results will be analyzed in terms of the shielding qualities of the spacecraft, as well as the secondary particle production within and activation of the hull. Also this known spectrum and intensity of particles incident on the crew members will be used to calculate the radiation dose delivered to the astronauts. This dose determination will then be compared with the dose determined by the radiochemical method used in this project and by conventional dosimetry techniques.

This cosmic-ray monitoring program will require 3 man-months for implementation of the project including assembly of the foil packages and 3 man-months per mission for determination of the radionuclide content of the returned foils and reduction and interpretation of the data. Since very low levels of induced radioactivity are expected in the foils, extremely

sensitive counting equipment, such as that proposed in Part I, will be necessary to make accurate determinations of the radionuclide concentrations. Battelle-Northwest is the world's pioneer in low-level multidimensional gamma-ray spectrometry and has many of these highly sensitive instruments available for measuring the long-lived radioactivities which will be present in the foils. Battelle's analyses of the cosmic-ray induced radionuclides present in the lunar material samples, in meteorites, and in pieces of space "junk" returned to earth adequately demonstrate the required levels of sensitivity and competence. Coupling this experience with the accurately determined excitation functions of the spallation products in proton irradiated iron and titanium recently completed at Battelle and the cosmic particle dosimetry experience of Battelle yields a task force well qualified for successful completion of the proposed research.

MASS BALANCE

The normal terrestrial metabolism of astronauts may be altered in the space environment due to weightlessness, unusual atmosphere, or other artifacts of space flight. One possible manifestation is the uptake or loss of certain elements by their bodies. These elemental gains or losses may be responsible for adverse physiological or psychological responses which may affect the successful completion of a mission. A definite loss of body calcium, potassium, and iron has been demonstrated, and although the calcium and potassium losses do not appear to be too serious at this time, the iron loss must be investigated further. The uptake or loss of trace elements, such as cobalt and zinc, may also be correlated with unusual physiological reactions or used for prediction of reactions such as in the early detection of disease.

In order to measure the gains or losses of elements by the astronauts, a mass balance study will be performed for at least one of the Project Skylab missions. This type of investigation will be necessary to measure the changes in some of the trace elements which may be so subtle that they could not be observed in any other manner. A technique of instrumental neutron activation analysis will be used to determine the concentrations of Ca, Na, K, Rb, Cs, Fe, Co, Zn, Cr, Sc, Br, Se, Hg, Ag, Sb, Au, and Sn in aliquots of all foods consumed and all urine and fecal specimens collected during the mission. With appropriate documentation of all diets and excretion samples, the mass balance of each of these elements will be determined as a function of time, and any gains or losses will be checked for correlation with any observed physiological or psychological anomalies. Any worsening conditions will be reported along with their possible consequences and remedies.

It is anticipated that this study will require 12 man-months of effort for the number of specimens predicted, based on the planned Project Skylab duration. Battelle-Northwest has had excellent success in determining the concentrations of these elements in aliquots of returned fecal specimens and postflight urine specimens from the Apollo series missions utilizing this technique of instrumental neutron activation analysis. Unfortunately, no inflight urine specimens were collected so the quantities of elements excreted had to be calculated on the basis of normal fecal excretion percentages. The food samples used on these missions have not yet been analyzed for all the above elements, but excellent mass balance results have been obtained for calcium, potassium, and iron based on intake values determined by NASA. Thus the capability to do an accurate mass balance study ($\pm$ 5%)

by neutron activation techniques has been demonstrated by Battelle-Northwest. Since plans for the first manned Skylab mission call for collection of aliquots of all feces and urine and documentation of all dietary intakes, the complete mass balance study should most certainly be implemented.

EXPENDITURES

The following table documents the expenditures according to task and total cost incurred from October 5, 1970 through January 3, 1971 for the work reported herein.

TASK	EXPENDITURES
Determination of the Radionuclide Content of Feces and Urine From Astronauts Engaged in Space Flight	$5,447
Neutron Activation Analysis of Feces and Urine From Astronauts Engaged in Space Flight	$6,809
Search For Lunar Atmosphere	$ 702
TOTAL COSTS	$12,958

REFERENCES

1. P. C. Rambaut, National Aeronautics and Space Administration, Manned Spacecraft Center, Private Communication (1970).

2. R. L. Brodzinski, "The Measurement of Radiation Exposure of Astronauts by Radiochemical Techniques," July 6, 1970 Through October 4, 1970, BNWL-1183 6 (1970).

APPENDIX A

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THE MEASUREMENT OF RADIATION EXPOSURE OF ASTRONAUTS BY RADIOCHEMICAL TECHNIQUES[a]

R. L. Brodzinski

ABSTRACT

Astronauts engaged in space flight are subjected to cosmic radiation which does biological damage to, and induces radioisotopes in, their bodies. Theoretically, the radiation dose received from the cosmic particles can be determined from a measurement of the quantity of induced radionuclides. The concentrations of these induced radioactivities can be determined by direct techniques, such as whole-body counting, or by indirect procedures, such as the analysis of the radionuclides excreted in the feces and urine. The latter approach has been utilized in the evaluation of radiation activation during the manned Apollo missions.

The principal gamma-ray-emitting radioisotopes produced in the body by cosmic-ray bombardment which have half-lives long enough to be useful are ^{7}Be, ^{22}Na, and ^{24}Na. The sodium isotopes were measured in the preflight and postflight urine and feces, and those feces specimens collected inflight, by analysis of the urine salts and the raw feces in large crystal multidimensional gamma-ray spectrometers. The ^{7}Be was chemically separated, and its concentration measured in an all NaI(Tl), anticoincidence shielded, scintillation well crystal.

(a) A paper to be presented at the National Symposium on Natural and Manmade Radiation in Space on March 1, 1971.

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The overall sensitivity of the experiment was reduced by variables such as low concentrations of excreted cosmogenic radionuclides, high concentrations of injected radionuclides, low sample sizes, long delay periods before analysis, and uncertain excretion rates. The astronaut radiation dose in millirads, as determined by this technique, for the Apollo 7, 9, 10, 12, and 13 missions was 430 ± 310, <325, 870 ± 550, <180, and <250 respectively. In view of these limitations this technique would be best applied to cases of unusually high exposures, such as that encountered from solar flares.

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APPENDIX B

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CALCIUM, POTASSIUM, AND IRON LOSS BY APOLLO VII, VIII, IX, X, AND XI ASTRONAUTS[a]

by

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January 18, 1971

(a) This paper is based on work supported by the National Aeronautics and Space Administration - Manned Spacecraft Center, Houston, Texas, under Contract AT(45-1)-1830 between the United States Atomic Energy Commission and Battelle-Northwest.

ABSTRACT

A technique of instrumental neutron activation analysis has been employed to determine the concentrations of seventeen elements in astronaut fecal samples collected during the course of the United States Apollo 7 through 11 space missions. The quantities of three of these are compared to dietary intake values in determining the elemental mass balance of the astronauts. Elemental losses of 635 mg Ca/day, 296 mg K/day, and 6.4 mg Fe/day were observed, and some possible consequences of the imbalance are discussed. Enhanced osteoporosis due to the weightless conditions of the space environment is shown to be an insignificant problem for reasonably short duration missions (~ 14 days). The applicability of various techniques for determination of calcium loss is discussed.

INTRODUCTION

The conditions of weightlessness and prolonged physical inactivity of astronauts during extended space flight have raised questions regarding the possibility of changes in the concentration of the elements within the body similar to the terrestrially observed phenomenon of osteoporosis, the loss of skeletal calcium. A decrease in skeletal density is a natural occurrence among the aged, particularly in women, and may be artifically accelerated during periods of bedrest, immobilization, and water immersion. A conference on the development of methods in bone densitometry was organized by the National Aeronautics and Space Administration to deal with the possibility of enhanced osteoporosis in astronauts actively engaged in space flight. The published results of this conference[12] and other conferences on the same subject[13,11] provide excellent summaries of the various bone densitometry methods which include X-rays, beta excited X-rays, radioisotopes, sonic vibration, and neutron activation analysis procedures. Earth-based X-ray methods have been employed for the Gemini, Biosatellite, and Apollo missions[12,8] although this technique deals with the density changes of only a specific bone(s) of the body.

A more complete investigation should cover the total loss of calcium from the astronauts bodies. Calcium comprises about 20% by weight of bone and is also extremely important in the body serum where an imbalance can be responsible for a host of adverse physiological responses such as nausea, diarrhea, hyperexcitability, and polyuria. The results of X-ray densitometry measurements on a particular bone(s), usually the os calcis

(heel) or a phalanx (finger), are customarily extrapolated to a loss of calcium from the entire body even though a nonrepresentative change in density, particularly of the os calcis, is highly likely. Measurement of the calcium loss and interpretation of the results to reflect the average bone density changes appears much more desirable. In addition to allowing conclusions to be drawn regarding various other maladies occasioned by calcium deficiencies, the inherent radiation dose from the X-ray exposure can be avoided.

Two methods for measuring total calcium loss are whole body <u>in vivo</u> neutron activation analysis[9] and mass balance of the ingested and excreted calcium. The <u>in vivo</u> activation analysis technique is limited by practical considerations to a precision of about ± 2% change in total body calcium and an accuracy of about ± 8%. This technique shows advantages for measuring serial changes of a few elements over long periods of time ($\gtrsim$ 30 days). The mass balance study is more suited for greater sensitivity and for measuring the changes in more elements, which are responsible for maintaining stability in other physiological and psychological areas. In practice an average mass balance is more rewarding than the ideal day to day mass balance study. While the phenomenon of osteoporosis is of primary concern, the changes in the body content of other essential elements are also important. Constituents such as cobalt, iron, selenium, sodium, and potassium play an important part in the metabolic processes of the body. Radical changes in their excretion rates by astronauts may result in physical and/or mental disparities which could alter the progress of a mission. Other elements, such as bromine, with as yet unspecified biological functions may also be important in this respect. Although the chemistry of the bone primarily involves calcium compounds, other metals can also play an important role as factors or co-factors in enzyme or hormone systems essential to the mineralization process. In order to examine the inflight mass balance of as many of the body elements as possible, a technique of instrumental neutron activation analysis has been applied to the fecal samples collected during the course of a mission and stored onboard the spacecraft and to the urine specimens collected immediately prior to and following the mission. The results of these analyses for each mission have been compared to a partial list of elemental intakes furnished by NASA[14], and the degree and possible consequences of the imbalances are reported herein.

EXPERIMENTAL PROCEDURES

A sensitive multielement technique of instrumental neutron activation analysis developed specifically for the measurement of minor, trace, and ultratrace elements in biological systems[15] has been employed to simultaneously measure the concentrations of Ca, Na, K, Rb, Cs, Fe, Co, Zn, Cr, Sc, Br, Se, Hg, Ag, Sb, Au, and Sn excreted in the feces of astronauts during extraterrestrial activity. The fecal samples were thoroughly mixed in their collection bags to insure homogeneity, and a few hundred milligram aliquot was transferred directly to a preweighed polyethylene irradiation capsule, freeze dried to a constant weight, and sealed in the polyethylene container. The samples, together with their comparator standards, were irradiated in a Hanford production reactor to an integrated thermal neutron exposure of $\sim 2 \cdot 10^{17}$ n cm^{-2}. The samples were permitted to decay several days prior to gamma-ray analysis.

All samples and standards were thoroughly mixed in 2% solutions of agar agar and transferred quantitatively to standard counting geometries consisting of 1/2-inch thick by 2-inch diameter polyvinylchloride rings. After the agar agar solution solidified, the samples and standards were counted for ten minutes on a spectrometer system utilizing a 20-cm^3 Ge(Li) detector housed in a 10-cm-thick lead, cadmium-copper-lined shield for determination of the neutron-induced radioisotopes ^{24}Na, ^{42}K, ^{47}Ca (^{47}Sc), ^{76}As, ^{82}Br, and ^{198}Au. The samples were then allowed to decay for approximately one month before being counted for 1000 minutes on the same diode for determination of the following radionuclides: ^{46}Sc, ^{51}Cr, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{75}Se, ^{86}Rb, ^{124}Sb, ^{134}Cs, and ^{203}Hg. All spectra were recorded in one half of a 4096 channel analyzer. Typical gamma-ray spectra of neutron-activated fecal material taken after appropriate decay intervals are presented in Figure 1. After a further decay period of approximately one month, the samples and standards were counted on large volume NaI(Tl) multiparameter gamma-ray spectrometers[16,18] for 1000 minutes to quantitatively determine ^{46}Sc, ^{60}Co, ^{65}Zn, ^{110m}Ag, and ^{124}Sb. These instruments utilize two principal sodium iodide crystals, between which the sample is positioned, and which are surrounded by an anticoincidence shield which provides both background and Compton reduction. The signals from the two principal sodium iodide crystals are fed to two analog to digital converters of a multiparameter analyzer which stores both single and coincidence events according to the energy loss in each detector. The three separate counts of each sample are to insure the maximum statistical accuracy for both the short- and long-lived radionuclides and to cross-check the results between different detectors.

The concentration of each element was calculated by direct comparison of the activity of each radionuclide in the samples with that in the standards. All results are considered to have uncertainties of ± 10%. The major uncertainties in the neutron activation procedure arise from two sources: counting statistics and sampling techniques. Counting statistics represent errors of less than 5% for the determination of all elements except Hg, Au, and Sn, which are measured to approximately ± 10%. The uncertainties arising from sampling techniques and contamination during the initial sample handling are believed to cause errors of only a few percent. Comparing the precision of this technique to other known methods of trace element analysis, the sampling error is equal to or lower than that for any other method. In addition, errors associated with measurement (other than statistical), calibration, and chemical separations (particularly reagent contamination), which are prevalent in other techniques, do not arise in this technique of instrumental neutron activation analysis.[15]

The amounts of calcium, sodium, potassium, and iron taken in by the astronauts during flight have been furnished by the National Aeronautics and Space Administration[14] based on an analysis and inventory of the foodstuffs used in the Apollo series missions. The foodstuffs have not yet been analyzed for the other 13 elements determined in the feces; therefore, only preliminary estimates of their imbalance can be made based on normal intake values.

RESULTS

Most of the fecal samples were undocumented with respect to the astronaut and the elapsed time into the mission, and only integrated excretion rates could be measured. In order to determine the average

daily fecal excretion rates, the total weight of each element measured in the feces was divided by the number of participating astronauts and the number of flight days involved. No inflight urine specimens were collected, but trace element analysis of the preflight and postflight specimens indicated urinary excretion percentages which were in the range of those normally expected.[4, 3] The quantities excreted in the urine, therefore, do not perturb the conclusions drawn from the quantities measured in the feces.

The results of the calcium balance study are presented in Table I for the Apollo 7 through 11 missions. For the Apollo 7, 10, and 11 missions the fecal samples were not identified as to astronaut; therefore, average values are given. The commander was the only participating astronaut in Apollo 8, and in Apollo 9 the samples were identified as belonging to the commander, the lunar module pilot, or the command module pilot. All calcium intake values given in the table were furnished by NASA.[14] Since the percentage of total calcium excretion by way of the feces normally varies from 69.4% to 91.6%[1, 17], an average fecal excretion percentage of 80% was used to determine the total amount of calcium excreted. The overall averages shown in the table are for a unit astronaut-day. The average of the Apollo 7, 10, and 11 missions are weighted by a factor of three and summed with the individual averages of the other missions. The total is then divided by 13, the number of participating astronauts, to arrive at the overall averages. The ratio of calcium excretion to intake is 1.83, which could be as high as 2.11 or as low as 1.60 depending on the percentages of excreted calcium in the feces. It is worthy to note that the average ratio was 2.81 for the Apollo 7, 8, and 9 missions and dropped to 1.23 for the Apollo 10 and 11 missions. This is due equally to an increased calcium intake[14] and a decreased calcium excretion for the latter two missions. The average rate of calcium loss determined in this work is 635 mg per day, a value that could be as low as 455 or as high as 846 mg per day if the percentage fecal excretion is at the above given extremes. Of major significance is the change in loss rate from 990 mg/day for the first three missions to 220 mg/day for the next two missions. It appears that body calcium loss dropped by approximately four- to five-fold during the course of the first five manned missions in the Apollo series.

A loss of 635 mg/day for a standard 70 kg man amounts to only 0.0605% of his total body calcium[16], or a loss of only 1% during the course of a 16-day mission. If indeed the present rate of calcium loss is only 220 mg/day, the total body inventory loss would be only 0.021% per day, or a loss of 1% in a 48-day mission. If the fecal excretion percentage were high during these missions, the present rate of calcium loss by the astronauts could be as low as 77 mg per day: a total body inventory loss of 0.0073% per day, which would require a 140 day mission for a loss of 1% of the body calcium. This is indeed an insignificant calcium loss for anything but the most extended missions.

The sodium analyses of the fecal samples are of questionable value because of the addition of uncertain amounts of sodium orthophenylphenol, a bactericide, to the specimens. The average daily intake and excretion of potassium are presented in Table 2. A fecal excretion percentage of 16.5%[1] was used to estimate the total amount of potassium excreted.

The average of all data in the table indicate that the potassium excretion exceeds the intake by a factor of 1.19, but, as with calcium, the ratio for the first three missions is high, 1.50, while the latter two show an average ratio of 1.00, perfect balance. This is due principally to reduced excretion in the latter missions. The rate of potassium loss for the five missions is 296 mg/day, which amounts to only 0.16% of the total body content,[16] but again this rate was dropped from 668 mg/day for Apollo 7, 8, and 9 to 48 mg/day for Apollo 10 and 11, a reduction factor of 14. As a loss rate this certainly seems within expectations, particularly when the average daily weight loss is 0.45%[2] of the total body weight for these astronauts.

Table 3 shows the average daily intake[14] and excretion of iron for these Apollo mission astronauts. Since most eliminated iron is normally found in the feces,[1] the measured fecal concentrations are assumed to represent all excreted iron. As the data indicates, the excretion exceeds the intake by a factor of 1.9 on the average, and there is no significant difference between the three earlier missions and the two later ones as was the case with calcium and potassium. The average rate of iron loss is 6.4 mg/day, and again there is no apparent difference between the earlier and later missions. This loss rate corresponds to 0.16% of the total amount of body iron[16] per day or a loss of 1% every six days, which could prove to be of very substantial significance.

DISCUSSION

Roentgenographic techniques were used by Mack, et al.[8] to study bone demineralization in the Gemini IV, V, and VII astronauts.

Their investigation was restricted to the os calcis, the talus, hand phalanges 4-2 and 5-2, and the capitate. A minimum loss of 2.46% in bone density was reported for the 14 day Gemini VII mission command pilot's os calcis. Loses for all sites and other missions ranged up to a maximum reported value of 23.20% for the eight day Gemini V command pilot's hand phalanax 5-2. If the reported values of bone loss can possibly be construed to represent total body calcium loss, a large discrepancy exists between these earlier missions and the Apollo series missions. However, it is likely that the reported bone mineral loss did not reflect true whole body calcium loss. These roentgenographic results themselves are perhaps dubious in light of the large variation in losses reported not only for different anatomical sites from the same astronaut but also for adjacent scans in the same bone.

Calcium losses as small as those determined here for the first five manned Apollo missions can only be measured by the mass balance technique. Average body calcium losses were 0.56%, 0.54%, 1.21%, 0.055%, and 0.26% of total body calcium for the Apollo 7 through 11 missions, respectively, assuming that all astronauts are composed of 1.5% calcium by weight.[10] The average loss rate is only 1% of total body calcium every 18 days which is certainly not significant for the reasonably short duration missions planned for the foreseeable future. In fact, at this measured rate of loss, a one and one-half year mission would be necessary to loose 30% of the body calcium. Such a bone density loss is not uncommon for "normal" osteoporosis.[6] If the calcium loss rate in future missions is actually as low as that for the Apollo 10 and 11 missions,

due to improved exercises and/or diet, it would take over four years in space to lose 30% of the body calcium.

Gains or losses of sodium and/or potassium could be very significant since proper electrolyte balance is essential to the normal functioning of the nervous system, as well as establishing the osmotic balances necessary for the transfer of essential material across cellular membranes. The potassium losses estimated in this work are demonstrated to be negligibly small. A perfect mass balance would be obtained if the assumed 16.5% fecal excretion of potassium were actually 19.6%. Sodium excretion values could not be estimated because of the addition of uncertain amounts of the bactericide sodium orthophenylphenol to the specimens. However, best estimates of sodium loss based on preflight and postflight urine concentrations indicate the balance was as good as that for potassium. These difficulties and the uncertainty of the fecal excretion percentage of all elements could be eliminated if an aliquot of each urination during the mission were collected and returned.

The necessity of iron for the synthesis of hemoglobin, transportation of oxygen in the bloodstream, transfer of oxygen to tissue cells, and erythropoiesis demands a close balance of this element in the body. The loss rate reported in this communication is a minimum rate since no allowances have been made for losses by mechanisms other than fecal excretion. Loss in the urine, hair, nails, sweat, etc., would make the reported mass balance even more negative. If the rate of iron loss determined for these short duration missions remains constant over much longer missions, iron deficiency anemia and its many manifestations could become a serious problem for astronauts, and means of reducing the loss or increasing the uptake will have to be considered before deep space missions can be undertaken without the risk of iron depletion. One possible reason for elimination of iron by the astronauts is that an oxygen rich atmosphere in the spacecraft reduces the normal or preflight hemoglobin concentrations. Since hyperoxygenation is not required by the body, the physiology of the body will eliminate the unnecessary iron as the erythrocytes mature and are destroyed, as happens constantly. If hemoglobin loss is the cause of the iron loss, the rate of reduction should decrease as the equilibrium hemoglobin concentration is reached. The reported hemoglobin concentrations[2] measured immediately postflight do not substantiate this theory and, in fact, indicate increased hemoglobin in two instances. However, in one of those instances, there was also an increase in hematocrit, and in the other there was a decrease in red blood cells. These two factors may offset the apparent hemoglobin increase. A serialized study would elucidate this possibility. The measured rate of iron loss in the astronauts is approximately six times the normally expected loss rate.[7] It has been suggested[5] that such a massive loss of iron could only be caused by hemorrhage, a possibility which could be checked by preflight administration of radiochromium tagged red cells to the astronauts.

If a precise elemental analysis of the foodstuffs used during those missions can be made utilizing the techniques of instrumental neutron activation analysis considered here, the mass balance for all elements measured in the excreta could be determined. Continued analysis of returned fecal samples will indicate if loss of calcium and potassium

continues at the apparently reduced rate of the Apollo 10 and 11 missions and if continued high losses of iron are indicated. Of equal or perhaps even greater importance is a mass balance analysis of certain other essential and trace elements. If measurements of excretion could be made as a function of time during the course of a mission, more subtle effects of the metabolism of essential or detrimental elements could be detected. Perhaps some losses are large in the early stages of the mission and diminish as the astronauts become acclimated to their environment, or perhaps the converse is true and the loss rates are becoming more serious with increased time in space. Acclimation to the spacecraft environment may very possibly alter the astronauts trace element metabolism in a way that would eventually effect essential enzyme processes. The technical difficulties of such a time study would include recording the time, quantity and type of all foods consumed and the time of each defecation by each astronaut. It would be very desirable if this record keeping system and the collection of inflight urine specimens can be instituted on missions of future projects such as Project Skylab in order that the above-mentioned questions can be resolved.

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TABLE 1

AVERAGE DAILY CALCIUM INTAKE AND EXCRETION BY APOLLO ASTRONAUTS

Mission	Astronaut	Intake(6) (mg)	Fecal Excretion (mg)	Total Excretion* (mg)	Ratio of Excretion To Intake	Mass Balance (mg/day)
Apollo 7	Average	836	1140	1430	1.70	- 590
Apollo 8	CDR	427.2	1150	1440	3.36	- 1010
Apollo 9	CDR	562.5	1190	1490	2.64	- 930
Apollo 9	LMP	494.3	1100	1380	2.78	- 880
Apollo 9	CMP	489.0	2260	2830	5.78	- 2340
Apollo 10	Average	832.9	730	910	1.10	- 80
Apollo 11	Average	1000.3	1090	1360	1.36	- 360
Averages		767.7	1120	1400	1.83	- 635

* Based on 80% fecal excretion

TABLE 2

AVERAGE DAILY POTASSIUM INTAKE AND EXCRETION BY APOLLO ASTRONAUTS

Mission	Astronaut	Intake(6) (mg)	Fecal Excretion (mg)	Total Excretion* (mg)	Ratio of Excretion To Intake	Mass Balance (mg/day)
Apollo 8	CDR	1229	499	3020	2.46	- 1795
Apollo 9	CDR	1677	253	1540	.916	+ 141
Apollo 9	LMP	1386	276	1670	1.21	- 286
Apollo 9	CMP	1708	403	2440	1.43	- 732
Apollo 10	Average	1340	176	1070	.797	+ 272
Apollo 11	Average	1751	350	2120	1.21	- 367
Averages		1527	300	1820	1.19	- 296

* Based on 16.5% fecal excretion

TABLE 3

AVERAGE DAILY IRON INTAKE AND EXCRETION BY APOLLO ASTRONAUTS

Mission	Astronaut	Intake[6] (mg)	Excretion* (mg)	Ratio of Excretion To Intake	Mass Balance (mg/day)
Apollo 7	Average	8.1	15.7	1.9	- 7.6
Apollo 8	CDR	5.0	13.3	2.7	- 8.3
Apollo 9	CDR	7.1	11.6	1.6	- 4.5
Apollo 9	LMP	5.9	13.2	2.2	- 7.3
Apollo 9	CMP	6.5	17.2	2.6	- 10.7
Apollo 10	Average	5.1	6.7	1.3	- 1.6
Apollo 11	Average	8.0	16.4	2.1	- 8.4
Averages		6.8	13.2	1.9	- 6.4

* Assuming 100% fecal excretion

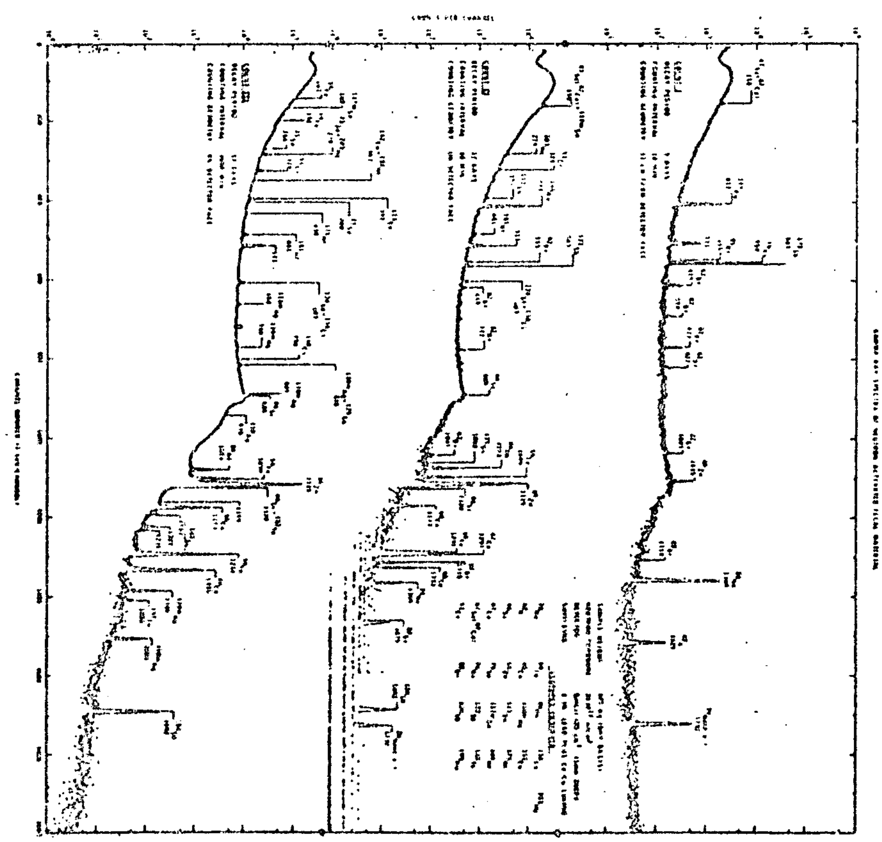

Fig. [illegible] Gamma Ray Spectra of Neutron Activated Fecal Material