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Argonne National Laboratory

RADIOLOGICAL PHYSICS DIVISION

ANNUAL REPORT

JULY 1964 THROUGH JUNE 1965

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FURTHER EVIDENCE FOR A HIDDEN TRANSITION IN BIPHENYL*

I. B. Berlman and O. J. Steingraber

A broad structureless peak, as observed in the absorption spectrum of biphenyl in a cyclohexane solution, is normally indicative of a single electronic transition. However, a hidden transition in biphenyl has been conjectured^(1, 2) and recently substantiated.⁽³⁻⁶⁾

Further evidence of a hidden transition has been obtained from fluorescence measurements of cyclohexane solutions of biphenyl and substituted biphenyls. The natural fluorescence lifetime, τ_0 , as computed from Förster's⁽⁷⁾ formula (an integral over an absorption band) is approximately 30 times smaller than that computed from the ratio, τ/Q , where τ and Q are the fluorescence decay time and quantum yield, respectively. This large discrepancy suggests that one

method (integral) is incorrect. We believe that the error arises from the assumption that the absorption band corresponds to a single transition, whereas in actuality it results from at least two transitions, with the transition leading to fluorescence being hidden in the long wavelength end of the absorption spectrum.

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* Submitted as a note to the Journal of Chemical Physics.

MIRROR SYMMETRY AND SPECTRA OF AROMATIC MOLECULES: PRELIMINARY REPORT

I. B. Berlman, F. Hirayama, and M. Inokuti

The absorption spectrum of an aromatic molecule in the visible and near ultraviolet region, under normal experimental conditions, is produced by transitions from the zero vibrational level of the ground electronic state to various vibrational levels of an excited electronic state. These transitions involve an excitation of a π electron into one of the lowest unoccupied orbitals. The fluorescence spectrum of a liquid solution corresponds to transitions from the zero vibrational level of the excited electronic state (singlet) to various vibrational levels of the ground electronic state. The transitions originate in the zero vibrational level of the upper state because vibrational relaxations are usually faster than radiative transitions. The oft-repeated and ambiguously worded statement that "mirror symmetry" exists between an absorption spectrum and the associated fluorescence spectrum has been based solely on visual inspection of observed spectra.

Under certain simplified assumptions concerning potential energy surfaces and the electronic part of the transition matrix element, Förster⁽¹⁾ has shown that mirror symmetry should occur between $\epsilon(\nu)/\nu$ and $f(\nu)/\nu^3$, where $\epsilon(\nu)$ is the molar extinction coefficient and $f(\nu)$ is the fluorescence intensity, both as a function of the wave number, ν , of the photon involved. The validity of this kind of mirror symmetry is being systematically and quantitatively studied by analyzing experimental data on many aromatic molecules.⁽²⁾ It is hoped that the analysis will bring out an improved understanding of the basic properties of the electronic excited state.

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SCINTILLATIONS AND ENERGY TRANSFER IN ARGON-NITROGEN MIXTURES*

Harvey A. Schultz

Pulse-height measurements are made on scintillations produced by the complete stopping of alpha particles in gaseous argon, nitrogen, and argon-nitrogen mixtures. The results are correlated with the published results of spectrographic studies to derive information about energy transfer in collisions among Ar and N₂ molecules.

The optical system responds to light within the spectral range 2200–6000 Å. Total pressures vary from 3.5 to 6 atmospheres. It is observed that the pulse height is greatest for pure argon. As nitrogen is added, the pulse height decreases, then increases, and finally

decreases again. From this behavior and the effect of total pressure, it is concluded that the detectable light consists of three components: (1) that emitted by argon excited directly; (2) that emitted by a nitrogen state, probably C³Π_u, excited by energy transfer from an argon state that does not emit in the detection range, apparently the lower metastable state; (3) that emitted by nitrogen excited directly. The states that emit components (1) and (2) are quenched by nitrogen in the ground state. For three pairs of competing processes, one pair associated with (1) and two with (2), values of the product (lifetime) × (cross section) × (relative velocity) are obtained by fitting kinetic equations to the pulse-height data. The breakdown of the products into individual factors is discussed.

* Abstract of a paper submitted for publication in the Journal of Chemical Physics.

ION-ION RECOMBINATION RATES IN THE GAS PHASE*

James C. Person

The rate of neutralization of ionic charges is one of the major factors in determining the ion concentration in any ionized medium. The positive ions may be neutralized by electrons (ion-electron recombination) or by negative ions (ion-ion recombination). Therefore, ion-ion recombination rates give important information concerning the radiation chemistry of systems containing electronegative gases.

This report gives general information, both experimental and theoretical, on ion-ion recombination rates

as functions of the total gas pressure. Particular emphasis is given to the results of Mahan and Person^(1, 2) and Carlton and Mahan⁽³⁾ on the role of neutral gas molecules in determining the pressure dependence and on the low-pressure rate for ions produced by photoionization of NO.

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* Abstract of a paper presented at the Gordon Conference on Radiation Chemistry, New Hampton, New Hampshire, July 27–31, 1964.

PHOTOIONIZATION, EXCITATION, AND DISSOCIATION*

James C. Person

This paper reviews the use of monochromatic vacuum ultraviolet light to obtain information about the

primary processes which occur when ionizing radiation interacts with individual molecules. Examples of

* Abstract of an invited paper presented at the Radiation Research Society Symposium on Effects of Vacuum Ultraviolet

Radiation: Implications for Radiation Biology, Philadelphia, Pennsylvania, May 25, 1965.

vacuum-ultraviolet studies which provide qualitative or quantitative information on the nature of the primary products are discussed; among these are the determination of electronic states, dissociation products, and molecular geometries. Also, examples are given of oscillator strength distributions, which are used for predicting the number of primary products produced

in the various states. Results are presented on the recently-discovered isotope effect in the photoionization efficiency for benzene as an example of a study which provides information on the intramolecular reaction rates of the primary products, as well as information on the oscillator strength distribution.

AN ISOTOPE EFFECT IN THE PHOTOIONIZATION EFFICIENCY FOR BENZENE*

James C. Person

It has been known for some time that polyatomic molecules possess excited states lying above I , the ionization potential, in which primary excitation does not necessarily lead to ionization.⁽¹⁾ Platzman showed that these *superexcited* states are continuously distributed up to excitation energies, E , considerably greater than I and possess a substantial fraction of the total oscillator strength of the valence electrons.^(2, 3) Moreover, he gave arguments showing that ionization occurs to a large extent via preionization of an intermediate superexcited state, rather than by direct ejection of an electron during the excitation act.[†] This led to prediction of an isotope effect in the ionization efficiency, η (the probability that excitation will produce an ion pair), since preionization processes, presumably nearly invariant under isotopic substitution, compete with atomic rearrangement processes, such as dissociation, which are slower in heavier isotopic molecules. This prediction has been confirmed in the cases where ionization is produced by collision with metastable atoms,^(9, 10) by β particles,⁽¹¹⁾ and by 70-eV electrons.⁽¹²⁾ Theoretical analysis of the β -particle result showed that there must be an isotope effect in photoionization,⁽³⁾ but such an effect has not been directly measured heretofore. The purpose of the present experiment is to test this theoretical conclusion and to obtain quantitative information on $\eta(E)$ for both C_6H_6 and C_6D_6 .

The experimental apparatus included a hydrogen discharge light source, a McPherson Model 225 vacuum monochromator (used with a 2-A band width), and a dual-beam detector system.⁽¹³⁾ Ionization currents were

collected by parallel-plate electrodes in the 5.1-cm-long ionization cell, and gas pressures in the cell, which had LiF windows, were measured with an MKS Baratron capacitive manometer. The isotopic purity of the perdeuterobenzene was over 99 atom % D (with the main isotopic impurity being 2.1% C_6D_5H), and chemical impurities were undetectable with a sensitivity of 0.1% in either the Volk Radiochemical Company C_6D_6 or in the Phillips Petroleum Company Research Grade C_6H_6 . The absolute light intensity was determined at each photon energy by measurements on nitric oxide, using Matsunaga's values of η .*

The measured values of η_H (for C_6H_6) and η_D (for C_6D_6) at 48 photon energies between 9.21 (just below $I = 9.25$ eV⁽¹⁷⁾) and 11.64 eV are plotted in Figure 1, together with the absorption cross sections, σ_H and σ_D . The points are connected by lines, but more points are required to bring out the complete structure. Table 1 contains the values of the photoionization cross section, σ_i ($\sigma_i = \eta\sigma$), as well as the values of η and σ for C_6H_6 and C_6D_6 . Estimates of the error in the σ measurements, δ_σ , are also given in Table 1, with the values being chosen so that, with a 90% level of confidence, the true value of σ should be between $\sigma - \delta_\sigma$ and $\sigma + \delta_\sigma$. Since the values of δ_σ were approximately equal for σ_H and σ_D at each E , only the average value of δ_σ is given in the table. The percentage error in η_D/η_H is estimated to be somewhat greater than the percentage error in the σ measurements at the same photon energy, but the percentage uncertainty in the absolute values of η (and σ_i) is larger because of the 10% uncertainty in η for NO.⁽¹⁸⁾

Our values of σ_H agree with those found by Goto⁽¹⁹⁾

* This is an amplified version of a paper published in *J. Chem. Phys.* **43**, 2553 (1965).

† Other criteria for the presence of preionization processes are peaks in $\sigma_i(E)$ ⁽⁴⁻⁷⁾ and lack of agreement between experimental ionization cross sections and cross sections calculated assuming direct ionization.⁽⁸⁾

* These values⁽¹⁴⁾ are recommended by Watanabe to supersede the values given in the literature.⁽¹⁵⁾ Notice that the η values in the published version of this report⁽¹⁶⁾ were based on Watanabe's values of η for NO.

FIG. 1. Absorption cross sections and photoionization efficiencies of C_6D_6 and C_6H_6 as functions of photon energy. The left-hand scale is for the absorption cross sections, σ_D and σ_H , while the right-hand scale is for the photoionization efficiencies, η_D and η_H . The points for C_6D_6 are represented as squares and are connected with broken lines, while those for C_6H_6 are circles connected with solid lines. Jesse's values for ionization by the Penning effect (Reference 10) are plotted as X's for η_{CD} and as +'s for η_{CH} .

below 10.5 eV, but they are 10–25% lower than his values at higher energies. Bunch, *et al.*,⁽²⁰⁾ found σ_H values about 15% higher than our values. No previous measurements of σ_D have been reported. The values of η_D and η_H may be compared with the efficiencies for ionization by the Penning effect, η_{CD} and η_{CH} , determined by Jesse⁽¹⁰⁾ (See Figure 1). Jesse's values of η_{CD}/η_{CH} are 1.16, 1.11, and 1.08 at 9.44 eV, 10.3 eV, and 11.6 eV, respectively, whereas our values of η_D/η_H at the same energies are 1.05, 1.08, and 1.03, respectively. Our values of η agree roughly with Jesse's values of η_c ; the differences may be due to experimental error, to the indirectness in the interpretation of Jesse's results, or to the different processes of imparting the excitation energy.

A comparison of our values of σ_D and σ_H shows shifts in the positions of the absorption maxima, and the average absorption at each photon energy seems to be

about 3% less for C_6D_6 than for C_6H_6 . The average value of η_D/η_H is 1.07 to 1.08 when the ratio is evaluated at each energy. Although it should be better to compare each η_D with the η_H at an energy corresponding to the isotope shift in absorption (which requires more data than are presently available), Figure 1 shows that any average of η_D will be greater than the average of η_H , so that the predicted isotope effect has been observed. A practical aspect of these results is confirmation of the prediction⁽³⁾ that deuterated compounds can be used to increase the efficiency of photon detectors when hydrogen-containing gases are used.^(21, 22)

The author acknowledges helpful discussions with Drs. R. L. Platzman and M. Inokuti on the interpretation of the results, and he also acknowledges the skillful assistance of Messrs. J. Ostapowicz, S. Omiecinski, R. F. Selman, and E. J. Fudala in the construction of the apparatus.

TABLE 1. OPTICAL PROPERTIES OF C_6H_6 AND C_6D_6 AT VARIOUS PHOTON ENERGIES

E (eV)	σ_H (10^{-17} cm^2)	σ_D (10^{-17} cm^2)	$\delta\sigma$ (10^{-17} cm^2)	σ_{iH} (10^{-17} cm^2)	σ_{iD} (10^{-17} cm^2)	η_H	η_D	η_D/η_H	E (eV)	σ_H (10^{-17} cm^2)	σ_D (10^{-17} cm^2)	$\delta\sigma$ (10^{-17} cm^2)	σ_{iH} (10^{-17} cm^2)	σ_{iD} (10^{-17} cm^2)	η_H	η_D	η_D/η_H
9.21	3.05	3.03	0.06	0.15	0.17	0.05 ^(a)	0.06	1.165	10.32	3.94	3.75	0.05	1.97	2.03	0.501	0.540	1.078
9.24	4.34	3.14	0.08	0.37	0.34	0.085	0.108	1.274	10.43	4.44	4.59	0.11	2.12	2.30	0.478	0.502	1.051
9.26	3.48	3.98	0.06	0.49	0.50	0.140	0.125	0.891	10.48	6.12	4.88	0.10	2.49	2.33	0.407	0.477	1.172
9.28	3.51	3.88	0.07	0.49	0.51	0.14	0.13	0.942	10.50	5.63	5.03	0.10	2.43	2.41	0.432	0.480	1.111
9.29	3.53	3.79	0.06	0.51	0.52	0.144	0.138	0.955	10.52	4.78	5.86	0.09	2.22	2.72	0.465	0.465	1.000
9.37	4.33	4.27	0.09	0.84	0.86	0.194	0.201	1.037	10.54	5.32	4.88	0.13	2.41	2.47	0.453	0.507	1.120
9.44	4.01	3.93	0.07	0.96	0.99	0.239	0.251	1.051	10.63	4.91	5.00	0.09	2.38	2.61	0.484	0.521	1.076
9.52	3.95	3.76	0.08	1.29	1.29	0.327	0.344	1.051	10.65	5.40	4.78	0.08	2.43	2.51	0.451	0.524	1.163
9.56	3.65	3.69	0.09	1.31	1.34	0.36	0.36	1.013	10.68	5.41	4.76	0.09	2.42	2.48	0.448	0.520	1.160
9.59	3.73	3.61	0.06	1.40	1.44	0.375	0.400	1.066	10.77	5.01	4.58	0.08	2.25	2.36	0.449	0.515	1.148
9.61	3.59	3.47	0.07	1.46	1.48	0.406	0.426	1.050	10.79	4.96	4.97	0.08	2.18	2.41	0.440	0.485	1.102
9.64	3.50	3.44	0.06	1.51	1.54	0.43	0.45	1.037	10.82	5.77	4.94	0.10	2.45	2.49	0.425	0.504	1.186
9.66	3.49	3.42	0.05	1.65	1.68	0.474	0.492	1.039	10.88	6.87	5.34	0.22	—	—	— ^(b)	—	1.244
9.69	3.48	3.33	0.06	1.63	1.64	0.469	0.493	1.052	10.92	6.95	6.36	0.20	2.85	3.13	0.41	0.49	1.200
9.81	3.41	3.20	0.06	1.78	1.82	0.523	0.568	1.087	11.03	8.85	8.09	0.18	3.10	3.26	0.35	0.40	1.150
9.83	3.41	3.21	0.06	1.84	1.87	0.539	0.582	1.080	11.06	8.69	8.20	0.19	3.09	3.32	0.356	0.405	1.139
9.89	3.42	3.25	0.06	1.86	1.91	0.545	0.587	1.076	11.08	8.72	8.71	0.20	3.11	3.45	0.356	0.396	1.113
9.94	3.47	3.32	0.05	1.91	1.96	0.551	0.589	1.069	11.11	8.22	8.75	0.21	3.05	3.53	0.371	0.404	1.089
10.00	3.57	3.49	0.06	1.94	2.01	0.544	0.577	1.060	11.20	7.52	8.14	0.22	2.74	3.14	0.365	0.386	1.057
10.08	3.68	3.59	0.06	1.98	2.03	0.537	0.565	1.052	11.23	7.94	8.26	0.20	2.98	3.39	0.375	0.410	1.093
10.13	3.69	3.57	0.06	1.96	1.97	0.53	0.55	1.041	11.25	8.06	7.85	0.22	3.08	3.34	0.382	0.426	1.117
10.15	3.65	3.56	0.05	2.05	2.11	0.56	0.59	1.056	11.39	7.05	7.32	0.25	2.94	3.15	0.417	0.430	1.031
10.23	3.75	3.60	0.05	—	—	— ^(b)	—	1.076	11.46	6.75	7.06	0.31	3.40	3.61	0.504	0.512	1.017
10.28	3.84	3.68	0.06	2.00	2.05	0.520	0.556	1.070	11.64	6.02	6.10	0.44	2.75	2.85	0.456	0.468	1.026

^(a) The values quoted to only two places are somewhat less reliable than the other values.

^(b) The value of η_H (which was determined in a separate experiment for each of the 46 other photon energies) was not determined at this photon energy.

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COMPARISON OF AN ISOTOPE EFFECT IN PHOTOIONIZATION AND IN ELECTRON-IMPACT IONIZATION OF MOLECULES*

James C. Person

We have recently observed that the photoionization efficiency is greater for C_6D_6 than it is for C_6H_6 .⁽¹⁾ (The ionization efficiency, η , is defined as the probability of an ionization event when a molecule is excited; it is a function of E , the excitation energy.) Observation of this isotope effect corroborates the previous conclusion that much of the ionization of molecules is produced by preionization of highly excited states in which atomic rearrangements, such as dissociation, are competitive with ejection of an electron. These states, called superexcited states, have been discussed by Platzman,⁽²⁻⁴⁾ who has shown them to be continuously distributed from the first ionization threshold, I , up to excitation energies a few Rydbergs above threshold and to possess a substantial fraction of the total oscillator strength of the valence electrons. On the basis of a comparison of values of η at the same E but arising from different ionizing agencies, he has argued that a major portion of the ionization must result from the preionization of these states, and furthermore predicted that η will be increased in a molecule by substitution of heavier isotopic species. This isotope effect was subsequently observed in experiments with deuterated and normal molecules in which the ionization was produced by collision with metastable atoms,^(5, 6) by beta particles,⁽⁷⁾ and by 70-eV electrons.⁽⁸⁾ In this report we make a comparison of our data from photoionization with data from electron-impact ionization as a first test of the theoretical relationship between the two isotope effects.^(2, 4)

When the kinetic energy of the incident electron, T , is much greater than I , the Bethe asymptotic formula^(2, 4) leads to the conclusion that the total ionization cross section for electron impact, $Q_i(T)$, is proportional to M_i^2 , where

$$M_i^2 = 1.24 \times 10^{17} \int_I^\infty \frac{\sigma(E)\eta(E)}{E} dE, \quad (1)$$

the optical absorption cross section, σ , being expressed in cm^2 . The Bethe formula also contains a logarithmic factor which is expected to be approximately the same for isotopic molecules. Hence the ratio of total ionization cross sections in the example under consideration is given by

$$\frac{Q_{iD}(T)}{Q_{iH}(T)} = \frac{M_{iD}^2}{M_{iH}^2}, \quad (2)$$

where the subscripts D and H refer to C_6D_6 and C_6H_6 , respectively. When the optical values of $\sigma(E)$ and $\eta(E)$ are available only within the energy range $I \leq E \leq E_a$ it may be useful to define a partial value of M_i^2 , namely $M_i^2(E_a)$, as the value given by the right-hand side of equation (1) when E_a is the upper limit of integration. Since the values of $\sigma(E)/E$ become relatively small and $\eta(E)$ tends toward unity* for energies above about 30 to 35 eV in C_6H_6 or C_6D_6 ,⁽⁹⁾ the value of M_i^2 (30 eV) will be a fairly good approximation to M_i^2 for these molecules.

Our experimental data⁽¹⁾ consist of values of $\sigma(E)$ and $\eta(E)$ for 46 energies from I (9.25 eV)⁽¹⁰⁾ up to 11.64 eV. The resulting ratio of integrals gives M_{iD}^2 (11.64 eV)/ M_{iH}^2 (11.64 eV) = 1.045 ± 0.02 . This value may be compared with the value of 1.03 ± 0.01 which Meyerson *et al.*⁽⁸⁾ obtained for Q_{iD} (70 eV)/ Q_{iH} (70 eV). The close agreement between these two numbers is gratifying in that it is the first qualitative test of equation (2). However, it should be emphasized that equation (2) has not been tested quantitatively because of two shortcomings in the comparison: the values of both E_a and T are much too small. Both of these circumstances weight the contribution to equation (1) from the low values of E at the expense of the high values. That the quantitative agreement is so good, notwithstanding, may be understood if η_D/η_H at higher values of E is also about 1.04, a surmise which is supported by Jesse's results,⁽⁶⁾ $\eta_D/\eta_H = 1.047$ at 16.7 eV and 1.043 at 20.2 eV.

When more data become available, it will be valuable to compare values of $Q_{iD}(T)/Q_{iH}(T)$ and $M_{iD}^2(E_a)/M_{iH}^2(E_a)$ for various deuterated and normal molecules, at several values of T and E_a . Equation (2) holds when $T > 500$ to 1000 eV, and M_i^2 is approximately equal to $M_i^2(E_a)$ when $E_a > 30$ to 50 eV, but the comparison

* Abstract of a paper presented at the Fourth International Conference on the Physics of Electronic and Atomic Collisions, Quebec, August 2-6, 1965.

* Above $E = 26.4$ eV, double ionization can occur, and at sufficiently great energies still higher degrees of ionization may result. One should, therefore, define a set η_n of probabilities of n -fold ionization. The sum of η_n approaches unity as E increases. However, in experiments in which a *current* is collected, like those in References 1, 6, and 8 (but not in all measurements of ionization cross sections, some of which *count* ions), it is $\sum \eta_n$ that is pertinent, and this "effective" η will exceed unity in the high- E range in many cases.

of the right and left hand sides of equation (2) at lower values of T and E_a will provide a means of exploring the relationship between $Q_i(T)$ and $M_i^2(E_a)$ in the region where the Bethe asymptotic formula is no longer valid.

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INFLUENCE OF ENERGY TRANSFER BY THE EXCHANGE MECHANISM ON DONOR LUMINESCENCE*

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The decay of donor luminescence in a rigid solution when modified by electronic energy transfer by the exchange mechanism is treated theoretically. The rate constant for the elementary process of energy transfer is taken to be of the Dexter form, $\text{const.} \times \exp(-2R/L)$, where R is the donor-acceptor distance

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and L is a positive constant. Calculations are made of the yield and decay time of the donor luminescence as functions of the acceptor concentration. The resulting relationship among the above quantities enables one to analyze experimental data in a quantitative manner and, thereby, to obtain information about an intermolecular exchange interaction. As an example of such an analysis, Ermolaev's data on triplet-triplet transfer between some aromatic molecules are compared with our results, and very good agreement is found with a choice of the single parameter L .

SOME PROPERTIES OF THE GENERALIZED OSCILLATOR STRENGTH AND THEIR RELATION TO INELASTIC SCATTERING OF CHARGED PARTICLES*

M. Inokuti and R. L. Platzman

INTRODUCTION

Provided that the velocity is great enough that the first Born approximation is justified, the inelastic scattering of a charged particle of any charge and any velocity and at all scattering angles, with excitation of the scattering atom or molecule from the ground state to a particular excited state, n (discrete or continuum), is entirely embodied in a single function, $f_n(K)$, of a single scalar variable, K . This is the generalized oscillator strength of Bethe, and it plays a central role in Bethe's theory of inelastic scattering and stopping power.^(1, 2) An intrinsic property of the atom or mole-

cule, it constitutes an extremely important measure of the response of the system to certain external perturbations. In Bethe's theory the differential scattering cross section is given by

$$dQ_n = \frac{4\pi a_0^2 z^2}{T/R} \frac{f_n(K)}{E_n/R} d \ln (Ka_0)^2, \quad (1)$$

where ze is the charge of the particle, $K\hbar$ the momentum change in the collision, E_n the excitation energy of the state n , R the Rydberg energy, and $T = mv^2/2$, m being the electron mass. (For T exceeding about 10^4 eV, elementary relativistic corrections are required.) The factor $f_n(K)$ is the essential, and in many ways the non-trivial part of this expression.

* Abstract of a paper presented at the Fourth International Conference on the Physics of Electronic and Atomic Collisions, August 2-6, 1965, Quebec, Canada.

The generalized oscillator strength was defined by Bethe as

$$f_n(K) = (E_n/R)(Ka_0)^{-2} \left| \sum_i \langle n | \exp(i\mathbf{K} \cdot \mathbf{r}_i) | 0 \rangle \right|^2. \quad (2)$$

For molecules, appropriate averaging over molecular orientation and over internal degrees of freedom must be carried out, but this will not be dealt with here. (In his preeminent experiments on the inelastic scattering of electrons, Lassetre defines $f_n(K)$ by equation (1), dQ_n being the experimental cross section. Thus his $f_n(K)$ is an experimental quantity which is equal to the right-hand side of equation (2) only in the domain of validity of the Born approximation.)

THE BETHE SURFACES

Surprisingly little is known of the functions $f_n(K)$ —indeed, considerably more is known from the experiments of Lassetre than from basic theory. For the case of atomic hydrogen, the functions have been obtained in closed analytic form⁽¹⁻³⁾ (although incompletely, as noted below), and some short tabulations of numerical values are available in the standard references. A few other theoretical calculations for one- and two-electron systems, mostly for low-lying excitations, complete the list. The progress of theory has, of course, been obstructed by the lack of trustworthy wave functions for excited (and ionized) states, which are required in evaluating (2).

Miller and Platzman⁽⁴⁾ have shown that the generalized oscillator strength is conveniently and usefully represented as a plot of $f_n(K)$ vs. $\ln(Ka_0)^2$. For example, the total scattering cross section for excitation to the particular state n is simply proportional to the area under this curve, the upper and lower limits of K being determined by kinematical relations. More generally, one may consider a *Bethe surface*, namely, the surface of $f_n(K)$, as a function of E_n and $\ln(Ka_0)^2$. The stopping cross section is then given by the volume under the surface, the bounds again being established by kinematical relations. In the derivation of his famous stopping-power formula, Bethe relied chiefly on the generalized sum rule,

$$\sum_n f_n(K) = Z,$$

and on the property of the surface that when $E_n \gg I_n$, where I_n is the ionization potential of the electron shell pertinent to the excitation E_n , then $f_n(K)$ behaves like a delta function, $\delta(K^2 a_0^2 - E_n/R)$. The topography of the surface in the neighborhood of the *Bethe ridge*, $E_n = K^2 a_0^2 R$, was discussed in greater detail by Fano.⁽⁵⁾ Apart from this feature, which is decisive for the stopping power but is of secondary importance for inelastic

scattering cross sections, the character of the Bethe surface is largely unknown, both in general and in particular cases.

It is the purpose of this paper to discuss some features of the surface, especially in the low- K region, with particular emphasis on the determination of optical properties from scattering data and vice versa.

It is important first to distinguish between optically (dipole) allowed and forbidden transitions at the same (or experimentally indistinguishable) E_n . Thus, for normal atomic hydrogen, there is a family of surfaces $f_{nl}(K)$ corresponding to the groups of transitions $1s\text{-}ns$, $1s\text{-}np$, $1s\text{-}nd$, etc. (each including the continuum), of which only the second is optically allowed. Each of these surfaces has its own characteristic topography. Their sum at fixed E_n , $f_E(K) = \sum_l f_{nl}(K)$, is the

function that is pertinent to the stopping power and that has been discussed by Bethe and by Fano. It is not always appreciated that experimental inelastic scattering cross sections are sometimes the individual $f_{nl}(K)$ and sometimes the "total" $f_E(K)$. Thus, when Lassetre *et al.*^(6,7) determined the cross section for excitation of the $1^1S\text{-}2^1P$ transition of helium, their experimental energy resolution permitted them to isolate that transition alone and to determine the corresponding $f_{nl}(K)$. However, for high n^1P excitation, the same energy resolution would necessarily include at least several other angular momenta of the same n . In the continuum all angular momenta are included, irrespective of energy resolution.

Theoretical information on the $f_{nl}(K)$ surfaces is incomplete, even for H. In Bethe's calculations parabolic coordinates were employed, thus leading to the "total" $f_E(K)$, all angular momenta being included. In the calculations of Massey and Mohr closed formulae were obtained for the individual $f_{nl}(K)$ to discrete states, but the corresponding resolution of the continuum seems not to have been accomplished.

LOW- K EXPANSION OF $f_n(K)$

The behavior of the generalized oscillator strength at low K values is equivalent to the differential cross section at small scattering angles. Straightforward expansion of equation (2) results in

$$f_n(K) = (E_n/R) \sum_{p=0}^{\infty} C_p (Ka_0)^p, \quad (3)$$

where

$$C_p = \frac{i^p}{(p+2)!} \sum_{t=0}^p (-1)^t \binom{p+2}{t+1} X_{on}^{(t+1)} X_{no}^{(p+1-t)} \quad (4)$$

and

$$X_{no}^{(s)} = \sum_i (n | x_i^s | o) / a_o^s, \quad x_i = (\mathbf{K} \cdot \mathbf{r}_i) / K. \quad (5)$$

Parity consideration immediately shows that the odd-power terms in (3) drop out, so that $f_n(K)$ is a function of $K^2 a_o^2$. We can write the first few terms explicitly as

$$\begin{aligned} f_n(K) = & (E_n/R) |X_{no}^{(1)}|^2 \\ & + (E_n/R) [|X_{no}^{(2)}|^2/4 \\ & - \text{Re } X_{on}^{(3)} X_{no}^{(1)} / 3] K^2 a_o^2 \\ & + (E_n/R) [|X_{no}^{(3)}|^2/36 - \text{Re } X_{on}^{(4)} X_{no}^{(2)} / 24 \\ & + \text{Re } X_{on}^{(5)} X_{no}^{(1)} / 60] K^4 a_o^4 + O(K^6 a_o^6). \end{aligned} \quad (6)$$

In the above equation the first term is simply the optical oscillator strength, f_n . Again parity consideration establishes that only values of $X_{on}^{(s)}$ with odd s are non-vanishing for an electric-dipole allowed transition, for which $X_{no}^{(1)} \neq 0$, and that only those with even s remain for a parity-invariant forbidden transition, for which $X_{no}^{(1)} = 0$.

ATOMIC HYDROGEN

Numerical evaluation of the generalized oscillator strength for transitions of normal hydrogen atoms to a variety of discrete nl states has been carried out for a wide range of values of K . Only a few features of the topography can be described in this abstract.

For allowed transitions to discrete states, $f_{np}(K^2)$ is monotonically declining (as remarked earlier⁽⁴⁾). This implies, by equation (6), that $X_{on}^{(3)} X_{no}^{(1)}$ is positive for all n (the wave functions being taken as real), a fact which is easily verified by computing these matrix elements directly. The functions $f_{np}(K^2)$ retain approximate linearity from $K^2 a_o^2 = 0$ to about 0.5 except for $n = 2$, in which case the curvature already begins to be appreciable at $K^2 a_o^2 = 0.2$. They are very slightly convex upwards near the origin for $n \geq 3$, while $f_{2p}(K^2)$ is appreciably concave there. All of this reflects the gradual changes in the coefficients within square brackets of equation (6) as n increases.

In contrast, the functions $f_{ns}(K^2)$, $f_{nd}(K^2)$, $f_{nf}(K^2)$, etc., all have a single, broad maximum, and, of course [cf. equation (6)], positive slope at the origin. Of these, only $f_{ns}(K)$ and especially $f_{nd}(K)$ are great enough to contribute significantly to $f_E(K)$.

The "total" $f_E(K)$ is monotonically declining for $n = 2$ and 3, but for $n = 4$, owing partly to 4s but chiefly to 4d, the coefficient of K^2 in equation (6) has changed sign and $f_E(K^2)$, thereby, acquires a maximum. All higher n possess this maximum, and at the ionization limit it has become fairly pronounced: it is there located at $K^2 a_o^2 = 0.13$, with $f_E(K)/f_E(0) = 1.06$.

Slightly beyond this maximum, in the range $0.2 \leq K^2 a_o^2 \leq 1.0$, $f_E(K^2)$ is approximately linear. As E increases the maximum becomes sharper and shifts to higher K , ultimately approaching the Bethe ridge.

HELIUM

The previous discussion has shown how experimental cross sections for inelastic scattering at small angles can provide, not only optical oscillator strengths, but also other atomic and molecular properties, the $X_{no}^{(s)}$ for $s > 1$, which are virtually unknown. We present some results for discrete He transitions, based upon the work of Lassettre *et al.*,^(6, 7) and compare them with somewhat primitive theoretical values.

Experimental data on $f_n(K)$ at the ionization limit⁽⁶⁾ cover the range of $K^2 a_o^2$ from 0.2 to about 1. In this range the experimental curve is almost linear, and was extrapolated linearly⁽⁶⁾ in order to obtain a value of the optical df/dE at the limit, an important atomic constant. Although there is no reason for a close correspondence of the behavior of He and H in this respect, the bending over of the curve for atomic hydrogen below $K^2 a_o^2 = 0.2$ suggests caution in accepting the result of linear extrapolation. (The actual value of df/dE for H at the limit is 20 % lower than that obtained by linear extrapolation of points lying in the range between 0.2 and 1.)

NEW SUM RULES

A set of sum rules containing $X_{no}^{(s)}$ has been derived. An interesting one concerns the coefficient of $K^2 a_o^2$ in equation (6):

$$\begin{aligned} & \frac{1}{4} \sum_n \frac{E_n}{R} |X_{no}^{(2)}|^2 \\ & = \frac{1}{3} \text{Re} \sum_n \frac{E_n}{R} X_{on}^{(3)} X_{no}^{(1)} = \langle \sum_i x_i^2 \rangle, \end{aligned} \quad (7)$$

where $\langle \rangle$ denotes the expectation value in the ground state. The first equality in (7) is one of a class of sum rules which follows immediately from the Bethe sum rule for generalized oscillator strengths together with (6): the sum over n of each factor in square brackets in (6) must independently vanish. (This result was given earlier by Silverman.⁽⁸⁾) The second equality is established by standard techniques using commutators. Note that the contributions to the two sums come from different sets (parities) of excited states and that $\sum_i x_i^2$ does not contain a correlation term such as $\sum_{i \neq j} x_i x_j$. (Thus under certain circumstances it is strictly proportional to the diamagnetic susceptibility.) This sum rule, among others, affords a check on the

consistency of data used in construction of the Bethe surface.

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THE LATENT PERIOD FOR RADIATION-INDUCED OSTEOSARCOMA

Patricia M. Failla

A review of the literature pertaining to radiation-induced osteosarcoma has uncovered some concepts and relationships that may be of value in considering the mechanism of bone tumor development. If human or animal bones are exposed to moderate doses of radiation, tumors can be detected after a period of time which is characteristic of the species. This period of time might be termed the latent period for induction of osteosarcoma.* In Figure 2 are plotted average values of this minimal latent period for five different species against the respective average life-span values. A direct linear relationship between these two time periods is apparent. Using somewhat different values for these parameters, Brues has suggested that the latent period varies as the two-thirds power of the life-span.⁽¹⁾

Life-span, however, is too general a parameter to be linked to a latent period for appearance of a specific type of neoplasm. But might not both life-span and latent period be related to metabolic rate? If this is the case, the most logical rate to consider here is bone turnover rate. Accordingly, bone turnover rates based on or calculated from the data of a variety of workers were collected for the five species under consideration. The values of latent period and turnover rate used are given in Table 2 along with references to the work on which they were based. It was found that life-span and latent period for bone tumor appearance were well correlated with the reciprocal of bone turnover rate, that is, with the length of time required to turn

* It is recognized that the experimental latent period differs from the period after which a single cancer cell starts the neoplastic process by a factor, k , depending on the mitotic time and the dimensions of the tumor when detected; it can be shown, however, that, on the assumption of constant rate of growth, k is proportional to the mitotic period times the logarithm of the tumor size necessary for detection. It follows that, as a first approximation, the uncertainty injected by the variation in tumor size at the time of initial tumor detection is not large enough to invalidate the argument presented here.

FIG. 2. The latent period for development of osteosarcoma in five species plotted against average life-span values for those species.

TABLE 2. CORRELATION OF BONE TURNOVER RATE WITH LATENT PERIOD AND LIFE-SPAN

Species	Life-span (years)	Latent period (days)	Bone formation rate (%/day)	1/Bone Formation Rate
Man	70	3650 ⁽³⁾	0.01 ⁽⁷⁾	100
Dog	15	800 ⁽⁴⁾	0.05 ^(8, 9)	20
Rabbit	5	250 ⁽²⁾	0.12 ⁽¹⁰⁾	8.3
Rat	3	200 ⁽⁵⁾	0.225 ⁽¹¹⁾	4.4
Mouse	2.5	150 ⁽⁶⁾	0.51 ⁽¹²⁾	2.0

FIG. 3. Life-span and latent period for osteosarcoma development as a function of the reciprocal of bone turnover rate

over a certain fraction of bone in adults of the different species. This correlation is illustrated in Figure 3.

It may be argued that a correlation of this sort is not unreasonable. A single neoplastic cell cannot initiate formation of a tumor unless or until it divides. It may have to divide several times so that a nucleus of altered cells exists before a tumor becomes inevitable and self-sufficient. The shorter the period of time before an average cell divides, the shorter the period of time before an existent tumor cell may be able to express itself. When bone turnover rates within a species are higher such as in young, growing animals, latent periods are generally shorter.⁽²⁾ Also latent periods tend to decrease with high radiation doses when cell damage and destruction is severe and, hence, normal cell proliferation rate must be increased to repopulate bone surfaces. Extending this line of reasoning and introducing the concept of possible time dependent recovery and repair of neoplastic change, it might be expected that species with slower bone turnover rates would have lower osteosarcoma incidences for the same radiation insult. Because of the exceedingly complex problems associated with both external and internal irradiation of bone, however, it is very difficult to assess the carcinogenic effect of doses to cells of interest in different species. Nevertheless, with correlations in mind such as those presented here, perhaps experiments can be designed to

test the relevance of normal bone metabolism rate to the time course and incidence of radiation-induced osteosarcoma.

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RADIATION RESPONSE OF ROTIFERS EXPOSED AT DIFFERENT STAGES

Patricia M. Failla

Cellular variations in radiosensitivity are well known, not only among different types of cells in the same organism, but among similar cells at different times. To a large degree such variations are undoubtedly a reflection more of what the cell is asked to do than an inherent difference in radiosensitivity. Since recovery from radiation damage is a factor, how soon the cell must perform has also to be considered. The rotifer, which has well-defined periods of cellular

activity, as well as other convenient characteristics, has been used to study such variations in radiation response.

Rotifers are microscopic, aquatic metazoans that have been used for longevity investigations.⁽¹⁻³⁾ The rotifer studied, genus *Philodina*, has a life-span of about 30 days at room temperature. These rotifers are all female and reproduce by laying eggs that develop parthenogenetically. A clone of rotifers can thus be built up, the genetically homogeneous members of which can be cultured individually for scoring of egg production, hatchability and survival time. (Figure 4 is a photograph of 2 mature animals; eggs to be laid soon are visible.) On the average, about 3-6 eggs per day are laid by rotifers of 3-12 days of age. The eggs hatch in about 24 hours at room temperature; all cell division is believed to take place during this period. Since there is no further cell division after hatching, any somatic radiation damage incurred after this time is not subject to repair by selective repopulation by the least injured cells. It is, however, susceptible to long-term recovery or repair processes which can operate without possible interference from preparations for division.

Radiation damage transmitted through the germ cells shows up in subsequent generations. The parthenogenetic nature of the reproductive process assures that genetic damage is not "diluted" by the introduction of unirradiated genetic material. Selection could operate by inhibiting the laying of badly damaged eggs; egg production, however, is a highly radioreistant parameter.

This is not felt, therefore, to be an important consideration. Hatchability of eggs irradiated at various stages, therefore, should indicate damage and any recovery from that damage in cells destined to divide at various times after irradiation. Comparison of results on hatchability and life-span should indicate the relative degree of genetic and somatic damage. Most of the experimental techniques used have been described previously.^(4, 5)

FIG. 4. Photograph of two mature rotifers; eggs to be laid soon are visible.

RESULTS

Using the criterion of hatching, the dependence of radiosensitivity on the stage of the "laid" egg when irradiated is dramatically illustrated in Figure 5. Hatchability of eggs irradiated during the first few (0-4) hours after being laid is completely prevented by less than 10,000 R. These eggs are presumably undergoing rapid cell division when irradiated. In contrast, eggs irradiated 16-17 hours after being laid hatch with 100% efficiency after as much as 100,000 R. Within about 7-8 hours after irradiation these eggs hatch into fully-formed rotifers which live an essentially normal life-span. The curve showing the hatchability of eggs irradiated at undetermined times between 0-17 hours after being laid is intermediate and a composite of the other two. The shape implies that about one-third of the eggs were in a sensitive stage and two thirds in a resistant stage when irradiated. Implications of these results will be discussed later.

Figure 6 shows the results of experiments in which rotifers were irradiated at different ages (i.e., at 1, 3, or 6 days of age) and the hatchabilities of their eggs laid at later times were scored. As was discussed in a previous report,⁽⁵⁾ it is of interest to see if the general radioresistance of eggs irradiated inside the rotifer can be accounted for by a slow recovery process operating in the interval between irradiation and laying. It is evident by comparing the three sets of curves in Figure

FIG. 5. The hatchability of eggs as a function of dose and of "age" at irradiation. The curves are labelled with the time after being laid that the eggs were irradiated. Hatching of the eggs occurs about 24 hours after they are laid. The number of eggs used for each point is indicated.

FIG. 6. The hatchability as a function of dose of eggs laid by 7-, 8-, and 9-day-old rotifers irradiated when they were 1, 3, or 6 days old.

6, that eggs irradiated inside 1-day-old rotifers are more radiosensitive than those irradiated within 3- or 6-day-old animals. In general, eggs irradiated within older animals are more radioresistant. Such a difference in responsiveness of eggs in rotifers of different ages might, however, mask some recovery phenomenon. It was hoped, therefore, that a comparison of the hatchabilities of eggs irradiated at one rotifer age and laid at different times thereafter would better demonstrate any recovery occurring between irradiation and laying.

Accordingly, the hatchabilities of eggs laid on the 7th, 8th, and 9th days of age were measured for each age group of irradiated animals. As can be seen in Figure 6, there is no significant difference except for the rotifers irradiated when 6 days old. In this case about 40% of the eggs laid on the 7th day are definitely more radiosensitive. This increased sensitivity when only one day intervenes between irradiation and laying might be indicative of a moderately rapid recovery which is incomplete until about 2 days after irradiation.

The criterion of hatchability implies, in general, that cell division must occur. Since there is no cell division after hatching, the effect of radiation on

rotifer life-span, on the other hand, indicates the response of non-dividing cells. In Figure 7 are plotted points from many different experiments relating the radiation effect on these two parameters. The average relative hatchabilities of various groups of eggs irradiated under various conditions are given on the ordinate; the corresponding average life-spans of rotifers hatching from these eggs are given on the abscissa. (The life-span values are based on a minimum of 20 animals.) There appears to be a reasonably positive correlation between these parameters when more than 50% of the eggs hatch but not when the hatchability is lower. This suggests that selection has occurred at the hatching level, eliminating the least fit rotifers from the life-span study. The data in Figure 7, in fact, might equally be interpreted to indicate a negative correlation when any significant degree of damage has been inflicted. Perhaps the most relevant observation is that, to date, irrespective of dose or other parameters, it has not been possible to reduce the life-span to much less than 50% of the controls. In experiments where rotifers received 50,000 R (or less) after hatching, the maximum reduction of life-span was only by 25%. Data have not been taken at higher doses.

DISCUSSION

The results of irradiating rotifers and their eggs under various conditions have emphasized the dependence of effect on stage or state at exposure. It is often not definite, though, whether the results represent

FIG. 7. The hatchabilities of groups of eggs irradiated under various conditions plotted against the respective average life-spans of the rotifers hatching from these eggs.

differences in radiosensitivity per se, differences in recovery or repair potential, or differences in criterion. In some instances, however, certain interpretations appear more plausible.

The "black and white" result, (Figure 5), of irradiating eggs at early and late times after they have been laid is an example. When the eggs are irradiated early, they are assuredly undergoing rapid cell division and are in a critical radiosensitive state associated with the division process. When irradiated at a time much closer to hatching—probably most of the cell divisions have been completed—the more radioresistant processes of differentiation are merely adding the finishing touches. If a cell division time at room temperature of about an hour is assumed, then it would take only about 9 out of the 24 available hours to reach the estimated rotifer complement of 500 or so cells. (This would be consistent with much embryological experience where the period of most rapid change and cell division takes place in roughly the first third of the gestation period.) The criterion of hatching then is probably much less stringent for a 16- or 17-hour egg than for one newly laid in which many cell divisions are still required. From this point of view the tremendous difference in radiosensitivity is much more reasonable.

The apparent greater radiosensitivity of eggs laid on the 7th, compared to the 8th or 9th day, by rotifers irradiated on the 6th day of age (Figure 6) is more difficult to interpret. The difference is, of course, by no means as pronounced, and there are several possible explanations. As mentioned previously, it could be the result of a recovery process which takes longer than one day to complete. The maximum effectiveness of such a process, however, could not be very large. There is also the possibility that, after a radiation insult, the more damaged eggs are laid first. However, there are almost always some eggs visible in a mature egg-laying animal (e.g., Figure 4). It appears probable that these would be laid first under any circumstances. More likely, these eggs that are visible and destined to be laid in a short time are in a more sensitive state. Perhaps they are more vulnerable because they are supporting syntheses or the like, preparatory to division; or, conversely, perhaps at this time they are less capable of repairing damage. There is no evidence at present to distinguish among these conjectures and possibilities.

It is interesting to speculate about the pronounced radiation refractoriness of rotifers exposed after hatching. The obvious conclusion is that non-dividing cells are functionally overtly unaffected even by large radiation doses. Extrapolating to other species, does this mean that radiation-induced acceleration of aging

is mediated mainly through cells that divide? Recent evidence and current thinking⁽⁶⁻⁸⁾ are running in this direction. If a cell is not required to divide, it can tolerate chromosome aberrations and has time to repair some of the damage. Also a highly-differentiated cell probably does not need its full genetic complement intact. In a rapidly-proliferating cell population damaged cells may be eliminated by selection, provided the stress is not too large or too prolonged. But, depending on the mitotic rate, there may be insufficient time for recovery. Also a defect small enough to permit division but detrimental in the long run will be propagated. These concepts then tend to make the radio-resistance of the rotifer less surprising.

SUMMARY

Rotifers have been exposed to various radiation doses at various stages in their life cycle. Effects on hatchability of eggs and on life-span have been the principal criteria examined. Newly-laid eggs were found to be relatively radiosensitive, while up to 100,000 R did not affect the hatchability of eggs irradiated 16 hours or so after being laid. When rotifers of different ages were irradiated and the hatchability of their eggs laid at subsequent times scored, the results suggest that eggs exposed in younger animals are somewhat more radiosensitive. If the exposed eggs are to be laid within a day they also appear to be

more vulnerable. Finally, there is no consistent correlation under different conditions between the hatchability of a group of eggs and the life-span of the rotifers that hatch. Some possible explanations and implications of these results are discussed.

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LiF THERMOLUMINESCENT DOSIMETRY FOR BETA RAYS*

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INTRODUCTION

A thermoluminescent dosimeter employing lithium fluoride as the phosphor has been developed by Cameron *et al.*⁽¹⁾ The commercially-available LiF (Harshaw Chemical Co., Cleveland, Ohio) exhibits a glow curve with the main peak at approximately 210° C. The material is identified as TLD-100 and is in the form of ground crystals of about 0.15 mm O.D. Although LiF dosimetry has been employed extensively in the area of clinical medicine,^(2, 3) it has not yet

made its mark within the framework of experimental radiation biology. The possibility of using TLD-100 for *in vivo*, direct-dose measurement in tiny body cavities (e.g., bone marrow) led us to investigate the response of LiF to beta radiations of varying energy. The following account will show that LiF thermoluminescent dosimetry indeed has great potential in the study of the biological effect of incorporated radioisotopes.

PROCEDURE

We have adopted Cameron's readout system with only a few modifications. A special high-temperature photomultiplier tube (Ascop #543D, normally used in well logging) provided the extremely low dark current of 10⁻¹¹ amps at room temperature. The crystals were heated in small, 0.005-in.-thick copper

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pan to a temperature which was controlled by varying both the line voltage and the timing cycle. In the reported work the temperature rose to 250° C in about 15 seconds.

Small amounts (5 mg) of TLD-100 were heat sealed in ¼-mm-wall catheter tubing* to form 1-mm O.D. x 6-mm long capsules, hereafter termed "dosimeters." After exposure, the capsules were cut open and emptied into the copper pans for observation. In all cases, precise weighing was carried out *after* the thermoluminescence measurement so that the output could be expressed per unit weight of LiF. The integral under the glow curve was taken as representative of the dose.

Even though the powder was annealed according to Cameron's recommended procedure,⁽¹⁾ we observed that the low-temperature glow peak persisted to a different extent for each batch. However, this peak decayed reasonably quickly and could be eliminated as a source of error by allowing 24 hours to elapse between exposure and reading.

In an attempt to improve the signal-to-noise ratio, particularly at low doses and with minute samples of LiF, various gas environments were investigated. The best results were obtained with helium, although nitrogen was nearly as effective. As expected, oxygen was the cause of a great deal of chemiluminescence, and so was water vapor. All of the work reported here was carried out with dried nitrogen flowing slowly over the heating pan.

Co⁶⁰ GAMMA-RAY CALIBRATION

The response of LiF to Co⁶⁰ radiation has been thoroughly investigated.^(1, 4) This radiation provided a convenient standard against which to evaluate the beta-ray response of our dosimeters. Exposure of the dosimeters to Co⁶⁰ radiation was carried out in cylindrical Lucite holders with 3-mm walls to provide electronic equilibrium. Figure 8 displays the relation of thermoluminescent response to the gamma-ray dose in rads. As observed by others,^(1, 4) superlinearity appears at dosages greater than 200 rads.

RESPONSE TO BETA RAYS

As there is a variation in beta flux through the internal volume of the dosimeter, the latter cannot be considered a point detector in the form used for this experiment. For this reason the response of the dosimeter system per unit of dose must be determined with the particular beta emitter being studied. Gelatin molds, 1 in. O.D. x ¾ in. high, containing known concentrations of beta-ray emitters provided very re-

producible isotropic sources of known beta-ray doses; they have been described elsewhere.⁽⁵⁾ As an added check, several distributed beta-ray sources were also made in the form of cylindrical polyester resin molds utilizing the technique of J. P. Hughes of this laboratory.⁽⁶⁾ The emitters consisted of H³, Ni⁶³, S³⁵, Ca⁴⁵, Tl²⁰¹ and Sr⁹⁰(Y⁹⁰). The dose rate in each case was computed using the well-known relation,⁽⁷⁾

$$R = 51.2 \bar{E} C \text{ rad/day}$$

where C is the concentration in $\mu\text{Ci/g}$ and $\bar{E}$ is the average beta-ray energy in MeV of the particular radioisotope.

The first beta-ray source employed was a gelatin mold containing 10 $\mu\text{Ci/g}$ of Sr⁹⁰(Y⁹⁰). The open gelatin surface was covered with a ¼-mil Mylar film, and the complete mold was sprayed with a light acrylic coat. The response of the LiF dosimeter is shown by the lowest curve in Figure 8; it is apparent that although the response parallels that of the dosimeter to Co⁶⁰ radiation, it also carries a significant loss in sensitivity. Elimination of self-absorption by elimination of the catheter tube wall and spread of LiF powder making up the dosimeter led to the results shown by the middle curve. Ultimate removal of the ¼-mil Mylar film provided agreement, within the experimental error, between the response to Sr⁹⁰(Y⁹⁰) and that for Co⁶⁰. For the other radioisotopes, LiF powder was lightly sprinkled on the bare surface of the beta-ray source in each case. Figure 9 shows the relative response of the powder, per rad, to the various beta radiations.

There are several possible factors which could explain the drastic drop in light output per unit weight per unit dose for a soft beta-ray emitter such as tritium. The most obvious factor is the relation of the physical size of a LiF grain to the range of the beta rays. If much of the grain volume is not even available to the beta ray, the light per unit weight is bound to be less.

A rough estimate of the LiF mass not available to beta-ray radiation can be calculated by using the average distance of dose distribution, $\bar{X}$, which, according to Loevinger *et al.*,⁽⁸⁾ is 0.108 times the maximum beta-ray range, R_0 . For a "spherical" LiF grain of diameter, L , the fraction of the total volume, $\pi L^3/6$, corresponding to the average depth of beta-ray penetration, $\bar{X}$, is given by,

$$F = 1 - (1 - 2\bar{X}/L)^3 = 1 - (1 - 0.216 R_0/L)^3.$$

This figure is a minimal correction because no account is taken of the energy displaced by the grain itself. This is compared in Table 3 with the observed variation in response.

* Intramedic Polyethylene Tubing, PE 160, Caly-Adams, Inc., New York.

FIG. 8. LiF thermoluminescence response to Co^{60} and $\text{Sr}^{90}(\text{Y}^{90})$

TABLE 3. EFFECT OF BETA-RAY DOSE DISTRIBUTION

Isotope	E_{max} (MeV)	Range (cm)	F , Calculated utilization	Observed relative response	Obs/calc
Ti^{204}	0.76	0.11	1	1	1
Ca^{45}	0.255	0.023	0.69	0.7	1
S^{35}	0.167	0.012	0.44	0.3	0.7
Ni^{63}	0.067	0.0026	0.11	0.02	0.18
H^3	0.018	2.1×10^{-4}	0.009	5×10^{-4}	0.055

FIG. 9. Relative LiF thermoluminescence response to beta-rays of different average energies.

Evidently, on the basis of this simple model, one cannot account for all the drop in response for the softer beta rays.

A factor which could conceivably explain the extra reduction is the possible effect of high specific ionization on light output. To check this possibility we resorted to radioactive tin as a source of conversion electrons of widely different energies: Sn^{113} provides 370-keV electrons, whereas Sn^{119} is a source of 36-keV electrons. At first we used a mixture of these two isotopes. A relatively weightless solution of this mixture was evaporated on Mylar and the emission rate

measured accurately by Kevin Flynn of our Chemistry Division.⁽⁹⁾ The thermoluminescent light emitted per unit total energy completely absorbed in a single crystal of LiF, 1 mm thick, was compared for each of the two electron energies supplied by the mixed source. The comparison was carried out by eliminating the contribution of the soft electrons with the aid of about 4.7 mg/cm² of aluminum foil. The percentage effect of this absorption on the residual energy of the harder electron was determined using a solid state *p-n* surface barrier detector.

A second, confirming experiment was carried out using the same tin isotopes but this time separated on an electromagnetic mass separator by George Lamick of the Chemistry Division. The two conversion electron sources were applied in turn to the same single crystal of LiF. In every case the crystal was exposed for times short enough to maintain a linear response, and backscatter corrections were applied.

These simple experiments proved unequivocally that the light output is independent of the specific ionization existing under these conditions.

FIG. 10. Comparison of depth-dose measurements in Lucite; LiF dosimeters versus extrapolation chamber.

Another reason for poor light emission which must be considered is the possibility that the grain surfaces may be damaged from the point of view of lattice structure and, therefore, incapable of storing energy. We have designed an experiment involving two very different LiF grain sizes which should provide enough variation in surface to volume ratio to confirm or deny the existence of a "dead" surface layer. This experiment is now in progress.

As LiF is slightly soluble in water, we were concerned with possible radiochemical effects in such an environment and carried out the following experiments. Two identical cylindrical, thick-walled Lucite containers were filled with LiF powder; water was added to one of these capsules. Exposure to 5000 R of Co⁶⁰ gamma rays produced no difference in response of the two batches of powder. (The wet powder was dried, of course, in a desiccator before readout.) Furthermore, as an added check, water was added to some of the dry, exposed, powder which was then dried and read out with no evidence of unusual response.

An unexpectedly enormous, but yet reproducible, response, however, was observed in the case of some LiF powder which had become contaminated with Ca⁴⁵ while being exposed to the Ca⁴⁵ gelatin source. The response was 250 times what one would expect from a source consisting of 200 μ Ci of Ca⁴⁵ per gram of gelatin. The contamination amounted to about 3 μ Ci in 10 mg of LiF. Based on the known specific activity, this corresponds to one part of Ca in 1000 of LiF. Although the problem is under investigation, we have not yet developed a sound explanation for this phenomenon.

Y⁹⁰ DEPTH DOSE

There is available in our laboratory a sealed-source, Sr⁹⁰(Y⁹⁰), beta-ray applicator on which depth dose measurements in Lucite have been made by Amrick S. Chhabra using a Failla extrapolation ion chamber.⁽¹⁰⁾ In contrast to the gelatin and resin sources, only the beta rays from Y⁹⁰ emerge from the sealed source.

Figure 10 shows the comparison of the LiF dosimeter depth-dose data with Chhabra's results with the extrapolation ion chamber. In the region below 8 mm in depth, i.e., greater than the beta-ray range, the LiF dosimeter is exposed to bremsstrahlung only. The bulk of the dosimeter and its covering is now a negligible factor, and thus the relative thermoluminescent output will be too high by the ratio of the ordinates of the upper to lower curves in Figure 8, namely, about 1.4. The excellent fit with Chhabra's extrapolation chamber data following this correction suggests that even though the dosimeters are not point

detectors, they may give surprisingly useful information about beta-ray dose distributions in depth.

A recent microdosimetric LiF application has been the measurement of dose to the femur marrow in a mouse which had been injected intraperitoneally with $5 \mu\text{Ci/g}$ of Sr^{90} (Y^{90}) and sacrificed after three days. We have found it quite practical to measure doses of the order of one rad using a single grain of LiF, and it has also been possible to note significant differences in the dosage to various parts of the femur marrow cavity.

CONCLUSIONS

The use of LiF thermoluminescence for *in vivo* and *in vitro* dosimetry for beta rays is quite feasible, provided careful precalibration is carried out on a sample of the specific batch to be employed. A reproducible technique for calibration is described and compared with the Co^{60} gamma-ray response. The practical convenience of applying this technique for the dosimetry of beta-ray applicators should not be overlooked.

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LiF THERMOLUMINESCENT RESPONSE TO FAST NEUTRONS

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INTRODUCTION

As part of a general program of dosimetry employing the thermoluminescent properties of LiF as developed by Cameron *et al.*⁽¹⁾ we have determined the response of Li^6F powder to a constant flux of neutrons of varying energies ranging from thermal to more than 1 MeV. A marked increase in light output at about 0.25 MeV is correlated with the same type of reaction which gives the well-known enormous response to thermal neutrons, namely, $\text{Li}^6(n, \alpha)\text{H}^3$.

EXPERIMENTAL PROCEDURE

It has become accepted practice⁽¹⁻⁴⁾ to utilize the two isotopic powders, Li^6F and Li^7F , in mixed neutron plus gamma radiation fields on the assumption that the Li^7 powder is not responsive to neutrons. The LiF powders, actually ground crystals of about 0.15 mm O.D., consisted of commercially-available Harshaw TLD-600 which is enriched in Li^6 (95.62%) and TLD-700 which is predominantly Li^7 (99.998%). The

gamma response of the two fluorides was determined with both Co^{60} and radium gamma rays and found to be very nearly the same. The small quantities (5mg) used provided dosimeters essentially free of the need for self-shielding corrections, even in the case of Li^6F with its enormous cross section for thermal neutrons. Replicate powder samples irradiated in both polyethylene and Teflon containers yielded equal light output. Glow curves were integrated manually in all cases to provide improved reliability over the usual capacitor integrations.

As an additional check on the presence of gamma rays during the neutron irradiation, CaF_2 † dosimeters were exposed simultaneously with the lithium powders. The existence of a gamma-ray field was confirmed.

The thermal response was determined using the Argonne Standard Graphite Pile.⁽⁵⁾ The response to

† Supplied by Edgerton, Germeshausen and Grier, Inc., through the kind offices of Dr. E. F. Blase of the Santa Barbara Division.

neutrons of higher energy was obtained from the $\text{Li}^7(p,n)\text{Be}^7$ reaction in a Van de Graaff accelerator. The fluence was determined in each case by means of U^{235} fission counters.

RESULTS AND DISCUSSION

The Li^7F response over the whole neutron energy range was negligible compared to that of Li^6F , even

Fig. 11. Energy level scheme for Li^8

Fig. 12. Energy level scheme for Li^7

in the presence of appreciable gamma radiation. Hence, the question of subtracting the Li^7F light output from that of the Li^6F is irrelevant. However, it is still instructive to analyze the potential interaction of fast neutrons with each isotope. Figures 11 and 12 give, respectively, the energy-level schemes for Li^8 and Li^7 nuclei. These diagrams are taken from the most recent compilation by Lauretsen and Ajsenber-Selove.⁽⁶⁾ The dominant contributor to the cross section of Li^7F in the region of interest is the reaction, $\text{Li}^7(n,n)\text{Li}^7$, with a pronounced resonance at 258 ± 3 keV and a maximum cross section of about 12 barns.^(7, 8) There is a small n,γ cross section for the formation of Li^8 with a half-life of 0.85 sec and the emission of an extremely energetic beta ray. This capture cross section cannot be responsible for a significant portion of the slight thermoluminescence, as there is no visible effect even

for thermal neutrons where the n, γ cross section of 40 mb is a thousand-fold greater than at the point of resonance. The $\text{Li}^7(n, n')\text{Li}^{7*}$ reaction which yields 0.48-MeV gamma rays rises abruptly from threshold but has a cross section of only 0.2 barns, even at 1.5 MeV. It is barely possible that the reaction, involving a recoil of the light Li^7 nucleus, may account for some of the thermoluminescence exhibited by the Li^7F in this region. However, this effect is slight and certainly negligible with respect to the response of Li^6 to neutrons of these energies.

It is a most fortunate coincidence that for Li^6 , also,

the most dominant contributor to the total cross section in this energy region is the reaction, $\text{Li}^6(n, n)\text{Li}^6$, with a pronounced resonance at 0.255 MeV, which is almost exactly the resonant point for Li^7 . That this is pure coincidence can be seen from the energy-level diagrams by noting the difference in the spins of the levels involved.

The most important additional contributor to the total cross section is the well-known reaction, $\text{Li}^6(n, \alpha)\text{H}^3$, which exhibits the same resonance at 0.255 MeV as $\text{Li}^6(n, n)\text{Li}^6$ with an associated cross section of 2.75 barns, and also has an enormous thermal

FIG. 13. Li^6F thermoluminescent response vs. neutron energy

cross section of about 950 barns. It is obviously *this* reaction which gives rise to the strong thermoluminescent response of Li^6 as contrasted with the reaction of Li^7 . However, it is only because the other n,n reaction is similarly spaced in energy for the two isotopes that it is appropriate to subtract the Li^7 response from that of the Li^6 in this region when one wishes to determine net neutron fluence in the presence of gamma radiation. In Figure 13 the Li^6 response is assumed to be wholly due to the n,α reaction and is compared with the appropriate cross section. The normalization of the relative thermoluminescent response, (light output per unit weight per unit fluence), to the cross-section data was carried out at an energy of 250 keV. The light output does seem to follow the general form of variation of the n,α cross section with energy, exhibiting an exceptionally high output at the resonance point. There remain, however, quantitative differences which may be explained away, for example, by particle escape from the powder on the high-energy side, or by the effect of thermal spikes (induced by high-energy α particles and protons) in emptying the thermoluminescent traps during the irradiation. There seems to be some evidence that the normal gamma response of Li^7F is reduced in the presence of fast neutrons. In any case, it is clear that LiF dosimetry in a mixed and polyenergetic field can only be carried out when the neutron and gamma-ray energy spectra are accurately known and the calibration is carried out in the same mixture of radiation. Further work is planned with a view to extending the energy range beyond 1.5 MeV. It is already apparent, however, that the light output from Li^6F is a very critical function of neutron energy, and, indeed, at higher energies where the fluorine reactions become significant (6–10 MeV), it may be necessary to employ the CaF_2 to account for its contribution.

CONCLUSION

The relative thermoluminescent response of Li^6F has been determined for neutrons of varying energies ranging from thermal to more than one MeV. A marked increase in light output about 0.25 MeV is attributed to the $\text{Li}^6(n,\alpha)\text{H}^3$ reaction. In this region, therefore, LiF dosimetry must be carried out very carefully so there will be no distortion due to the presence of moderated neutrons in the region of the 0.25-MeV resonance.

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LiF THERMOLUMINESCENCE FOR NEUTRON IMAGE STORAGE*

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A number of photographic methods for detecting thermal neutron images have been described⁽¹⁻³⁾ and applied to neutron radiographic inspections.^(4, 5) The methods can be divided into two main categories, the direct exposure method in which film is used in the

neutron imaging beam either by itself or in conjunction with some type of converter screen, and the transfer method in which the neutron image is detected by a screen of some potentially radioactive material an autoradiograph of the screen later providing a film image. One feature which these methods lack is the ability to integrate neutron image information in the presence of interfering gamma radiation for long

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periods of time, as would probably be required in most thermal-neutron imaging situations involving non-reactor neutron sources. This note describes a thermoluminescent image detection method which appears to offer some advantages in this respect.

When a thermoluminescent phosphor is exposed to ionizing radiation, many of the freed electrons become trapped at lattice imperfections in the crystalline solid. They remain trapped when the phosphor is stored at the temperature (or lower temperatures) at which the exposure was made. If the temperature is raised, the probability of escape is increased and the electrons are released, subsequently recombining with opposite-charge carriers with the emission of light, the intensity of which is proportional to the ionizing exposure. In an intensity versus time plot, the peaks of emitted-light intensity become narrower at faster heating rates, although the areas under the peaks remain constant.

The Harshaw Chemical Company, Cleveland, in cooperation with John R. Cameron of the University of Wisconsin,⁽⁶⁾ has developed activated Li^6F crystals specifically for neutron dosimetry. The material is identified as TLD-600 (95.6% Li^6) and is extremely sensitive to thermal neutrons.

For imaging purposes, a thin (for good resolution) sheet of Li^6F , either single or multicrystalline, extending over a reasonable area, is all that need be exposed to the neutron imaging beam. Once the neutron exposure is complete, the light can be released either by heating the LiF to a temperature of 210°C , or by irradiating the LiF with ultrasound.⁽⁷⁾ The resultant light image can be visually observed or detected on film. The use of film, preferred in most cases, can be accomplished simply by placing film in contact with the LiF during the heating or ultrasonic irradiation process. Because of heating, or ultrasonic coupling problems, it is usually more convenient to use a camera to photograph the LiF during the period of light release; in the preliminary work done at this Laboratory a Polaroid camera has been used. A neutron exposure curve for this arrangement is shown in Figure 14. The Li^6F detector in this case was a multicrystalline layer about 1 mm in thickness and 5 cm in diameter. It was formed by pressing the Li^6F into a stainless steel cup, then firing in air at 800°C for 2 hours.

Although the data in Figure 14 are not impressive from a speed point of view, this aspect could be improved by the use of better LiF layers (single-crystal material would be preferred) and/or improved methods of recording the light output.

The advantages of this method are predicated on its ability to integrate thermal neutron image information for long periods of time without saturating, even

FIG. 14. Polaroid film reflection density ($\log I_0/I_e$, where I_0 is incident light intensity and I_e is reflection light intensity) obtained on photographing thermoluminescent light releases from a variety of thermal neutron exposures of a Li^6F detector, as described in the text. The film used was Polaroid Type 47, 3000 speed. Point A represents a thermal neutron exposure of 10^{11} n/cm².

in the presence of interfering gamma radiation. The transfer exposure photographic technique⁽¹⁻³⁾ can be used to eliminate essentially the influence of gamma radiation on the neutron image, but the length of time one can accumulate information is limited because the activity of the recording screen will eventually become saturated. One does not have this saturation problem if the direct exposure photographic method is used, but the thermoluminescent type of detector offers a superior neutron-to-gamma response ratio. It has been shown^(4, 8) that metal converter screens and X-ray film used as direct-exposure, thermal-neutron detectors yield about equal film response for an exposure of 10^5 n_{th}/cm² or 1 mR of Co^{60} gamma radiation. With the use of neutron scintillators instead of metal converter screens, this relationship can be improved so that a thermal neutron exposure of only about 10^4 n/cm² is

required to equal the film response of 1 mR of Co^{60} gamma radiation. Thermoluminescent detectors employing Li^6F , have an even better relative neutron-gamma response; work in this Laboratory indicates that one needs only about 5000 n/cm² (thermal) to produce the same amount of light as that produced by a gamma-ray exposure of 1 mR. Even if the two methods were comparable in their relative neutron-gamma response ratio, the reciprocity-law-failure response of the scintillator technique, particularly at low light levels, is a disadvantage.⁽⁹⁾ At lower thermal neutron intensities, such as one might anticipate from a small accelerator or radioactive source arranged to yield a thermal neutron beam, the response of the scintillator direct-exposure detectors would be impaired because of the lower film response to the low light levels from the scintillator. The thermoluminescent detector, however, could be exposed to the neutron beam long enough to accumulate the energy needed for a large light release after the exposure. Reciprocity-law-failure responses, therefore, would not influence this detector.

We believe these advantages of thermoluminescent image detectors, namely the ability to accumulate thermal neutron image information for extended

periods without saturation or reciprocity-law-failure response problems, and equal or better relative neutron-gamma responses than other available direct detection methods, will contribute to the advancement of thermal neutron imaging techniques, particularly those employing non-reactor neutron sources. The thermoluminescent technique appears to be especially useful as applied to thermal neutron beams of low intensity.

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MODIFICATION OF COMPUTER PROGRAM 1977/RPY 146. COSMIC-RAY NEUTRON BACKGROUND (NEUTBAK)

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A program has been coded⁽¹⁾ in FORTRAN for the CDC 3600 computer to derive the incident neutron flux from the experimental distribution of proton scintillations with respect to pulse-height analyzer channel number. This program has now been modified to enable data to be read in from magnetic tape and to be fitted to a smooth curve. The modifications are as follows:

Card 5 LMAX, INOPT
FORMAT (2I6)

LMAX is the number of energies in the table comprising the standard calibration curve for the pulse-height analyzer.

INOPT is a flag controlling the read-in option:

INOPT = 1 gross data are read in from table on punched cards (Table 5)

INOPT = 2 gross data are read in from magnetic tape

Table 4 (SCHAN(L), DSCHAN(L), SE(L), L = 1, LMAX)

FORMAT (6F12.6)

Card 7 JMAX, JCHAN, T

FORMAT (2I6, E12.6)

Table 5 should be omitted if the data are being read from magnetic tape. (The paper tape output of the analyzer may be converted to magnetic tape by means of an auxiliary program developed by J. Corcoran of the Radiological Physics Division.)

DATA-SMOOTHING FEATURES OF THE PROGRAM

Since the gross data fed into NEUTBAK contain the normal statistical fluctuations, before any approximations to the derivative can be made, the data must be fitted to a smooth curve. This is done by means of a function, SM00TF(J,X,Y), where

J is an index telling which value of the gross data is to be projected onto the fitted curve,

* Student Aide, Summers 1963 and 1964.

X is the experimental channel number, rounded off to the nearest integer,

Y is the experimental channel number (not rounded off).

Upon being called, SMØØTF picks the Jth value from the array of gross data (CØNTS(J)). Using this as the center, it picks 41 consecutive gross data values (CØNTS(J - 20), CØNTS(J - 19) ... CØNTS(J + 20)) and fits these to a power series

$$Y = \sum_{i=0}^{NDEG} A(i)(Z - X)^i \quad (1)$$

$$X - 20 \leq Z \leq X + 20.$$

The degree of the power series, NDEG, lies between 1 and 10. In each case, NDEG is adjusted by SMØØTF until the following condition is satisfied:

$$\sqrt{CØNTS(J)} \cong \sqrt{\frac{\sum_{i=1}^{41} [CØNTS(J - 20 + i) - \bar{Y}_i]^2}{41}} \quad (2)$$

where

$$\bar{Y}_i = \sum_{j=0}^{NDEG} A(j)(i - 21)^j$$

is the smoothed value of the data at a given point.

If in trying to satisfy the above condition SMØØTF is found to increase NDEG of the polynomial to 10, it will return the value it obtains regardless of whether the condition has been satisfied. However, it will also print the following error message:

SECTION OF DATA TOO ROUGH FOR PROPER
SMOOTHING, VALUE FOR FLUX AT____
MEV MAY BE INACCURATE,

inserting in the blank the energy value for which the flux was being computed.

For the actual least-square fitting of the data, SMØØTF uses LSTSQR, a subroutine package written by Gary Feldman (Solid State Division) and employing the method of orthogonal polynomials.

REFERENCE

1. Jacob Kastner, B. G. Oltman, L. D. Marinelli and J. H. Klems. Argonne National Laboratory Radiological Physics Division Annual Report, July 1963 through June 1964. ANL-6938, p. 76.

A COMPUTER PROGRAM, RPY 157X, TO DERIVE THE COSMIC-RAY NEUTRON BACKGROUND WHEN MULTIPLE SCATTERING IN THE DETECTOR IS SIGNIFICANT

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The program is divided into two components: (a) PROGRAM RANDSCAT, which is a Monte-Carlo calculation of multiple scattering in neutron detectors for isotropic incident flux, (b) PROGRAM PART-DIFF, which calculates the energy spectrum of the incident neutrons by iteration of an expression calculated by RANDSCAT.

PROGRAM RANDSCAT

DESCRIPTION OF THE PROBLEM

An isotropic neutron flux is incident on a right circular cylindrical crystal of scintillating material. The resultant light pulses are analyzed according to energy and recorded in a pulse-height spectrum. Events for which a recoil proton is not produced, such as gamma scattering, are eliminated by pulse-shape discrimination. The light output versus energy response of the crystal is known.

The problem is to determine the absolute incident neutron flux ($\text{cm}^{-2} \text{sec}^{-1} \text{MeV}^{-1}$) from the observed recoil proton pulse-height spectrum, when it is known that the amount of double and higher scattering is significant.

The following assumptions are made: (1) the contribution to the spectrum of neutrons with energy greater than 14.0 MeV is negligible; (2) neutron-proton scattering is isotropic in the center-of-mass system.

APPLICABILITY

Crystal. The program is written for a scintillation crystal which is a right circular cylinder, and which is composed of hydrogen and carbon.

Energy Range. 0.1-14.0 MeV, inclusive. The resolution is 0.1 MeV.

Incident Flux. The program is written for an isotropic incident flux but may be easily modified for consideration of beam experiments. The necessary modifications are outlined in the Appendix.

* Student Aide, Summers 1963 and 1964.

MACHINE

CDC-3600, FORTRAN coded.

INPUT INFORMATION REQUIRED

The program requires eleven data cards and three tables, each of which may consist of several hundred cards. If recycle options are used, some sections of the data deck may be repeated. Data requirements are explained in detail in the section entitled "Data Input to RANDSCAT."

PROGRAM OPTIONS

After execution the program may be recycled, starting from any of several points, in order to change various portions of the input data. A considerable portion of the output of the program may also be controlled by option parameters. Both of these features are fully explained in the section entitled "Data Input to RANDSCAT."

A third option is the criterion according to which data accumulation is terminated. The total number of incident neutrons may be specified as input information, in which case the program will stop generating data when this number of neutrons has been produced. Alternatively, a channel number may be specified together with the number of counts to appear in that channel of the proton recoil spectrum. In this case data accumulation will continue until the required number of counts has been collected in the specified channel. This is also explained more fully under "Data Input to RANDSCAT."

The fourth option concerns the elastic-scattering cross section of carbon. This may be considered either as isotropic in the center-of-mass system, or as angle-dependent, in which case it is approximated by a six-term Legendre series using tabulated Legendre coefficients, such as those given in Kalos and Goldstein,⁽¹⁾ simply by changing an output parameter. Although the carbon elastic-scattering cross section is by no means isotropic in the energy range of interest, assumption of an isotropic cross section will greatly shorten program execution time and can sometimes be used without appreciable error.

RUNNING TIME

Input time is approximately two seconds. Execution time varies with the input flux and the crystal size, since these determine the extent of multiple scattering, and with the choice of carbon cross section. For a 12.7-cm by 12.7-cm crystal using an isotropic carbon cross section, execution time was approximately 13 milliseconds per incident neutron. For an angle-dependent, carbon cross section execution time is increased by a factor of five. Output time varies, de-

pending on the optional output. Writing the distribution functions on tape requires approximately three minutes, and each graph requires about 12 seconds. Compilation time is one minute, 10 seconds.

METHOD

An assumed neutron distribution is fed into the program as data. The program then proceeds by generating neutrons at random from the assumed distribution and tracing their histories in the crystal. During the tracing of these histories, the program simultaneously tabulates information for the following independent approaches to the problem:

(a) An actual experiment is duplicated as closely as possible. Recoil protons are analyzed according to their energies and tabulated in a spectrum using the experimental response curve of the scintillator material. For informational purposes these protons are also tabulated in a spectrum of protons produced only by neutrons which scattered once, and a spectrum of those produced only by neutrons which scattered more than once. The input distribution is then adjusted until the resultant pulse height spectrum matches that obtained experimentally; it is then reasoned that the input spectrum is the same as that producing the experimental spectrum.

(b) Distribution functions defined as follows are tabulated:

ZETA1(E, E_p) is the fraction of those neutrons incident at energy E on the crystal which scatter once and lose a total energy E_p to protons inside the crystal.

ZETA2(E, E_p) is the fraction of those neutrons incident at energy E on the crystal which scatter more than once and lose a total energy E_p to protons inside the crystal. The recoil proton spectrum is then given as a function of proton energy by

$$N(E_p) = \int_{E_p}^{\infty} [ZETA1(E, E_p) + ZETA2(E, E_p)] \eta(E) dE, \quad (1)$$

and since ZETA1 and ZETA2 are now known as functions of E and E_p , differentiation with respect to E_p yields an integral equation for $\eta(E_p)$:

$$\eta(E_p) = \frac{1}{ZETA1(E, E_p) + ZETA2(E, E_p)} \cdot \left\{ \frac{-dN(E_p)}{dE_p} + \int_{E_p}^{\infty} \frac{\partial}{\partial E_p} [ZETA1(E, E_p) + ZETA2(E, E_p)] \eta(E) dE \right\}. \quad (2)$$

The term $dN(E_p)/dE_p$ can be determined from the experimental pulse-height spectrum, and the equation

is then solved by iteration, provided that the integral term is small. Once a neutron distribution is obtained by this method it may be checked by using it as an assumed spectrum for method (a) and comparing the resultant pulse height spectrum with the original experimental spectrum.

DATA INPUT TO RANDSCAT

Card 1

NCYCLE, ICYCLEOP, INOUTOPT, ISPECOPT,
ICARBOPT

FORMAT (516)

NCYCLE is the number of times the program is to be cycled.

ICYCLEOP is a number which controls the amount of data to be changed before the program recycles. This is more fully explained in the Data Input Appendix.

INOUTOPT is a code number controlling the optional output of the program. This is also explained in the Data Input Appendix.

ISPECOPT determines the way in which the generation of neutrons is terminated. If ISPECOPT = 1, both a number of counts and a channel number must be specified on card 3. In this case the program will stop generating neutrons and begin analyzing and outputting when the specified channel in the observed spectrum has accumulated the specified number of counts. If ISPECOPT = 2, a number of neutrons must be specified on card 3. In this case the program stops generating neutrons after the specified number of neutrons has been produced.

ICARBOPT determines whether or not the differential cross section of carbon is considered isotropic in the center-of-mass system. If ICARBOPT = 2 the carbon cross section will be considered isotropic; if ICARBOPT = 1 the carbon cross section in the center-of-mass system will be computed using tabulated Legendre coefficients (F(I,J)). In either case, the Legendre coefficients must be read in.

*****† Card 2

DIAM, HEIGHT

FORMAT (2E20.10)

DIAM is the crystal diameter (centimeters).

HEIGHT is the crystal height (centimeters).

Card 3

NSPEC, ICHNSPEC (IF ISPECOPT = 1)

NNEUT (IF ISPECOPT = 2)

FORMAT (2I10)

NSPEC is the number of counts desired.

ICHNSPEC is the number of the channel in which these counts are to appear.

NNEUT is the number of neutrons desired.

Card 4

DENSELE

FORMAT (E20.10)

DENSELE is the electron density of the crystal in cm^{-3} .

**** Card 5

EMINTAB, DELTETAB, NUMTAB

FORMAT (2F12.6, I6/

EMINTAB is the lowest energy for which cross sections are read in.

DELTETAB is the difference between consecutive energies for which cross-section values appear in the table of cross sections.

NUMTAB is the number of cross sections of each type appearing in the table.

Table 1

(SIGH(J), J = 1, NUMTAB), (SIGCEL(J), J = 1, NUMTAB), (SIGCNNG(J), J = 1, NUMTAB)
(SIGCN3AL(J), J = 1, NUMTAB), ((F(I,J), J = 1, NUMTAB), I = 1,6)

continuation of FORMAT: (6E12.6))

SIGH(J) is the value in cm^2 of the hydrogen elastic-scattering cross section at energy EMINTAB + (J-1)DELTETAB.

SIGCEL(J) is the value of the C^{12} elastic-scattering cross section at the same energy.

SIGCNNG(J) is the value (at the same energy) of the cross section for the reaction $\text{C}^{12}(\text{n}, \text{n}'\gamma)\text{C}^{12}$, where the intermediate carbon nucleus C^{12*} is excited to the 4.4-MeV level.

SIGCN3AL(J) is the value (at the same energy) of the cross section for the reaction $\text{C}^{12}(\text{n}, \text{n}')^3\text{He}^4$.

NOTE: Although it is not equally evident from all cross-section tables, the cross sections for the latter two reactions must be set exactly equal to zero below the threshold energy of the reaction. If this is not done, errors and/or error messages may result.

F(I,J) is the value (at same energy) of the Ith Legendre coefficient for the carbon differential cross section in the center-of-mass system. I = 1, ... 6.

Cards 6 & 7

XMcarb, XMHYO, XMNEUT, QGAMMA, Q3-
ALPHA, ATHYD, ATCARB

† Point at which the program will begin reading on a recycle for ICYCLEOP-2, 3, etc. See Data Input/Output Appendix.

FORMAT (6E12.6)

XMCARB is the atomic mass of carbon in atomic mass units.

XMHYD is the atomic mass of hydrogen (a.m.u.).

XMNEUT is the mass of a neutron (a.m.u.).

QGAMMA is the "Q" value for the reaction $C^{12} + n \rightarrow C^{12*} + n'$ in MeV. Note that "Q" must be negative, since the reaction is endoergic.

Q3ALPHA is the "Q" value for the reaction $C^{12} + n \rightarrow C^{12*} + n' \rightarrow n' + 3He^4$. Note that this must also be negative.

ATHYD is the number of hydrogen atoms per cubic centimeter in the crystal.

ATCARB is the number of carbon atoms per cubic centimeter in the crystal.

*** Card 8

NUMTAB

FORMAT(I6/

NUMTAB is the number of entries in the tabulated calibration data to be read in. Note that the variable name NUMTAB appears for a second time to serve a different, although similar function. This is possible because Table 1 and Table 2 are read into different subroutines, and NUMTAB is a variable which is local to its subroutine.

Table 2

(EPROTSTD(J), PPROTSTD(J), J = 1, NUMTAB)

continued FORMAT: (6F12.6))

EPROTSTD(J) is the Jth energy in the tabulated calibration data.

PPROTSTD(J) is the corresponding pulse height from the calibration curve. This need not be an integer.

Card 9

STDGAMMA, EXPGAMMA, CUTOFF

FORMAT (2F12.6, I6)

STDGAMMA is the pulse height for any monoenergetic gamma source according to the calibration curve.

EXPGAMMA is the pulse height produced by the same energy gamma ray at the current-gain setting.

CUTOFF is the lowest channel in which pulses are to be recorded. This must be a positive integer or zero.

** Card 10

(TITLE(J), J = 1, 10)

FORMAT (10A8)

TITLE is a title filling up to 80 columns on card 10.

In recycling, this title is associated with the particular neutron flux being used (card 11 and table 3).

Card 11

NTAB, EMIN, DELTE

FORMAT (I6, 2E12.6/

NTAB is the number of points for which the incident neutron flux is read in.

EMIN is the first energy value for which the flux is read in.

DELTE is the difference between consecutive energy values.

Table 3

(ETA(J), J = 1, NTAB)

continued FORMAT: (6E12.6))

ETA(J) is the incident flux in $cm^{-2} MeV^{-1} sec^{-1}$ at the energy EMIN + (J-1)DELTE.

The RANDSCAT data input deck is shown in Figure 15.

REFERENCE

1. M. Kalos and H. Goldstein. *Neutron cross section data for carbon*. Report NDA 12-16, Nuclear Development Corp., White Plains, New York.

APPENDIX

Data Input/Output

OUTPUT AND RECYCLE OPTIONS IN PROGRAM RANDSCAT

I. Recycle options

Whether or not the program is to recycle after completing a given run, and if so, the amount of new data it is to read in before beginning a new round of scattering, is controlled by an integer called ICYCLEOP. The following options are possible:

ICYCLEOP

Interpretation

- 1 Terminate the program.
- 2 A new flux is to be used. Transfer control to CALL INCENRGY statement and rerun.
- 3 A new calibration curve, gain, and neutron flux are to be used. Transfer control to CALL PULSEHT statement and rerun.
- 4 New cross-section tables, calibration curve, gain, and neutron flux are to be used. Transfer control to CALL DYNAMICS statement and rerun.
- 5 A new crystal is to be used. Read in all data except Card 1 and rerun.

For convenience in preparing input data, in the preceding data input Table 2,3, etc. asterisks have been placed at the point at which the program will begin reading on a recycle for ICYCLEOP = 2,3, etc.

II. Possible output.

A. *Unconditional output.* Each time RANDSCAT

FIG. 15. RANDSCAT data input deck

is run or cycled, it will print out the following, regardless of the options chosen:

1. A tabulation, consisting of the total number of incident neutrons, the number which scattered once, the number which scattered twice, and the number scattering more than twice.
 2. Interaction profiles for first and second scattering. These are (1) a breakdown of all neutrons scattering for the first time into the number which scattered elastically from hydrogen, which scattered elastically from carbon, which initiated a $C^{12}(n,n'\gamma)C^{12}$ reaction, and which initiated a $C^{12}(n,n')^3\text{He}^4$ reaction, and (2) a similar breakdown for all neutrons scattering a second time. Note that the breakdown is without reference to the further scattering of the neutron; that is, the first scatter profile includes those neutrons which scattered a second time, etc.
 3. The number of neutrons which departed from the crystal with less than 0.1 MeV energy.
 4. The number of neutrons which produced pulses outside the range of the pulse-height analyzer.
 5. The flux which was actually incident on the neutron detector during the Monte-Carlo calculation.
- B. *Optional output.* The program puts out in addition

the following output which is controlled by the output parameter IOUTOPT:

1. An observed pulse-height spectrum.
2. A pulse-height spectrum produced by all neutrons which scatter only once.
3. A pulse-height spectrum produced by all neutrons which scatter more than once.
4. The first- and higher-scatter distribution functions $\xi_1(E, E_p)$ and $\xi_2(E, E_p)$ for use in the equation

$$N_p = \int_{E_p}^{\infty} [\xi_1(E, E_p) + \xi_2(E, E_p)] \eta(E) dE \quad (3)$$

III. Output options

Because of the enormous potential output from PROGRAM RANDSCAT, and because of the time required to write this output on tape (~10 min), the major portion of the information output has been made optional. Optional output is controlled by a four-digit code number called IOUTOPT. Each digit of this number controls certain types of output or limited combinations of these, so that the number IOUTOPT itself specifies a combination of output types. By constructing IOUTOPT according to his desires, the user should be able to obtain the output he wishes, at the same time eliminating unwanted output.

Table 4 lists the permissible entries in IOUTOPT, together with the options they control. The numbers down the left side of the table ("digit numbers") give the position in IOUTOPT of the digits in question. These positions are numbered left to right, beginning with the "1000" bit:

	1	2	3	4	← digit numbers
IOUTOPT:	0	0	0	0	

The numbers across the top of the table correspond to digit values. Thus, each row of the table corresponds to a digit position, and each column corresponds to a digit value; each entry in the table, then, has corresponding to it a digit value and a digit position, given by its column and row number, respectively. The entries in the table are output options. A listed option is obtained by placing the corresponding digit value in the corresponding digit position of IOUTOPT. Since IOUTOPT is a four-digit number, four separate options must be chosen, one from each row in the table. As can be seen, a large number of combinations is possible. An X placed in a table position means that the corresponding value is not permitted for that digit.

For example, IOUTOPT = 1322 would produce the following:

- (a) a graph of the flux actually incident on the crystal.
- (b) tape #31 containing the observed proton spectrum, $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$.

(c) a print-out of the observed, 1st and 2nd scatter proton spectra.

(d) a graph of the observed proton spectrum.

IV. Requirements for optional output

When requesting optional output from RANDSCAT, either or both of two EQUIP cards may be necessary:

1. If any graphs whatsoever are requested, the following EQUIP card must be placed in the deck:

?EQUIP, 7 = SV

In addition, a CALCOMP tape label and plotting request must be filled out at the 3600 scheduling desk and submitted with the job. If the RANDSCAT source desk (FORTRAN) is being used, the CALCOMP binary deck must be included in the package.

2. If any output is being requested on Tape #31, the following EQUIP card is necessary:

$\text{?EQUIP, 31 = (TAPE TITLE, 1, 1), SV}$

Also, a tape-save request must be filled out at the 3600 scheduling desk.

Conversion of RANDSCAT to Beam Experiment

As written, RANDSCAT assumes an isotropic incident neutron flux; explicitly stated, this assumption means that neutrons of any given energy have equal probability of hitting the crystal at any point on its surface, and that once incident at a point, they may

TABLE 4. OUTPUT OPTIONS

Digit number	Digit value					
	0	1	2	3	4	5
1	Do not graph flux	Graph actual incident flux	No optional output whatsoever. Ignore all other digits of ioutopt	X	X	X
2	Do not write a tape	Write observed proton spectrum on tape #31	Write $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$ on tape #31	Write observed proton spectrum, $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$ on tape #31	X	X
3	Produce no optional print-out	Print observed proton spectrum	Print observed, 1st, and 2nd scatter proton spectra	Print $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$	Print observed proton spectrum, $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$	Print observed, 1st and 2nd scatter proton spectra, $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$
4	Do not graph proton spectra, $\zeta_1(E, E_p)$ or $\zeta_2(E, E_p)$	Graph $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$ as functs or E_p for selected values of E	Graph observed proton spectrum	Graph observed, 1st, and 2nd scatter proton spectra	Graph observed proton spectrum, $\zeta_1(E, E_p)$, and $\zeta_2(E, E_p)$	Graph all spectra, $\zeta_1(E, E_p)$, and $\zeta_2(E, E_p)$

have any direction which causes them to enter the crystal.

It may prove useful to be able to apply RANDSCAT to experimental situations in which the neutrons originate in a beam. The modifications required to adapt the program to this application are small in scope and, therefore, practical. Adaptations to two different experimental situations are outlined below.

A general word about modifications in incident flux: On cards numbered 38 through 48 the type of incident flux is specified by writing the probability functions for the occurrence of points of incidence and incident directions. By appropriate replacement of this section the program can be modified to fit any experimental situation which satisfies the requirements on crystal shape and composition and neutron energy range. Any number of cards may be added to this section, and the statement numbers 10021 and 10022 are not referenced by any other part of the program.

EXPERIMENT I

A beam from an aperture of radius BEAMAP is directed at the side of the crystal perpendicular to the crystal axis and directed through the crystal center. The distance from the beam aperture to the center of the crystal is BEAMDIST, and the beam must encompass the entire crystal.

Cards 39 through 48 should be removed and the following cards inserted:

Card number	Statement
39	BEAM1=BEAMAP*U1
40	BEAM2=PI*RANF(-1)
41	ZIN=HEIGHT/2.0*RANF(-1)
42	XIN=DIAM/2.0
43	PHI=PI/2.0+ATANF((XIN-BEAM1*COSF (BEAM2))/(BEAMDIST 1-DIAM/2.0))
44	POLPHI=ASINF((DIAM/2.0+BEAM1*SINF (BEAM2)/COSF(ASINF 1(DIAM/2.0/BEAMDIST)))/(DIAM/2.0/BEAM- DIST*BEAM1*SINF 2(BEAM2)))*RANF(-1)

where the numbers preceding the statements on cards 44, 46, and 47 are continuation symbols. Card 48 is omitted.

EXPERIMENT II

Beam from an aperture of radius BEAMAP directed at one of the faces of the crystal along the crystal axis. The distance from the beam aperture to the center of the crystal is BEAMDIST. Note that the beam must be wide enough to include the entire crystal face.

Cards 39 through 48 should be removed and the following cards inserted:

Card Number	Statement
39	BEAM1=BEAMAP*RANF(-1)
40	ZIN=HEIGHT/2.0
41	XIN=DIAM/2.0U1
42	POLPHI=2.0*PI*RANF(-1)
43	IF(RANF(-1)-0.5) 10021, 10021, 10022
44	10021 PHI=ATANF(ABSF(XIN-BEAM1)/ (BEAMDIST-HEIGHT/2.0))
45	GO TO 10020
46	10022 PHI=ATANF(ABSF(XIN+BEAM1)/(BEAM DIST-HEIGHT/2.0))

Cards 47 and 48 should be omitted.

In either Experiment I or Experiment II the numerical values for BEAMAP and BEAMDIST are entered in the program by means of two data statements:

```
DATA(BEAMAP=... )
DATA(BEAMDIST=... ),
```

where the numerical values are placed to the right of the equal sign. The quantities should be given in centimeters. The data statements must be placed at the beginning of the program among the other non-executable statements.

PROGRAM PARTDIFF

DESCRIPTION OF THE PROBLEM

A previous program, RANDSCAT, has calculated the energy distribution functions

$$\zeta_1(E, E_p) \quad \zeta_2(E, E_p)$$

for single- and higher-order scattering of low energy neutrons in an organic scintillator crystal. These calculations have been done by Monte-Carlo methods. The energy spectrum of the incident neutrons can be calculated by iteration from the equation

$$\eta(E_p) = \frac{1}{\zeta_1(E, E_p) + \zeta_2(E, E_p)} \left[-\frac{dN_p}{dE_p} + \int_{E_p}^{\infty} \left(\frac{\partial}{\partial E_p} [\zeta_1(E, E_p) + \zeta_2(E, E_p)] \eta(E) dE \right) \right] \quad (1)$$

The purpose of PARTDIFF is to calculate the function

$$\frac{\partial}{\partial E_p} [\zeta_1(E, E_p) + \zeta_2(E, E_p)]$$

from the energy distribution functions calculated by RANDSCAT.

METHOD

Values of $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$ are read in for E varying in 0.1-MeV steps from E_{MIN} to E_{MAX} , and for E_p varying, also in 0.1-MeV steps, between E and 0.1 MeV. The program first adds together the two distribution functions $\zeta_1(E, E_p)$ and $\zeta_2(E, E_p)$ to get

$\zeta(E, E_p)$, which it treats as a function of E_p for each value of E . Given a specific value of E_p at which the derivative is to be calculated, this value is taken as the center of an 11-point interval. The function zeta is then approximated in this interval by a least-square fit to the tabulated values read in. Although specifically written into the program, the method by which this fitting is done is essentially the same as that outlined in the appendix of PROGRAM NEUTBAK; it involves adjusting the degree of the polynomial approximation until the closest approach to the condition

$$\sigma \sqrt{\zeta(E, E_p^{(i)})} \quad (2)$$

is reached, where σ is the standard deviation of the curve with respect to the tabulated values and $E_p^{(i)}$ is the value of E_p at which the derivative is then obtained from the polynomial expression by the formula

$$\left. \frac{\partial \zeta}{\partial E_p} \right|_{E_p^{(i)}} = \sum_{j=0}^n j a_j (E_p^{(i)})^j \quad (3)$$

MACHINE

CDC-3600, FORTRAN coded.

RUNNING TIME

Compilation time is approximately 20 seconds. Execution time for a test case consisting of half the maximum amount of input data possible was 11 minutes, 10 seconds.

INPUT INFORMATION

The program requires two cards and one magnetic tape of roughly 9800 records. This is described in detail under "Data Input for PARTDIFF" below.

OUTPUT

The program outputs one tape (Logical Unit no. 29) of approximately 4900 records, containing the calculated derivative at intervals of 0.1 MeV throughout the specified energy range.

ACCURACY

The principal parameter which can easily be varied, should greater accuracy in fitting be necessary, is the number of points over which the fit is taken. This is specified by the value given to M on card PD-5 of the program. M may be increased up to 21 without further program changes; beyond this arrays must be re-dimensioned. M should be kept odd, and increasing it will, of course, slow up the program. The maximum degree of the fitting polynomial (1) cannot be raised without exceeding the machine word size or putting parts of the program into double precision. ERROR MESSAGES: In testing the program, it was found

that the principal indication that something was drastically wrong with the data the program was processing was that the square-root function would be called with respect to a negative argument in the calculation of $\sqrt{\zeta(E, E_p^{(i)})}$. Should this happen, the program prints out the following message:

AN ERROR HAS OCCURRED IN FITTING, PROGRAM IS RETRYING THIS COMPUTATION together with the index values (I and J , corresponding to E and E_p , respectively) and the degree of the polynomial (NDEG) for which the error occurred. The program then repeats the fit for this case. Should the error occur a second time the following message is printed:

THE ERROR HAS OCCURRED AGAIN DURING RETRIAL. PROGRAM TERMINATED, INTENTIONAL DUMP OF MEMORY PRODUCED. DISREGARD FURTHER ERROR MESSAGES.

The program then attempts to read two more records from the input tape, causing the monitor to interrupt for an unchecked end of file and to produce a diagnostic dump of the memory.

DATA INPUT TO PARTDIFF

Card 1 ITAPE FORMAT (I6)

ITAPE is an integer parameter controlling the way in which PARTDIFF will read in its data tape. The following options are possible:

ITAPE=1 must be used if in the preparation of tape 1 (LUN No. 31) by PROGRAM RANDSCAT the calculated pulse-height spectrum has been written out on magnetic tape. In this case tape 1 will appear in the form (a) below, and PARTDIFF will read the first 400 numbers on the tape into an unused section of storage.

ITAPE=2 must be used if the calculated pulse-height spectrum has not been written on tape. In this case tape 1 has the form (b) below, and PARTDIFF will take the first 9800 records on the tape as its input data.

Card 2 EMIN, EMAX FORMAT (2F12.6)

EMIN AND EMAX are, respectively, the minimum and maximum incident neutron energies for which the distribution functions have been calculated by RANDSCAT; they are the limits within which PARTDIFF is to differentiate the tabulated functions which it reads from tape 1.

Tape 1 (a) (HOLD(J), J=1,400), ((ZETA(I,J), J=1, 140), I=1,140), ((DZETDEP(I,J), J=1,140), I=1, JLIM)

(b) ((ZETA(I,J),J=1,140),I=1,140),((DZET-
DEP(I,J),J=1,140),I=1,JLIM)

FORMAT (4E20.10)

Tape 1 is denoted, both in RANDSCAT and in PART-
DIFF, as LUN No. 31.

HOLD(J) is, as mentioned above, an area of storage
not used by the program, into which the irrelevant
pulse-height spectrum is read from the tape.

ZETA(I,J) is the array into which the first of the
two distribution functions (denoted ZETA1(I,J)
in RANDSCAT) is read. This array subsequently
becomes the function to be differentiated (ZETA1
+ ZETA2).

DZETDEP(I,J) actually denotes the function $(\partial/\partial E_p)(\zeta_1(E, E_p) + \zeta_2(E, E_p))$ which is to be the
result of the calculation. For the purposes of input,
however, it is simply used as a convenient array

in which to read ZETA2(I,J). This is subsequently
added to ZETA1(I,J) and stored in ZETA(I,J).

JLIM is a number constructed by the program from
EMAX, and is utilized to stop the program from
reading in unnecessary data. JLIM-EMAX/0.1.

One word of explanation should be added to avoid
confusion. The forms (a) and (b) above are summaries
of the read-in operations performed by PARTDIFF,
and, therefore, use the array names appropriate to this
program. Tape 1, however, has been written by RAND-
SCAT in either of the following forms:

- (a) (SPECTRUM(J),J=1,400),((ZETA1(I,J),J=1,
140),I=1,140),((ZETA2(I,J),J=1,140),I=1,140)
- (b) ((ZETA1(I,J),J=1,140),I=1,140),((ZETA2(I,J),
J=1,140),I=1,140)

which may serve to clarify the explanation of DZET-
DEP above.

SPECIFIC PRIMARY IONIZATION IN GASES BY HIGH-ENERGY ELECTRONS

F. F. Rieke and W. Prepejchal

INTRODUCTION

The term specific primary ionization (SPI) refers
to the number of primary ionization acts per unit
path under standard conditions. All ionization acts
are weighted equally, regardless of the state of ioniza-
tion that results (single, double, etc.) or of multiple
ionization that results from secondary acts such as
ionization by delta rays. The theoretical significance
of the SPI has been emphasized by Fano⁽¹⁾ in discussing
some measurements made by McClure.⁽²⁾ Fano pointed
out that the SPI is directly related to the total dipole
strength for ionization, an important atomic property
deserving of systematic study.

In McClure's experiments, a technique developed
at the Bartol Foundation for studies of the properties
of cosmic radiation was applied to monoenergetic
electrons of energies 0.2–1.6 MeV, and the gases studied
were H₂, He, Ne, and Ar. McClure expressed the
intention of extending the measurements to other gases,
but the plan was not carried out. The present experi-
ments were undertaken to exploit more fully the po-
tentialities of the experiments started by McClure,
both by widening their scope and by increasing their
precision.

APPARATUS AND METHOD

The apparatus is illustrated schematically in Figure
16. Beta rays from the source, *J*, are selected for

energy by the magnetic analyzer, *M*, pass through the
thin-window gas-filled counter, *C*, and fall upon the
particle detector, *D*. Ideally, (1) counter *C* gives rise
to a pulse in channel *c* unfailingly and promptly when-
ever an ionization occurs within the gas, and (2) a
pulse in channel *d*, from the particle detector, *D*, is a
reliable indication that an electron selected by *M* has
passed through *C*. (It is not necessary, however, that
D respond to every electron that passes through *C*.)

Channel *c-d* measures coincidences between pulses
in *C* and *D*. If, in some interval of time the numbers of
counts accumulated in *c* and *c-d* are *x* and *y*, the effi-
ciency of counter *C* is given by

$$\epsilon = y/x \quad (1)$$

and, since*

$$\epsilon = 1 - \exp(-SLp) \quad (2)$$

* The average number $\bar{n}$ of ionizations in the path *L* is
given by

$$\bar{n} = SLp. \quad (4)$$

The probability $P(n)$ that a primary electron ionizes *n* times
in the path, *L*, is then given by

$$P(n) = \bar{n}^n e^{-\bar{n}}/n! \quad (5)$$

and

$$P(0) = e^{-\bar{n}} = 1 - \epsilon \quad (6)$$

whence equation (2).

Fig. 16. Apparatus for measuring specific primary ionization. *M*, magnetic analyzer; *J*, beta source; *C*, gas counter; *D*, silicon particle detector.

the specific primary ionization S is given by

$$S = -(\ln(1 - \epsilon))/(Lp), \quad (3)$$

where L is the length of path of the primary through C , and p is the gas pressure reduced to standard conditions.

Actually, of course, the system does not quite fulfill the conditions (1) and (2) stated above; minimizing and correcting for the departures from ideal behavior is, technically, the heart of the problem.

In reconstructing McClure's apparatus, obvious second-edition improvements have been made. His apparatus employed for M (Figure 16) a conventional 180° analyzer, ours, a double-focusing analyzer designed specifically for this application. The latter instrument has the advantages of placing the detecting system well away from the magnet and of utilizing the source, J , more efficiently with better energy resolution. Where for D a telescope of two thin-walled GM counters in coincidence was used previously, a silicon barrier-layer detector is now used. Instead of 1-mil aluminum windows for C , $\frac{1}{4}$ -mil Mylar flash coated with copper is now used; the lighter windows reduce the correction for energy loss in the first window and, more important for low-energy primaries, greatly reduce the loss from the beam through scattering by the windows.

That the new apparatus is fully adequate for the purpose is shown by the following data. As a source of negatrons, Pr^{144} in equilibrium with Ce^{144} is used. Its continuous beta-ray spectrum extends to 2.98 MeV; as a source in the experiments it is usable over the range 0.11–2.75 MeV. The energy resolution and transmission of the analyzer are approximately 1%

and 0.1%. With the strongest source we have used, the count rates in channel d of Figure 16 are 260 cpm at 0.11 MeV, 1.7×10^4 cpm at 1.1 MeV, and 400 cpm at 2.7 MeV; with analyzer current zero, the background rate in channel d is 3 cpm, and with a typical gas filling in C , the background in channel $c \cdot d$ is $\frac{1}{10}$ cpm. At the higher energies, where scattering is small, 75% of the primaries that enter C reach D ; at 0.11 MeV, 7%.

The gas-handling system has been designed to minimize contamination. Greased stopcocks and liquid-filled manometers have been avoided entirely. Gas pressure enters directly into the determination of the SPI; it is measured with a Wallace and Tiernan gauge, 0–200 torr, that has been calibrated against mercury manometers. The errors do not exceed 1% for pressures above 5 torr.

The principal uncertainties encountered in the experiments are in determining how well the counter, C , fulfills the condition that it should respond reliably to, and only to, ionization events in the gas. Inasmuch as the gas under study must serve as the counting gas in C , each gas presents its own problems with respect to counting. In addition, disturbances (wall effects) arise from interaction of the windows with the primary electrons and with the secondaries produced very close to the windows.

WALL EFFECTS

Secondary emission of electrons by the windows must introduce some error and was considered by McClure. If the probability that a primary electron of energy, E , in passing through the two windows gives rise to a secondary electron is $2\delta(E)$, the observed

efficiency ϵ' of counter C is related to the gas-associated efficiency ϵ according to

$$(1 - \epsilon') = (1 - 2\delta)(1 - \epsilon) \quad (7)$$

and when $\ln(1 - \epsilon')$ is plotted against p , then according to equation (3) a straight line should be obtained with slope equal to LS and intercept $\ln(1 - 2\delta)$ at $p = 0$. McClure carried out such a test with H_2 and found that the data could be fitted by drawing a line through the origin, which would imply $\delta = 0$. From this circumstance he concluded that wall effects were negligible. More recently, however, Schultz and Pomerantz⁽³⁾ have measured the secondary yield of 0.3- to 1.6-MeV electrons passing through thin layers of C, Ni, and Al. From their results, it appears that 2δ should amount to 0.02–0.03 at energies above 0.5 MeV and should rise well above 0.05 at 0.1 MeV. That this effect was not apparent in McClure's data (and is not indicated systematically by ours) must mean that compensating effects are present.

The loss of electrons by diffusion to the windows is a second phenomenon that might be expected to make the counter C depart from ideal behavior. The effect of diffusion in a quite similar situation is treated at some length by Loeb⁽⁴⁾ in discussing experiments wherein photoemission from a metal surface is used to provide electrons for studies of the motion of electrons in gases. The photoelectrons are emitted with initial energies of the order of magnitude of 1 eV. Their direction of motion is randomized in the first few collisions with gas molecules, but their energies are not brought into equilibrium with an applied electric field until many collisions have occurred. Thus many of the electrons are able to migrate back to the emitting surface in spite of the electric field that tends to draw them away from it. The situation is similar in the case of secondary electrons ejected from surfaces by fast primary electrons except that these have, according to Schultz and Pomerantz,⁽³⁾ energies up to 20 eV; the average is about 4 eV. In counter, C , the electric field at the windows has typically a strength of 30 V/cm; under these conditions, one would judge from Loeb's discussion, well over half of the secondaries from the window must diffuse back to the windows. Thus, in equation (7) one should use an effective secondary-emission coefficient δ' that is considerably smaller than the true coefficient δ .

Back-diffusion affects also the secondary electrons ejected from gas molecules situated within a few mean-free-paths from the windows. It can be shown, however, that values of the SPI practically uninfluenced by back-diffusion can be obtained by observing the efficiency ϵ' at several different pressures for each value of E . A secondary electron of energy, W , ejected at a dis-

tance, x , from a window will have a probability $Q(W, x/\lambda)$ of being lost by diffusing to a window. The mean-free-path, λ , depends upon both p and W ; the relation is of the form

$$1/\lambda = pf(W),$$

so that when Q is averaged over W and x , one obtains

$$\bar{Q} = a/p,$$

and in (2) one must replace SLp by $SLp(1 - 2\bar{Q})$. When this is done, and (2) is combined with (7) one obtains

$$\ln(1 - \epsilon') = SLp - [2SLa + \ln(1 - 2\delta')] = SLp - b \quad (8)$$

One factor has been neglected in the above discussion of back-diffusion, namely, the effect of variations in the electric field strength, X , at the windows. In practice, the voltage applied to counter, C , increases with p ; accordingly both δ'/δ and a depend systematically on p . However, because the secondaries for the most part have several eV of kinetic energy, while X is not very large and varies rather slowly with p (less rapidly than proportionally), it is a good approximation to treat both δ'/δ and a as being independent of p .

According to equation (8), if for each gas and primary energy, E , a series of values of ϵ' is observed at different pressures and $\ln(1 - \epsilon')$ is plotted against p , the points should fall on a straight line with slope SL and intercept b at $p = 0$, as was pointed out by McClure. We differ from McClure, however, in the following: It is *not* allowable to treat b as a constant of the apparatus; it must be reevaluated for each combination of gas and primary energy. Although this dictum may at first appear to be rather inconsequential, actually it can make a difference of several per cent in the value of S derived from a set of measurements if, in the reduction of the data, one does, or does not, treat b as a fixed point. On the other hand, it is to be expected that b will vary with E in a regular fashion for each gas. That is to say, in fitting straight lines to plots of data for a particular gas, the value of b for each E must be chosen with due regard for its indicated value for neighboring E 's.

COUNTING MECHANISMS

For the counter, C , McClure used a GM tube with a series resistance of 10^9 ohm to quench the discharge. With this arrangement it was possible to make measurements on pure H_2 but impossible to carry them out with the rare gases unless about 10% of H_2 was added to them; with pure rare gases the counter broke into continuous discharge. Our experience has been much

the same, and we have not been able to circumvent the difficulty by using trigger circuits instead of series resistance to quench the GM discharge. We were also unable to make the tube function satisfactorily as a GM counter when filled with methane. It now appears unlikely that conventional GM counting can be used for very many *pure* gases other than hydrogen. However, proportional counting has been employed successfully to secure data for methane, ethane, and propane, and it seems likely that it can be applied to additional organic gases. For still other gases it is probable that some further development in counting technique will be necessary.

With either GM or proportional counting, the question arises of how reliably a single ionization event is detected. That the counter should show a flat and reasonably long plateau has been taken as a prerequisite for the accumulation of data, but this condition is not complete assurance that single free electrons are detected with 100% efficiency. In the case of proportional counting, a good estimate of the correction to be

FIG. 17. Specific primary ionization in hydrogen
 $M_i^2 = 1.985 \beta^2 S$. $\text{Log}_e E'' = \text{log}_e E + (1 + E/mc^2)^{-2} + \text{log}_e (1 + E/2 mc^2) - 1$, E and mc^2 in keV.
 + $\text{H}_2 e^-$; $\circ$ $\text{D}_2 e^-$; $\times$ $\text{H}_2 e^+$; $\triangle$ $\text{D}_2 e^+$; $\bullet$ $\text{H}_2 e^-$ (McClure)

applied for missed counts can be made in the following way. The distribution of pulse heights is measured with a multichannel pulse-height analyzer. By extrapolating the distribution to zero pulse height, one can estimate the fractional number of pulses that fall below the discrimination level, which is set just high enough to exclude noise pulses. In this way it has been found with methane, for example, that the correction is less than 3% under the worst condition (low pressure of filling gas) and for the most part is less than $\frac{1}{2}\%$.

EXPERIMENTS

At the outset, we must say that we are not satisfied with our control of instrumental errors, so our discussion of experiments must be taken as a report of status rather than of final results.

A complete set of measurements has been made on H_2 and D_2 with electrons of energies 0.11–2.7 MeV and with positrons of energies 0.20–0.38 MeV. The results are shown in Figure 17, where they are plotted in a manner that relates them to the Bethe theory of ionization. According to the Bethe theory, the points plotted in the way shown should lie on a straight line; the slope of the line is equal to M_i^2 , the total dipole strength for ionizing collisions.⁽¹⁾ Our data for H_2 and e^- lie nicely on a straight line with S -values uniformly 5% smaller than McClure's, but the difference between H_2 and D_2 varies irregularly with primary energy, and this behavior is clearly symptomatic of erratic malfunction of the apparatus, for the uncertainties from counting statistics are an order of magnitude smaller than the discrepancies. Because we know no reason to believe the $\text{H}_2 e^-$ measurements are more reliable than the others, all are equally uncertain, so that further checks will have to be made.

Complete sets of data have been obtained for methane, ethane, and propane. It seems not worth while, however, to give further numerical results until the uncertainties mentioned above in connection with hydrogen have been cleared up.

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THE DOSES FROM THOROTRAST AND MIGRATED DESCENDANTS: STATUS, PROSPECTS, AND IMPLICATIONS*

L. D. Marinelli

The requirements of adequate dosimetry in Thorotrast-injected patients and most of the difficulties encountered have already been stated or implied by the preceding speakers.

However, since our knowledge is still incomplete, the general requirements of macro- and microdosimetry will be summarized first in general terms, and complemented later by suggestions in improvements needed to elucidate dosimetric questions which are still uncertain.

The requirements of macrodosimetry are

- (1) Collection of representative samples.
- (2) Localization of activity *in vivo*.
- (3) Collateral studies with short-lived daughter products.
- (4) Correlation of results between (1) and (2).

The attainment of these objectives is beset by many experimental difficulties; for instance, the measurement of the short-lived, but highly significant, daughters from Ra^{224} down to Tl^{208} is hampered by the weak activities involved and by the small number of useful representative samples available, since these can be obtained only if a high degree of time coordination is attained between physician, pathologist and physicist. Some of these difficulties may be overcome or eased by techniques involved in item (2) above. Thus Dr. Kaul has already mentioned the successful combination of whole-body counting with surgical procedures. I may add that localization *in vivo* by means of collimated scanning deserves to be attempted and exploited to the fullest: Mr. May of our Laboratory has measured the radioactivity of the legs of four Thorotrast patients and found it consistent with the estimates obtained from analysis of cortical bone (see elsewhere in this report).

Of great interest is also the possibility of coordinating the exhalation rate of Th^{220} with the activity of Pb^{212} and daughters in the respiratory tract, since Dr. Schales of Frankfurt mentions the detection of this activity over the chest of patients treated with Ra^{224} . Pertinent information can also be supplied by collateral studies in man or laboratory animals by the judicious administration of members of the thorium chain. I refer to the studies on dogs described by Stover

at this meeting (see also Reference 1), by Eridani *et al.*⁽²⁾ concerning bismuth in the rat and to the investigations of Maletskos⁽³⁾ and Schales⁽⁴⁾ concerning the kinetics and metabolism of Ra^{224} and daughters in man.

I wish to mention at this point that experiments of this type should be designed to evaluate the biological half-life of a given daughter in the relevant biological compartment; hence, the usefulness of experiments with longer lived isotopes of Ra, Pb, Bi and Po should also be considered.

SHORT-TERM STUDIES

Another type of collateral study consists in comparing the equilibrium of Th^{228} daughters in the tissues of various species at relatively short times following the injection of Thorotrast.

The results shown in Table 5 contain data obtained by Parr, Simmons and Lucas of Argonne after attainment of the short-term equilibrium of Ra^{224} and Pb^{212} vs. Th^{228} in the liver and spleen of dog, rat and man. The data on rat extend from 35 days to 2 years; those in man cover results collected by various workers from a few weeks to many years. One cannot but remain impressed by the following facts: (1) the $\text{Ra}^{224}/\text{Th}^{228}$ ratios at short times after injection are remarkably similar in liver, regardless of species; there is a definite increase in man at later times, fully consistent with data presented at this meeting and with Hursh's observations on Ra^{224} excretion and retention from zero over 1000 days;^(12, 15) (2) the liver $\text{Ra}^{228}/\text{Th}^{232}$ ratios in man, calculated at equilibrium from long-term burdens, are very similar to the $\text{Ra}^{224}/\text{Th}^{228}$ equilibrium ratio at short times; (3) at shorter times in rats and dogs the $\text{Ra}^{224}/\text{Th}^{228}$ ratio in spleen is lower than in liver, but in man it seems to be higher.

These results are consistent with the idea that radium atoms, in escaping by recoil from the recently deposited colloidal particle, may spend more time in the spleen than in the liver of man and relatively less in the other two species. This effect is not, and should not be, evident with Ra^{228} ; because of its much longer radioactive half-life this isotope has more time to escape into the circulation.

One cannot be as explicit about the $\text{Pb}^{212}/\text{Ra}^{224}$ ratio; the results seem very consistent in man; however, the values in animals require confirmation beyond 38

* Presented at the Panel on Dosimetry and Toxicity of Thorotrast, International Atomic Energy Agency, Vienna, October 1965. Report to be published.

TABLE 5. EQUILIBRIUM OF THE Th^{228} DAUGHTERS AFTER THOROTRAST-IV INJECTION
($\text{Ra}^{224}/\text{Th}^{228}$; $\text{Pb}^{212}/\text{Th}^{228}$; $\text{Pb}^{212}/\text{Ra}^{224}$)

Animal	Burden	Liver			Reference	Spleen		
		Ra/Th	Pb/Th	Pb/Ra		Ra/Th	Pb/Th	Pb/Ra
Beagle	21 d	0.55	0.19	0.34	Parr ^(5, 6)	0.37	0.19	0.51
Rat	35-38 d	0.55	0.40	0.73	"	0.43	0.23	0.53
Rat	1.0 y	0.49	—	—	Simmons ⁽⁷⁾	0.32	—	—
Rat	1.5 y	0.52	0.25	0.48	"	0.39	—	—
Rat	2.0 y	0.50	0.16	0.32	"	0.44	—	—
Man	~50 d	0.59	0.32	0.54	Parr, ^(5, 6) Griem ⁽⁸⁾	0.69	0.26	0.38
Man	14 y	0.66	0.32	0.48	Rundo ⁽⁹⁾	0.75	0.23	0.30
Man	Long-term	0.90	0.40	0.44	Kaul, <i>et al.</i> ⁽¹⁰⁾	0.90	0.40	0.44
Kidney	Long-term	0.80	0.39	0.49	Oberhausen ⁽¹¹⁾	0.80	0.39	0.49

Reported values of $\text{Ra}^{228}/\text{Th}^{232}$ at long times: Liver, ~0.62 (Rundo); 0.45 (Parr, Lucas⁽¹²⁾); 0.48 (Kaul); Spleen, 0.69 (Rundo); 0.55 (Parr); 0.48 (Kaul); 0.49 (Hursh⁽¹³⁾) Whole-body, 0.49 (Cohn *et al.*⁽¹⁴⁾); 0.40 (Dudley⁽¹⁵⁾).

days, since Parr's technique was not fully implemented in obtaining most of the data.

The apparent time invariance of this ratio and its species dependence may be due to the escape of the noble gas thoron from the organs in question.

The values of Oberhausen⁽¹¹⁾ obtained from the kidney of man many years after retrograde pyelography fit in extremely well with the readings in the reticuloendothelial system; namely the $\text{Ra}^{224}/\text{Th}^{228}$ ratio is high in aged deposits and the $\text{Pb}^{212}/\text{Ra}^{224}$ ratio is similar to the values in liver and spleen, irrespective of time. These findings raise the question as to whether the equilibrium status of the chain, at least as far down as Th^{228} , is a property of the colloidal particle and not of the tissue in which it resides. As to the $\text{Ra}^{224}/\text{Th}^{228}$ ratio, it is evident that its increase with time of deposition is consistent with the various mechanisms discussed by Faber and Müller.⁽¹⁷⁾

MICROLOCALIZATION

In his conclusions Dr. Kaul mentioned the need of exploring the localization of these Thorotrast aggregates in the reticuloendothelial system. I am sure that we all agree with him. A few suggestions as to methods which might be useful in this quest are given below:

- (a) Electron microscopy
 - (b) Microradiography
 - (c) Autoradiography
 - (d) Tissue cultures
 - (e) *In vitro* studies
- for study of aggregates
- to determine types of cells at risk
- for study of intra- or extra-cellular migration of daughters

One point might be worth mentioning: The difficulties of correlating dosimetric parameters with the untoward effect of Thorotrast administration are, of course, increased when one considers the colloidal dep-

osition in the reticuloendothelial system, but this situation is not present in tissues where translocation occurs. The spotty distribution of radiation sources, *per se*, should not lead to undue concern, since the same problem is being faced by investigators interested in the toxicity of bone seekers.

THE BALANCE OF THOROTRAST DAUGHTERS

The concentrations of Th^{232} and daughters in various tissues are shown in Table 6.

The following point should be made: The radioactive equilibrium *in vivo* throughout the reticuloendothelial system is practically the same as that estimated by Dr. Kaul.

A question arises as to the deposition in the spleen, which is calculated to be about 10% in the table. This is in contrast with the values of 21% and 17% obtained by Rundo⁽⁹⁾ and Kaul.⁽¹⁰⁾ The justification for the value in the table is based on the measurements of Parr in 4 human cases at 50 days post-injection and one case at 11 years. However, since the correct figure depends on accuracy of representative sampling, duration of burden, shrinkage, etc., it is obvious that more study is needed.

Another question arises on the concentrations in the marrow; measurements reported by Hursh,⁽¹³⁾ Parr⁽⁵⁾ (extrapolated to 1500 g wt) come to about 10% to 15% of the Th^{232} burden. The value of 30% which Dr. Kaul has obtained from his experiments and ours seems to rely on the extrapolation from the weight of bone sample to the entire bone marrow. This procedure is extremely difficult to justify because contamination, fractional marrow weight, etc., interfere with precise evaluation. There is no question in my mind that special attention will have to be devoted to this type of assay.

A task of some importance is also the measurement

TABLE 6. WHOLE-BODY BALANCE OF THOROTRAST DAUGHTERS' ACTIVITIES
Nanocuries per organ (at equilibrium); 50-cc injection

Tissue	Wt (g)	Th ²³²	Ra ²²⁸	Th ²³²	Ra ²²⁴	Em ²²⁰ + Po ²¹⁶	Pb ²¹² (Th B)	Bi ²¹² (Th C)	Po ²¹² + Tl ²⁰⁸
Whole body	70,000	1,250	625	625	556	450	500	500	500
Liver	1,600	950	425	420	378	80% of Ra ²²⁴	190	130	Same As Th C
Spleen	175	120	60	58	52		26.5	18	
Red marrow	1,600	160	80	32	29		26	40	
Lung	800	6	3	2.4	2		24	24	
Lymph node and lymph	1,500	5	20	17	17.5	80% of Ra ²²⁴	22.5	22	Same As Th C
Blood	5,300	—	4	4	11		72	150	
Kidney	310	1.5	0.3	0.6	2		2	3	
Skeleton	7,100	6.5	16.5	21.5	43		40	40	
Soft tissue	51,600	—	16.2	70.5	20		100	76	

of the biological half-life of thoron in the reticuloendothelial system and elsewhere; this noble gas, undetained by chemical processes, should escape faster than any other member of the chain and should yield information on the diffusion rate. Moreover, this type of measurement may clarify the reason why the ratio Tl^{208}/Ac^{228} for the whole body *in vivo* varies from 0.66 to 0.94,⁽¹⁵⁾ although the exhalation rates obtained by various authors agree rather well among themselves.

In Table 6 the fraction of Em^{220} plus Po^{216} produced by Ra^{224} in the reticuloendothelial system which disintegrates therein has been assumed to be 80% as suggested by Grillmeier, Stahlhofen, and Kaul;^(10, 16, 18, 19) it is based on the exhalation rates experimentally determined in various laboratories and on a reasonable average transit time in blood and lung. In general, these reservations apply also to the lung, the lymph nodes, and the blood.

The concentration of Pb^{212} in the lung is important for at least three reasons: (1) the thoron concentration in air exhaled by Thorotrast patients is higher than working level concentrations of Em^{222} in uranium mines, (2) the lung dose contributed directly by exhaled thoron cannot be measured *in situ*, and (3) the disintegration of Pb^{212} and daughters in the pulmonary circulation does contribute to lung doses.

Since exhaled thoron moves in the lung in a direction opposite to that of inhaled radon accompanied by dust, of limited help are the calculations presented at the 1964 Hanford Symposium and at the 1963 joint meeting of the IAEA, ILO and WHO on Radiological Health and Safety in Mining and Milling of Nuclear Material.^(20, 21) In my opinion, if it were not for the uncertainty in the transport times involved, the data of Dr. Lafuma's experiment⁽²²⁾ with parabiotic pairs of mice (one of which exhaled the radon inhaled by the other) would be directly applicable. The best that we

can do at this time is to utilize the concentration of Pb^{212} found in the lung by Parr.^{(5)*} To a first approximation, the concentration that he measured is consistent with (a) an exhalation rate of thoron of about 10% of the Ra^{224} in the body,⁽¹⁹⁾ (b) with an average lifetime of the thoron atom in the lung of 0.4 min,⁽¹⁶⁾ (c) the amount of Pb^{212} in a volume of 300 cc of trapped blood in that organ, and (d) the amount of thoron left in the lung at exitus. To avoid misunderstanding, it is well to state that the average doses to the lung were calculated by assuming that the activity of Pb^{212} extrapolated to the time of death represented the equilibrium rate of disintegration of Em^{220} plus Po^{216} in the lung of the living patient. No attempt has been made to extend the calculations to the respiratory passages.

As to the kidney, some attempt should be made to study the organ contents *in vivo*, since the concentrations of Pb^{212} plus Bi^{212} which are expected following intravenous injections of these elements in dogs and rats^(1, 23, 24) have not been reported in man.

We conclude our comments on Table 6 by recalling that it represents a compromise of data on exhalation, blood concentrations, tissue samplings at various times, excretion of Ra^{224} and Ra^{228} , and whole-body counting of the ratio Tl^{208}/Ac^{228} *in vivo*. The dosimetry of bone and marrow will be treated from the epidemiological point of view; hence some details will be discussed later.

DOSE RATE TO VARIOUS TISSUES FROM EACH MEMBER OF THE THORIUM CHAIN

The most doubtful part of my presentation is Table 7, where I have tried to describe the dose rates im-

* A detailed calculation of dose accruing to the various parts of the lung was presented by Grillmaier *et al.*;⁽¹⁷⁾ their values straddle the average dose estimated here.

TABLE 7. MAXIMUM DOSE RATES PER 50-CC THOROTRAST INJECTION

Rads per year										
Element	$T^{1/2}$	$K^{(a)}$	Liver	Spleen	Marrow	Bone	Kidney	Lung	Blood	Soft tissue
Th ²³²	1.4×10^{10} y	74.5	44.0	66.0	7.4	0.007	0.35	0.5	—	—
Ra ²²⁸	5.8 y	—	—	—	—	—	—	—	—	—
Th ²²⁸	1.90 y	100	26.3	34.0	5.0	0.30	0.2	0.7	0.08	0.14
Ra ²²⁴	3.64 d	105	30.2	34.5	2.1	0.63	0.68	0.2	0.22	0.04
Thoron + ThA	51 sec; 0.16 sec	234	36.0	43.0	5.5	1.31	1.5	6.9	1.96	0.07
ThB (Pb ²¹²)	10.6 hr	—	—	—	—	—	—	—	—	—
Bi ²¹² (ThC)	1 hr	38	2.8	4.0	0.9	0.21	0.4	1.0	0.50	0.05
Po ²¹² (ThC')	0.3 μ sec	109	8.2	11.4	2.7	0.61	1.1	3.3	1.42	0.15
T ²⁰⁸ (ThC'')	3 min	—	—	—	—	—	—	—	—	—
Total			147	192	23.6	3.1	4.2	12.6	4.2	0.45

^(a) Dosimetric constant, rads per year per nCi/g.

parted to various tissues by each member of the Th²³² family. A modicum of modesty is implicit in the blank spaces accorded to the beta-ray emitters, inasmuch as the accuracy of the data does not warrant acknowledgement of their existence.

The pertinent elements, their radioactive half-life, and the dosimetric constant, K , are shown in the first, second, and third columns, respectively. The dose rates for liver and spleen are, of course, the highest; if they are multiplied by 0.3 to account for self-absorption in the deposits, these values are practically identical with those given by Kaul. As shown, the doses to the skeleton, kidney and circulating blood are relatively close to the maximum permissible limits set for the working population; hence, they are of more than passing interest. Attention must be paid to the fact that a quality factor for α radiation equal to ten or more raises these values well above acceptable limits. Therefore, pathological observations of these tissues is highly desirable from the standpoint of radiation protection.

The marrow dose looms important, since leukemias and pancytopenias have been reported; some autoradiographs are necessary to identify more precisely the colloidal deposition. Owing to the extremely weak radioactivity, exposure of the order of years is necessary unless "enriched" Thorotrast is used. No hope of registering translocated Ra²²⁴ plus daughters in marrow must be entertained because of their very short half-life.*

THE SKELETAL DOSE

As shown in the table, the dose rates are twice the values calculated by Dr. Kaul. This discrepancy should

* Excellent autoradiographs of aspirated marrow smears were presented by Harriss:⁽¹⁷⁾ it is not clear, however, what fraction of the dose generated by marrow α rays is expended in bone.

not be surprising at all for two reasons: (a) The bone samples available are usually contaminated with marrow, and (b) the equilibrium of the Th²³² chain in bone mineral runs exactly opposite to that existing in the reticuloendothelial system. The main question is whether, in bone, Ra²²⁴ is in equilibrium with Th²²⁸ or whether it exists with higher activity because of migration from the reticuloendothelial system.

The values selected here are based on an excess of Ra²²⁴. It has been assumed that, since Ra²²⁴ is excreted, this element must have reached the blood from either the skeletal or the reticuloendothelial system. In either case, it can be shown that it must be present in bone in amounts above those found for Th²²⁸. I have taken for granted the computations of Reynolds^(25, 26) which agree with the observed excretion rate of Ra²²⁴, and, by implication, I assume that they should predict correctly the Ra²²⁴ deposition in bone.

I am not sure that the Ra²²⁴ analysis of Dr. Kaul⁽¹⁷⁾ in the femur (<30 days post mortem) contradicts what I have just said. By contrast I wish to state that in four patients whose tissues were analyzed by Parr 50 days after injection, and soon after death, the predictions of Reynolds' analysis were checked by activity measurements within experimental error in two cases; and in two others the discrepancies were no larger than 50%. Under those conditions, however, the Ra²²⁴/Th²²⁸ ratio in the reticuloendothelial system is lower than at later times, and, therefore the value of this ratio in bone was higher than Kaul's.

As to the dose due to thoron plus thorium A, data obtained by Mays,⁽²³⁾ Stover,⁽¹⁾ and by Maletskos⁽³⁾ do confirm the assumption that Em²²⁰ is expanded almost entirely in bone. What we need most at the present time is some realistic value of the partition of Ra²²⁴ by the soft vs. mineral tissues, since it was not considered in Reynolds' calculation. We are encouraged,

TABLE 8. DOSE RATE TO BONE

Exposure	Millirads per year						Rems per year		
	External K^{40} $\gamma + \mu^\pm$		From α Radiation				Quality factor		
			Ra ²²⁶ + d	Ra ²²⁸ + d	Pb ²¹⁰ + d	Total α	1	10	100
Natural background ^(a)	100	15	0.9	0.7	4.1	5.7	0.12	0.17	0.68
“High” Ra ²²⁶ water	100	15	7.0	7.7	4.4	19.1	0.135	0.31	2.03
Thorotrast injection assay ⁽¹⁰⁾	100	15	0.9	3,100	4.1	3,100	3.2	31.0	310
<i>in vivo</i> ⁽³⁸⁾	100	15	—	6,000	—	6,000	6.0	60.0	600
Uranium mines	5,000 ^(b)	15	15.0	(5)	200	220	5.2	7.2	27.0
Ra ²²⁶ injection (0.5- μ Ci burden)	100	15	14,500	—	6,800	21,000	21.1	210	2,100
Residence over monazite	2,600 ^(c)	15	6.0 ^(d)	(2.3)	4.6	13.0	2.6	2.7	3.9

(a) Midwest U.S.A.

(b) According to maximum permissible limits.

(c) First approximation: data from Guarapari, Brazil.⁽²⁷⁾(d) From Chhabra's estimates at Karala.⁽²⁸⁾

however, by the fact that these investigations are taking place at MIT.

EPIDEMIOLOGICAL IMPORTANCE OF DOSES FROM THOROTRAST AND MIGRATED DAUGHTERS

In comparing the clinical and pathological findings in Thorotrast patients with other epidemiological series, we shall neglect liver and spleen, since no other epidemiological study involving radiation effects could possibly be compared to this group of patients in regard to either the dosimetric parameters or the possibility of chemical toxicity. A possible exception might be the large populations of Hiroshima and Nagasaki and, to a much lesser extent, the populations living in regions where the background radiation is about one order of magnitude above that experienced elsewhere. In any event, the comparison is subject to many provisos, such as co-carcinogenicity of ThO₂, extremely different dose rates, the influence of heterogeneous α radiation versus photon radiation (relative biological effect), etc.

The dose to the skeleton of Thorotrast cases, however, is of particular importance, despite its low magnitude. Table 8 shows the dose rates accruing to the populations most likely to supply epidemiological information on the effects of radiation on the skeleton. The total dose rates are shown at the right under the assumption of quality factor of 1, 10, and 100 for α radiation. The highest values pertain to the eventualities foreseen by the Ad Hoc Committee on Relative Biological Effects (ICRP).⁽²⁹⁾ Some comments are in order at this time. Studies on the USA population drinking water relatively rich in Ra²²⁶ is at present

composed of 600,000 people. Results of a retrospective study will be available soon.

The highest dose rates are found in the Ra²²⁶ dial painters in whose midst no untoward effects have been shown below a contemporary burden of 0.1 μ Ci.

The lack of bone pathology in known Thorotrast cases, numbering as of today more than 2000 and bearing burdens from $\frac{1}{6}$ to $\frac{1}{2}$ of this amount, adds a much needed support to the choice of the maximum permissible limit of Ra²²⁶, which is based on studies of the smaller population of radium dial painters. We hope that comparable information will be forthcoming from studies of miners and, above all, from residents of monazite regions, who are much more numerous.

It is of some interest to examine the implications of the estimate made by the United Nations Committee on the Effects of Atomic Radiation⁽³⁰⁾ on the incidence of osteosarcoma in the radium poisoning cases. This incidence has been stated to be about 4 cases/10⁶/year/rad, as compared to 1 or 2 for the incidence of leukemia in the irradiated populations of Hiroshima and Nagasaki and in the X-ray treated patients suffering from ankylosing spondylitis. The Thorotrast population offers an opportunity to estimate within itself the ratio of the incidence of osteogenic sarcoma to that of leukemia and to compare it to the ratio of the dose rates accruing to skeleton and marrow. If linear extrapolation applies, the incidence of osteogenic sarcoma should be from 2 to 4 times the leukemia incidence rate multiplied by the ratio of the skeletal dose rate to that of the marrow.*

* These remarks apply to the radium dial painters: The leukemia rate should be about $(1.5/4.0) \times 0.1 \approx 0.04$ the osteosarcoma rate if these assumptions apply.

Since this dose ratio has been estimated as low as 1/20 (1.5/25) (Kaul) and as high as 6.0/23 $\approx$ 1/4 (author), the osteosarcoma rate should range from as low as $(2 \times 0.05) \approx 0.1$ to as high as $(4 \times 6.0)/23 \approx 1.0$ times the leukemia incidence within the Thorotrast population. This ratio, conceivably, could be extended from 0.3 to 3.0 if one assumes that the oncogenic effectiveness per rad in bone (but not in marrow) is three times as high for Th^{228} as for Ra^{226} , as some of the results at the University of Utah seem to imply from the incidence of tumors in the beagle skeleton.

It is obvious that if the higher figures were correct, our dedicated medical colleagues would have confirmed it already. Lack of bone lesions at this stage may imply that the latent period for osteogenic sarcoma is much longer than for leukemia, or that the quality factor for α radiation is remarkably different for the two effects.

The possibility remains that α radiation in bone from Thorotrast may be less carcinogenic than in the radium poisoning cases because it is more evenly distributed. This issue, to my knowledge, is still undecided.

I shall not dwell any longer on this point, but simply remark that this elementary calculation illustrates

very vividly the importance of follow-up in the Thorotrast population.

It is obvious also that to enhance the usefulness that laborious epidemiological investigations deserve, the dose rates accrued to bone and marrow must be determined to a higher degree of accuracy.

EPIDEMIOLOGICAL STUDIES INVOLVING THE LUNG

We turn our attention to the doses absorbed by the lung under the various types of exposure indicated in the first left-hand column of Table 9.

In the first two categories the doses to the various portions of the respiratory tract are shown; they were obtained directly or extrapolated from Jacobi's data.⁽³¹⁾

It is obvious that mining operations lead to the highest doses in the lower bronchial tree. Next in importance is the Thorotrast series wherein the average doses to the *whole* lung is estimated to be only $\frac{1}{2}$ the dose to a *portion* of the bronchial epithelium of the miner.

Lack of lung pathology in the Thorotrast group is encouraging, in the sense that it suggests that it may be possible to obtain effective control of lung pathology in miners by paying as much attention to the curtailment of inhaled dust as that has been paid to the dilu-

TABLE 9. DOSE RATE TO LUNGS

Exposure	Millirads per year						Rems per year		
	Tissue	External radiation	α Radiation				Quality factor		
			$\text{Rn}^{222} + d$	$\text{Th}^{228} + d$	Internal ^(c) α	Total α	1	10	100
Natural background ^(a) 0.1 pCi/l. Rn + 0.2 pCi/l. Tn	Alveoli	115	4.4	0.9	0.1	5.4	0.120	0.170	0.66
	Bronchi	115	5.6	0.1	0.1	5.8	0.121	0.17	0.70
	Bronchi (SQ)	115	140	4.2	0.1	145	0.260	1.56	14.6
	Trachea	115	27	1.0	0.1	28	0.143	0.4	3.0
Mining operations ^(b) 100 pCi/l. Rn + 100 pCi/l. daughters	Alveoli	5000	720	—	20	740	5.7	12.4	790
	Bronchi	5000	720	—	20	740	5.7	12.4	790
	Bronchi (SQ)	5000	21,000	—	20	21,000	26.0	215	2,100
	Trachea	5000	38,000	—	20	3,800	88	43	385
50 cc Thorotrast 3.6×10^4 pCi min ⁻¹ 0.5 μCi Ra^{226} 5 pCi/l. Rn exhaled	Entire lung (Av)	115	—	12,600 ^(d)	—	12,600	12.7	126	1,260
	Entire lung (Av)	115	8.5 ^(e)	—	—	9	0.12	0.2	1.0
Cigarette smoker ^(f)	Bronchial epithelium	115	6.6	—	—	6.6	6.6 min. 40 max.		

^(a) Jacobi (Table 6).⁽³¹⁾

^(b) Jacobi (data in Table 5 $\times 40 \times 168^{-1} \times 10$).⁽³¹⁾

^(c) $\frac{1}{4}$ Average dose to osteocytes (20 vs. 80% retention at continual intake).

^(d) ThA + ThB + ThC from Pb²¹² tissue analysis (consistent with exhalation rates).

^(e) From Pohl's data on pure Rn inhalation: Blood: lung ratios in mice.⁽³²⁾

^(f) From Radford *et al.* on Polonium in cigarettes.⁽³³⁾

TABLE 10. DOSE RATE TO MARROW

Exposure	Millirads per year					Rems per year			
	External K ⁴⁰ γ + μ [±]		α Radiation				Quality factor		
			Ra ²²⁶ + d	Ra ²²⁸ + d	Pb ²¹⁰ + d	Total α	1	10	100
Natural background ^(a)	100	15	0.1	0.07	0.4	0.6	0.11	0.12	0.17
“High” Ra ²²⁶ water	100	15	0.7	0.77	0.44	1.9	0.12	0.13	0.31
Residence over monazite	2,600 ^(b)	15	0.6 ^(c)	(0.23)	0.46	1.3	2.6	2.6	2.7
Uranium mines	5,000	15	1.5	0.5	20	22	5.0	5.2	7.2
Ra ²²⁶ burden (0.5 μCi)	100	15	145	—	680	2,100	2.2	21	210
Thorotrast injection (50 cc)	100	15	0.1	24,000	0.4	24,000	24.1	240	2,400

^(a) Midwest U.S.A. (via bone concentration and Kononenko formulae).⁽³⁴⁾

^(b) Preliminary data from Guarapari, Brazil.⁽²⁷⁾

^(c) From Chhabra's estimates of bone burden at Karala.⁽²⁸⁾

tion of radon by forced ventilation. However, one must realize that much cannot be said at this time.

Much has been written on Po²¹⁰ contained in tobacco and on its deposition in some regions of the bronchial tree; in our laboratory Holtzman has confirmed the existence of higher Po²¹⁰ concentration in the lungs of smokers as compared to non-smokers. The dosimetric implication of these findings is in the preliminary state.*

It is pertinent to ask at this point whether the lungs of the patients irradiated for ankylosing spondylitis have not been subject to considerable amounts of radiation and whether an epidemiological survey on lung damage in this population does not deserve as much attention as the leukemia survey.

Anticipating some findings of lung pathology, it may not be entirely amiss to extend the estimates of the United Nations Scientific Committee on the Effects of Atomic Radiation to the lung of the Thorotrast patient in order to establish whether a more exact statistical study is warranted as epidemiological observations accumulate. We observe that for a typical 25-cc Thorotrast injection, the lungs of our patients will receive a dose rate of 6.3 rads of α radiation per year. If a quality factor of 2.5 is assumed, this rate is equivalent to about 15 rems per year. Three other assumptions will be made: (a) that the average time at risk for each patient is 15 years, (b) that the incidence of radiation-induced carcinoma of the lung is equal to that of leukemia, namely about $1.5/10^6$ /year/rad, and (c) that the latent period is about 5 years. The incidence, calculated by multiplying these numbers, comes out to be 1.6 cases per thousand, a figure not entirely

beyond detection if careful follow-ups of non-smokers (women?) among Thorotrast cases are pursued. If the relative biological effect of the thorium family is higher than that considered here, the higher incidence would be much more easily detected.

THE DOSES TO THE MARROW

Last, but not least, we must consider the dose to the marrow which has come under very close scrutiny by the UN Scientific Committee, inasmuch as both the ABCC* study and the spondylitis experience seem to indicate a radiation produced incidence of one case per million per year per rad.

If one considers that in Table 10 the doses to the marrow of Thorotrast patients are on the conservative side, one cannot but be impressed by the importance of the Thorotrast group, especially when the data of da Silva Horta,⁽³⁵⁾ Faber,⁽³⁶⁾ and Telles⁽³⁷⁾ imply that derangements of marrow have been observed.

If one applies the United Nations Scientific Committee formulas to a 25-cc injection of Thorotrast with the same proviso adopted in the case of the lung, one comes up with an incidence of 3 cases per thousand on the assumption of the dose rates considered here, and about 4 cases per thousand if the doses proposed by Dr. Kaul are more representative.

In conclusion I wish to state that every effort must be made to obtain good dosimetric and epidemiological information pertaining to the marrow, the lung, and bone. Knowledge already at hand counsels this line of conduct most emphatically.

Studies to include the kidney and lymphatic system of these patients should be considered since, under equilibrium conditions, the absorbed doses to these tissues may be considerable. At a later time, as more

* At the XI International Congress on Radiology in Rome there were reports of excess Po²¹⁰ in smokers of magnitudes much smaller than Radford's.³⁸

* Atomic Bomb Casualty Commission.

information is acquired, a comparison of dosimetric and pathological findings in the kidneys of miners may be justified because the concentration of polonium therein may be considerable.

Finally, I would like to encourage the statisticians connected with these studies to begin some preliminary evaluation of the incidence of pathology versus the man-rad-years at risk in order to enrich the very modest patrimony of facts pertaining to the delayed effects of low-level chronic irradiation.

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PRELIMINARY ANALYSIS OF A METHOD FOR WHOLE-BODY COUNTING

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A preliminary study of the mathematics underlying whole-body counting methods is in progress. As a first approximation the human body is replaced by a straight line of unit length along the x -axis, and the detector is assumed to move along an arc which is specified in polar coordinates (r, θ) by the equation

$$r = F(\theta), \quad \alpha \leq \theta \leq \beta \quad (1)$$

where r is the distance from the center of the body to the detector and θ is the angle between the radius vector and the positive x -axis (Figure 18).

The radioactive sources in the body are specified by a density function $F(x)$, i.e., each element $(x, x + dx)$ of the body emits $F(x) dx$ photons per unit solid angle per second, and it is required to measure

$$\int_{-1/2}^{1/2} F(x) dx.$$

Denote by $\nu(\theta)$ the angular velocity of the detector as it travels along the path defined by equation (1), i.e., $\nu(\theta) = d\theta/dt$. Then the total number of particles counted by the detector as it describes its path is given by

$$N = k \int_{\theta=\alpha}^{\beta} \int_{x=-1/2}^{1/2} \frac{F(x)}{\nu(\theta)(F^2(\theta) + x^2 + 2xF(\theta)\cos\theta)} dx d\theta, \quad (2)$$

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where k is a constant which depends only on the properties of the detector.

The problem is to find a curve, $r = F(\theta)$, $\alpha \leq \theta \leq \beta$, and a function $\nu(\theta)$ such that the (percentage) variation with x of the integral,

$$\int_{\beta}^{\alpha} \frac{d\theta}{\nu(\theta)(F^2(\theta) + x^2 + 2xF(\theta)\cos\theta)},$$

is as small as possible. This is equivalent to the condition that for a point source of fixed strength the total count made by the detector is independent of the posi-

FIG. 18

FIG. 19

tion of the source in the body. Under this condition equation (2) becomes

$$N = C \int_{x=1/2}^{1/2} F(x) dx, \quad (3)$$

where C is a constant which can be determined by calibration.

One solution is to make $F(\theta)$ very large; however this is unsatisfactory from the points of view of both space and sensitivity. A better approach is to use a linear path as illustrated in Figure 19. If the detector moves with constant linear velocity V along the path illustrated in Figure 19 it can readily be shown that

$$I = \int_{\alpha}^{\beta} \frac{d\theta}{v(\theta)(F^2(\theta) + x^2 - 2x F(\theta) \cos \theta)} \quad (4)$$

$$= \frac{1}{Vd} \left[\arctan \frac{a-2x}{2d} + \frac{a+2x}{2d} \right].$$

As $(a-x)/d$ becomes large, I is asymptotically π/Vd independently of x . In fact the percentage variation in I can be made arbitrarily small by choosing the ratio (Path length - Body length)/ d sufficiently large. This result is analogous to Naversten's.⁽¹⁾

This introductory analysis, of course, takes no account of attenuation which would be present in a genuinely three-dimensional body. It is planned to develop these ideas and apply them to the latter case.

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COMPUTER PROGRAM FOR ASSAY OF COMPLEX MIXTURES OF GAMMA-EMITTING RADIONUCLIDES

Henry F. Lucas, Jr.

A computer program (RPY-139) for assay of complex mixture of γ -ray emitters was initially written in FORTRAN IV for an IBM 704;⁽¹⁾ due mainly to the replacement of this machine by a CDC 3600 computer, the program was revised.

Unfortunately, after transfer to the new computer not all parts of the program had been thoroughly tested, and not all were found to be working well. Except for the shift and stretch portion that always returned to zero (which was obviously wrong), all other programming errors resulted in an error exit from the computer or extra running time, but otherwise gave correct results. Running times currently vary from 0.2 to 1.0 min per sample, with a further reduction expected as additional modifications are made in the tape search routines.

Access to the present CDC 3600, as well as to the previous IBM 704, is difficult to obtain unless one has a very short problem. Consequently, a fast, efficient and easily used program is of considerable importance. Delays between submission of problem and receipt of output currently vary from 4 to 36 hours. Any errors by the user will, of course, increase this delay by a like amount, especially if no diagnosis of the error is given. Inclusion of ways to test the user's input data are still continuing. A detailed description of the program has been prepared and is available for those requiring precise assay of the components of very

complicated mixtures of gamma-ray spectra obtained on a multichannel analyzer. Because of the restriction that all radionuclides be known and exist as calibrated spectra, this method is recommended as a routine method of assay only when the number of possible radionuclides is known and less than twenty.

In testing this program, it was found that the shift and stretch routine previously described by Parr⁽²⁾ did not always converge on a good estimate of the correct value. Evaluation of the shift stretch routine was made by counting the 5.7×10^4 cpm thorium ore sample for repeat 100-min periods. The spectrum obtained is shown in Figure 20. The peaks centered at 0.24 and 3.2 MeV were used to evaluate Z and G . Each sample count was then processed through the least-squares program, using as a standard the second run in the series (No. 5551): results are summarized in Table 11 for the corrected, but otherwise unmodified, program as Method A. Values of chi-squared, s , Z and G were within expectation for only random statistical effects over channels 20 to 508.

Further evaluation of these data can be made from a study of the difference between the computed and observed spectra. Since counting rates vary by a factor of 10^3 from low to high channels, the ratio of the difference δ to the standard error (σ) has been computed. This ratio has a nominal value of 1.0 and units of σ . This ratio is plotted in Figure 21 for run No. 5550

which appears from the values of χ^2 in Table 11 to be a very good fit. However, significant deviations are noted for the 2.62-MeV peak centered on channel 380 where nearly 25 channels on each side of the peak deviate from the mean by about 2σ and are highly correlated in sign. Another area appears around channel 100. Although the absolute magnitude is small, it is certain that the effect must be related to the linearity of the system.

While the first five runs in Table 11 indicate good fits, the last five give rather poor fits. The cause can be seen from the variation in the ratio of δ/σ in the region of the photopeaks drawn in Figure 22. From the sigmoid shape it is known that the shift and stretch part of the program has converged on the wrong value. The error, in this case, in the value of G corresponds to 1 channel or 0.2%.

A better estimate of the value of Z and G is obtained by a slightly revised method of calculation. The method originally described by Parr⁽²⁾ requires that a radioactive source be selected having at least two peaks, one at a low energy for establishing zero-intercept correction (Z) and a second at a high energy for establishing gain-shift correction (G). This method assumes that the energy calibration is initially established by a spectrum of the selected source which is defined as the primary shift and stretch reference. Any other spectrum of this same source is known as a shift stretch reference spectrum. If any instrumental drift in either Z or G occurs between the times these two spectra are accumulated, then from Reference 2 these spectra over the range of the photopeak will appear as shown diagrammatically in Figure 23a. The difference between these two spectra is shown in Figure 23b. Let n_0 be the channel number for zero energy intercept, and

FIG. 20. Gamma-ray spectrum of thorium-ore source used as calibration reference.

TABLE 11. EVALUATION OF SHIFT-STRETCH PROGRAM

Run No.	Method	Zero shift (channels)	Gain shift (%)	Relative intensity	$\chi^2/F^{(a)}$	$S^{(b)}$
5550	A ^(c)	-0.0040	0.10	0.9998	1.031	0.497
	B ^(d)	-0.0019	0.03	0.9997	1.000	0.024
5552	A	+0.0002	-0.09	1.001	0.983	-0.257
	B	+0.0010	-0.09	1.001	0.982	-0.273
5553	A	+0.0207	-0.16	0.9994	1.000	+0.027
	B	+0.0057	-0.13	0.9994	0.978	+0.321
5554	A	+0.0138	-0.20	0.9995	0.954	-0.071
	B	-0.0036	-0.15	0.9995	0.965	-0.540
5555	A	+0.0211	-0.26	1.001	1.045	0.714
	B	+0.0190	-0.25	1.001	1.037	+0.585
5556	A	+0.0802	-0.53	0.9999	2.014	13.09
	B	-0.0089	-0.26	1.0000	1.143	2.176
5557	A	+0.0531	-0.48	0.9990	1.404	5.79
	B	+0.0015	-0.33	0.9993	1.062	0.974
5558	A	+0.0967	-0.61	0.9973	2.253	15.62
	B	-0.0121	-0.28	0.9979	1.156	2.37
5559	A	-0.0476	-0.21	1.001	1.213	3.18
	B	-0.0147	-0.30	1.001	1.114	1.750

(a) Chi-squared over degrees of freedom (F).

(b) $S = \sqrt{2\chi_F^2} - \sqrt{2F - 1}$ where F = degrees of freedom.

(c) As given by Parr, Reference 2.

(d) As given by this report.

let n_2 and n_5 be the channel numbers of the center of the two peaks used to determine Z and G , respectively. Let n_1 , n_3 , n_4 and n_6 be channel numbers which are approximately one F.W.H.M. unit on each of either side of the two peaks. If A_j denotes the counting rate in channel j in the primary shift and stretch reference and a_j that in the secondary reference spectrum, then the areas corresponding to X and Y in Figure 23b are, for the lower peak, from Reference 2

$$X = \sum_{n_1}^{n_2} (A_j - a_j) \quad \text{approximately,} \quad (1)$$

and

$$Y = \sum_{n_2}^{n_3} (A_j - a_j) \quad \text{approximately.} \quad (2)$$

Then the drift in position of the lower peak is given by

Δn

$$= \frac{\sum_{n_1}^{n_2} (A_j - a_j) - \sum_{n_2}^{n_3} (A_j - a_j)}{2A_{(n_2)} - A_{(n_1)} - A_{(n_3)}} \quad \text{channels approximately.} \quad (3)$$

FIG. 21. Ratio of δ/σ with good compensation of instrumental gain and zero shifts

From inspection of this equation it can be seen that small differences in the summation of A_j and a_j between channels n_1 and n_3 will not affect the estimation of channel drift. However, in practice we are working with a nonsymmetrical histogram rather than a smooth symmetrical curve; as a consequence it has been found that differences in area of as little as 0.3% result in a rather large error in the initial estimate of Δn . Further, successive iterations may converge slowly or not at all.

Two changes have been made in the method described by Parr.⁽²⁾ First, for the estimate of Z , a new $\hat{a}_j$ is calculated as follows

$$\hat{a}_j = \left[\frac{\sum_{n_1-2}^{n_3+2} (A_j)}{\sum_{n_1-2}^{n_3+2} (a_j)} \right] a_j. \quad (4)$$

The value of $\hat{a}_j$ is then substituted for a_j in equation (3), and a similar normalization is then made over channels n_4 to n_6 for estimation of G . This change by itself improves the rate of convergence and has been found to yield reliable estimates of Z and G for variations in count rate between A_j and a_j of a factor of ten.

FIG. 22. Ratio of δ/σ with poor compensation of instrumental gain and zero shifts

A second improvement in the estimation of Z and G is obtained when the channel number corresponding to n_1 , n_3 , n_4 and n_6 coincide with the F.W.H.M. of the peak, rather than at a point equal to one F.W.H.M. unit each side of the center of the peak as previously suggested.⁽²⁾ The degree of improvement by this revised method on the estimate of Z and G is shown by a reduction in the value of χ^2 in Table 11 (Method B). This revised method had little effect on the already very good estimates for runs 5550 to 5555, differing on the average by only 0.006 channel in Z and 0.03 %

in G . In contrast, for runs 5556 to 5559, the new values of Z differ by as much as 0.1 channel and average 0.07 channel while the new values for G on the average differ by 0.21 %. The residual error in the estimate of Z and G can be evaluated from the plots of δ/σ , as for Figures 21 and 22, and are found to be within 0.01 channel for Z and 0.1 % for G , which is the limitation imposed by counting statistics. The possibility of obtaining better estimates of Z and G by an incremental iterative as well as a least squares curve fitting method is being evaluated.

FIG. 23a. Diagrammatic illustration of change in position of photopeak due to instrumental drift
FIG. 23b. "Difference" curve

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MEASUREMENTS OF WATER VAPOR, RADON CONCENTRATION, AND DIFFERENTIAL PRESSURE IN THE AIR SYSTEM TO THE UNDERGROUND COUNTING FACILITY August 1964-July 1965

Richard B. Holtzman and Henry F. Lucas, Jr.

The Radiological Physics Division underground counting facility described by May *et al.*⁽¹⁾ is supplied with radon-free air by a system described by Lucas.⁽²⁾

In order to control the system better, to learn more about the parameters of the system, and to reduce the maintenance of the system, several measuring devices

FIG. 24. Radon absorption apparatus, Building 203

have been incorporated into it. The nature and uses of these instruments are described here.

I. MEASUREMENT OF WATER CONTENT OF DRIED AIR

The system for removal of radon from the air is shown in Figure 24 (Figure 31 of Reference 2). The input air for the system is taken from the basement of the Physics Building (A wing). Since this wing is ventilated with fresh air, the water and carbon dioxide contents are essentially those of air 2 meters above the ground. In the radon-removal system, this air is filtered, water is removed by adsorption on Linde Molecular Sieve, and then the radon is adsorbed on a bed containing 150 lbs of activated coconut charcoal cooled to -70° to -90° C. Water must be removed from the air before passing through the charcoal bed, since the water may reduce radon retention,⁽³⁾ and, more important, a large accumulation of water would reduce the air flow rate. As described below, it has been found that in this particular system 80 to 250 g water will reduce the air flow through the bed to less than 3 SCFM (standard cubic feet per minute). Thus at a water vapor content of the air at 1 ppm (one gram water vapor per 10^6 g air) and a flow rate of 10 SCFM of air, the charcoal would receive 450 mg H_2O per day or about 80 g in 6 months.

The air drier units are capable of removing up to 22.5 kg water with the concentration at the outlet at about 0.6 ppm. After this point is reached and more air (and water vapor) is passed through the bed, the concentration in the outlet air increases very rapidly and reaches 200 ppm, on some occasions within 6 hours. Concentrations of this level were also found from leak-

age by defective valve packing, improperly closed valves, or incomplete bake-out of the drier bed. For these and the previous reasons, it is essential that the water content of the air entering the charcoal bed be known at all times.

Recording, moisture-measuring equipment sensitive from 0.1 to 1000 ppm is available from Meeco, Beckman, or Consolidated Electrodynamics Corporation. These instruments adsorb water from the air on phosphorous pentoxide coated electrodes. At a constant rate of air flow through the instrument, the electrical current required to electrolyze this water is proportional to the water concentration in the air.⁽⁴⁾ Use of this type of instrument provides a means of optimizing the operation as follows:

First, it allows optimum regeneration cycles. In the winter with the intake air at 72° F and a relative humidity of 20% or less, a bed will operate satisfactorily for 7 days or more. In the summer when the temperature is 80° F or more and a relative humidity greater than 50% is common, the bed may then operate for only 3 or 4 days. In our experience, the bed may break through on the morning of the 4th day if there has been one day with a relative humidity in excess of 60% during the period of operation.

Second, the conditions for regeneration of the dryer bed may be adjusted with this meter. A nominal time for regeneration is about 4 hours as monitored by the temperature of the exhaust air. However, use of the meter has shown that unless the bed is regenerated for about 7 hours, the water-vapor levels may be excessively high, and thus the charcoal bed will be blocked by water more quickly.

FIG. 25. Pressure across charcoal bed *vs.* time. (Air passing directly from room into charcoal bed through by-pass valve around dryer. Point A, Air passing through dryer bed, by-pass valve closed.)

Third, it appears from our measurements that if the levels of water vapor from the drying bed are kept at less than 4 ppm, the charcoal bed may not accumulate water at all. This information is derived from two observations: (a) after about 6 months of operation with water vapor concentrations in the range of 1 to 3 ppm, only about 1 g of the expected 100 g of water was observed to come off the charcoal bed upon regeneration; (b) the vapor content of the air from the charcoal bed itself appears to range from 3 to 4 ppm. On the latter point however, there is some question as to how well these figures represent the charcoal bed exit air, since the air must pass through the heat exchanger and 20 to 30 feet of pipe, and it may be contaminated with outside air.

The effects of water on radon retention had been studied earlier using a 7-g, 3-cm-long charcoal trap.⁽³⁾ In order to study similar effects and to correlate the amount of water on the bed with flow rate and pressure drop across the bed in this system which utilizes 150 lbs of charcoal in a bed with a mean depth of nearly 24 inches,⁽²⁾ a relatively large amount of water was placed on the bed by passing through it room air of known humidity. The by-pass valve on the dryer was opened and the air passed through the charcoal bed at

10 SCFM, the input pressure (plotted in Figure 25), being adjusted to maintain this flow rate. After 83 minutes the maximum attainable pressure of 27 oz/in.² was reached and the flow rate then decreased. From the flow rate of 10.0 SCFM, a relative humidity of 50% and a temperature of 78° F, it is estimated that approximately 280 g water had been placed in the system.

On changing to water-free air, the pressure was reduced to 12.6 oz/in.² which increased to 27 oz/in.² after an additional 80 minutes. As is shown in Figure 26, the flow rate then dropped to a minimum of 5.8 SCFM after 125 min, after which it rapidly rose to 10.0 SCFM.

Subsequent operation of the bed is shown in Figure 27 for a period of nearly 30 days. The pressure head required to maintain a flow rate of 10.0 SCFM is given *vs.* time. A few minutes after the time the flow rate (Figure 26) reached 10.0 SCFM, the back pressure dropped to about 15.5 oz/in.² and then over a period of about 2 days dropped to 6.5 oz/in.², where it remained for about a week. The pressure eventually dropped to and remained at about 5.4 oz/in.² for more than 20 days, except that small peaks were introduced on the 10th and 16th days after the drier bed had reached saturation, and the water levels approached 200 ppm for periods of 7 to 12 hours.

The variation in the pressure and the flow rate appears to be caused by frost build-up, perhaps at a point of high turbulence followed by a redistribution to other colder areas. The location of the initial con-

FIG. 26. Flow rate *vs.* time after flow reduction observed. (Pressure at blower 27 oz/in.².)

FIG. 27. Pressure across bed vs. time of operation

densation, whether in the heat exchanger, cooling coil, fiber-glass filter before the charcoal bed, or in the bed itself, is unknown. However, the rapid changes in flow rate with time suggest that the heat exchanger is the unit involved. For instance, the heat exchanger operates at a minimum temperature of about -20°C which is appreciably higher than -70°C at the outlet of the charcoal bed. Reduction of the air flow caused by the collection of frost in the coldest portion of the heat exchanger would in turn result in a temperature rise and permit the water to be transported to other parts of the system. Because of the increased surface areas of the chiller coil and the charcoal bed, the 280 g of water experiences a pressure drop of only 2.8 oz/in².

These results indicate that under the present operating conditions of a flow rate of air of 10 SCFM and a water vapor concentration below 3 ppm, accumulation of water in the bed is not a problem, and the system

should operate for 1.5 to 2 yrs, and, possibly even indefinitely, without regeneration.

II. PRESSURIZATION OF UNDERGROUND COUNTING ROOM

Because of the contribution of Rn^{222} daughters in the vault air to the background of γ -scintillation crystal counters, the underground counting facility was designed to contain a minimum amount of radon. However, because of incomplete sealing of the room, concentrations as high as 5 pCi/l. Rn have been found.⁽²⁾ To minimize and control radon buildup, the room is kept under a small positive pressure by the continual addition of 10 SCFM radon-free air from the radon-removal system. With this flow rate the pressure differential between the counting room and the foyer is maintained at about 0.15" W.C. (inches water column) which is sufficient to maintain the Rn^{222} concentration at about 0.015 pCi/l. This concentration is less than 10% of the 0.1 to 0.4 pCi/l. found in the outside atmosphere.^(5, 6) For several reasons this pres-

FIG. 28. Typical traces of differential pressure recorder. A, cooling valve off; B, door open, normal operation; C, gusty weather

sure differential appears to be the minimum necessary for maintenance of low radon levels: (a) The pressure differential between the room and the space between the sheet metal liner and the concrete wall of the room is about one-half that between the room and the foyer. The pressure differential between the room and some local areas is believed to be even lower than that observed so far. Since the radon concentration in these spaces ranges from 50 to 3000 pCi/l.,⁽²⁾ extremely small absolute pressure changes in room air can seriously affect the radon level. (b) Strong or gusty winds produce pressure differentials comparable to those produced by other sources within the room. (c) Low-pressure weather centers passing over the region can cause a rise in the atmospheric radon levels in the room, which correspond to those in the outside air as measured on CAM-5 air monitors inside and outside the room.⁽⁷⁾ (d) Finally, as previously shown,⁽²⁾ discontinuous changes in the heat load, and hence, mean

air temperature of the room, can cause a relatively large pressure change. Thus, full operation of the air-cooling system could reduce the differential pressure 0.3" W.C., and thereby, produce a negative pressure of 0.15" W.C.

A directional-flow indicator (FM-17)* which has a fast response and an output sufficient to drive a potentiometric recorder has been used to record pressure fluctuations. Range and calibration are manually made against a liquid-in-glass manometer. This instrument measures the direction of flow for positive or negative pressures, but it is very insensitive in the region of 10% of its full scale reading.

The main value of this recorder has been to detect improper functioning of the temperature control for the facility. This system operates by circulating cold water (about 50° F) through a coil over which air is passed.

* Hastings-Raydist, Inc., Hampton, Va.

The temperature is controlled by a thermostatically operated proportioning valve in the cooling-water line. However, if the cooling capacity of the unit is too large, the valve operates near the cutoff point, and it will at times actually shut off. The heat load in the room is then sufficient to produce, in local regions, a large increase in air temperature which, in turn, is observed on the recorder as a rapid, large rise in pressure of up to 0.15" W.C. Because of a time delay of 5 to 10 min in transmission of these temperature changes to the thermostat, the system overcools and produces a large negative pressure excursion. This excursion brings the pressure differential near zero or to negative values for a few minutes each hour, thus allowing the entrance of atmospheric radon. A typical recording of a pressure change of this type is shown in Figure 28A.

These pressure excursions are minimized by limiting the cooling capacity of the system through adjustment of the valves controlling the circulation of water. The pressure differential is then fairly constant, showing variations of only about 10% about an average value in calm weather, as shown in Figure 28B. Figure 28C shows a similar record made at time of high winds when excursions reach ± 0.1 " W.C.

III. RADON AIR MONITOR

Two methods are used to monitor the radon levels in the vault. First, the radon is analyzed absolutely and directly by the method of Lucas^(5, 6) in which the radon from a known volume of air is collected in a charcoal trap cooled to dry ice temperatures.

This method, which is tedious and discontinuous, has been supplemented by a continuous air monitor, Argonne National Laboratory Model CAM-5.⁽⁷⁾ This detector consists of a flat counter with rectangular dimensions of 12" $\times$ 6". It is sensitive to α and β particles separately, and it faces a filter paper through which air is drawn at a rate from 10 to 30 m³/hr. The count rate for each type of particle is recorded on its particular chart, and the fractional difference of the two count rates is recorded on a third chart. The counter background may be removed by an electronic adjustment.

The β counter is of marginal use because it is not shielded and is thus sensitive to γ rays from the room walls and to any radioactive sources likely to be in the room. Consequently, the difference recorder is also of marginal value.

The α detector, on the other hand, has proved more valuable. This counter, when carefully adjusted, is sensitive to the alpha activities deposited on the filter at a flow rate greater than a few cubic meters per hour. Thus, at a flow rate of 20 m³/hr and at the normal

operating radon concentration of about 0.015 pCi/l., one observes about 10 cpm above a background of 7 cpm.

This count rate correlates with the assumptions that Rn²²² is in radioactive equilibrium with its daughters (deposited on the filter) and that the over-all counting efficiency for alpha particles from deposits on the paper is 35%. The radon concentrations in the controlled atmosphere of the facility may then be monitored continuously to about $\pm 20\%$, when calibrated against the actual Rn²²² levels measured by the charcoal-trap method.

Several phenomena have been monitored with this instrument which could have been observed only with great effort by the other sampling technique. First, loss of pressure differential when an entrance door was not securely latched causes a rise in the levels of radon of about 20% or more. Second, when high winds or an exceptionally low pressure area pass through the area, the radon levels rise as much as a factor of 3. The exact cause is not known.

CONCLUSION

The addition of a water analyzer, pressure differential recorder, and continuous air monitor has proved necessary to the operation of the air system in this facility. In addition they have made it possible to operate the system more efficiently: (1) to adjust and optimize the drying bed regeneration cycle times; (2) to detect leaks in the radon-free air system; and (3) to detect readily malfunctions in the air-temperature system. The air monitor has proved useful in estimating the effects of various conditions on radon levels in the room. It has proved very valuable and is considered necessary to monitor the radon levels maintained in this facility.

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THE MOSSBAUER EFFECT FROM BONE CRYSTAL SURFACES

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INTRODUCTION

The Mössbauer effect offers a promising means of investigating both the electronic structure and the lattice dynamics of atoms at surfaces.⁽¹⁾ If fresh, untreated bone from various locations within the skeleton of an experimental animal could be studied by means of the Mössbauer effect, it might be possible to determine whether tracer atoms are sitting on crystal surfaces, or whether they have the more uniform environment typical of crystal interiors. Perhaps we could also obtain some information about the nature of the chemical bonds to nearest neighbors. Thus, we might hope to distinguish between recrystallization and surface exchange as the mechanism of uptake of diffuse activity in bone. In regions of new bone formation we might be able to tell whether the larger alkaline earth ions, such as barium or radium, have been incorporated into the volumes of forming crystals or whether they have been excluded during crystallization and reside on crystal surfaces. The approximate equivalence of the specific activity of forming bone and of the blood from which it was formed suggests that even radium may be incorporated into bone crystals under physiological conditions. On the other hand, if the crystallization of individual bone crystals is sufficiently slow, one might expect the exclusion of such large foreign ions by a process analogous to the purification of a crystal by zone melting. It would be valuable to know how the larger alkaline earth atoms behave under physiological conditions because one would then have a better basis for predicting their long-term release from bone.

The Mössbauer effect is essentially a method by which one may measure changes in gamma-ray energy with extreme precision. Measurements to within one part in a million million are usual, and in one case, the measurement of the loss of energy by gamma-ray photons traveling upward a distance of some twenty meters in the gravitational field of the earth⁽²⁾, the precision was better than one part in 10^{15} . With ordinary techniques the atomic environment of the nucleus which emits a gamma ray has a completely negligible effect upon the gamma-ray energy. But with the Möss-

bauer effect, detectable shifts in gamma-ray energy are produced by small changes in the density of atomic electrons at the nucleus (the *s* electrons); this shift is called the isomer shift, and it makes the energy of a Mössbauer gamma ray sensitive to the valence state of the emitting atom. Furthermore, if there exists an electric field gradient at the position of the nucleus of a magnitude that one would expect from the electrically-asymmetrical position of an atom at a bone crystal surface,⁽¹⁾ then there will be a quadrupole splitting of the emitted gamma-ray energy. The number of lines in this splitting is determined by the spins of the excited and ground states of the emitting nucleus. The magnitude of the separation between the lines is determined by the strength of the electric field gradient at the nucleus and the magnitude of the electric quadrupole moments of the two nuclear states.⁽³⁾

Now how is such precision possible? Essentially, one takes advantage of the fact that when the gamma-ray energy is not too high and when the emitting atom is bound in a solid, then the recoil energy of the emitting atom is small enough that there is a chance for the recoil momentum to be delivered to the solid or crystal as a whole. This quantum effect provides a massive gun platform for a few of the outgoing gamma rays, so that no recoil energy at all is deducted from their nuclear gamma energy. Such a gamma ray, emitted without recoil, will be resonantly absorbed with a tremendous cross section if an absorber containing the same nuclide that emitted the gamma ray is placed in its path. Again, there will be only a small chance that the absorption will be without recoil, but by making the absorber fairly thick one can resonantly absorb most of the incoming gamma rays. Almost immediately, the absorbed gamma rays will be re-emitted, but they will be reemitted in all directions and most of them will be missed by a counter placed behind the absorber. This is the Mössbauer effect: *the resonant scattering of gamma rays emitted without recoil by the nuclei of atoms bound in solids.*

The key point in this emission-absorption process is that the distribution of gamma-ray energy within the emitted line (or lines) is limited only by the Un-

certainly Principle as applied to the sharpness of the energy level of the nuclear excited state and to its lifetime. If one were dealing with an excited state with a meanlife of $\tau = 6 \times 10^{-9}$ second, then its full width at half maximum would be

$$\Gamma = \frac{\hbar}{\tau} = \frac{6 \times 10^{-16} \text{ eV-sec}}{6 \times 10^{-9} \text{ sec}} = 10^{-7} \text{ eV.} \quad (1)$$

If the gamma-ray energy were $E = 100$ keV, Γ/E would be 10^{-12} .

Now the trick in most Mössbauer experimentation is to move the absorber slowly back and forth in a line between the source and a counter whose pulse-height selector is set to count only the gamma ray of interest. The relative motion between source and absorber introduces a tiny Doppler effect, which shifts the gamma-ray energy as seen by the absorber by the amount ΔE where

$$\frac{\Delta E}{E} = \frac{\text{relative velocity}}{\text{velocity of light}} = \frac{v}{c}. \quad (2)$$

Since $c = 3 \times 10^{11}$ mm/sec, a relative velocity of only $v = 0.3$ mm/sec is sufficient to sweep across the width of such a gamma-ray line ($v/c = 10^{-12}$). Actually, since the linewidths of both source and absorber are involved, sweeping one across the other produces an absorption dip in the counting rate that has a width of 2Γ . It is customary to express these energy widths and energy shifts in terms of the equivalent Doppler velocity, v , as given by expression (2). In the figures of Mössbauer spectra shown here and in the accompanying report, the counting rate is plotted as the ordinate (considered as a per cent change from the counting rate observed away from the resonance) and the velocity of the absorber relative to that of the source is plotted as the abscissa. Positive velocities represent movement of absorber toward the source.

Very few radioisotopes can be expected to show a Mössbauer effect, primarily because of the requirement that the recoil energy be small. In practice this limits one to gamma-ray energies not more than about 150 keV, even if one cools both source and absorber to the temperature of liquid helium. This was, in fact, done in the work reported here. By reducing the temperature one decreases the amplitude of atomic vibrations and increases the probability of a recoilless emission or absorption. Furthermore, the excited state which emits the gamma ray should be a metastable state with a lifetime the order of nanoseconds so that its width is small enough to be useful. It should be the first excited state so that it decays to a narrow level, the ground state.

If one is interested in alkaline earth metabolism, there are then three possibilities. One might inject a

stable alkaline earth isotope into bone and then use the bone as the *absorber*. Unfortunately, I was unable to find in the Nuclear Data Sheets a single such isotope that filled the above requirements. Second, one might inject a radioisotope of long half-life into bone and then, as before, use the bone as the *absorber*. In this case the radioactivity of the isotope is unwanted background. One possibility of this kind is being tried now in the Physics Division, namely Ba^{133} and the 12-keV gamma ray from its first excited state. (This should not be confused with the present use of the 81-keV gamma ray following electron capture in Ba^{133} .) The third possibility is to inject into bone one of the alkaline earth radioisotopes whose decay products emit Mössbauer gamma rays and then use the bone as the source. The only possibilities found are:

- (1) 7.2-year Ba^{133} (81 keV, 6.31 nsec),
- (2) 85-min Ba^{139} (166 keV, 1.7 nsec),
- (3) 70-min Sr^{85m} (150 keV, 0.8 nsec),
- (4) 4.7-day Ca^{47} , 3.4-day Sc^{47} (160 keV, 0.18 nsec),
- (5) 2.5-hour Ba^{129} , 31-hour Cs^{129} (40 keV, 0.7 nsec),
- (6) 38-hour Sr^{83} , 83-day Rb^{83} , 1.9-hour Kr^{83m} (9 keV, <100 nsec).

In numbers (4–6) it is the second or third decay product which emits the Mössbauer gamma ray, so there would be considerable question as to their translocation. The most promising nuclide is Ba^{133} , which decays to Cs^{133} by electron capture.

Until the present work, the Mössbauer effect had not been observed in Ba^{133} - Cs^{133} , even though several attempts had been made. The project started, therefore, with a hunt for the Mössbauer effect in simple compounds containing Ba^{133} , other compounds with Cs^{133} being used as absorber. Using the very sophisticated apparatus of G. J. Perlow (Physics Division) we found the effect, as described elsewhere in this report.

PREPARATION OF Ba^{133} SOURCE ON BONE CRYSTAL SURFACES

A series of cross-section blocks 5 mm thick were cut from the midshaft of the tibia of an adult beagle dog (68A). The dog had been sacrificed on 8 October 1964 following an unsuccessful uranium injection. The bones had been taken and kept in absolute alcohol. After two months, they were acetone-dried for 25 hours and refluxed in 70% ethylene diamine for 48 hours to remove most of the organic material. They were then washed in five changes of distilled water for 24 hours. After drying, the weight of each block was about 450 mg, primarily bone mineral.

In order to develop a technique of depositing Ba^{133} on the surfaces of bone crystals with no chance for deeper incorporation (to provide a clear-cut test of the resulting Mössbauer spectrum), a series of aqueous exchange experiments was performed using low specific

FIG. 29. Concentration of Ba^{133} in aqueous solutions containing a bone block, ten bone sections, and bone powder as a function of time after the injection of $\text{Ba}^{133}\text{Cl}_2$. Each curve refers to 450 mg of ethylene-diamine-treated bone in 3.0 ml of water.

activity $\text{Ba}^{133}\text{Cl}_2$. The volume of distilled water used as the exchange medium was kept very small (3.0 ml) in order to maximize the uptake of Ba^{133} and minimize its concentration in the solution at the end of the exchange period. On subsequent drying there would then be negligible precipitation of $\text{Ba}^{133}\text{Cl}_2$, and most of the Ba^{133} would have the desired environment. One bone block was hung on a fine wire in a 5-ml beaker. Another was cut into ten sections and hung on wires in another 5-ml beaker in such a way that all section surfaces had free access to the liquid. A third was ground into a fine powder with a mortar and pestle and placed in a third 5-ml beaker together with a magnetic stirring pellet. After about an hour's equilibration, an activity of 4 μCi of $\text{Ba}^{133}\text{Cl}_2$ at about pH 4 was added to each beaker. At intervals thereafter, small (0.05 ml) samples were removed to measure the relative solution activity. The data are shown in Figure 29. With the magnetic stirrer turned off, the powder was allowed to settle, before the sample was taken. The length of this settling period did not affect the early part of the curve appreciably, but the failure of complete settling made the later points for the powder too high. Therefore, after 24 hours the powder was allowed to settle for six hours without further stirring; in Figure 29, a dotted line connects the more accurate points for which the powder sample had almost completely settled. It was clear that most of the Ba^{133} would exchange onto the bone in a short time if one

used a powder sample. From the work of Dallemagne and Richelle⁽⁴⁾ it appears that if such an exchange is carried on for only one or two hours, then there is not time for more than a few per cent of Ca^{45} ions to penetrate by diffusion and recrystallization more deeply than the surfaces of crystals. The penetration of Ba^{133} should be no faster than this. During an exchange period of two hours, Figure 29 shows that at least 98% of the Ba^{133} should have left the solution in the exchange with bone. Therefore, a powder sample exchanged for two hours should provide a Ba^{133} source in which all but a few per cent of the Ba^{133} ions reside on bone crystal surfaces.

The preparation of a high activity Mössbauer source followed the same treatment as the powder sample described above. The prior equilibration of the powder with the distilled water, magnetic stirrer running, was extended to 20 hours. The activity injected into the 3 ml of water and bone powder was then 10 millicuries. The quantity of high specific activity Ba^{133} was chosen in such a way that the stable barium carrier added was only 4 mg, exactly the amount of stable barium added in the previous low specific activity experiments. The pH of the $\text{Ba}^{133}\text{Cl}_2$ before injection was about 4.0, as determined by the color change of a methyl orange indicator. The exchange time of the Ba^{133} with the bone powder was 2 hours. The wet powder was then immediately transferred to a sintered glass filter attached to a vacuum pump. After ten minutes most of the excess water had been removed, and the damp slurry was transferred to a Teflon source holder with a milled well which kept all the source centered in the Mössbauer apparatus. About 8 millicuries were actually delivered to the source holder. The holder was capped and immediately placed in a dry ice freezer. The time between the start of exchange and freezing was less than 4 hours. Within a few hours the source was transferred to the liquid helium Dewar of the Mössbauer apparatus. It was then counted for two days.

RESULTS

The Mössbauer spectrum of the Ba^{133} bone (surface) source is shown in Figure 30. A computer program fitted by least squares a single Lorentzian line. The magnitude of the dip in counting rate was 0.24%. The line appeared to be a single unsplit line with a full width at half maximum of 0.90 ± 0.03 mm/sec. This is wider than the natural width, $2\Gamma = 0.54$ mm/sec. Most of this increased width is probably due to absorber broadening (change in shape of the line as it passes through the absorber), though some of it may be due to a small, unresolved quadrupole splitting. The position of the line is 0.003 ± 0.02 mm/sec. There is thus no detectable isomer shift relative to CsF (1.2

FIG. 30. Mössbauer velocity spectrum of an 8-millicurie Ba^{133} source deposited on the surfaces of bone crystals in the presence of water. Counting time was two days.

g/cm^2 of which was used as the absorber). As in the accompanying paper, this seems to imply that any damage that had been incurred at the crystal site by the electron capture transition had been repaired by the time the 81-keV gamma was emitted, leaving the emitting cesium atom in the singly-ionized state Cs^+ .

The similarity of the Mössbauer spectra of the bone surface source and that of simple $\text{Ba}^{133}\text{Cl}_2$ (shown in the accompanying paper) is a bit puzzling. Some quadrupole splitting was expected. There appear to be two possible explanations. First, the electric field gradient which was expected at the bone surface is being cancelled out by a polarized layer of water molecules along the crystal surfaces. Or second, the quadrupole moment of the first excited state of Cs^{133} is too small to yield a detectable quadrupole splitting. Other work with Cs^{133} has not yet detected any case of resolvable splitting. However, if the water layer explanation is

correct, a new bone source made up by exchange in alcohol followed by complete drying should reveal it. It is also planned to ash the present source in order to promote crystal growth and to drive off the water. Perhaps, if the Ba^{133} atoms are excluded from the crystals during their growth, a spectrum with quadrupole splitting will result.

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MÖSSBAUER EFFECT IN Cs^{133} *

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We have observed the Mössbauer effect of the 81-keV gamma ray from the first excited state of Cs^{133}

following the decay of Ba^{133} . The 7.2-year Ba^{133} decays by electron capture. Cs^{133} is of interest as a 100%-

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TABLE 12. PROPERTIES OF THE Cs^{133} TRANSITION

Energy (keV)	$J_{\text{exc}}^{\pi} \rightarrow J_{\text{gnd}}^{\pi}$	Q_{gnd} (b)	μ_{gnd} (nm)	$E/2M1$	α	Half-life (sec)	Γ_n (mm/sec)
81	$5^{+} \rightarrow 7^{+}$ $\frac{1}{2} \quad \frac{1}{2}$	-0.003	+2.58	$\approx 2\%$	1.7	6.3×10^{-9}	0.27

FIG. 31. Velocity spectra with a Cs_2CO_3 absorber containing 280 mg/cm^2 of Cs.

TABLE 13. SUMMARY OF DATA

Source	Absorber	Peak absorption (%)	Line width (mm/sec)	Isomer shift (mm/sec)
$\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$	CsCl	0.32 ± 0.02	1.1 ± 0.1	-0.005 ± 0.04
	Cs_2CO_3	0.42 ± 0.02	0.95 ± 0.05	-0.009 ± 0.01
BaAl_4	CsCl	3.4 ± 0.1	0.84 ± 0.02	-0.27 ± 0.01
	Cs_2CO_3	3.3 ± 0.1	0.85 ± 0.02	-0.32 ± 0.01

abundant isotope of an alkali metal. We have listed some properties of the transition in Table 12.

The experiments reported here were done at liquid helium temperature with either a $\text{Ba}^{133}\text{Cl}_2 \cdot 2\text{H}_2\text{O}$ source or one made by alloying barium with aluminum and presumably corresponding to the formula⁽¹⁾ $\text{Ba}^{133}\text{Al}_4$. Absorbers of CsCl and Cs_2CO_3 were used. Figure 31 shows representative spectra and Table 13 summarizes the results. The values for the peak absorption have been corrected for all known sources of background.

Examination of the data reveals the following. (a) There is only a single absorption dip in all cases, and it is fitted well with a single Lorentzian. (b) The recoilless fraction, f , of the BaAl_4 source is about 7.5 times that of the BaCl_2 , and the line is narrower by about 15%. (c) An isomer shift is observed for the BaAl_4 source, but the BaCl_2 source shows none of statistical significance. The statistics are good enough to reveal a small difference between the chloride and carbonate absorbers with the BaAl_4 source.

In the decay of the BaCl_2 source, it is most likely that the cesium is born in a state of high ionization as a result of the vacancy cascade which follows electron capture. The absence of isomer shift with respect to absorbers in which the Cs is in the form of Cs^+ indicates that the emitter is also Cs^+ and, hence, that the $5s^25p^6$ closed-shell configuration is attained in times short compared to the 10^{-8} sec scale of the gamma-ray emission. We conjecture that this healing process occurs by a diffusion of the vacancies from the original site to ones remote from it. An estimate using the effective mass approximation indicates that the charge transfer will occur several orders of magnitude faster than the decay of the nuclear state.⁽²⁾

We may estimate very roughly from the observed line broadening that the CsCl absorber had an effective thickness $f n \sigma_0 \approx 4$. From this we have an equivalent Debye temperature $\theta \approx 90^\circ$ for the BaCl_2 source and $\theta \approx 140^\circ$ for the BaAl_4 source. It has been pointed out⁽³⁾ that an impurity bound in the lattice with the same forces as a regularly sited atom will have an effective Debye temperature $\theta_i \approx \sqrt{m_i/m_h} (\theta_h)$ where the m 's are atomic masses and the subscripts i and h refer to impurity and host, respectively. Using $\theta = 400^\circ \text{K}$ for Al, we would predict that the BaAl_4 might have $\theta = 180^\circ$.

The isomer shift between the BaAl_4 source and the absorbers can be used to obtain an estimate of the change in the nuclear charge radius between the ground-state and the excited state. For the calculation of the change in electronic charge density at the nucleus, we can assume an effective cesium configuration of $5s^25p^66s^n$ for the sources, where n is nearly zero for BaCl_2 and $n \approx 1$ for BaAl_4 . We may safely take $n \approx 0$ in the absorbers. From the expression of Bodmer,⁽⁴⁾ the magnitude of the shift is

$$\Delta\nu = 6.8 \times 10^{-23} \frac{\delta R}{R} |\psi_{6s}(0)|^2 \text{ mm/sec.}$$

We can calculate $|\psi_{6s}(0)|^2$ either from the hyperfin coupling constant of atomic cesium or by using the Fermi-Segré formula. In either case $|\psi_{6s}(0)|^2 = 2.0 \times 10^{25} \text{ cm}^{-3}$, from which we have $\delta R/R = 2.3 \times 10^{-4}$. From the sign of the shift we can conclude that

the charge radius of the $5/2+$ excited state is greater than that of the $7/2+$ ground state. The same spins and parities appear for the ground state and first excited state in two nearby odd- Z nuclei, namely, I^{127} and I^{129} whose ground states are $5/2+$ and $7/2+$, respectively. The Mössbauer effect has shown^(5, 6) that the charge radii of the $5/2+$ states is greater than that of the $7/2+$ states in these cases also.

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CONCENTRATION OF RADIUM AND STRONTIUM IN BONE, BLOOD, AND SOFT TISSUE IN RELATION TO CALCIUM

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RADIUM

Many measurements have been made on the intake of radium in drinking water and in food arising from naturally occurring sources; the level of radium activity in human bone associated with these sources has also been documented.⁽¹⁻³⁾

Less information is available on the concentration of radium in soft tissues, but those figures which have been reported are in good agreement. About 20-30% of naturally occurring radium in the body is found in the soft tissues in man as a result of continuous ingestion from the normal diet. In addition, the level of radium in bone ash has been found to be of the same order as the level of radium in soft tissue ash.^(1, 4-6) Since bone ash contains 37% Ca, compared with about 1% Ca in soft tissue ash, it appears that the Ra/g Ca in soft tissue is about 40 times the Ra/g Ca found in bone. Lucas⁽¹⁾ in a comparison of the radium content of muscle and bone found that muscle contained 0.70 times the Ra/g ash found in bone. If muscle contains 0.25% Ca/g ash,⁽⁷⁾ then the Ra/g Ca in muscle is about 100 times the Ra/g Ca in bone.

So far as is known, no measurements have been reported on the radium concentration in the blood from naturally-occurring sources. It would seem to be of interest to know whether the Ra/Ca ratio is more similar to that found in bone or that in soft tissue.

In the absence of direct measurement it is possible to calculate the radium concentration to be expected in the blood using recent experimental data on dietary absorption, renal and faecal clearance from the blood, and dietary intake. If we assume that the amount of radium absorbed is equal to the amount excreted endogenously in the urine and faeces, we can calcu-

late the daily endogenous excretion by multiplying the dietary intake by the (fractional) absorption. Then the daily endogenous excretion divided by the number of liters of plasma cleared daily, gives the concentration of radium per liter expected in the plasma. The following data have been used for the calculation:

- (1) Hallden, Fisenne and Harley⁽⁸⁾ studied the relationship between the concentration of radium in diet and bone in persons in New York and San Francisco. The values for dietary intake obtained by these authors are listed in Table 14, together with values for the Chicago area reported by Lucas.⁽¹⁾
- (2) The absorption of radium in simulated dial paint has been measured by Maletskos, Keane, Telles and Evans⁽⁹⁾ and found to be 15-20%. The higher figure of 20% has been used for the present calculation, since the radium in the paint was in a very insoluble form and it is possible that the radium in diet might be more readily absorbed.
- (3) The values used for plasma clearance of radium are those obtained by Mays, Lloyd, Christensen, Atherton and Pitchford⁽¹⁰⁾ where they found that the endogenous excretion corresponded to a daily clearance of 70 liters of plasma when an 80-year-old man was injected with Ra²²⁶.

On the basis of these figures for absorption and plasma clearance the radium concentrations expected in the plasma from the dietary intakes have been calculated and are listed in Table 14. It can be seen that the calculated values of the concentration of Ra/g Ca in the plasma are of the same order of magnitude as the values measured in bone by Hallden *et al.*⁽⁸⁾ and Lucas.⁽¹⁾

TABLE 14. COMPARISON OF $\text{Ra}^{226}/\text{g Ca}$ IN DIET, PLASMA, BONE AND SOFT TISSUE

Location	Total dietary Ra (pCi/day)	Calculated plasma conc. (pCi Ra/g Ca)	Measured bone (pCi Ra/g Ca)	Soft tissue (bulk) (pCi Ra/g Ca)
New York	2.3 ⁽⁸⁾	0.066	0.032 ⁽⁸⁾	0.4–0.5 ^(1, 4, 6)
San Francisco	1.7 ⁽⁸⁾	0.049	0.026 ⁽⁸⁾	
Chicago	1.6 ⁽¹¹⁾	0.046	0.034 ⁽¹¹⁾	3.2 ⁽¹¹⁾ (muscle)

TABLE 15. COMPARISON OF STABLE $\text{Sr}/\text{g Ca}$ IN DIET, PLASMA, BONE AND SOFT TISSUE

Location	Total dietary stable Sr (mg/day)	Calculated plasma (mg Sr/g Ca)	Measured bone (mg Sr/g Ca)	Soft tissues (mg Sr/g Ca)
New York	1.6 ⁽²⁰⁾	0.40	0.44 ⁽¹⁶⁾	0.27–1.78 ⁽⁷⁾ (mean 0.90)
Chicago	1.9 ⁽²⁰⁾	0.48		
San Francisco	2.0 ⁽²⁰⁾	0.50		
North America (average)			0.42 ⁽¹⁶⁾	
United Kingdom	1.6 ⁽²¹⁾	0.40	0.31 ⁽²¹⁾	
World-wide survey				

Values for soft tissue were not included in the report by Hallden *et al.* and those listed in the last column of Table 14 represent the range of values reported by other workers after converting from radium concentration per gram of ash (or wet weight) to $\text{Ra}/\text{g Ca}$. It can be seen that these values are 10 to 200 times higher than the $\text{Ra}/\text{g Ca}$ in bone or plasma; in the studies by Lucas *et al.* the value obtained for muscle was about 100 times higher than the value for bone when the muscle and bone were obtained from the same cadavers.

The values for whole blood are probably higher than those for plasma, since the red cells have been shown to contain appreciable quantities of radium,^(11, 12) although virtually all of the Ca in the blood is associated with plasma.⁽¹³⁾ However, even if one takes account of the possible errors in the above calculation, the assumption that the radium concentration in blood is the same as that in soft tissue⁽⁶⁾ can no longer be made in the light of these recent experimental data.

The calculated values for plasma concentration are actually higher than the observed values for bone, a difference which may or may not be real, since there is probably individual variation of this magnitude in plasma clearance and in absorption.

Further evidence that soft tissues can retain appreciable amounts of Ra have been demonstrated by

Mays *et al.*⁽¹⁰⁾ where they found 20% of the whole-body retention in the soft tissues 141 days after a single intravenous injection in man. At this time the Ra/Ca ratio for soft tissue/plasma was about 500.⁽¹⁴⁾ Hence it would appear that the soft tissue fraction is not a short term exchange component as might have been expected from animal experiments.⁽¹⁵⁾

STRONTIUM

Under conditions of normal dietary intake, the concentrations of strontium relative to calcium are more similar in bone, blood and soft tissue than is the case for radium, although some differences have been reported. Strontium and calcium concentrations in soft tissues of the normal human adult have been reported by Tipton and Cook,⁽⁷⁾ but these refer to unrelated cadavers. However, if one evaluates the Sr/Ca ratio for the 29 soft tissues listed, the values range from 0.36 to 1.8 mg Sr/g Ca except for a value of 0.27 for brain. The values reported for bone in a world-wide survey which involved over 700 samples of bone from 5 continents by Thurber, Kulp, Hodges, Gast, and Wampler⁽¹⁶⁾ range from 0.28 to 0.93 mg Sr/g Ca with a mean value of 0.45. These values appear to lie towards the lower end of the range of values for soft tissues.

Values reported for the normal strontium concentration of human serum vary by about a factor of ten: 3–30 $\mu\text{g Sr}/100 \text{ ml}$.^(17–19) As for radium, one may calculate the concentration of strontium in the plasma if one knows the dietary intake, absorption, and plasma clearance.

The data used for the calculation are listed below:

- (1) The dietary intake of Sr has been reported by Rivera and Harley⁽²⁰⁾ for different cities in the U.S.A. and by Burton and Mercer⁽²¹⁾ for the U.K. These are given in Table 15.
- (2) The absorption of Sr is taken as 30%.⁽²²⁾
- (3) The plasma clearance of Sr has been estimated as 12 liters per day to the endogenous excreta.⁽²³⁾

On the basis of these assumptions the Sr/Ca ratio calculated for plasma is 4–5 mg Sr/g Ca which corresponds to 4–5 $\mu\text{g}/100 \text{ ml}$ plasma—a value very similar to that measured by Harrison *et al.*⁽¹⁹⁾ This value is of the same order as that reported by other workers for bone (Table 15).

Since Sr, unlike Ca, is not under strict homeostatic control, variations in dietary intake will alter this ratio; also variations in plasma clearance in different individuals may vary by about a factor or two. However, it would appear from this computation that the Sr/Ca ratio in plasma is of the same order of magnitude as that found in bone and in soft tissue.

A study of the Sr/Ca ratios in different tissues of the same individual might, however, be expected to reveal differences which are too small to be observed when unrelated cadavers were examined. It is, therefore, of interest to note that Harrison, Sutton, Shepherd, and Widdowson⁽²⁴⁾ found the Sr/Ca ratios in the soft tissues of the human foetus were about 2.5 times the Sr/Ca ratio in foetal bone; however, in this case equilibrium conditions of dietary intake and excretion of Sr had not been established.

As far as is known, no other human data are available where the Sr/Ca ratios have been measured in the soft tissue, blood, and bone of the same individual under conditions of normal dietary intake; however, differences have been observed in the strontium concentrations of different bones of the same individual by Rivera.⁽²⁵⁾ The strontium concentrations expressed in $\mu\text{g Sr/g ash}$ can be converted to $\mu\text{g Sr/g Ca}$ by assuming bone ash contains 37% calcium. In each of 12 individuals measured, the strontium concentration in the femur shaft was higher than that in the vertebrae. The Sr/Ca ratio femur shaft/vertebra ranged from 1.03 to 1.80 with an average value of 1.28.

Similar differences between Sr/Ca ratios in different bones have been observed in an animal experiment⁽²⁶⁾ when adult rabbits were maintained on a standard control diet. The Sr/Ca ratio for femur shaft/vertebrae in 6 animals ranged from 1.27 to 1.37 with a mean value of 1.33; those bones which showed the greatest rate of turnover, as evidenced by radioactive uptake and release, had the lowest stable Sr/Ca ratios. Furthermore, the Sr/Ca ratio in the plasma of these animals was found to be 1.6 times the average Sr/Ca ratio for the whole skeleton; a small number of soft tissue measurements also showed higher Sr/Ca ratios than that found in bone.

SUMMARY

The Ra/Ca ratios found in soft tissues have been shown to be about one or two orders of magnitude higher than the Ra/Ca ratios found in plasma and bone in humans from naturally-occurring Ra in the normal diet. The Ra/Ca ratios in plasma and bone, however, appear to be similar although differences of the order of a factor of 2 could not be detected by the present treatment of the results. Unlike Ra, the Sr concentration per gram Ca in soft tissue has been shown to be of the same order as that found in blood and bone, although again differences of a factor of two cannot be ruled out. Since a difference in the Sr/Ca ratio was observed in different bones in the human adults, those with the highest rate of turnover having the lowest Sr/Ca ratios, there is a suggestion that a discrimination between plasma and bone may occur within a

factor of two, as has been found in adult rabbits where similar differences between different bones were observed.

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STUDIES ON BONE-SEEKING RADIOISOTOPES*

Robert E. Rowland

I would like to bring to your attention our current knowledge of the levels of radioactivity in the human skeleton. This discussion will be restricted to the natural radioactive isotopes, and thus will omit any reference to the current levels of man-made radioisotopes in the skeleton. The reason for this follows from my opinion that our greatest need today is an understanding of the effects produced, if any, from the low levels of radiation which are naturally and always present in the human skeleton.

Let us start by reviewing our current knowledge of the dose rates delivered to man by his surroundings. Table 16 tabulates the total skeletal dose rate from external sources, cosmic rays and gamma rays originating in the earth's surface, and from the internal sources, those natural radioelements found in the skeleton. Note that the dose rate has been calculated as that delivered to a layer of cells, 10 μ thick, adjacent to bone surfaces. Higher dose rates will be obtained if the dose delivered to the bone mineral itself is considered, but as this type of calculation is probably not meaningful, this discussion will be restricted to the dose rates delivered to these bone cells.

When we examine in detail the contributions to the bone cell dose rates shown in Table 17, we find that the beta-emitting isotopes present in high concentration, C^{14} and K^{40} , account for somewhat less than half of the total. The alpha-emitting daughters of the radium series contribute more than half of the total bone cell dose rate.

For these calculations I have used an RBE of 10 for alpha particles, as suggested by the 1962 report of the United Nations Scientific Committee on the Effects of Atomic Radiation, following the recommendations

of the International Commission on Radiological Protection. The total dose rate in this table is greater than that listed in Table 16 for the internal emitters (30 mrem/yr) for it includes the latest data, developed by Holtzman,⁽¹⁾ on the levels of RaD (Pb^{210}) found in the skeleton. It is apparent that the latter makes the largest contribution to the total dose of the alpha emitters in the skeleton.

Now, to the best of our knowledge, these naturally occurring alpha-emitting isotopes are uniformly deposited throughout the bone mineral. We can consider that they are present in the diet from early childhood, and that all bone formed contains these elements. Subsequent remodeling and replacement of bone with new mineral, a fairly important process during childhood, does not change the uniformity of the mixing, unless a significant change occurs in the intake of one of these elements. Thus, these naturally-occurring alpha emitters should be considered to be uniformly distributed throughout bone and to be present there throughout an individual's entire lifetime.

Our present knowledge of the toxicity of these alpha emitters is still based on the experience of the radium dial painters. These individuals acquired their radium as adults. Subsequent autoradiographic study of their bones has demonstrated that the radium deposition, even as much as 40 years after exposure, is very uneven.⁽²⁾ This nonuniformity is of interest, for it tells us that bone remodeling processes turn over, by replacement, existing bone at a relatively low rate. Moreover, from a dosimetric point of view it indicates that a range of dose levels exists in such bones. Nonuniformity factors of the order of 200 to 1 have been found in the bones from radium cases.⁽²⁾ The lowest level, the diffuse distribution, is remarkably well correlated with the total body burden. If the total body content is

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divided by the total bone mass, to obtain an average distribution, it is found that the actual diffuse distribution is about one-half of the average distribution.

For a first approximation, we could define the dose rate to a 10- μ -layer of bone cells for a given radium case by calculating the average radium concentration from the measured body burden. If we consider a radium case containing 0.6 μ Ci Ra²²⁶, the dose to the cells of interest is 10⁴ times as great as the dose to an average bone from the natural radium content. This level of 0.6 μ Ci is chosen for illustration, for it has been found that levels higher than this produce considerable bone damage and often neoplasms, whereas lower levels seldom have produced significant damage.⁽³⁾

When we use the data obtained autoradiographically to sharpen our approximation of the dose rates to the bone cells, we find that about 99% of the bone surfaces are diffusely labeled and 1% of them are in-

TABLE 16. DOSE RATES FROM NATURAL RADIATION SOURCES (From the Report of the United Nations Scientific Committee on the Effects of Atomic Radiation: Supplement 16(A/5216))

Source	Dose rate within a 10- μ layer of cells lining bone surfaces (mrems/yr)
External	
Cosmic rays	50
Terrestrial radiation	50
Internal	
Elements of Ra and Th series	13
Potassium-40	15
Carbon-14	2
	—
	Total 130

TABLE 17. TYPICAL LEVELS OF NATURAL RADIOISOTOPES IN THE HUMAN SKELETON (MID-CONTINENTAL U.S.A.)

Isotope	Skeletal content, pCi	Dose rate within a 10- μ layer of cells lining bone surfaces	
		mrads/yr	mrems/yr (RBE = 10)
C ¹⁴	12,000	2	2
K ⁴⁰	7,200	17	17
Ra ²²⁶ and daughters	60	0.52	5.2
Ra ²²⁸ and daughters	40	0.83	8.3
Pb ²¹⁰ and daughters	340	1.15 ^(a)	11.5 ^(a)
		Total 44	

^(a) Dose rate calculated for 320 pCi Pb²¹⁰ (RaD); the remaining 20 pCi are derived from Ra²²⁶ and are included with Ra²²⁶ and daughters for dose calculations.

TABLE 18. COMPARISON OF THE TERMINAL BONE-CELL DOSE RATES EXPERIENCED BY A RADIUM CASE WITH THE NORMAL BONE-CELL DOSE-RATE

Hypothetical radium case (assumed body content, 0.6 μ Ci Ra ²²⁶ ; assumed hot spot-to-diffuse ratio = 200 to 1)	Dose rate to a 10- μ layer of cells lining bone surfaces (mrems/yr)	Dose-rate ratio to:		
		Natural Ra ²²⁶ level (5.2 mrems/yr)	Total alpha dose rate (25 mrems/yr)	Total bone cell dose rate (130 mrems/yr)
Dose rate based on average Ra ²²⁶ level in bone	52×10^3	10 ⁴	2×10^3	400
Dose rate based on hot-spot levels in bone	5200×10^3	10 ⁶	2×10^5	40,000
Dose rate based on diffuse levels in bone	26×10^3	5×10^3	10 ³	200

tensely radium labeled. The typical terminal dose rate to the cells from these two deposition patterns is indicated in Table 18. It is appropriate to indicate at this time that we do not know whether it is the intense dose levels or the lower dose from the diffuse distribution, or both, that is responsible for the neoplasms associated with radium poisoning, although current thinking tends to point toward the diffuse distribution.⁽⁴⁾

Table 18, containing the terminal dose-rate distribution arising from a typical radium case with a body content of 0.6 μ Ci Ra²²⁶ and a hot spot-to-diffuse ratio of 200 to 1, compares the calculated terminal bone cell dose rate delivered by the natural level of Ra²²⁶ to that delivered by all the alpha-emitting isotopes in bone, and to the total bone cell dose rate. It is interesting to note that if the diffusely distributed Ra²²⁶ was the significant source of the alpha dose to bone cells, then our radium case containing 0.6 μ Ci Ra²²⁶, or 10,000 times the natural radium level, delivers terminally only 200 times the normal "background" dose per year to the cells lining bone surfaces. It is tempting to speculate from such data, and, depending upon one's point of view, they can be used to show that: (1) it must be the dose delivered early in the radium patient's exposure history that is significant, for the terminal diffuse level is too low to be meaningful; or (2) it is the dose delivered by the hot-spot distributions rather than the diffuse distribution that is significant; or (3) the RBE for alpha particles must be considerably greater than 10 at low dose levels; or (4) there is a remarkable increase in effect with an increase in dose rate.

There is merit to all of these suggestions, but rather than trying to unravel them now, I would like to introduce a new subject which has unexpected conse-

FIG. 32. An autoradiograph of a portion of a section from the tibia of an adult dog sacrificed 12 minutes after administration of Ca^{45} .

quences regarding the dose delivered by alpha-emitting isotopes to the cells adjacent to bone.

In recent years, Ca^{47} has been widely used to determine bone-formation rates. This gamma-ray emitting isotope of calcium may be followed in the body by suitable detectors, and the body content and blood plasma levels employed, with reference to a suitable model, to calculate the skeletal accretion rate. Renewal rates of the order of 0.5% per day, or 18% per year, are typical results of such measurements on human subjects, when the method of Bauer, Carlsson, and Lindquist is employed.⁽⁵⁾

Bone renewal rates of this order of magnitude would clearly turn over the complete skeleton in a relatively short time. If this were the case no radium would be left in the bones of radium cases 20, 30 or 40 years after acquisition of this bone-seeking isotope. I have been, therefore, very much interested in the short-term exchange of calcium between the blood and bone and have, from autoradiographs of dog bones at short times after administration of Ca^{45} , found that there is a very large short-term exchangeable component in bone. This component is large enough to convince me that present models used in the calculation of bone-formation rates are inadequate, and lead to erroneously high values in mature animals.

More important, however, is the fact that these studies may have a bearing on the dose delivered to cells adjacent to bone surfaces by an alpha-emitting

isotope fixed in the mineral phase of bone. Figure 32 shows the distribution of Ca^{45} in compact cortical dog bone 12 minutes after isotope administration. Figure 33 shows this distribution after 1 hour, and Figure 34 illustrates the pattern 5 days after isotope administration.

The significant point is this: all the surfaces of bone that are in contact with the blood supply acquire this tracer (Ca^{45}) by exchange very rapidly, and a few days later we find that the bone surfaces have lost their intense label and that the deeper portions of the bone have been labeled. By making quantitative autoradiographic measurements one can determine how much Ca^{45} was taken up by these surfaces, and since the specific activity of the blood is known, one can calculate how much calcium was exchanged between blood and the bone surfaces. In each twenty-four-hour period sufficient calcium moves from blood to bone to replace all of the calcium atoms lying within 3000 Å of the bone surface, or, what is probably more likely, 10% of the calcium atoms lying within 3 μ of the bone surface are replaced each day.

Now what does this imply for our consideration of the dose delivered to bone cells by an incorporated alpha-emitting radioisotope? For the natural levels of Ra^{226} , Ra^{228} , and Pb^{210} it means very little, for as long as the level of these isotopes stays constant in the blood, the bone mineral and bone-bound isotopes removed by exchange will be replaced with equally

FIG. 33. An autoradiograph of a portion of a section from the tibia of an adult dog sacrificed 1 hour after administration of Ca^{45}

radioactive materials. When we consider our reference standard, Ra^{226} in dial painters, the situation is quite different. The dial painters were exposed to radium for only a short period of a few months to a few years, and after the radium level in their blood dropped below that of the bone (say a year or so after exposure), then this exchange process can be considered to start "cleaning" off the bone surfaces. If, as a consequence of this daily exchange, year in and year out, the outermost few microns of bone have been cleared of radium, what effect will this have on the dose to the cells adjacent to bone surfaces?

Table 19 shows the fractional reduction in bone-cell dose that results from the exchange-clearing of radium from exposed bone surfaces. This reduction has not been considered previously in the dosimetry of radium bones and, indeed, would be difficult to show autoradiographically, for the $30\text{-}\mu$ range of the alpha particles in bone would tend to mask the existence of a radium-free area along the surfaces. Nevertheless such a radium-free layer may well exist, and would certainly then act to reduce the bone-cell dose from acutely acquired radium.

There is also another rather well-known phenomenon which acts to reduce the surface dose in a radium patient. This is continued bone growth. Marshall has shown how hot-spot burial drastically reduces the surface dose from these intense deposits in growing bone.⁽⁶⁾ Since radium hot spots are found to occur in microscopic volumes of bone growing at the time ele-

vated radium levels were present in the blood, and since continued growth in such regions may well be expected to occur after the radium is no longer present in the blood, hot-spot burial is an expected process and, indeed, is a primary reason why the diffuse distribution in radium cases is expected to be the primary cause of significant cell irradiation.

Burial of the diffuse distribution may also occur, but this phenomenon has not yet been considered in the dosimetry of radium cases. Since bone is a living tissue, continually forming and reforming, it is not surprising to find radium-free areas in the bones of dial painters. These radium-free areas represent bone mineral formed long after the exposure to radium. Figure 35 illustrates how a thin layer of new bone is often seen adjacent to the endosteum. The micro-radiograph on the right shows clearly the new layer, while the autoradiograph on the left indicates that this new layer is acting as an effective barrier to the irradiation of the adjacent bone. While such remodeling of bone does not take place over all bone surfaces, it is not an infrequent phenomenon.

To summarize, then, high level radium cases, on whom all our present evaluations of toxicity are based, are characterized by a non-uniform deposition pattern of this isotope. Their exposure history started in adulthood and their period of exposure was short compared to their lifetime. Dose distributions for these bones have been calculated from the observed hot-spot and diffuse distributions, and it has been shown that the

FIG. 34. An autoradiograph of a portion of a section from the tibia of an adult dog sacrificed 5 days after administration of Ca^{45}

TABLE 19. DOSE REDUCTION TO CELLS LINING BONE SURFACES DUE TO AN ISOTOPE-FREE LAYER OF BONE

Layer thickness (μ)	0	1	2	3	4	5
Dose reduction (%)	0	6.3	13	19	25	31

dose distribution to the cells thought to be largely responsible for the toxic effects, from the diffuse distribution, is only a few hundred times as great as the "normal" or background dose to the same cells. Furthermore, this calculated dose is probably too high, be-

FIG. 35. A microradiograph (right) and an autoradiograph (left) of a segment of a femur showing the existence of a band of bone adjacent to the endosteum which is relatively radium-free. The autoradiograph covers the outlined area shown on the microradiograph.

cause of the cleaning action of exchange working on bone surfaces. Last, bone remodeling often puts new, unlabeled bone adjacent to bone surfaces, reducing the number of cells at risk in these cases.

In contrast, the normal population has been found to be uniformly labeled with alpha-emitting isotopes throughout their lifetimes. This normal distribution is unaffected by exchange and remodeling processes, for the newly deposited mineral contains the same tracer concentration as the old bone. Thus it is significant at this time to point out that it is difficult to calculate the expected risk due to relatively constant low radiation levels to large populations on the basis of the observed toxic effects in the radium cases. The difference in dose distributions between the two groups may be smaller than that expected on the basis of the total isotope content alone.

Thus we are faced with new data that may indicate that the dose response for alpha emitters in bone may be very steep. These considerations point out the necessity of reevaluating the effects of natural levels of radioactivity on mankind.

RESORPTION AND BONE PHYSIOLOGY*

Robert E. Rowland

The bones of individuals who acquired Ra^{226} either through occupational exposure or medical administration provide us with an unusual opportunity to visualize a tracer distribution of an isotope 30 to 40 years after it was administered. It is suggested that the total quantity of bone removed by resorption during the interval between isotope fixation and the time the bone sample was acquired can be determined from autoradiographs of these bones.

In actuality the specific activity of the plasma drops far enough below that of the bone about five years after exposure to Ra^{226} so that all new bone formed subsequently appears autoradiographically as a "white spot." A study of the fraction of cortical bone sections

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covered by these "white spots" was made for five selected radium cases; this fraction was measured to range between 5.5 to 57.2% and when transformed into uniform resorption rates, yielded values ranging from 0.30 to 3.03% per year.

These values are much lower than bone formation rate figures obtained from *in vivo* counting of Ca^{47} and interpretation by conventional isotope kinetic models. However, they are in excellent agreement with the bone turnover rates deduced from studies of the uptake of Sr^{90} by the general population. While it is not suggested that radium-labeled bones are "normal," and while far too few bone sections were included in this study for definitive results, the data are nevertheless suggestive that bone resorption rates in the adult human skeleton are quite low.

* Abstract of Paper 19, *Bone Biodynamics*, ed. H. M. Frost. Little, Brown & Co., Boston, 1964, pp. 335-351.

THE RETENTION OF Ba^{133} IN BEAGLES

J. E. Farnham and R. E. Rowland

INTRODUCTION

This report supersedes two earlier reports on the whole-body retention of Ba^{133} in two beagles.^(1, 2) One animal was followed for 1508 days; the second animal is still alive more than 2200 days after the isotope injection.

In order to ascertain whether barium behaves in a manner similar to the other alkaline earth elements following intravenous injection into the dog, we measured the plasma clearance, excretion, and whole-body retention of Ba^{133} in two beagles. In addition, we have determined the Ba^{133} concentration in various bone samples from one of the dogs. This isotope has a half-life of 7.2 years, decays by electron capture, and emits a series of gamma rays. Thus, its half-life is excellently suited for long retention studies, the radiation dose is minimal (since no beta particles are emitted), and the body burden is easily determined by means of scintillation counters.

METHODS AND RESULTS

The injection material was in the form of $BaCl_2$ in 0.075 *N* HCl, at a concentration of 10 μ Ci/ml, with a stable barium level of 10 mg/ml of solution.

Dog A22B was 8 months old (245 days) and weighed 7.2 kg at time of injection. Its weight 2184 days after injection was 7.9 kg. This dog received intravenously 6.1 μ Ci Ba^{133} , as described above, neutralized with NaOH immediately before injection. Dog 576 was at least four years old at time of injection and weighed 10.1 kg. This animal received an intravenous injection of 10 μ Ci Ba^{133} and was sacrificed after 1508 days.

TABLE 20. BLOOD SPECIFIC ACTIVITY

Time	% Injected dose/mg Ca	
	Dog 576	Dog A22B
1 hr	2.83×10^{-1}	2.73×10^{-1}
6 hr	1.17×10^{-1}	6.31×10^{-2}
1 day	5.15×10^{-2}	1.76×10^{-2}
2 days	2.04×10^{-2}	8.83×10^{-3}
3 days	1.18×10^{-2}	3.59×10^{-3}
7 days	3.80×10^{-3}	1.66×10^{-3}
14 days	1.10×10^{-3}	6.28×10^{-4}
1002-1091 days	—	8.60×10^{-6}
1100-1195 days	7.40×10^{-6}	—
1450-1550 days	4.65×10^{-6}	—
1765-1865 days	—	3.50×10^{-6}

The plasma clearance studies, on the blood samples taken within the first 14 days, were performed by measuring the Ba^{133} content of whole blood and assuming that the plasma fraction of the blood was constant. At each sampling of the blood about 4 ml were obtained in a heparinized syringe from which 3 ml were removed, sealed in a glass vial and counted in a NaI (Tl) well counter. The observed values are listed in Table 20 and plotted in Figure 36.

The Ba^{133} concentrations for the last four observations were determined by gamma-ray analysis of pooled samples of plasma. The plasma was collected over periods of about three months by taking approximately 150 ml of whole blood from the appropriate dog every two weeks, separating the plasma and storing it until a sufficient quantity had been obtained for analysis. At sacrifice a terminal blood sample of 300 ml was taken from dog 576.

The body burdens were measured by placing a 5" x 4" NaI(Tl) crystal, connected to a 256-channel analyzer, in a reproducible position with respect to the dog in the steel room of the Division of Biology and Medicine. Immediately after the original injection, each animal was counted, so that the original count included all of the injected activity. All subsequent counts were expressed as a fraction of the original count. The retention of the barium tracer is tabulated in Table 21 and shown in graphical form in Figure 36.

Ba^{133} emits two strong gamma rays, one at 81 keV and one at 360 keV, as well as other less intense gamma rays. It was of interest to note that the shape of the spectrum, as recorded by this particular NaI(Tl) crystal, remained unchanged throughout the period of observation, namely minutes to years after injection. This indicates that the effective absorption and scattering of the gamma radiation was essentially the same after the isotope was deposited within the bone as it was when the isotope was still in the blood. Thus, in this case, the technique of recording an original burden measurement immediately after the injection, before any excretion has taken place, is valid as the 100% point, and the spectrum thus obtained may be compared directly to the later spectra, even though the location of the isotope within the dog is not the same at later times.

Urine and fecal samples were collected separately from each animal for 3 successive days. The urine samples were digested with concentrated nitric acid and made up to a 250 ml volume in a volumetric flask.

From each flask a 3-ml. aliquot was taken, sealed and counted in the same NaI(Tl) well counter used for the plasma clearance studies. The Ba^{133} content of the urine was determined by comparison with standards made from the injection solution.

The fecal samples were placed in separate crucibles, dried with heat, and then ashed in a muffle furnace at 600° C. The ash was dissolved in concentrated nitric acid and washed into a 250-ml volumetric flask. One-milliliter aliquots were then sealed in glass vials and counted in the same manner as the urine samples to determine the total Ba^{133} content of the feces. The excrement data are shown in Table 22.

Dog 576 was sacrificed on the 1508th day after the administration of the tracer. Seven bones, a femur, tibia, humerus, radius, ulna and two lumbar vertebrae, were fixed in alcohol and then air dried. Each of the 5 long bones was cut into 5 approximately equal lengths. The pieces were coded as proximal end, proximal shaft, mid-shaft, distal shaft, and distal end. All these bone segments plus the two vertebrae were placed in separate, preweighed crucibles and ashed at 750° C overnight. The crucibles were reweighed to determine the ash weight of each sample. The ashed bone was then dissolved in 2 N HCl and transferred to 25-ml

TABLE 21. RETENTION OF BARIUM TRACER

Days from injection	Fractional retention		Per cent of injected dose per gram calcium	
	Dog 576	Dog A22B	Dog 576	Dog A22B
0	1	1	0.667	0.995
20	0.491	0.667	0.327	0.635
27	0.464	0.647	0.309	0.616
34	0.427	0.589	0.285	0.561
41	0.420	0.589	0.280	0.561
48	0.418	0.610	0.279	0.581
83	0.371	0.509	0.247	0.485
139	0.332	0.460	0.221	0.438
188	0.307	0.401	0.205	0.382
293	0.252	0.361	0.168	0.344
363	0.224	0.352	0.149	0.335
454	0.213	0.319	0.142	0.304
693	0.173	0.280	0.115	0.267
995	0.153	0.291	0.102	0.277
1002	0.157	0.303	0.105	0.289
1499	0.128	0.264	0.085	0.251

TABLE 22. EXCRETION OF Ba^{133} BY TWO BEAGLE DOGS

	Sample (24-hr)	Total μ C/sample	Fecal/urine ratio
Dog 576	feces (day 3)	3.17×10^{-1}	1.14
	urine (day 3)	2.78×10^{-1}	
	feces (day 4)	1.28×10^{-1}	1.51
	urine (day 4)	8.50×10^{-2}	
	feces (day 5)	1.16×10^{-1}	1.10
	urine (day 5)	1.05×10^{-1}	
Dog A22B	feces (day 4)	2.68×10^{-2}	1.62
	urine (day 4)	1.65×10^{-2}	
	feces (day 5)	1.82×10^{-2}	0.79
	urine (day 5)	2.30×10^{-2}	
	feces (day 6)	7.19×10^{-3}	0.72
	urine (day 6)	9.91×10^{-3}

FIG. 36. Retention and plasma levels of Ba^{133} in beagles as a function of time. The measured retention values have been expressed in terms of per cent of injected dose per gram of calcium by assuming that the skeletal calcium was 1.5% of the total body weight.

volumetric flasks. Aliquots of 3 ml from each flask were placed in separate polyethylene vials and counted in a NaI(Tl) well counter. The observed values, listed in Table 23 were calculated by comparison with the standards made from the injection solution.

In order to compare the relative retention of each of these bones and bone segments with an earlier distribution, Ba^{133} was administered to a beagle which was sacrificed 7 days later. This dog (No. 156), was more than 7 years old, weighed 6.8 kg, and was given 10.5 μ Ci Ba^{133} . The same bones described above were analyzed for their Ba^{133} content; the results are listed in Table 24.

TABLE 23. Ba^{133} CONCENTRATION IN DOG BONE
Dog 576, 1508 days after administration of Ba^{133}

Bone	Per cent of injected dose per gram ash $\times 10^{-2}$					
	Proxi- mal end	Proxi- mal shaft	Mid- shaft	Distal shaft	Distal end	Total bone
Femur	4.04 (2.77) ^(a)	2.47 (1.47)	1.83 (1.58)	2.57 (1.93)	4.60 (3.75)	3.5 [11.50] ^(b)
Tibia	4.22 (2.55)	2.74 (1.59)	2.33 (2.47)	2.70 (1.60)	3.92 (1.20)	3.2 [9.41]
Humerus	3.19 (3.59)	3.07 (1.10)	2.30 (2.19)	2.19 (2.03)	3.86 (2.66)	3.0 [11.59]
Radius	4.25 (0.88)	3.09 (0.79)	2.16 (1.24)	2.59 (0.95)	3.82 (0.77)	3.1 [4.63]
Ulna	3.20 (2.26)	3.37 (1.18)	3.61 (0.82)	4.20 (0.42)	5.75 (0.20)	3.5 [4.88]
Lumbar vertebra						3.26 [2.92]
Lumbar vertebra						3.24 [2.75]

(a) Bracketed () numbers are the ash weights of each bone segment, in grams.

(b) Bracketed [] numbers indicate the total ash weight of the whole bone, in grams.

DISCUSSION

It is evident that the retention of Ba^{133} in these animals is not adequately described by a power function. Figure 36 shows clearly that the plot of retention versus time does not yield a straight line on log-log coordinates; this is particularly evident for the older animal, No. 576.

The plasma concentrations do yield a straight line on log-log coordinates from day one to 14; however, the values for the interval between 1000 and 1900 days indicate that the plasma concentration did not continue to fall as rapidly during the entire exposure interval.

It is of interest to note that "cross over," the time at which the specific activity of the blood drops below that in the skeleton, occurred at 14 days in the younger dog and about 35 days in the 4-year-old animal. These values appear to be close to those predicted by the theory of Marshall.⁽³⁾

The specific activity, in terms of per cent of injected dose per gram of ash, of each bone and bone segment, listed in Tables 23 and 24, can be employed to study the relative loss of tracer from the various bone seg-

ments. It is probably not valid to compare the actual quantity of Ba^{133} retained in the two dogs because of their different ages (4 yrs vs. 7 yrs), for Decker *et al.*⁽⁴⁾ have shown a marked difference in retention with age. However, the specific activity of the tracer in each bone segment, relative to the specific activity of the whole bone, is probably a valid quantity to compare between the two animals. These relative specific activities have been calculated and are listed in Table 25. To demonstrate the changes that have occurred, the ratio of the relative specific activity of each segment at day 7 to that at day 1508 has been calculated and listed in this table. Ratios greater than unity identify segments in which the rate of loss has been greater from the segment than from the bone as a whole, whereas ratios less than unity designate the opposite. Obviously, a ratio of unity would indicate no change in relative specific activity between the two sampling times.

It is significant that the changes in isotope distribution between the two time intervals are not great. The largest change occurred in the vertebral bodies, which had a specific activity between 1.5 and 2 times that in the long bones at 7 days, and had fallen to the level of

TABLE 24. Ba^{133} CONCENTRATION IN DOG BONE
Dog 156, 7 days after administration of Ba^{133}

Bone	Per cent of injected dose per gram ash $\times 10^{-2}$					
	Proxi- mal end	Proxi- mal shaft	Mid- shaft	Distal shaft	Distal end	Total bone
Femur	8.9 (1.66) ^(a)	4.30 (1.12)	4.15 (1.11)	3.88 (1.04)	9.48 (1.97)	6.80 [6.90] ^(b)
Tibia	7.85 (1.63)	3.38 (1.35)	3.34 (0.99)	3.08 (0.94)	4.05 (1.07)	4.65 [5.99]
Humerus	13.4 (1.85)	4.92 (1.25)	3.96 (1.10)	3.94 (1.13)	6.25 (1.65)	7.18 [6.98]
Radius	6.13 (0.59)	3.50 (0.65)	3.21 (0.58)	2.44 (0.59)	5.81 (0.60)	4.20 [3.01]
Ulna	4.87 (1.48)	3.94 (0.90)	3.82 (0.52)	3.69 (0.30)	5.85 (0.21)	4.42 [3.40]
Lumbar vertebra						8.84 [1.96]
Lumbar vertebra						10.1 [1.96]

(a) Bracketed () numbers are the ash weights of each bone segment, in grams.

(b) Bracketed [] numbers indicate the total ash weight of the whole bone, in grams.

TABLE 25. RATIO OF SPECIFIC ACTIVITIES OF BONE SEGMENTS TO SPECIFIC ACTIVITY OF ENTIRE BONE

	Proximal end	Proximal shaft	Mid-shaft	Distal shaft	Distal end	Total bone
Femur						
7 day	1.13	0.633	0.611	0.571	1.39	1.00
1508 day	1.15	0.706	0.523	0.735	1.31	1.00
Ratio: 7/1508	1.14	0.90	1.17	0.78	1.06	
Tibia						
7 day	1.68	0.728	0.718	0.663	0.869	1.00
1508 day	1.32	0.855	0.728	0.844	1.22	1.00
Ratio: 7/1508	1.27	0.85	0.99	0.78	0.71	
Humerus						
7 day	1.87	0.684	0.551	0.549	0.871	1.00
1508 day	1.07	1.02	0.767	0.731	1.30	1.00
Ratio: 7/1508	1.75	0.67	0.72	0.75	0.67	
Radius						
7 day	1.46	0.833	0.762	0.579	1.38	1.00
1508 day	1.37	0.996	0.696	0.835	1.23	1.00
Ratio: 7/1508	1.06	0.84	1.10	0.69	1.12	
Ulna						
7 day	1.09	0.890	0.866	0.836	1.32	1.00
1508 day	0.915	0.962	1.03	1.20	1.64	1.00
Ratio: 7/1508	1.19	0.92	0.84	0.70	0.81	

the long bones by 1508 days. There were a few equally large changes in some of the long bone segments (for example, the proximal end of the humerus), but in general the specific activity changes between the two times in the long bones were not excessive.

SUMMARY

It is planned to continue the plasma and body content measurements on the remaining dog, A22B, as long as possible, making further measurements once each year. When this dog is eventually sacrificed, the specific activity of the same bone and bone segments will be measured and compared with those listed here.

To date, the retention of Ba^{133} by these animals is clearly not well described by a single power function; no attempt has been made to fit these data with a series of exponentials.

The analysis of the tracer content in segments of various bones suggests that, while changes are occurring, these changes are not rapid. Even four years after the isotope administration (into a mature animal) those bones or portions of bone usually considered to turn over rapidly still contain relatively high specific activity levels when they are compared to the regions of compact cortical bone where the turnover is known to be low.

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THORIUM AND URANIUM IN THE NATURAL ENVIRONMENT: A REVIEW OF PRESENT KNOWLEDGE

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INTRODUCTION

We have been interested in establishing the relationship between the naturally-occurring radioactive elements in food and water consumed by man with that found in his bone. Earlier work has been confined to radium and its daughter elements, as these may be readily determined by direct counting after suitable simple separation processes.⁽¹⁾ However, as the specific activities of the other naturally-occurring α -active elements, i.e., Th^{232} and U^{238} are too small to allow a direct counting method to be employed, no measurements have been made. As a result, very little is known about

the distribution of these two elements in the human body and the food chain, and the contribution they make to the total radiation dose from the naturally-occurring radioelements in the body. In addition, with the commissioning of many new power reactors fueled with these two elements and the concomitant hazards associated with such operations, it would be valuable to establish the normal body burdens.

There are two facets to this problem. One is to estimate the approximate concentration of the elements in normal samples: this involves a knowledge of (1) the concentration of the elements in foodstuffs and

potable waters; (2) the discrimination against the absorption of the element from the gastrointestinal tract (it is tacitly assumed that the air-borne concentrations of these elements, and thus absorption through the walls of the lung, are negligible); and (3) the distribution of the element in the body. The other is to devise a suitable method of analysis for thorium and uranium in the concentration ranges expected. This paper will be concerned with the first facet of the problem.

1. THE DISTRIBUTION IN FOODSTUFFS AND POTABLE WATERS

Thorium and uranium are widely distributed in many minerals as trace elements and would be expected to be found in low concentrations in most biological materials and water.⁽²⁾

There are no quantitative data available on the thorium content of food and relatively few values for its concentration in water. In a recent paper, Hill⁽³⁾ showed by α -spectrometric measurements that Th^{232} is present in English wheat bread. Osmond has shown that the thorium content of the hot springs in Florida is 0.1–2 ppb,⁽⁴⁾ and in another paper it was shown by neutron activation analysis that its concentration in most areas is less than 1 ppb.⁽⁵⁾

On the other hand there are many more data available concerning the distribution of uranium in nature. The concentration of uranium in tap water varies from 0.11–0.13 ppb at Argonne⁽⁶⁾ to 2.5–640 ppb in Pittsburgh, Pa. Cambridge, Mass., has 25–42 ppb; Rochester, N.Y., 18–30 ppb; and Oak Ridge, Tenn., 15 ppb. The Mississippi River at St. Louis, Mo., has 1.83 ppb and the Missouri River, 2.39 ppb.⁽⁷⁾ The extremely high value found in Pittsburgh tap water may be due to effluent from mining operations being dumped in the river. Scott and Barker⁽⁸⁾ have surveyed the surface waters of the whole of North America and report that the uranium concentration varies between 0.1 μg U/l. to 120 μg U/l. They suggest that the average concentration for the whole country would be 0.1–10 μg U/l., i.e., 0.1 to 10 ppb.

There are a few more data available on the concentration of uranium in foodstuffs than for thorium, but even these are very meager. Some years ago Hoffman⁽⁹⁾ reported on the concentration of uranium in many different foods. However, he makes no distinction between "fresh" and "dried" weight, so the figures are not particularly meaningful. He found that corn and beans contained 0.1 μg U/kg; cabbage, 0.2 μg U/kg; wheat bread, 0.08 μg U/kg; animal muscle, 0.4 μg U/kg; beef liver, 8.0 μg U/kg. More recently, Koch and Roesmer⁽¹⁰⁾ have determined the concentration of uranium, mainly in meats, by neutron activa-

tion analysis. For wet tissue they find that chicken contains about twice as much uranium as other meats, 7 μg U/kg; in addition, they found that eggs contain 8.8×10^{-4} μg U/g. Aten *et al.* have determined the concentration of this element in fish.⁽¹¹⁾ They found that the concentration varied between 2 μg U/kg for gurnard to 60 μg U/kg for haddock. Surface sea water has a concentration of 1 μg U/liter.⁽¹¹⁾ Hill has demonstrated the presence of U^{238} in foodstuffs and drinking water in England by α spectroscopy, but has made no quantitative measurements.⁽³⁾ He has also demonstrated the presence of uranium by α activity in human bone. He made all his measurements on ashed samples or the residues of evaporated water samples without further chemical treatment.

2. DEPOSITION IN THE BODY AND DISCRIMINATION ACROSS THE WALL OF THE GASTROINTESTINAL TRACT

A great deal of work has been reported on the deposition of thorium in the body after administration by injection. Thorium oxide in the colloidal form was used for many years as an X-ray contrast medium. It was found that a very large proportion of the thorium, once it has reached the blood stream, is deposited in the body and is then not readily excreted either in feces or urine. This is to be expected because thorium, in whatever form it is injected, is readily hydrolyzed at body pH to insoluble hydrated oxides.

Several groups of workers have attempted to study the oral uptake of thorium by animals. As early as 1907, Souman and Brown fed thorium nitrate or citrate to rabbits and found that it was excreted in the feces but not the urine.⁽¹²⁾ Analysis of the animal tissue for thorium gave negative results. Lanz *et al.*⁽¹³⁾ fed rats 10 μCi Th^{234} as ThCl_4 and sacrificed them four days later. They found that the absorption from the gastrointestinal tract was less than 0.05%. Similarly, Patrick⁽¹⁴⁾ found no absorption from 25 mg of thorium labelled with Th^{234} administered orally to mice. Mattis⁽¹⁵⁾ gives a figure of <0.01% of the dose absorbed across the gastrointestinal wall. He has also shown that orally administered doses of 30 mg/kg to rats led to an absorption of 0.06% of the dose and that 90–100% of this deposited in the skeleton.⁽¹⁶⁾ Larger doses apparently produced no detectable absorption.

Scott⁽¹⁷⁾ using doses of 1.5–4.0 mg Th/kg body weight found the thorium recovered with no loss in the feces and no evidence of absorption. Boeker⁽¹⁸⁾ has repeated this work, and his results are in agreement with the data that have been published earlier; that is, absorption is $\leq 0.06\%$. Probably a more realistic figure would be $\sim 0.01\%$.

A considerable amount of work has been done on the deposition of uranium in the body. Neuman⁽¹⁹⁾ has

published extensive data on the distribution of uranium in the bodies of rats after intravenous injection. He found that 50% of the administered dose was excreted almost immediately in the urine, and more was excreted over a longer period time, up to 85% of the total dose. These data are for uranium (VI); uranium (IV) behaves similarly to thorium in that the excretion is primarily in the feces, whereas with uranium (VI) it is via the urine. Between 10 and 20% of the total dose is retained in the body and 80–90% of this appears to be stored in the calcified parts of the bones. There appears to be a greater deposition in the bones of males than females. The quantity of uranium in the bones remained essentially constant after 40 days.

In contrast to the extensive data for uranium administered intravenously there are very few data for the absorption of the element across the gastrointestinal tract. Voegtlin and Hodge reported experiments where dogs were fed with uranium, and they showed that the skeletal retention was less than 0.05% over one year. The feeding levels were far above normal levels, and the uptake was not proportional to the quantity fed, suggesting a saturation effect.⁽²⁰⁾ Hamilton fed carrier-free U^{233} to rats with about 0.01% retention in their skeletons.⁽²¹⁾ Bernard and Struxness⁽²²⁾ give a figure of 0.33 for the fraction entering the bone from the blood, and Hamilton⁽²¹⁾ gives a figure of 10^{-4} for the fraction entering the bone from the gastrointestinal tract. This makes the over-all fraction of uranium entering the bone from the gastrointestinal tract to be $\sim 3.3 \times 10^{-5}$, which is about half the value estimated for thorium, and appears to be rather low.

3. DISTRIBUTION OF THE ELEMENTS IN THE BODY

From the studies carried out using animals, it was found that greater than 90% of the thorium that entered the blood stream was deposited in the bone. The biological half-life of the element in the bone is $\sim 70,000$ days. On the basis of these observations, it might be expected, provided the ingestion rate of thorium is constant, that the burden of thorium in the bone will increase with age. No measurements have been made of the concentration of natural thorium in bone. However, recent measurements by X-ray spectroscopy of human blood have shown that the thorium concentration for normal healthy people is less than 0.01 ppm.⁽²³⁾

From the sparse data available it is possible to make two estimations of the concentration of thorium likely to be found in human bone.

A maximum value may be calculated from the concentration of thorium found in blood. If the standard man has five liters of blood and a skeletal mass that

reduces to 2.6 kg of ash, then if there is only 10 per cent of the total thorium in the blood (*vide supra*) the total skeleton contains 50 μg of thorium, which means that a 1-g sample of bone ash will contain roughly 0.02 $\mu\text{g/g}$ ash.

Another estimation of the concentration likely to be found in bone may be made from the intake of thorium from food and water. As a first assumption, let us take the concentration of thorium in food to be equal to that in water, i.e., $\sim 10^{-3}$ ppm. The daily intake of thorium in food and drinking water for a standard man (70 kg) is 1 liter water, 1 kg food, i.e., 2×10^{-6} g Th.

Assuming that 7×10^{-5} of this total thorium passes across the gastrointestinal wall,⁽²⁴⁾ the total thorium entering the body each day is 1.40×10^{-10} g Th.

It would appear from other work that the thorium that gets into the blood stream is deposited irrevocably in the skeleton with almost 100% certainty. A standard man has a skeletal mass of 7 kg which gives 2.6 kg ash. Hence, each day there should be a deposition of 5.5×10^{-14} g Th/g ash. Over a period of 30 years (10,000 days) this would amount to 5.5×10^{-10} g Th/g ash, assuming a uniform distribution of the thorium.

The disparity between the values obtained in these two calculations is to be expected in view of the gross assumptions being made.

In the case of uranium, it is known that only 30% of the element which finds its way into the blood is deposited in the bone and that this has a biological half-life of 300 days. It might be expected then, that as the uranium in the blood is in equilibrium with that entering by crossing the gastrointestinal tract and with that being excreted in the urine, the concentration of uranium in the bone will remain constant with age as long as there is no drastic change in the amount of the element ingested.

Hoffman has studied the deposition of uranium in the body in some detail. It would appear that the concentration of uranium in the bones of people who have not been exposed to large quantities of the element is of the order of 0.01 $\mu\text{g/g}$ ash.⁽⁹⁾ In a later paper, he showed that cortical bone contains $1.3\text{--}1.6 \times 10^{-3}$ $\mu\text{g/g}$ ash and lamellae contain 4.8×10^{-3} $\mu\text{g/g}$ ash.⁽²⁵⁾ Other organs of the body have higher uranium concentrations than bone. The highest values reported are for the seminal vesicle or ovary where the concentration is $\sim 3.7 \times 10^{-7}$ $\mu\text{g/g}$ tissue. The uranium concentration in blood was found to be 4×10^{-4} $\mu\text{g/ml}$.⁽²⁵⁾

Workers at Berkeley have determined the concentrations of 66 elements in the blood of healthy adults by X-ray spectroscopy. They found that the uranium concentration in the blood is 0.02 ppm with a standard

error of mean 0.03 ppm, and the 99% confidence limits of the mean are 0.00 to 0.10 ppm.⁽²³⁾

Finally, it is of interest to note that Feretti and Schwartz⁽²⁶⁾ found the concentration uranium in the bones of normal rabbits to be about 3×10^{-8} g U/g ash.

An estimate can be made for the concentration of uranium likely to be found in bone from normal intake in a manner similar to that used for thorium. The uranium content of food appears to be of the order of 10^{-9} g U/g and for drinking water, 10^{-9} g U/ml. If an average person eats 1 kg of food and drinks 1 liter of water each day, his total intake into the gastrointestinal tract is 2 μ g U/day.

However, only 3.3×10^{-5} of it is deposited in the bone, so a total of 6.6×10^{-11} g uranium enters the bone per day. Assuming uniform distribution in the bone (2.6 kg of ash), the daily deposition of uranium is 2.5×10^{-14} g U/g ash. If the deposition is cumulative, then after 30 years (10,000 days), the concentration of uranium would be 2.5×10^{-5} μ g/g ash. This figure is in marked disagreement with the measured values of $\sim 10^{-8}$ g U/g ash of bone and 2×10^{-8} g U/ml of blood.

It is evident from this survey that very little is known about the distribution of thorium and uranium in biological materials, and much remains to be learned. In view of the apparent disparities between the two values calculated for thorium, and between the calculated and observed values for uranium, it seems that analytical techniques are required to analyze for these two elements at the nanogram and subnanogram level on a routine basis before any further progress may be made.

When such a method is sufficiently developed many possibilities of its use may be envisaged. First of all there is the need to determine the concentrations of thorium in water supplies and food and to extend the data already available for water. Next, it would be interesting to study bone samples from populations with widely differing concentrations of the elements in their diet. As an example, it would be particularly interesting to study the populations of Cambridge, Mass., and Rochester, N.Y., because of the high uranium concentration in their tap water. After such data have been obtained then it would be instructive to see whether the assumptions made in the calculations are valid, particularly as to whether the concentration of

thorium in bone is a function of time and the concentration of uranium in bone constant with age.

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THE ESTIMATION OF THORIUM AND URANIUM AT THE SUBMICROGRAM LEVEL IN BONE

David N. Edgington

INTRODUCTION

A survey of the literature has shown that the concentrations of thorium and uranium likely to be found in most biological materials are less than one part per million and probably less than one part per billion (see preceding paper). In order to detect concentrations of this order, extremely sensitive analytical techniques are required, and the purity of the reagents used becomes a matter of prime importance. The lower limits of detection for uranium using the various analytical techniques available have been summarised in a recent report.⁽¹⁾ Under the most favorable conditions spectrophotometric methods are reliable to 0.1 μg total of the element sought, the limiting factors being the absorbancy of the complex and the sensitivity of the instrument. Fluorometric methods may be employed for the analysis of uranium down to 10^{-4} μg ⁽²⁾ and thorium down to 10^{-2} μg total of the element sought; but in the latter case there are many elements which interfere.⁽³⁾ In all of these methods, however, complicated separation procedures are required with the concomitant dangers of sample contamination from the reagents used. For the analysis of biological materials these methods are extremely laborious, time consuming and nowhere near sensitive enough.

Neutron activation, followed by the radiometric assay of the induced radioactive nuclides, has been used for the determination of very small concentrations of thorium and uranium. Activation analysis is generally advantageous on four counts; viz., there is greater sensitivity for the element sought; errors due to reagent contamination may be eliminated—particularly if the sample can be irradiated without any prior chemical treatment; as long as an inactive carrier may be added after irradiation the chemical separations need not be quantitative as only radiochemical purity has then to be achieved; and finally, it is possible to analyze for several other elements at the same time.

The sensitivity depends on the neutron cross section of the element sought, the half-life of the radioactive nuclide formed, the neutron flux, and the time of irradiation. Thorium and uranium undergo several different nuclear reactions with neutrons and, therefore, the sensitivity will depend largely on the nuclide chosen for radiometric assay.

When thorium-232 and uranium-238 are irradiated in a reactor with neutrons they form the short-lived radioactive nuclides Th^{233} and U^{239} (half-lives 22.4 min and

23.5 min respectively). As long as the matrix being analyzed is relatively simple and, therefore, these nuclides may be separated from it in a very short time, this is the most sensitive method for the analysis of uranium and thorium.^(4, 5) Using an irradiation time of 20 min and a neutron flux of 10^{13} n/cm²/sec a sensitivity better than 10^{-6} μg is obtained. Unfortunately most biological matrices are far from simple and it is difficult to complete a satisfactory separation within the lifetime of these nuclides.

An alternative procedure is to count the delayed neutrons emitted by the fission products of Th^{232} , U^{235} and U^{238} . This method is very attractive in that no chemical separations are required at all and the process is essentially nondestructive.^(1, 6) However, with the reactors now available the lower limits of detection by this method are 10^{-1} μg for Th and 10^{-2} μg for U. Another method is to isolate one of the fission products formed: uranium has been determined by separating out the Ba^{140} - La^{140} formed in the fission of U^{235} .^(7, 8) A sensitivity of 10^{-4} μg may be obtained with long irradiation times of about a week. For bone, however, this method is not feasible owing to the difficulty of separating barium or lanthanum from calcium.

The final possibility is to use the daughter products of Th^{233} or U^{239} . Their decay schemes are:

As U^{233} and Pu^{239} are alpha emitters, they would present a very convenient method of assay but have to be ruled out for submicrogram determinations because of their very low specific activity. Their parent nuclides, Pa^{233} and Np^{239} , have half-lives sufficiently long to permit the lengthy separations required for a complex matrix like bone. With a neutron flux of 10^{13} n/cm²/sec and an irradiation time of 20 min a maximum sensitivity of 10^{-4} μg is attainable provided suitable low-background counting equipment is available. Longer irradiation times would, of course, increase the sensitivity proportionately.

Several papers have described the determination of thorium or uranium at the submicrogram level utilizing the radioactivity of Pa^{233} or Np^{239} , but not in a matrix as complex as bone.^(9, 11) This paper will describe the development of a separation procedure for these two

nuclides from bone and present some preliminary results obtained from representative bone samples.

EXPERIMENTAL METHOD

Weighed samples of cleaned, dry bone are placed in platinum crucibles and ashed at 600° C for 16 hours. 0.5- to 1.0-g samples of the ash are carefully weighed into polyethylene "flip-top" capsules, which are then sealed with tape to prevent their accidental opening. The capsules are then irradiated in the large pneumatic-tube facility in CP-5 for 20 min (neutron flux $\sim 2 \times 10^{13}$ n/cm²/sec). The irradiation of ashed bone rather than dry bone is to be preferred because the "wet ashing" of the latter takes a fairly long time relative to the half-life of Np²³⁹ and also presents a much greater opportunity for accidental spillage and the concomitant hazards. Bone ash on the other hand dissolves readily in strong hydrochloric acid.

After irradiation the bone ash is dissolved in the minimum volume of 9 *M* HCl so that the concentration of Ca₃(PO₄)₂ $\leq$ 0.2 g/ml and the solution transferred to an anion exchange column. The columns used are made of polyethylene tubing 6 mm in diameter, resin column 25 cm long. The column contains Dowex 1-X8, 100-200 mesh which has been previously washed with 9 *M* HCl. The column is then eluted with 9 *M* HCl to remove all the nonanionic species and the anionic species which are weakly adsorbed. The eluant is collected in 5-ml aliquot portions for gamma counting. The total volume of acid required depends on the type of bone being analyzed and the time between irradiation and elution, but generally the gamma radioactivity in any aliquot portion is reduced sufficiently (25% above background, in this case 90 cpm) after approximately 80 ml of solution have passed through the column.

The protactinium and neptunium are then eluted from the column using 8 *M* HCl which contains 0.3 *M* HF. These nuclides are quantitatively removed from the column in 25 ml of eluant. At this point the decontamination of the Pa and Np from other radioactive species is better than by a factor of a million. The only contaminant detected is Sc⁴⁷ which is the daughter of Ca⁴⁷ produced in the n, γ reaction of Ca⁴⁶. This is removed by passing the eluant through a second similar column 10 cm long, which has been pretreated with 8 *M* HCl, 0.3 *M* HF. The eluant from this column is collected in a polyethylene vial for counting.

In the preliminary studies reported here the samples have been counted in a 2" well-crystal connected to a 256-channel pulse analyser and the concentrations of Pa²³³ and Np²³⁹ estimated from the peak heights of the gamma spectra. For more accurate work the nuclides should be plated out and the beta disintegrations counted in a proportional counter. For this purpose the

fluoride is complexed by adding an excess of Al³⁺ ions, the acidity adjusted to 6 *M* HCl, and the protactinium extracted into diisobutyl carbinol.⁽¹²⁾ The neptunium is extracted from 2 *M* HCl into 0.2 *F* mono- or di-(2-ethylhexyl) phosphoric acid.⁽¹³⁾ The organic extracts are then plated out.

DISCUSSION AND RESULTS

The main problem to be solved in neutron activation analysis is generally one of separation. This may be done chemically or instrumentally using pulse-height analyzers to unscramble the complex gamma spectra obtained. In complex matrices like bone, however, the low energy bremsstrahlung from the calcium-45 and phosphorus-32 effectively masks the radioactivity from the trace elements, and chemical separations have to be used. Furthermore, as there are no isotopes of protactinium or neptunium which may be used as inactive carriers, any chemical separation has to be essentially quantitative as well as give a high level of decontamination from the other products of neutron activation.

Two methods of separation were considered: solvent extraction and ion exchange. Solvent extraction techniques are attractive in that they are rapid and, in many cases, quantitative. Preliminary experiments with long-chain amines or alkyl phosphates in inert diluents showed that the extraction of Th²³³ and U²³⁹ or Pa²³³ and Np²³⁹ was quantitative, but many other nuclides were extracted at the same time. Further experiments showed that stripping of the desired components from the organic phase was difficult and not sufficiently quantitative. It may be possible to employ this technique, however, in conjunction with gamma-ray spectrometry and a least squares analysis of the spectra.⁽¹⁴⁾

Preliminary experiments with anion exchange columns were also encouraging. Both protactinium in the pentavalent and neptunium in the tetra- or pentavalent state are strongly adsorbed onto strongly basic anion exchange resins from hydrochloric or nitric acid.^(15, 16) Adsorption from nitric acid is to be preferred because very few elements form anionic species with nitrate ions, and, therefore, the separation problem would be simpler. Protactinium or neptunium is adsorbed quantitatively onto the resin from 8 *M* nitric acid, values of *K_a* (concentration of ion adsorbed per gram of resin concentration of ion per milliliter of solution) being 50 for Pa(V) and 12 for Np(V) and 4000 for Np(IV). Neptunium (V) may be eluted readily with 3 to 4 *M* nitric acid, while protactinium is not eluted until the acid concentration is reduced to below 1 *M*; therefore, a separation is feasible.⁽¹⁶⁾ However, when an attempt was made to effect this separation in the presence of

calcium phosphate, very little protactinium or neptunium was adsorbed onto the column. Initially a concentration of 0.2 g $\text{Ca}_3(\text{PO}_4)_2$ per milliliter of 8 M HNO_3 was used, but reduction of concentration to 0.05 g/ml was no improvement so no further attempts were made to use nitric acid as the eluant.

Both elements are very strongly adsorbed onto anion exchange columns from hydrochloric acid solutions stronger than 5 M . Kraus and his coworkers have studied the hydrochloric acid system in detail.⁽¹⁵⁾ The only ions which are not adsorbed under these conditions include the alkali, alkaline earth, non-transition metal trivalent cations and anions like PO_4^{3-} and SO_4^{2-} . Preliminary experiments showed that the strong adsorption of protactinium or neptunium onto Dowex 1-X8 is unaffected by the presence of calcium phosphate, at least up to a concentration of 0.2 g/ml of 9 M hydrochloric acid. Neither of the elements is readily eluted from the column using dilute acid, probably because of the formation of complex hydrolysis products. They are, however, readily eluted with strong hydrochloric acid containing a small concentration of fluoride ion. This is because Pa(V) and Np(IV) have a far greater tendency to complex with fluoride ions than with

FIG. 37. Separation of protactinium and neptunium on Dowex 1-X8.

FIG. 38. Separation of protactinium and neptunium from other elements on Dowex 1-X8.

chloride ions. In the presence of even a small concentration of fluoride ion they form the doubly charged complex MF_7^{2-} , which is not as strongly adsorbed as the singly charged anionic complex formed in the presence of high concentrations of chloride ions, MCl_6^- .

Kraus found that if the fluoride concentration is only 0.004 M HF protactinium is eluted in 9 M HCl.⁽¹⁷⁾ Under these conditions the protactinium tends to tail, but if the fluoride ion concentration is raised to 0.012–0.024 M protactinium is readily eluted. Neptunium, on the other hand, does not form such a strong fluoride complex and is not eluted under these conditions; if the eluant is changed to 8 M HCl which is 0.3 M in HF, the neptunium then elutes readily.⁽¹⁸⁾

Figure 37 shows a typical separation of protactinium and neptunium. One gram of calcium phosphate was dissolved in 5 ml 9 M HCl which was then spiked with strontium-85 (as a tracer for the calcium) and a small amount of Np^{237} in equilibrium with its daughter Pa^{233} . The anion exchange column was 21 cm long, 0.6 cm diameter and contained Dowex 1-X8, 100–200 mesh. The flow rate was approximately 0.3 ml/min; 5-ml aliquot portions were collected. The recovery of the

TABLE 26. NEUTRON ACTIVATION ANALYSIS OF ASHED COW FEMUR SPIKED WITH URANIUM

Experiment number	Spike ($\mu\text{g U}$)	Net count/min	Net cpm ^(a) per $\mu\text{g U}$
4	0.34	445	1310
10	0.008	16	1250
18	7.5	11,400	1520
19	None	6	—
20	None	7	—
30	3.75	5,700	1520
33	3.75	5,800	1540
34	0.024	42	1500
35	0.12	227	1830
36	0.072	128	1700
37	0.3	400	1320
38	0.004	13	1500
			Average 1500

^(a) Correction applied for the uranium content of unspiked ashed cow bone.

TABLE 27. NEUTRON ACTIVATION ANALYSIS OF ASHED BONE SAMPLES

Experiment number	Type of bone	Weight of ash (g)	Net cpm	$\mu\text{g U/g ash found}$	$\mu\text{g Th/g ash found}$
19	Cow femur	1.000	6	0.004	
20	Cow femur	1.000	7	0.004	0.004 ^(a)
22	Human—from uranium miner	0.814	129	0.11	0.006 ^(a)
23	Human—normal exposure?	0.814	5	0.004	
31	Human sternum from a uranium miner	0.584	68	0.08	
33	Human rib from a uranium miner	0.545	51	0.06	
25	Human fibula from a Thorotrast patient	1.031	321		2.0
27	Human fibula from a Thorotrast patient (repeat)	0.849	266		2.0

^(a) Estimated from the residual gamma spectrum after the mixture of Np^{239} and Pa^{233} has been allowed to decay for 21 days or more.

Sr^{75} , Pa^{233} and Np^{237} was essentially quantitative, ($\pm 2\%$).

Two trace elements present in bone which might interfere with this process are cobalt and zinc. They are fairly strongly adsorbed onto anion exchange columns. Figure 38 shows the separation of these two elements. Ferric ions could be eluted from the column between cobalt and zinc, using 1 M HCl. Kraus had shown previously that the addition of fluoride had no effect on the elution of Fe^{3+} with hydrochloric acid.⁽¹⁷⁾ The recovery of these elements was essentially quantitative.

In order to test the procedure, samples of ashed cow bone were spiked with varying concentrations of uranium. These, together with unspiked samples of bone ash from various other sources, were irradiated in the reactor. After irradiation they were dissolved and put on the anion exchange column as described in a previous section. In these studies it has been assumed that the neutron flux in the pneumatic tube remains essentially constant. Table 26 shows the results obtained for spiked and unspiked cow bone. The net counts per minute recorded in column three are the counts observed in the channel corresponding to a gamma energy of 106 keV (see below) corrected for background and radioactive decay. The concentration of uranium in the spike varied from 7.5 μg down to 0.004 μg . The fourth column in the table shows the net counts per minute per microgram of uranium. The average value of 1500 cpm Np^{239} per $\mu\text{g U}$ is well within the statistics expected in this system, particularly as no check was kept on the neutron flux from irradiation to irradiation. Samples of cow bone spiked with thorium gave a value of 365 cpm Pa^{233} per $\mu\text{g Th}$.

Table 27 shows the results obtained for the analysis of thorium and uranium in a variety of bones by neutron activation. Apart from the analysis of the bone from a Thorotrast patient, thorium was determined by counting the Pa^{233} activity remaining after the Np^{239} had decayed away.

These results show that it is possible to determine thorium and uranium down to 10^{-3} μg by counting Pa^{233} and Np^{239} in a gamma spectrometer and that except in people who have been exposed to abnormal concentrations of these two elements, the levels of thorium and uranium to be found in bone is at the part per billion level. Future work will be devoted to increasing the sensitivity of the method using gamma counting techniques by carefully controlling the conditions and by analyzing the gamma spectra obtained by computer techniques. The sensitivity can be increased quite considerably by increasing the time of irradiation; however, this will increase greatly the activity of the unwanted nuclides as well, but this will be necessary anyway to determine other elements of interest.

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STRONTIUM RETENTION IN MICE TREATED WITH THYROID HORMONES

David J. Simmons and Patricia M. Failla

Strontium, like calcium and the other alkaline earth elements, is a bone seeker. Its metabolism in the body resembles that of calcium with only quantitative differences. Strontium is incorporated into bone by accretion into newly forming apatite mineral in regions of active skeletal growth, and may enter mature bone crystals by a process of heteroionic exchange at crystal-lite surfaces and/or intracrystalline diffusion and recrystallization. In autoradiographs, the accretive process results in hot spots, while the exchange mechanism is responsible for what is termed the diffuse reaction. Quantitation of this compartment⁽¹⁻³⁾ suggests that the diffuse reaction is about half the average specific activity of the skeleton in young growing animals; in older non-growing animals with relatively fewer sites of active bone formation in their skeletons, the diffuse component may be larger.⁽⁴⁾ Radiostrontium seems firmly fixed in bone once it "enters" the apatite lattice, and it is known that the skeletal uptake of the element is most rapid within an hour after injection. By several weeks after injection, most of the non-skeletal strontium has been excreted predominately via the urine.

Radiostrontium may be lost from the skeleton by resorption of bone. In the growing animal, there exist sites of high skeletal "turnover." These are generally considered to be the trabecular bone in the growing ends. Compared to calcium, smaller amounts of the radiostrontium liberated into the blood are redeposited in new sites of bone formation. This results from the discrimination against strontium in the blood at the level of the kidney, salivary glands,⁽⁵⁻⁷⁾ and perhaps the lowered reabsorption of the isotope secreted via the digestive juice from the stomach into the digestive tract.⁽⁸⁾ These discriminatory mechanisms against strontium entering from dietary sources have suggested various experimental approaches directed toward altering the nature of the normal metabolic processes

of absorption. However, while the initial discrimination against strontium by the body is fortuitous in view of the long residence time in bone and the often-demonstrated relationship between the skeletal burden and the occurrence of bone tumors,⁽⁹⁻¹⁵⁾ no satisfactory methods exist for the removal of the isotope once it has been deposited in the skeleton.

An ideal experimental protocol to lower a long-term skeletal burden of radiostrontium would involve exaggerating several metabolic parameters. It would first be advantageous to increase bone resorption while maintaining a high level of bone formation to avoid the possibility of inducing spontaneous fractures and other metabolic disorders such as osteoporosis. The higher blood levels of strontium derived from resorbed bone might then be lowered by increased urinary and fecal elimination as well as increased excretion via saliva^(6, 7) and sweat.⁽¹⁶⁾

The Use of Thyroid Hormones to Lower Long-Term Body Burdens of Radiostrontium

Studies, principally in man, suggest that thyroid hormones might create an internal environment ideally suited to stimulate removal of long-term skeletal burdens of radiostrontium. The hormones principally secreted from the thyroid are thyroxine (T_4) and triiodothyronine (T_3). The peripheral action of these hormones is similar, but while T_4 is bound more tightly to the plasma proteins (albumin fractions),⁽¹⁷⁾ the action of T_3 is more rapid and powerful but of shorter duration, perhaps owing to its more rapid excretion via urine and feces.⁽¹⁸⁾ T_4 , T_3 , and their acetic acid and propionic acid analogues are active in mineral metabolism in addition to their role in homeostatic mechanisms. The acetic acid analogues relieve some of the symptoms of hypothyroidism in rats without any appreciable effect on the basal metabolic rate.⁽¹⁹⁾ It will become clear in the following discussion that nearly all of the studies

dealing with the effect of thyroid hormones on mineral metabolism have involved human subjects, but there is evidence that similar events could be expected in experimental animals. In general, the administration of thyroid hormones promotes calcium excretion in man, and strontium excretion is known to parallel that of calcium.

The Effect of Thyroid Hormones on Calcium Metabolism in Man

Patients with thyrotoxicosis or hyperthyroidism of varying etiologies, exophthalmic goiter⁽²⁰⁻²²⁾ and thyroid clear-cell adenoma,⁽²⁰⁾ exhibit (a) increased bone formation and resorption rates,⁽²³⁻²⁶⁾ (b) increased serum calcium and urinary calcium and phosphorus,* and (c) increased fecal calcium excretion.⁽²⁷⁻³⁵⁾ The latter appears to be a unique property of thyroid hormones. In hypothyroid patients, tetraiodothyroacetic acid (TETRAC) promotes fecal calcium excretion while triiodothyroacetic acid (TRIAC) stimulates urinary calcium elimination.^(35, 36) These effects, moreover, have been manifest in individuals in normal nitrogen equilibrium.^(20, 21, 34) On the other hand, hypothyroid patients or individuals treated with propylthiouracil (to reduce thyroid function) usually show lower bone formation and resorption rates, and lower serum, urinary, and fecal calcium values than normal.† These defects of hypothyroidism in mineral metabolism have been corrected by thyroid hormone therapy. One might expect, then, that thyrotoxic individuals would exhibit a large metabolic pool of calcium, and, indeed, this has been confirmed in many studies.^(24, 25, 26, 34, 40, 41, 42, 43) Skeletal kinetics, as measured by both strontium-85 and calcium-45, indicate that the skeleton is sensitive to different levels of thyroid function, and that the metabolic behavior of the two isotopes is similar.⁽³¹⁾ The fact that thyroxine has no calcium mobilizing effect on dead bone *in vitro*⁽⁴⁴⁾ suggests that thyroid hormones have a direct effect on bone cell metabolism.

Microscopic evidence of bone destruction in hyperthyroid patients has been described by Askanazy and Rutischauer.⁽⁴⁵⁾ Thyrotoxic individuals may develop osteoporosis as a result of increased bone resorption⁽²³⁾.

* Bijvoet *et al.*⁽³⁷⁾ consider that high plasma phosphate values might cause parathyroid hyperplasia and hyperfunction, and that in thyrotoxic individuals, hyperphosphatemia would result from the ensuing lower tubular reabsorption of phosphate in the kidney. Bijvoet and Majoor⁽³⁸⁾ have recently contended the data presented by Nordin and Fraser⁽³⁹⁾ that thyrotoxic patients had a normal phosphate excretion index. They contend that their methods of calculation did not take into account that thyroid hormone raised the renal tubular maximum reabsorptive rate for phosphorus in relation to the glomerular filtration rate.

† In cretins, calcium absorption through the gut is increased, perhaps owing to an increased sensitivity to vitamin D.⁽³⁷⁾

26, 30, 46, 47) as well as osteomalacia.^(26, 48-50) Chomette *et al.*⁽⁵¹⁾ found radiographic evidence of osteolytic metastases throughout the skeleton in an individual with thyroid carcinoma, but it is not known if the tumor was functional (thyroid hyperactivity) or if the skeletal lesions might have resulted from neoplastic growth alone.

Biochemical evidence clearly supports the concept of increased bone formation and resorption in human hyperthyroidism. Serum and urinary hydroxyproline concentrations derived in large part from the catabolism of bone collagen sources, are higher than normal in affected patients.⁽⁵²⁻⁵⁵⁾ Serum alkaline phosphatase concentrations, which in the absence of functional liver damage are indicative of the degree of bone formation, are also elevated in subjects with thyrotoxicosis,^(31, 49) as opposed to the condition in myxedema. On the other hand, Lutwak⁽²⁴⁾ detected decreased serum phosphatase values in an individual suffering from myositis ossificans progressiva following treatment with T₃. Guyer⁽³²⁾ has reviewed the literature relative to observed human thyrotoxicosis in which normal serum alkaline phosphatase concentrations occur concomitant with hypercalcemia.

Effect of Thyroid Hormones on Calcium Metabolism in Experimental Animals

In small laboratory animals, haversian bone is virtually nonexistent. Hyperthyroidism, therefore, does not lead to active intracortical bone formation or resorption, and the appendicular skeleton is not decalcified.⁽⁵⁶⁾ Certain histologic and biochemical changes in mice and rats, however, parallel the human data and suggest alterations in mineral metabolism.

The ability of transplanted thyroid tissue to induce local osteoclastic resorption of mouse parietal bone *in situ** was reported by Chang.⁽⁵⁷⁾ Resorption *in vitro* is pronounced when cultures of mouse calvaria also contain fragments of human thyroid adenoma.⁽⁵⁸⁾ Silberberg and Silberberg⁽⁵⁹⁾ reported that T₄ accelerated resorption of metaphyseal bone in mice, and similar results were reported in rats treated with TETRAC.⁽⁶⁰⁾ While growing rats and mice made hypothyroid show lower resorption rates, replacement therapy with T₄ alone or with growth hormone⁽⁶¹⁾ can reestablish the normal rate of metaphyseal bone resorption or increase it above normal. Young, growing rats treated with thyroid hormones also exhibit high serum and urinary hydroxyproline concentrations.^(62, 63)

While there is strong evidence that thyroid hormone

* While thyroid hormone does not in itself cause osteoclast differentiation in bone, Doty and Talmage⁽⁶⁸⁾ suggest that it must be present in order for parathyroid hormone to exert its effect on these cells.

can induce bone resorption, the information about the effect of the hormone on bone formation is less clear. The high bone alkaline phosphatase concentrations detected in shaft and epiphysis of growing rats treated with T_4 ^(64, 65) suggest increased rates of osteoblastic bone formation. T_4 accelerates intramedullary bone matrix formation in birds.⁽⁶⁶⁾ However, Vaes and Nichols⁽⁶⁷⁾ reported that the incorporation of glycine, a collagen precursor, into rat metaphyseal bone *in vitro* was inhibited nearly 25% by high doses of DL- T_4 (10^{-4} M); the authors suggest that the metabolic changes are consistent with those expected to produce the osteoporosis of human thyrotoxicosis.

Finkelstein and Schachter⁽⁶⁸⁾ reported that T_4 decreased calcium transport across the gastrointestinal tract in intact or hypophysectomized (HPX) rats. Moukhtar and his coworkers,⁽⁶⁹⁾ on the other hand, found that T_4 had little effect on calcium (Ca^{45}) metabolism after HPX, but that growth hormone (GH) and T_4 given together could successfully replace a functional hypophysis with respect to calcium metabolism (pool size, bone formation and resorption rate). The synergistic effects of thyroid and pituitary GH on the normal development of bone at the histologic level have long been appreciated.^(61, 70-75)

Effect of Thyroid Hormones on Strontium Uptake and Retention in Bone

In view of the repeated clinical and experimental observations that thyroid hormones increase bone remodeling and calcium excretion (man), there have been remarkably few attempts to investigate the effect of the hormone on the deposition and retention of radiostrontium in bone. Hamilton⁽⁷⁶⁾ reported that the deposition of Sr^{89} and Sr^{90} in the bones of cretinoid rats was inhibited, but that pretreatment of these animals with GH alone or with T_4 (2 μ g/day for 8 days) increased the 48-hr skeletal uptake of strontium to control levels. Ogawa and his coworkers⁽⁷⁷⁾ recently found that the 72-hr skeletal (femur) uptake of Sr^{90} could be reduced nearly 20% by simultaneously administering pituitary thyroid stimulating hormone (TSH: 500 μ g/day), but the effect seemed to be the result of a high excretion rate, which apparently lowered the availability of the isotope to bone. Under the same experimental conditions, however, T_4 administration (50 μ g/day) had no significant effect upon either the urinary excretion of strontium or upon the retention of strontium in the femurs. The dose of T_4 used in Hamilton's study was within normal physiologic limits for rats⁽⁷⁸⁻⁸⁰⁾ and mice⁽⁸¹⁾ (1-2 μ g/day) and, therefore, might not have been expected to exert a very large effect on bone and calcium-strontium excretion. In view of the fact that TSH is said to elevate urinary hydroxyproline excretion

slightly (man)⁽⁸²⁾ and serum calcium concentrations (rabbits)⁽⁸³⁾ while these effects are pronounced after T_4 and T_3 treatment as noted previously, it is difficult to explain Ogawa's findings.

The studies cited above have tested the ability of thyroid hormones to remove radiostrontium at times early after administration, i.e., within 2-3 days. In the present experiments, we have used albino mice to test the effects of various thyroid preparations on the whole-body retention of radiostrontium at times long after administration, when the isotope was "bone-fixed."

METHOD

Young, 30-day-old, CF₁ albino mice each received a single i.p. injection of 1.5 μ Ci strontium-85 in 0.2 ml saline 15 days before hormone therapy was begun.

Whole-body counting of mice was begun on the 15th day after isotope administration. The animals were placed in perforated polyethylene centrifuge tubes mounted on a plastic disc which was recessed on its lower surface. The assembly was fitted over a 4" x 4" NaI crystal in a "cave" shielded by 6" of steel having a lead-cadmium-copper liner. The crystal was connected to a multichannel analyzer modified for use as a scaler. The whole-body counts obtained at 15 days were corrected for decay and were considered to represent 100% retention. Thereafter, each mouse served as his own control. Whole-body retention was measured at weekly intervals throughout the experiment, and the weight of each mouse was recorded at the time of counting.

Preliminary Experiments

Groups of 10 mice were injected intraperitoneally with L-thyroxine (T_4), L-triiodothyronine (T_3), tetraiodothyroacetic acid (TETRAC), and triiodothyroacetic acid (TRIAC). Each hormone was administered in daily doses of 10 μ g for 6 weeks. This dose is about 5 times the normal thyroid secretion rate for T_4 in mice,⁽⁸¹⁾ and, therefore, can be considered thyroid suppressive. Six weeks after the end of the treatment period, the injections were resumed at the same dose level for an additional 4 weeks. Mice which had been treated initially with the acetic acid analogues of thyroxine received either 10 μ g T_4 (TETRAC group) or T_3 (TRIAC group) during the second treatment period.

The mice were sacrificed 3 days after the end of the experiment by ether anaesthesia. At autopsy, the bones from the fore and hind limbs of all animals were recovered and fixed in either 95% alcohol or 10% neutral formalin. The soft tissues surrounding the femurs, tibiae, humeri and ulnae fixed in alcohol were removed; the bones were X-rayed, dried at 100°C for 16 hours,

FIG. 39. A plot of body weight vs. time in male CF₁ mice treated with daily doses of T₄, T₃, TETRAC, and TRIAC which shows that toxic effects were obtained only in animals treated with T₃. Mice originally treated with TETRAC and TRIAC were given T₄ and T₃ respectively from days 91–112.

ashed at 600°C, and weighed again to determine the ratio of dry to ash weight.

Dose Dependence Studies

The experimental protocol was identical to that of the preliminary studies. Groups of 10 mice were injected i.p. with 1.12 μCi Sr⁸⁵ two weeks prior to thyroid hormone treatment. L-T₄ was administered i.p. in doses of 5, 10, and 20 $\mu\text{g/day}$; L-T₃: 5 and 10 $\mu\text{g/day}$; TETRAC: 30 $\mu\text{g/day}$; TRIAC: 30 $\mu\text{g/day}$. The controls were not treated, and the experiment was terminated after 6 weeks. The whole-body retention of Sr⁸⁵ was measured at weekly intervals and compared to the controls.

RESULTS

Preliminary Experiments

Figure 39 shows the weight gain performance of the mice. Except for mice treated with T₃, the growth was

nearly identical with that of the controls. The dose of T₃ employed proved toxic, and some mice died during the initial 6-week period, but the growth of the survivors seemed normal during this period. The T₃ group thereafter lost weight, but it will be seen that the pattern of strontium retention was similar to that for T₄.

Table 28 gives the measurements of the long bones obtained from the X-rays. There were no significant differences between any of the groups, but the lengths of bones from the mice treated with T₃ were consistently low. No differences in the dry weight of the bones or in the ratio of ash weight to dry weight were observed (Table 28).

Effect of T₄ and T₃ on Strontium Retention

While the thyroid preparations did not affect bone growth, differences in whole-body retention of strontium were apparent. Compared to the controls (Figure 40) the retention of Sr⁸⁵ was reduced nearly 10% within 3–4 weeks after treatment with T₄ and T₃, and the

TABLE 28. EFFECT OF THYROID HORMONES AND THEIR ANALOGUES ON MOUSE BONE

Group	Femur			Tibia			Humerus			Ulna		
	L (cm)	DW ^(a) (g)	AW/DW ^(b)	L (cm)	EW (g)	AW/DW	L (cm)	DW (g)	AW/DW	L (cm)	DW (g)	AW/DW
Control	1.58	0.047	0.637	1.81	0.036	0.631	1.27	0.019	0.635	1.43	0.012	0.655
L-Thyroxine (T ₄)	1.62	0.048	0.645	1.89	0.038	0.619	1.28	0.023	0.616	1.48	0.011	0.620
L-Triiodothyronine (T ₃)	1.48	0.043	0.590	1.73	0.038	0.650	1.25	0.021	0.572	1.36	0.012	0.630
Triiodothyroacetic acid (TRIAC)	1.61	0.044	0.599	1.84	0.038	0.641	1.24	0.024	0.607	1.39	0.015	0.620
Tetraiodothyroacetic acid (TETRAC)	1.60	0.046	0.596	1.87	0.034	0.576	1.27	0.022	0.596	1.44	0.016	0.593

(a) DW = Dry weight.

(b) AW/DW = ratio of ash weight to dry weight.

differences were statistically significant ($p < 0.02$). The abilities of T₄ and T₃ to potentiate this loss of Sr⁸⁵ were equal.

It was desirable to see if this initial loss would be maintained. If, for instance, only short-term deposits had been removed, the curves might have converged with time. However, the differences were maintained during the second 6-week period of non-treatment. Resumption of treatment at the same dose level after 12 weeks failed to reduce further the Sr⁸⁵ body burdens.

FIG. 40. Comparison of whole body retention of Sr⁸⁵ given intraperitoneally to untreated male CF₁ mice with time and to mice treated with T₄ and T₃. The values have been corrected for the physical decay of the isotope.

FIG. 41. Comparison of whole body retention of Sr⁸⁵ given intraperitoneally to untreated male CF₁ mice with time and to mice treated with TETRAC and TRIAC. Mice originally treated with TETRAC and TRIAC were given T₄ and T₃ respectively during the final 4 weeks of the experiment. The values have been corrected for the physical decay of the isotope.

Effect of the Acetic Acid Analogues (TETRAC, TRIAC) on Strontium Retention

While the "native" hormones proved effective in reducing the long-term skeletal burdens of radiostrontium, the acetic acid analogues had no observable effect at the daily dose employed (10 μ g). Figure 41 shows that the Sr⁸⁵ retention in mice treated with

TABLE 29. THE EFFECT OF THYROID HORMONES ON BODY WEIGHT

Wks of treatment	Total weight gained (g)							
	Control	Thyroid hormones: $\mu\text{g/day}$						
		T_4			T_3		TET-RAC	TRIAC
		5	10	20	5	10	30	30
1	2.1	0.7	1.2	1.8	3.2	1.6	0.6	1.1
2	3.3	3.0	4.6	3.3	4.6	3.0	1.5	2.3
3	3.5	3.5	6.5	3.7	4.8	—	2.4	3.0
4	6.1	6.3	7.2	6.1	7.9	4.7	3.9	5.6
5	7.7	7.0	7.9	6.2	7.9	5.4	6.2	6.3
6	8.6	8.6	8.8	7.2	8.8	6.2	6.5	6.9

TETRAC or TRIAC was unaltered during the first 6-week treatment period. These animals were treated with T_4 (TETRAC group) and T_3 (TRIAC group) during the last 4 weeks of the experiment in view of the initial success with these hormones. No reduction in the body burdens occurred.

Because these preliminary studies suggested that thyroid hormones could exert an influence on radiostrontium retention in bone at times long after administration, it seemed important to determine the dose level which would be most effective and produce a protracted response.

DOSE DEPENDENCE STUDIES

Body Weight

Since the average weights of the mice in each of the groups at the time of thyroid therapy differed somewhat, the results in Table 29 are expressed in terms of the grams gained during the 6-week period of treat-

ment. The data show that weight gain was largely dependent on the dose of thyroid hormones employed. The average weight gain for the control mice was 8.6 g. Toxic effects of the hormones were noted after 5 weeks of treatment with 20 μg T_4 (mortality 40%) and 10 μg T_3 (mortality 10%); but these animals and those treated with TETRAC and TRIAC began to show a slower rate of weight gain after 3–4 weeks.

Strontium Retention

The whole-body retention of Sr^{85} was found to be somewhat related to the type and dose level of thyroid hormones. The data compiled in Table 30 suggest that treatment with T_4 and T_3 lowers the retention of Sr^{85} 10–12% compared with the controls after 2–3 weeks. Large doses of T_4 seemed to be slightly more effective than small doses, i.e., 20 μg > 10 μg > 5 μg , but the differences were not statistically significant (Fisher *t*-Test). The effect of T_3 , on the other hand, did not seem to be related to dose. The retention of Sr^{85} was also lowered 5% in 6 weeks by daily treatment with 30 μg TETRAC and TRIAC, and the hormones were equally effective. Data from the preliminary experiment with mice injected with 10 μg TETRAC and TRIAC have been included in Table 30 to show that the effect of TETRAC and TRIAC on Sr^{85} retention was dose dependent, but that a 3-fold increase in the daily dose was required to initiate loss of the radioisotope. Furthermore, the action of these acetic acid analogues of T_4 was much less effective and slower than T_4 and T_3 , and statistically significant effects only became apparent after a treatment period of 5 weeks.

DISCUSSION

These experiments suggest that thyroid hormones and their acetic acid analogues can remove long-term

TABLE 30. WHOLE-BODY RETENTION OF STRONTIUM-85^(a)

Wks of treatment	Thyroid hormones ($\mu\text{g/day}$)								
	T_4			T_3		TETRAC		TRIAC	
	5 μg	10 μg	20 μg	5 μg	10 μg	10 $\mu\text{g}^{(b)}$	30 μg	10 $\mu\text{g}^{(b)}$	30 μg
1	99.2	97.5	98.1	98.3	96.9	100.7	98.9	102.1	98.9
2	97.7 ^(c)	94.3 ^(c)	92.0 ^(c)	—	—	100.6	—	101.2	—
3	93.1	92.2	90.4	91.8 ^(c)	92.6 ^(c)	100.5	97.6	102.7	97.6
4	92.1	90.9	88.8	89.4	89.7	97.7	96.2	100.7	96.3
5	90.0	88.8	87.2	89.2	88.2	103.6	94.3 ^(c)	103.2	95.5 ^(c)
6	90.3	87.7	87.7	88.9	87.6	101.9	94.8	103.6	94.6

^(a) Values expressed as a percentage of control (100%).

^(b) Data taken from the preliminary experiment.

^(c) Earliest time at which values are significantly different (Fisher *t*-test) from the controls

$\begin{cases} T_4, T_3 < 0.001 \\ \text{TETRAC, TRIAC} < 0.02. \end{cases}$

"bone-bound" deposits of radiostrontium in mice. The amount of Sr^{85} actually removed in these studies was small (T_4 , T_3 = 10–12%; TETRAC, TRIAC = 5%), and the process seemed to be completed within 6 weeks of treatment. The maximum effect of T_4 and T_3 was independent of dose, in the range used, and occurred within 2–3 weeks—some 3 weeks earlier than that of TETRAC and TRIAC. In the preliminary studies, additional therapy continued beyond this time proved ineffective. In view of published findings cited previously, there is little question that thyroid hormones increase the activities of the cells involved in bone formation and resorption. In man, it appears that the magnitude of the induced changes may be the same.⁽²⁴⁾ That this may also be true in mice is indicated by the similarity of the values obtained for the dry weights of the bones. Accordingly, it seems reasonable to assume that the reduction of skeletal strontium is directly related to the relative abilities of the hormones to promote bone resorption and urinary clearance of calcium-strontium.

It is not known why the hormones uniformly failed to promote strontium removal beyond 4–5 weeks. One possibility is that the mice developed an early resistance to each of the dose levels employed.⁽⁸⁴⁾ However, the growth of the mice must also be considered. Mice have a short period of bone growth relative to their life-span. We did not confirm the findings of Silberberg and Silberberg⁽⁵⁹⁾ that T_4 administration leads to the early cessation of growth in mice. The time of most rapid growth (and epiphyseal maturation) corresponds most closely to the experimental periods before and during treatment when the hormones might have been expected to exert a strong effect on strontium retention. It is probable that in mice the resorptive mechanism responsible for removing radiostrontium is dependent upon the presence of an active population of osteoclasts competent to resorb bone and the apatite-bound isotope. With age, however, the formation of osteoclasts probably becomes reduced, and, at least in rats, thyroid hormones do not increase the formation of new osteoclasts from undifferentiated cells.⁽⁶³⁾ It is generally considered that the trabecular regions in the ends of the long bones and vertebrae have the highest rate of cellular activity and bone turnover, and that the trabeculae accrete higher concentrations of radiostrontium than the compact bone of the shaft. However, in the bones of the mice used in this study, most of the trabeculae originally present at the time of isotope administration were certain to have been resorbed during the 2-week pretreatment period. The new trabeculae formed during this time, therefore, would carry only a diffuse label. Presumably, then, cortical bone represented the structural "compartment" with relatively higher concentrations

(hot spots) of radiostrontium at the time the hormones were administered—but the cortex of mice does not contain many areas of active internal remodelling. There was no evidence from the X-rays of gross cortical bone demineralization. These circumstances seem to suggest that either thyroid hormones do not exert a very prolonged effect on Sr^{85} removal, or that the isotope had been removed completely from areas in the bone sensitive to these hormones.

Whatever the mechanism, there was no apparent relationship in these experiments between the ability of the mice to sustain normal body weight–bone growth increments with time and the efficacy of the hormones to diminish whole-body Sr^{85} retention. The only groups which failed to gain as much weight as the controls were those treated with toxic doses of the hormones, and high doses of TETRAC and TRIAC. The data on the relative potency of thyroid preparations on differential Sr^{85} retention does not confirm the observations of Swanson and Werff ten Bosch⁽⁸⁵⁾ who suggested that a single injection of T_4 advanced skeletal maturation in newborn female rats more than a single injection of T_3 . If this were true and unless there were a species difference, we might have expected a greater reduction of the Sr^{85} body burden after T_3 treatment. Other data on the relative potency of thyroid preparations on soft tissue metabolism, however, bear some relationship to the differential effect of T_4 , T_3 and TETRAC, TRIAC on strontium metabolism. The acetic acid analogues have a much smaller effect on goiter prevention,⁽⁸⁶⁾ and on oxygen consumption of tissues incubated *in vitro*^(87, 88) than T_3 and T_4 . TETRAC is also less effective than T_3 in alleviating certain of the clinical signs of myxedema in man,^(89, 90) and at least *in vivo* these compounds do not have a latent period of action. That TRIAC and TETRAC would have a small effect on strontium metabolism might have been predicted, since in man they exert a relatively weak response on fecal and urinary calcium excretion.⁽³⁵⁾

In general, these studies have shown that the rate of removal of "bone-bound" radiostrontium from mice can be maximally increased by nontoxic levels of thyroid hormones.

SUMMARY

Young growing CF_1 albino mice were injected with Sr^{85} . From the 15th day after isotope administration, the animals received daily doses of L-thyroxine (T_4 –5, 10, 20 μg), L-triiodothyronine (T_3 –5, 10 μg), tetraiodothyroacetic acid (TETRAC–10, 30 μg) or triiodothyroacetic acid (TRIAC–10, 30 μg) for a period of 6 weeks. In a preliminary study, groups of mice injected at the 10- μg level received no treatment for a second 6-week period, and were then injected with the same dose level for an

additional 4 weeks (total period, 16 weeks). The whole-body retention (WBR) of Sr^{85} , estimated at weekly intervals, was found to be related to the species and dose level of hormone administered. Treatment with T_4 and T_3 at all dose levels lowered the WBR of Sr^{85} 10–12%, and the effect was maximum after 3–4 weeks. The effects of TETRAC and TRIAC were markedly dose dependent; 10- μg levels of each hormone were ineffective, but 30 μg lowered the WBR 5% after 4–5 weeks. Toxic effects of the hormones were noted for T_4 (20 μg) and T_3 (10 μg). While the mechanism by which the thyroid hormones effect the reduction of the WBR of radiostrontium is not understood, it is certain that the isotope was almost entirely “bone-bound” when the hormone treatments were begun.

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AUTORADIOGRAPHIC INVESTIGATION OF COLLAGEN FORMATION AND ENDOCHONDRAL OSSIFICATION IN MICE AND THE EFFECT OF ESTROGEN*

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The ability of estrogen to stimulate endosteal bone formation in the skeleton of the mouse has been demonstrated many times since the original research of Gardner and Pfeiffer.⁽¹⁾ It is not known why this response to estrogen occurs, nor why it appears to be specific (among mammals) to mice.⁽²⁾ The reaction begins in the metaphyses of growing long bones and eventually extends along the entire shaft. Ultimately, if treatment is prolonged, the marrow elements may be completely displaced by the centripetal growth of bone trabeculae. Vaes and Nichols⁽³⁾ demonstrated *in vitro* that bone collagen formation, as measured by the uptake of radio-

glycine, was enhanced in estrogen-primed mice. Autoradiographic studies with tritiated thymidine⁽⁴⁾ in mice have shown that estrogen treatment increased the rate at which metaphyseal and endosteal osteoblasts were formed from undifferentiated reticular cells in the marrow. While, after estrogen treatment, the increase in osteoblast numbers may be adequate to explain the enhanced collagen synthesis observed *in vitro*, it is not known if the hormone increases the ability of the individual osteoblasts to form collagen. To resolve this question, further studies of bone formation in mice have been pursued by high resolution autoradiography following the administration of H³-proline and H³-glycine at different times after estrogen treatment.

MATERIALS AND METHODS

Male, CF₁ albino mice, 30 days of age, were injected with one subcutaneous dose of 1 mg estradiol valerate

* The preliminary experiments were performed during the tenure of a postdoctoral fellowship in the laboratory of Dr. Franklin C. McLean, Department of Physiology, University of Chicago, Chicago, Illinois, and were supported by the United States Public Health Services Grant No. A-4225 Met., the Atomic Energy Commission (At[11-1]-787) and by United States Public Health Research Fellowship DPD-12,985.

(Delestrogen*) to stimulate endosteal bone formation. The controls were not treated with estrogen. Tritiated proline ($1 \mu\text{Ci/g}$ body weight)† was administered intraperitoneally to 15 control and 15 estrogen-treated mice 24 hours after hormone treatment, and 3 animals from each series were sacrificed by decapitation thereafter at 1, 4, 8, 16, and 24 hours.

A second series of mice was injected subcutaneously with H^3 -glycine ($0.5 \mu\text{Ci/g}$ body weight)‡ on the seventh day after estrogen treatment when the endosteal bone reaction had been well established. Four untreated control mice and 4 estrogen-treated mice were sacrificed by decapitation 1, 2, 4, 12, and 24 hours after isotope administration. The times at which the labeled amino acids were administered were based on data⁽³⁾ which indicated (a) that the differentiation of osteoblasts from the precursor cell population was increased as early as 6 hours after estrogen treatment, and (b) that the population of metaphyseal osteoblasts capable of being flash labeled with tritiated-thymidine (DNA synthesis) was nearly doubled after 24 hours.

At autopsy, the femurs and tibias were removed, fixed in 10% neutral formalin, decalcified in 10% EDTA (pH 7.4) and embedded in paraffin. Serial longitudinal sections were cut on a rotary microtome at 7μ . Following deparaffinization, the slides were dipped in Kodak liquid nuclear emulsions NTB-2 (H^3 -proline study) or NTB-3 (H^3 -glycine study) according to the technique of Messier and Leblond.⁽⁶⁾ The slides were exposed in a freezer, developed, and routinely stained with hematoxylin and phloxine. Sections were also stained with PAS prior to autoradiography, and these were counterstained with hematoxylin following exposure and development.

RESULTS

In the controls, most of the metaphyseal (femur-distal; tibia-proximal) and endosteal cells labeled within the first hour after either radioproline or radioglycine administration were osteoblasts. Although proline is a more specific tracer for collagen formation than glycine, the disposition and relative intensity of the autoradiographic label from either amino acid at the same times after injection was identical. The grain counts over osteoblasts from 1–24 hours after injection of radioproline are presented in Table 31. Since Tonna⁽⁶⁾ reported peak labeling by H^3 -glycine within 30 minutes

TABLE 31. NUMBER OF GRAINS COUNTED PER METAPHYSEAL OSTEOBLAST^(a) AT DIFFERENT TIME PERIODS FOLLOWING H^3 -PROLINE ADMINISTRATION TO MICE

Time (hr)	Femur		Tibia	
	Control	Estrogen-treated	Control	Estrogen-treated
1	13.1 ± 3.4	15.3 ± 4.2	14.0 ± 4.0	16.1 ± 7.2
4	8.2 ± 4.0	9.7 ± 5.9	9.7 ± 3.2	9.9 ± 5.1
8	8.8 ± 3.7	6.2 ± 3.8	6.3 ± 2.7	6.9 ± 3.8
16	5.1 ± 1.9	4.9 ± 1.8	6.1 ± 2.9	5.4 ± 1.1
24	3.9 ± 1.1	5.4 ± 2.4	5.7 ± 2.1	4.6 ± 1.4

^(a) Mean $\pm$ S.D. of 50–75 cells counted.

after injection, the availability time of injected radioglycine and radioproline is probably of the order of minutes.

A greater proportion of the undifferentiated reticular cells was labeled by glycine than by the proline—probably because glycine is utilized by every cell as a substrate for intracellular protein and nucleic acid synthesis as well as for collagen synthesis by osteoblasts. Silver grains were also observed over a few young osteocytes which were being buried in the bone, but mature osteocytes were rarely labeled. Osteoclasts were only infrequently and lightly labeled. The presence of extracellular silver grains between the osteoblasts and the surfaces of bone trabeculae as early as 1 hour after injection indicates that these cells were utilizing the labeled amino acids for collagen formation. The reactive bands were about 2μ thick and probably represented a salt-soluble collagen fraction. The secretion of labeled amino acids from the cells was virtually complete by 16 hours after injection (Table 31) when autoradiographs showed reduced silver grains lying over the recently deposited surfaces of trabeculae. On some trabeculae at 24 hours, the bands of silver grains appeared to have moved further away from surfaces and were sealed off by younger unlabeled bone lamellae. These reactive bands of mature collagen were somewhat thicker at 24 hours (4μ) than the original surface deposits at 1 hour, no doubt because the osteoblasts had begun to utilize and secrete a greater proportion of unlabeled amino acids for collagen formation and the radioactive product had been progressively diluted.

It was also usual to find trabeculae delineated by surface grains and lined by labeled nonosteogenic spindle-shaped cells 16 to 24 hours after isotope administration. These are apparently resting surfaces which were growing at the time glycine and proline were administered. The lack of further growth and burial of the label can be attributed to a periodic modulation of the osteoblasts to undifferentiated reticular

* Delestrogen was generously supplied by Edward C. Reifstein, Jr., M.D., Squibb Institute, New Brunswick, N.J.

† L-Proline-3,4,- H^3 hydrochloride (Lot 64-191-3), New England Nuclear Corp., specific activity = 371 mCi/mmole.

‡ Glycine-1- C^{14} , New England Nuclear Corp., specific activity = 0.66 mCi/mmole.

FIG. 42. The graph compares the movement of the ossification front, away from the proximal epiphyseal cartilage of the tibia at times after labeling with H^3 -proline in control and estrogen-treated mice.

cells;⁽⁷⁾ osteoblastic activity along any trabecula is not continuous.

In estrogen-treated mice the endosteal reaction, expressed by large numbers of newly formed trabeculae in the distal metaphyses of the femurs, was established a week after eströgen treatment. However, while estrogen is known to stimulate osteoblast formation within 6 hours⁽³⁾ the serial autoradiographs of the bones exposed to radioproline (24 hours after injection) and radioglycine (7 days after injection) did not provide evidence that estrogen similarly altered the normal pattern of amino acid uptake of collagen formation by these newly formed osteogenic cells. Table 31 shows, for example, that the rate at which the cellular proline label was depleted and incorporated into collagen was identical in the control and estrogen-primed mice. Approximately 60% of the initial activity had been lost from the cells after 24 hours.

Because the labeled amino acids are rapidly fixed in the collagen of newly forming trabecular bone at the ossification front, the silver grains mark the position of the front at the time of injection. The distance the label moves away from the epiphyseal growth cartilages with time after injection reflects the rate of *endochondral ossification* which is, in part, a measure of the proliferative activity of the chondrocytes in the cartilages. The comparative displacement of the band of silver grains from radioproline in the bones from the control and

estrogen-primed mice during the 2nd day after hormone treatment has been plotted in Figure 42. The overall growth in length of the bones due to cell divisions in the cartilages of the knee joint was $135 \mu/\text{day}$ in the control and $66 \mu/\text{day}$ after estrogen treatment.

DISCUSSION

The choice of glycine and proline as tracers for collagen formation in autoradiographic and biochemical studies has been predicated on the knowledge that these amino acids are the largest contributors to the dry, ash-free collagen of bone.⁽⁸⁾ While molecular glycine and proline may be incorporated intact into the peptide linkage of collagen, a certain fraction of the available proline is first hydroxylated to yield collagen hydroxyproline.⁽⁹⁾ Although proline is the more specific tracer for collagen formation, the initial pattern of uptake and secretion of both amino acids in osteoblasts is quite similar.

These studies have again demonstrated that estrogen has the capacity to alter the microenvironmental conditions in bone and can promote endosteal bone formation. Quantitative studies with tritiated thymidine previously suggested that the hormone could stimulate the modulation of undifferentiated precursor cells to the osteoblast class.⁽³⁾ However, the hormone seemed not to have affected collagen formation by the individual osteogenic cells. The pattern of uptake of the labeled amino acids and the subsequent rate at which the label was moved out of the osteoblasts to bone surfaces was not altered by estrogen treatment. Moreover, the results obtained from the grain counts (H^3 -proline) were in good agreement with those described previously for normal mice injected with H^3 -glycine.⁽¹⁰⁾ Maximum labeling of cells was observed at 1 hour, and the label was found over the mature collagen lamellae of trabeculae 16–24 hours later. Estrogen, then, appears to stimulate only processes which influence cell differentiation and has no effect on collagen synthesis by mature osteoblasts. This difference in the response of mouse bone tissue to female sex hormone might have been predicted, for estrogen treatment had failed to reduce the time required for the self-burial of H^3 -thymidine-labeled osteoblasts in bone.⁽³⁾ It is evident that the amount of new bone formed in the shafts of mice treated with estrogen simply reflects a large population of competent osteoblasts. The effect of estrogen on bone formation in mice has variously been ascribed to some unspecified local insult to the primitive connective tissue cells of the marrow,⁽¹¹⁾ or, alternatively, to malnutrition (hypoxia) owing to the constriction of the arterial terminals in the metaphyses by connective tissue hyperplasia.⁽¹²⁾ Because Brooks and Lloyd⁽¹³⁾ failed to find any altered bone vascular supply in mice

following estrogen treatment, it is probable that the endosteal reaction does not reflect a change in the gross nutritional status of the bone.

Because it is well known that estrogen treatment impedes both cartilage cell mitosis and mucopolysaccharide formation,⁽¹⁴⁾ it would be reasonable to assume that the hormone exerted its primary action on some regulatory cell organelle. Recently, the electronmicrographic studies of Silberberg *et al.*⁽¹⁵⁾ demonstrated hypertrophy of the Golgi zone and accelerated organelle development in articular cartilage cells of mice as early as 2 hours after hormone treatment. These changes, which were maximum after 16 hours, were related to a disturbance of carbohydrate synthesis by these chondrocytes, i.e., decreased production of mucopolysaccharides, and delayed endochondral ossification. In the present study, the radioproline marker demonstrated that estrogen had suppressed endochondral ossification (longitudinal bone growth) 24 hours after treatment.

SUMMARY

The effect of estrogen on the rate of collagen synthesis and new bone formation in the mouse was investigated by high resolution autoradiographic methods. H³-proline and H³-glycine were administered on the first and seventh days, respectively, following estrogen treatment, and the mice were sacrificed at various intervals during the 24 hours following each tracer injection. The position of the radioproline label on metaphyseal trabeculae indicated that the control bones grew in length 135 μ /day, whereas the bones from mice injected with estrogen 24 hours previously grew only 66 μ /day. Grain counts indicated that (a) the uptake of the labeled amino acids by osteoblasts, and (b) the

subsequent transfer of the label with time after injection to surfaces of newly forming metaphyseal and endosteal bone was not affected by prior estrogen treatment. Silver grains were observed over the bone 16–24 hours after tracer administration. It was concluded that estrogen stimulates only the processes which promote the differentiation of osteoblasts in the bones of mice, and that the hormone has no effect on the functional capacity of individual osteoblasts to synthesize and form collagen.

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A PRELIMINARY STUDY OF GAMMA RAYS EMITTED BY THOROTRAST PATIENTS:

- a) Estimate of Effective Depth of Liver in Phantom
- b) Estimate of Gamma Ray Activity in the Lower Leg

H. A. May and L. D. Marinelli

INTRODUCTION

Four individuals who received injections of colloidal Th²³² and Th²²⁸ (Thorotrast) approximately 15 years ago have been examined in the whole-body counter. Initial injections for X-ray visualization of blood vessels of the cranial cavity were made at the Department of Radiology of a midwestern medical school. The evaluation of present body burden of these patients was undertaken in cooperation with that institution, in order to

evaluate the cost and feasibility of a full-scale epidemiological study.

SCOPE AND METHODS

The primary purpose of this investigation is to evaluate the relationship between radiation dose and biological damage over long periods of time. In this case, the organs receiving the greatest exposure are the liver and spleen, with lesser amounts being received by lymph

nodes, kidneys, bone marrow and (in cases of significant extravasation) injection site tissue. An accurate assessment of accumulated dose requires quantitative knowledge of the local metabolic behaviour of each of the radioactive daughter products during the initial period following injection as well as the steady-state or equilibrium distribution.

Direct gamma spectrometry of the whole body may contribute to an understanding of this latter period by contributing the following information:

- (1) Total body burden of Ac^{228} (MsTh 2), Pb^{212} (Th B), Bi^{212} (Th C), and Tl^{208} (Th C').
- (2) Lack of secular equilibrium between γ -ray emitters in the chain, presumably due to loss by recoil from the colloidal particle, with subsequent transport and elimination by normal body processes.
- (3) Extent of deposition within the skeleton (primarily, within the red bone marrow), or within a specific portion of same.⁽¹⁾
- (4) Further information on the relative distribution of activity among the vital organs or other soft tissues. Although the problems of scanning and directional detection at the γ -ray energies concerned appear difficult and have not been entirely resolved (*vide infra*), such effort should contribute results which are not otherwise available to direct experimental approach.

In this study, two large NaI crystals have been used simultaneously, maintained in a fixed position relative to the patient for the duration of each count. Pulses from each are fed to individual multichannel analyzers.

The first count is made with an 11.5" diameter by 4" thick crystal suspended over the patient, at a distance of 1 meter from the lower surface of the crystal to the supporting "bed". Since counts are made with the patient prone and supine, a flat bed is preferred, although if curved into an arc of 1-meter radius, a slightly more uniform response to activity along the length of the patient is obtained. However, since 90 to 95% of the activity is believed to be in the liver and spleen, the arc offers no overwhelming advantage.

The second count is obtained after lowering the crystal until it almost touches the patient; by this means a certain degree of discrimination may be obtained between gamma rays originating in the abdomen and the extremities. However, as the spectrum extends to 2.615 MeV, additional discrimination by means of collimation would involve great bulk and weight. A crystal-to-bed distance of 35 cm has been adopted as standard, although an occasional obese individual may necessitate a greater separation. A second crystal, 7" diameter by 3.5" thick, facing upward, is located beneath the bed, with a spacing of 2.5 cm from its upper

surface. The spectra from both crystals are accumulated simultaneously.*

Although the detection sensitivity is much greater at this spacing, it is also far more dependent upon the source volume and location within the body, and upon the amount of scattering and absorption from surrounding tissues. Can this limitation be overcome by making use of all the information contained in spectra from two detectors at a fixed separation? As a particularly simple possibility, the *in vivo* ratio of counting rates from the two detectors observed in a selected energy band might be utilized to give an indication of the "effective depth" of the source within the body, by reference to suitable phantom calibrations. Substantial independence of this ratio throughout the energy range would facilitate the estimate of depth. From a knowledge of the effective depth, an independent self-absorption correction of the total activity present may be made. Preliminary tests, in which point sources of ThO_2 in a 16-cm thick Presdwood phantom were used to calculate the position and activity of a phantom liver, gave results having acceptable accuracy.† (See Appendix I.)

COINCIDENCE TECHNIQUES

The decay scheme of Ac^{228} exhibits a number of cascade gamma rays, the principal pairs, with their relative intensities being⁽²⁾

278 keV	and	790 keV	(3)
328 keV		790 keV	(3)
408 keV		960 keV	(2)
460 keV		980 keV	(2.1)
460 keV		966 keV	(1.3)

In the decay of Tl^{208} , all lower-energy gamma rays are in coincidence with the 2.615-MeV line. The most intense of these are:

277 keV	(1)
511 keV	(25)
583 keV	(87)
860 keV	(12)

Thus it appears that operating the two detectors in

* Although two 11.5" x 4" crystals spaced symmetrically above and below the patient's midplane offer statistical advantages, budgetary limitations restricted us to the much less efficient procedures described here.

† Usefulness of the method in the present application appears to rest upon the accuracy with which these results can be extended to phantoms having a range of thickness compatible with that of the bodies they simulate. Likewise, the effect of variations among individual patients in size, shape, and location of the liver and spleen must be considered and evaluated. Computer matching and stripping of standard spectra by means of least squares techniques also appear to offer great possibilities and are under investigation.

FIG. 43. Block diagram: electronic circuitry in fast-slow coincidence.

coincidence may lead to less complex spectra and a resulting ease of interpretation. By gating only on pulses of 1.6 MeV or more, response is completely limited to the gamma rays of Tl^{208} . At lower gating energies, both Ac^{228} and Tl^{208} contribute to the spectrum, and by a judicious choice of the energy band employed for gating, response to Ac^{228} may be maximized. From such coincidence spectra, the determination of the *relative* amounts of the two daughters is considerably simplified.

We have demonstrated that coincidence rates from typical Thorotrast patients in the geometry described above permit accumulation of statistically-significant data in counting periods of forty to sixty minutes. The electronic connections employed are indicated in the block diagram of Figure 43. Gating requirements are established by a conventional fast-slow coincidence system.⁽³⁾ Pulses from both detectors are double-delay-line shaped and fed to zero-crossing detectors. A fast coincidence resolving time of roughly 80 nanoseconds is used. By carefully equalizing delays, much shorter times may be used without significantly reducing the real coincidence rate. However, chance coincidence background is always negligible, and this resolving time adequately allows for less-than-optimum delay adjustments, or minor gain changes. Pulses from the 7" x 3.5" crystal are energy-selected and, after slow coincidence, are employed to gate the analyzer which stores pulses from the large detector. The same gate supplied to the second analyzer serves to monitor the energy band selected by the single-channel analyzer and is only neces-

sary during initial adjustment. We have found the single-channel analyzer to be remarkably stable over periods of months, during which it has been repeatedly turned off when not in use. Simultaneous recording of both the straight and coincidence spectra, or of two spectra gated by different energy regions, would undoubtedly make better use of the counting time. We have not yet tried this, largely from a desire to keep all of the data from each detector associated with its own analyzer. Results obtained so far suggest that the coincident rate depends upon source-to-detector orientation much more strongly than in the noncoincidence mode. Analysis of these data, together with phantom measurements to determine the dependence upon patient size and isotope distribution, is incomplete; hence, interpretation of the results must be deferred.

Evaluation of the skeletal burden located primarily, but not entirely, in the marrow, is also desired. Since the principal marrow sites, i.e., the sternum, vertebrae, and pelvic crests, are located in rather close proximity to the much more active deposits in liver and spleen, direct counting is out of the question. A method of detecting the lesser amounts of activity within the tibia and fibula has been investigated. The geometry employed is illustrated in Figure 44. Sensitivity to gamma rays from the soft tissue deposits is greatly reduced by coincidence requirements* and by a relatively modest amount of shielding below the patient's knees. With the

* In this case, as is well known, the counting rate is proportional to the product of the solid angles subtended by the source at the two detectors.

FIG. 44. Relative position of patient, detectors and shielding, as employed for leg counting.

two crystal faces spaced 14 cm apart, centered roughly between the distal surface of the patella and the external malleolus and with 5 cm of lead shielding as indicated, the following background counting rates are typically recorded by the upper crystal:*

- (a) no patient, 14 cpm
- (b) with thorium-free patient, 15 cpm
- (c) as in (b) plus 25-cc bottle of Thorotrast placed alternately at the lower tip of the sternum and small of the back, to simulate a typical deposit within the soft tissues only, 16.5 cpm.

RESULTS

Data from the 11.5" x 4" crystal were accumulated on a 512-channel Nuclear Data analyzer, those from the 7" x 3.5" on a 400-channel RIDL instrument. Data output were punched on paper tape which was processed initially with a CDC 160A computer. For some processing requiring greater core memory capacity (spectrum normalization and fitting, digital plotting via Cal Comp plotter, etc.), the data are transferred via magnetic tape to the CDC 3600.

The raw data from Thorotrast patients have been corrected for estimated potassium and cesium burdens by subtraction of the spectrum obtained from a Thorotrast-free individual of comparable height and weight.

* In the energy region 200 keV-2.8 MeV, and in coincidence with gamma rays detected by the lower crystal between 485 keV and 2.92 MeV.

Table 32 lists net counting rates observed in selected energy bands for the four patients studied. Typical backgrounds are also included. Estimates of activity in the lower leg and feet are given in Appendix II.

Special thanks are due to Dr. W. B. Swanson and Dr. F. J. Hodges of the University Medical Center in Ann Arbor, Michigan for making the patients available for this study and supplying essential information relevant to this investigation. Mr. Paul Hess contributed to the design and construction of phantoms and in the taking and reduction of data.

APPENDIX I

INTRODUCTION

A method of correcting whole-body counting data for the effects of self-absorption loss has been investigated, which is applicable when it is known *a priori* that the activity to be measured is concentrated in a specific region or organ. The immediate application to the case of liver deposits in Thorotrast-injected patients has already been mentioned, and the discussion will deal with techniques adapted to this specific end, although the general method is believed to have greater usefulness.

It is desired to determine the amount of gamma-emitting element located in an organ whose position within the body, and whose size and shape, are known only roughly. Two crystal detectors are employed, lo-

cated on opposite sides of the body and separated by a fixed distance, so positioned that the line joining them and coinciding with their axes also intersects the center of the region of interest. The two detectors should subtend nearly equal solid angles.

On the basis of preliminary measurements, it appears that the *ratio* of counting rates in the two detectors, in a given energy band, uniquely determines the location of an effective "center of activity" of the unknown source along the axis as established above. The location, i.e., the distance from either detector (or any other fixed reference point) to the center of activity may be evaluated by reference to calibration data obtained with a suitable phantom, in which the location of a point source of the same radionuclide is systematically varied. Since the intensity of the calibrating source may also be known with precision, the same calibration may be used to estimate the amount of activity present in the unknown.

EXPERIMENTAL PROCEDURE

The point source employed was a 25-cc glass bottle of the type used for packaging Thorotrast. It has been observed that the dextrin buffering of the colloidal Thorotrast fails after extended storage time, permitting clumping of the material and consequent nonuniform distribution within the bottle; therefore, a measured amount of ThO_2 powder was uniformly distributed within the source bottle in agar medium. The phantom consisted of $\frac{1}{4}$ " thick Presdwood sheets, 20 x 24 cm in size. Twenty-five of these provided a phantom thickness of 16 cm. Counts from both detectors at a separation of 37 cm were accumulated for 20 min at each of 15 source locations, spanning the entire range of phantom thickness. A plot of R_i versus position in the phantom was obtained, where R_i is the ratio of counting rate in the $11.5'' \times 4''$ crystal to that in the $7'' \times 3.5''$ crystal, in the i th energy band. The five energy regions employed were those of Table 32, namely:

- 1, 200–430 keV
- 2, 430–700 keV
- 3, 0.83–1.10 MeV
- 4, 1.45–1.75 MeV
- 5, 2.4–2.8 MeV.

R values were observed ranging from about 3.0 at a distance of 2.5 cm below the upper surface of the phantom (19 cm from the face of the $11.5'' \times 4''$ crystal) to 0.25 at the other extreme of the phantom, 13.5 cm below the upper surface. A small but consistent variation of the ratio with energy was observed at fixed source position.

The unknown employed was a ThO_2 -loaded "liver" molded of Mix D⁽⁴⁾—a paraffin-polyethylene mixture

TABLE 32. NET COUNTING RATES OBSERVED IN SELECTED ENERGY BANDS FOR THE FOUR PATIENTS STUDIED

Patient data						
Patient	Weight (lbs)	Height	Age (yrs)	Date injected	Amt. injected (cc)	
JJ	185	5'10"	43	1949	30	
MM	105	5'	62	1949	28 (?)	
RP	180	5'10	49	1949	30	
HR	186	5'11"	62	1952	60	

Net counting rate (cpm)						
Patient	Energy band					
	200 – 430 keV	430 – 700 keV	0.830 – 1.1 MeV	1.45 – 1.75 MeV	2.4 – 2.8 MeV	Total
At 1 meter, 11½" x 4" crystal						
JJ ^(a)	7,074	948	567	130	172	19,158
MM	1,465	621	379	65	116	5,680
RP	1,255	507	306	80	96	4,351
HR	4,680	1,957	1,134	242	358	16,332
Bkgnd ^(b)	568	362	127	113	24	2,114

At 35 cm, 11½" x 4" crystal						
JJ	41,426	6,274	4,056	1,082	1,182	118,830
MM	10,200	4,527	3,051	597	829	38,582
RP	10,472	4,747	2,920	660	861	37,405
HR	30,350	13,356	8,063	1,740	2,476	108,500
Bkgnd	1,005	781	190	223	24	3,700

At 10 cm, 7" x 3½" crystal (under table)						
JJ ^(a)	33,150	3,430	1,977	432	477	104,460
MM	6,911	2,908	1,797	354	359	25,494
RP	4,227	1,823	1,034	234	258	16,992
HR	13,770	6,039	3,108	736	904	54,847
Bkgnd	391	295	76	44	5.4	1,620

At 35 cm, 11½" x 4" crystal in coincidence						
JJ	42.7	20.6	4.95	1.5	6.5	104
MM	62	44	5.8	1.5	8.9	135
RP	33	28	4.2	0.75	4.8	79
HR	97	81	12	4.0	13	229
Bkgnd	2.2	2.5	1	0.5	0.4	8

In special "shin-counting" geometry, 11½" x 4" crystal in coincidence						
JJ	8.7	10	1.4	0.6	2.1	25.3
MM	7.1	7.2	0.8	0.6	1.7	20
RP	5.1	5.8	0.55	0	1.5	14.3
HR	14.0	12.6	1.6	0.6	2.8	35.5
Bkgnd	3.7	4.05	1.5	0.77	0.58	15.0

^(a) Patient had received ≈ 1 mCi Hg^{197} for brain scan approximately 4 months previous to count. The numbers in Cols. 1 and 6 reflect the residual burden, apparently concentrated in kidneys.

^(b) All the background data in Table 32 were obtained by counting an average adult, and thus include a normal, or typical, contribution from K^{40} and Cs^{137} .

TABLE 33. SUMMARY OF RESULTS ON SMALL (850 G) LIVER CONTAINING 0.98 G ThO_2

Depth to center line of paraffin	5.1	8.0	11.1
Mean ratio (net cpm $[11.5 \times 4]/$ net cpm $[7 \times 3.5])$	2.73	1.54	0.739
Calculated "point equivalent depth" (cm)	3.83 ± 0.06	6.8 ± 0.1	9.2 ± 0.2
Difference, geometrical center line to "point equivalent depth" (cm)	1.3	1.2	1.9
Calculated activity ThO_2 (g)	0.929 ± 0.011	0.93 ± 0.02	0.894 ± 0.04

All errors are one standard deviation.

with small quantities of magnesium and titanium oxides added to match more nearly the effective Z of water or tissue. It has been shown⁽⁶⁾ that this material is very closely water-equivalent in the energy range of interest. The "liver" dimensions were roughly 21 x 17 x 7 cm; its mass of 850 g was somewhat less than that of a normal adult male. An outer layer of epoxy plastic approximately 1 mm in thickness was applied to avoid surface damage and loss of radioactivity, and it was then embedded in a rectangular block of plain paraffin in order to facilitate reproducible positioning within the Presdwood phantom. Additional Presdwood sheets having a large rectangular cut-out to accommodate the paraffin block were utilized.

Data were taken with the "unknown liver," containing 0.98 g ThO_2 , at three depths within the phantom. All numbers were corrected for background, and the net counting-rate ratios converted to "effective point-equivalent depths." These calculated depths, which are remarkably consistent over the range of energies employed, differ from the reference distance as measured to the midplane by a nearly constant amount. The activity of the unknown was then calculated from the observed counting rate of the reference point source when located at the same depth. In practice, linear interpolation from the nearest calibration depths was employed to estimate this counting rate. The results so obtained are shown in Table 33.

Calibration and "unknown" counts were also made in the coincidence mode, but analysis of these data has not been completed.

CONCLUSION

While these measurements do not cover a sufficiently large range of conditions to be conclusive, the agreement (of the order of 5%) between the amount of ac-

tivity known to have been incorporated into the "unknown" and that calculated, as well as the consistency in depth localization, is reassuring. It suggests that calibration data utilizing a small source may be used to estimate the position and intensity of a larger, irregularly-shaped radioactive body. The use of a small, regularly-shaped source is usually more convenient from a physical standpoint, and insures that its "effective center" and geometric center coincide, i.e., that it behaves like an idealized point source.

The uncertainties introduced by lateral displacement of the "unknown liver" in the phantom were evaluated roughly, and do not appear to be significant for displacements of 4 to 6 cm at the spacing employed. In human counting, greater uncertainties may perhaps exist if the measurements are made by individuals without the requisite knowledge of normal variations in anatomy among individuals and the ability to determine organ position and orientation by palpation, auscultation or other methods of physical examination. It would seem that this limitation is not fundamental. It should be noted that radiographs were available of the Thorotrast patients counted, which revealed the spleen quite well but did not prove of great value in demonstrating the liver.

APPENDIX II

Calibration of the counting data in coincidence over the shins was accomplished by means of a leg phantom containing a known amount of ThO_2 . A length of 4-mm OD Tygon tubing was loaded with the radioactive material and inserted into a hole drilled through the long axis of a human tibia. The ends were sealed with epoxy. The tibia and matching fibula were then inserted into a hollow plastic manikin leg of the type sold for the display of nylon hosiery, care being taken to approximate their anatomically-correct location. The leg was filled with water, retained by a Lucite end-plate and filling plug at the knee. Counts were made with this phantom placed in the standard human shin counting geometry, illustrated in Figure 44.

The amount of Tl^{208} , principal contributor to coincidence events, which was actually present in the phantom, was then determined from an estimate of the degree of equilibration of the ThO_2 powder used. This was determined by comparison of the gamma spectrum and relative decay rate with that from an old bottle of Thorotrast, having an expiration date of 1937 and hence at least 95% equilibrated.

The leg burdens of the four individuals listed in Table 32, as corrected for lack of equilibrium of injected material (and assuming primary separation to have taken place three years prior to injection date) are as follows:

MM	0.04 g ThO ₂ in equilibrium
HR	0.07 " " "
RP	0.03 " " "
JJ	0.05 " " "

By assuming that the portion of the skeleton viewed by our setup equals 18%,⁽⁶⁾ and by assuming that the whole-body $\text{TI}^{208}/\text{Th}^{232} = 0.4$ as before, we can calculate the skeletal content as:

MM	0.22 g $\simeq$ 14 % of TI^{208} body burden $\simeq$ 5.6 % of Th^{232}
HR	0.39 g $\simeq$ 8 % of TI^{208} body burden $\simeq$ 3.2 % of Th^{232}
RP	0.17 g $\simeq$ 12 % of TI^{208} body burden $\simeq$ 4.8 % of Th^{232}
JJ	0.28 g $\simeq$ 16.5 % of TI^{208} body burden $\simeq$ 6.6 % of Th^{232} .

Considering the preliminary character of these measurements, we find these figures in fair accord with measurement of skeletal samples containing marrow.⁽⁷⁾

GAMMA-RAY BACKGROUNDS IN THE RPY VAULT: STABILITY AND RADON DEPENDENCE

J. B. Corcoran and F. Markun

The RPY low-level gamma ray counting facility (called the "vault") has been previously described.⁽¹⁾ It includes an iron room and other shielding devices in an underground chamber and features a controlled supply of essentially radon-free air.⁽²⁾ This report describes a series of measurements to determine gamma-ray background stability in the vault under normal operating conditions and to assess the contribution radon makes to the background.

EQUIPMENT CONFIGURATION

Equipment consisted of two NaI (TI) scintillation crystals positioned in the approximate center of the Iron Room. The smaller crystal (7" x 3" crystal) is 7 inches in diameter and 3 inches thick with a single 5-inch quartz photomultiplier tube. This crystal assembly has a very low intrinsic background with spectral details barely visible. The larger crystal (11" x 4" crystal) is 11½ inches in diameter and 4 inches thick. It has seven 3-inch glass photomultiplier tubes which contribute about 20% of the background and evidence themselves by considerable spectral detail.

It should be noted that a nonnegligible portion of the counts observed in coincidence may originate, in fact, from the $\text{Ac}^{228}\text{-Th}^{228}$ decay. The extent of this contribution, relative to the $\text{TI}^{208}\text{-Pb}^{208}$ must differ for the *in vivo* and *in vitro* cases. The above data have not been corrected for this.

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The two crystals were hooked up to entirely independent electronic systems. The 11" x 4" was connected to a Nuclear Data 512-channel analyzer and the 7" x 3", a RIDL 400-channel analyzer. Individual high-voltage supplies and pre-amplifiers were also used. The two analyzers were run concurrently on 40-minute auto-repeat cycles. Daily adjustments kept the synchronization drift to less than a maximum of two minutes.

BACKGROUND STABILITY

Under normal vault conditions background stability was established by a series of 55 runs starting May 1, 1965, and extending through May 3. The radon-removal system was operating normally, maintaining the vault radon level at 0.018 ± 0.006 pCi/l. The punched paper tape output from the analyzers was processed on the CDC 160-A computer by the 1839/RPY data processing system⁽³⁾ which reduced the data to counts per minute and summed the counts in nine energy bands. The sums were output from the 160-A on punched cards which were used as input to the CDC 3600 com-

FIG. 45. Background stability study, 7" x 3" crystal, 0.1-1.0 MeV

FIG. 47. Background stability study, 7" x 3" crystal, 2.0-3.0 MeV

FIG. 48. Background radon, 7" x 3" crystal, 0.1-1.0 MeV

puter, which did the statistical computations and graphic presentations. Figures 45 through 53 are prints of the 35-mm film records of the DD-80 cathode-ray tube display unit of the CDC 3600.

Figures 45-47 and 51-53 are plots of the background

count rates for each crystal during this series of runs. Each point is the sum of the channels over the specified energy band. The number to the left of the plot is the mean value in counts per minute for the set. The vertical scale increments of the plot are in terms of standard

FIG. 49. Background radon, 7" x 3" crystal, 1.0-2.0 MeV

deviations of the set, the value of which is given by θ on the plot.

RADON CALIBRATION

Radon calibration consisted of determining the crystal count rates in the presence of known concentrations of radon. Figures 48-50 and 54-56 show this

relationship. At 1 p.m. on May 3, 1965, as shown on the plot, the radon-removal system was shut off and left off until noon of May 5. The radon level in the presence of the crystals was monitored by means of air samples drawn through a copper tube which ran from inside of the Iron Room to a radon testing station outside of the vault counting area. The radon concentra-

FIG. 50. Background radon, 7" x 3" crystal, 2.0-3.0 MeV

tion was determined by adsorption on cooled charcoal followed by counting on the alpha-scintillation counter described by Lucas.^(4, 5) The triangles on the plots are the radon levels measured and refer to the calibration scale at the right hand edges of the plots. The units are picocuries of radon per liter of air. The scale factors to the left again pertain to background measurements

with MU being the mean value of the corresponding set under normal operating conditions and the increments being in terms of the standard deviation for the normal operating condition set.

The plots illustrate that the increase in count rate of the crystals is linear with respect to radon concentration. This becomes evident as soon as the gamma-ray

FIG. 51. Background stability study, 11" x 4" crystal, 0.1-1.0 MeV

FIG. 52. Background stability study, 11" x 4" crystal, 1.0-2.0 MeV

FIG. 53. Background stability study, 11" x 4" crystal, 2.0-3.0 MeV

FIG. 54. Background radon, 11" x 4" crystal, 0.1-1.0 MeV

contribution from the radon becomes statistically significant.

Table 34 summarizes the data shown on the plots. The mean and standard deviation values are for normal operating conditions and are taken from Figures 45-47 and 51-53. The values in the column labeled Radon are taken from Figures 48-50 and 54-56 and are the count

rates from a concentration of 1 picocurie of radon per liter of air. The Radon Normalized column is obtained by dividing the radon count rate by the total surface area of the crystal. The BKG % S.D. column is the standard deviation divided by the mean. The BKG % Radon column is the count rate from the concentration of radon equal to one-half the control limits (which, as

FIG. 55. Background radon, 11" x 4" crystal, 1.0-2.0 MeV

FIG. 56. Background radon, 11" x 4" crystal, 2.0-3.0 MeV

TABLE 34

Energy span (Mev)		Mean (c/m)	S.D. ($\pm$ c/m)	Radon (c/m/ pCi/l.)	Radon nor- malized (c/m/ pCi/l/ in ²)	Δ BKG (% S.D.)	Δ BKG (% radon)
7" x 3" Crystal							
0.100	0.400	154.27	2.03	40.2	0.281	1.3	0.16
0.400	0.700	90.35	1.72	17.2	0.120	1.9	0.11
0.700	1.000	49.79	1.03	6.7	0.0468	2.1	0.08
1.000	1.300	27.09	0.79	5.6	0.0391	2.9	0.12
1.300	1.600	18.15	0.72	3.6	0.0251	4.0	0.12
1.600	2.000	11.72	0.48	3.4	0.0237	4.1	0.17
2.000	3.000	16.69	0.59	1.5	0.0105	3.5	0.05
0.100	3.000	368.04	3.20	72.0	0.503	0.9	0.12
1.200	1.400	12.92	0.54	3.8	0.0265	4.2	0.18
11" x 4" Crystal							
0.100	0.400	559.51	4.00	88.0	0.249	0.7	0.094
0.400	0.700	273.69	2.31	34.6	0.0980	0.8	0.076
0.700	1.000	143.10	1.86	14.8	0.0419	1.3	0.062
1.000	1.300	94.67	1.63	16.3	0.0462	1.7	0.10
1.300	1.600	134.44	1.71	8.5	0.0241	1.3	0.038
1.600	2.000	45.67	1.10	8.8	0.0249	2.4	0.12
2.000	3.000	55.31	1.12	3.3	0.0094	2.0	0.036
0.100	3.000	1,306.74	6.57	164.0	0.465	0.5	0.075
1.200	1.400	60.28	1.38	9.6	0.0272	2.3	0.096

mentioned earlier in this report, is 0.006 pCi/l) divided by the mean.

CONCLUSIONS

The Radon Normalized column of Table 34 agrees substantially for both crystals used in this series. This calibration should be valid as a rough estimate for any crystal of comparable size and shape in an iron room of approximately 8 cubic meters inside volume. The BKG % Radon column shows that the normal operating con-

ditions in the vault maintain the contribution of radon to less than 10 % of the observed background fluctuations. The seemingly greater stability of the 11" x 4" crystal is probably due primarily to the constant bias contributed by the considerable activity in the seven photomultiplier tubes.

If the implications of the Radon Normalized column are extended to an iron room subject to the radon excursions of normal environmental air, the radon contribution becomes appreciable. Moses, *et al.*⁽⁴⁾ show that normal atmospheric changes, as well as diurnal and seasonal variations, can cause a range of radon concentrations from less than 0.1 to considerably more than 1.0 pCi/l. In terms of crystal backgrounds this means an influence of as much as 20 or 30 per cent, depending (inversely) on the cleanliness of the crystal.

While background fluctuations due to radon may not be as sporadic as those due to Ar⁴¹ and certain other conditions, radon must be considered where background rates over extended periods of time are used.

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MULTICHANNEL ANALYZER DATA PROCESSING

J. B. Corcoran

The data processing system for multichannel analyzer data has been expanded by the addition of CHANALYZ, a program written for the CDC 3600 computer. This program takes over where the 1839/RPY⁽¹⁾ system leaves off. The 1839/RPY system for the CDC 160-A computer reads the punched paper tape output from the analyzers, allows limited arithmetical operations, prints out the data, and, optionally, writes it on mag-

netic tape which becomes the input medium to CHANALYZ.

CHANALYZ is organized into four principal sections: (1) *control* which reads and interprets punched cards to select options and enter parameters; (2) *input* which includes a number of routines to accommodate the various types of analyzers; (3) *operations*; and (4) *output*.

The operations section consists of a string of optional operations arranged in modular form. The string is designed to be expanded as needs arise. At present the operation modules include a variety of arithmetical, editing, spectrum stripping, scaling, and normalizing routines. To be added in the near future are gain-adjusting and least-squares options.

After each operation module, any or all of the following output options may be exercised: (1) printout of data channel by channel, (2) summation and printout of any number of subgroups of channels, (3) paper and ink plot of the data on the Cal-comp plotter,* and (4) a

* Calcomp Model 580 plotting system.

35-mm film record of the data displayed on the CRT display system† attached to the CDC 3600. The graphic outputs (3) and (4) may be of any selected band of channels, with either linear or logarithmic vertical scaling, and may be single-spectrum plots, multispectrum overlays, or overlays of any of the operation module stages.

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† Data Display DD80A cathode-ray tube display system.

A MULTITUBE PREAMPLIFIER SYSTEM

J. B. Corcoran, Dale Suddeth, and O. J. Steingraber*

One of the difficulties associated with large, multitube scintillation crystals has been the balancing and checking of the individual photomultiplier tubes. The system described here was designed to allow quick and frequent

* Electronics Division.

calibration checks without switching the high voltage supply off and on, or disturbing any of the equilibrium conditions of the over-all system.

The crystal is a Harshaw Chemical Company 11½" x 4" NaI(Tl) crystal with seven RCA debased phototubes

FIG. 57. Crystal assembly

FIG. 58. Details of preamplifier system

(Figure 57). The voltage divider string is soldered directly to the tube leads. The assembly as purchased from Harshaw included gain and focus pots, a signal, and high-voltage BNC connectors. For our purposes, we rough balanced the individual tubes using the Harshaw assembly, then replaced the pots with fixed resistors, and wired the tubes directly to the circuit board shown in Figure 58. The board contains an individual preamplifier for each phototube and an adder. The output from each preamplifier goes through a switch and a trim pot into an operational amplifier which allows individual gain adjustment and provides linear summing

of the signals. Figure 59 is the schematic diagram for this circuitry.

The upper surface of the circuit board is a ground plane, which is the usual practice of the Electronics Division in designing low-signal-level circuitry. The preamplifiers are the voltage-sensitive type and utilize field-effect transistors at their front end to provide low input capacity, high input resistance, and low noise level.

The cost of this type of preamplifier assembly is not incommensurate with the cost of the crystal, and it provides considerable calibration advantages over the conventional arrangement.

FIG. 59. Preamplifier schematic

RADAR DETECTION OF AN IONIZED COLUMN IN THE LOWER ATMOSPHERE

Harry Moses, S. L. Halverson,* Jacob Kastner, T. V. Banfield,† G. E. Stout,‡ and E. A. Mueller‡

I. INTRODUCTION

On April 30, 1965, at the Argonne Meteorological Field Site, an ionized atmospheric column produced by gamma rays emanating above a vertically pointed reactor fuel rod was observed by radar. A rather thorough literature search and discussions with outstanding radar meteorologists indicate that this is perhaps the first time such an experiment has been successful. The work was carried out through a cooperative effort between the Argonne National Laboratory and the Illinois State Water Survey.

This experiment is important because it indicates the possibility of obtaining wind velocity measurements to hundreds or thousands of feet above the ground once every few seconds. At the present time, no practical method for doing this exists.

An ionizing source and a radar set may be used to measure wind in the following way: A gamma-ray pulse from a radioactive source or an X-ray pulse marks the air column above by ionizing it. The marked column is then tracked by radar. By measuring the displacement of this column over a short time interval, the wind velocity is determined, since it is valid to assume that the ionized or marked column moves with the wind.

Information can be provided by a radar-gamma ray system which would be of particular importance to pilots landing jet aircraft, especially for the elimination of missed approaches. Automatic landing systems, currently being evaluated, will handle wind shears from 4 to 6 knots in headwind and/or crosswind components per hundred feet. § In the approach zone, wind-shear information is essential wherever the above design criteria are exceeded. This occurs from time to time in the low-level jet which appears principally in an area bounded by San Antonio, Omaha, Pittsburgh and Tallahassee, during thunderstorms, and during severe meteorological conditions. A gamma ray-radar system may also be used for determining the ventilation rate over a city or an industrial complex in connection with air pollution problems. To determine this, a number of ionizing sources would be located at suitable points and a single radar system would scan the ionized columns. Thus, nearly simultaneous wind profile measurements would be obtained at the selected locations.

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† Reactor Operations Division.

‡ Illinois State Water Survey, Urbana, Illinois.

§ Personal communication from Dr. George P. Cressman, Director U. S. Weather Bureau.

II. THE RADAR SYSTEMS

Two X-band radars, a modified AN/APS-4 and an AN/MPQ-33, the latter provided by the Illinois State Water Survey, were used to observe the ionized column of air during the test. The relative positions of the radar sets and the ionized column are shown in Figure 60. Each radar observed the column independently. The distance from the AN/MPQ-33 radar antenna to the ionized column was approximately 1,345 ft, while the distances from the AN/APS-4 transmitting and receiving antennas were 435 ft and 428 ft, respectively.

The AN/APS-4 radar used in the test was modified to permit operation in a non-duplexed mode, i.e., the transmitter and receiver were provided with separate antennas. This eliminated the need to blank the receiver during transmission and thus permitted operation at extremely close ranges. Initially, it was believed that the observed phenomenon would be weak, thus making it necessary to reduce the microwave propagation path length to increase the probability of observing the ionized column. The AN/APS-4 was, therefore, operated at close range.

The electrical characteristics of the AN/APS-4 radar are shown in Table 35. This table also includes, for comparative purposes, the characteristics of the AN/MPQ-33 radar.

The transmitting and receiving antennas of the AN/APS-4 were of the parabolic dish type with gains of 31 dB and 27 dB, respectively. The antennas were mounted on tripods and positioned manually. Radio-frequency absorbing material was placed in the direct geometric ray path between transmitter and receiver to reduce extraneous coupling to levels below the noise threshold of the receiver (-65 dBm). Hence, the coupling radiation was restricted to a path from the transmitter to the ionized column and thence to the receiver.

The AN/MPQ-33 radar is a much more sophisticated and versatile instrument than the AN/APS-4. However, because of the receiver recovery time restriction, a minimum range length of 200 meters (≈ 656 ft) was required. The range length of 1,345 ft finally selected was determined by the choice of a convenient unobstructed path between the radar and ionized column. The radar van also required a firm supporting foundation. The range length was not critical, since the observed signal from the ionized column was strong.

FIG. 60. Radar-ionized column test site

III. THE IONIZING SOURCE

A fuel element from the Argonne CP-5 reactor was used as the ionizing source for this experiment. This fuel element experienced operation at about 4.5 MW reactor power for 270 days followed by 12 days of decay after shutdown. The relative abundance of gamma-ray energy within seven subgroups is given in Table 36 for pertinent times after shutdown.

The fuel element used was 25 inches long and 3 inches in diameter. It was placed in a shielded cylindrical container which is 9 feet long and has an internal bore 5.5 inches in diameter. A photograph of the shielded container on the Silent Hoist transporting vehicle is shown in Figure 61. This equipment is quite versatile; it allows the fuel element to be tilted from the vertical to the horizontal, and also a pulley arrangement allows the fuel element to be raised within the cylindrical container. As a rough approximation, it may be assumed that the ionization took place within a circular cone with an apex angle of approximately 3.8° , i.e., about 2.8×10^{-3} steradians when the fuel element rested at the bottom of the 9-foot well.

On the day of the experiment, the intensity at the exit was measured with a calibrated Victoreen thimble chamber and found to be $910 \text{ R/hr} \pm 8\%$ when the element was in the lower position of the fuel-rod shielded container. When the fuel element was raised about one-half way up, it was found to give an intensity of 5,000 R/hr on a portable "Cutie Pie" instrument. Because of

the inaccuracy of the portable instrument, it is likely that the intensity was in the 4,000–5,000 R/hr range. An accurate measurement of the dose rate at the exit with a thimble chamber was not feasible because of the high background around the shielded cylinder.

Although only the dose rate at the exit was measured on the day of the experiment, it was desirable to have information on the radiation field created by the gamma-ray beam to correlate with the radar measurements at various azimuth angles. To accomplish this, the radiation field was measured on May 6, 1965, 18 days after shutdown, with the fuel element in a horizontal position. From Table 36, giving the relative abundance of gamma energies on the day of the experiment and those 6 days later, it is possible to assess the intensity of the radiation field at the time of the radar measurements. The fields at distances of 75, 150, 225, and 300 feet from the opening of the shielded fuel element container were measured. This was done by placing personnel film badges and dosimeters at 5-foot intervals on a 20 ft x 20 ft vertically positioned, rectangular grid made of light metal. The exposure dose rate on the axis of the beam as measured by a Juno dose-rate meter varied from approximately 1,000 R/hr at the aperture to 0.2 R/hr at 300 ft, corresponding to equilibrium ion concentration of 1.9×10^7 and 2.7×10^5 ion pairs/cc, respectively. The apparently higher reading on the 18th day as compared with that on the 12th day after shutdown is probably due to the inac-

TABLE 35. RADAR CHARACTERISTICS

Characteristic	AN/APS-4 (modified)	AN/MPQ-33
Frequency	9.381 GHz	9.440 GHz
Peak power output	53.25 kW	100 kW
Pulse width	0.63 μ sec or 2.1 μ sec	0.166 μ sec
Pulse repetition rate	1000 pps $\pm$ 80 pps 350 pps $\pm$ 30 pps	$\approx$ 1000 pps
Minimum range	0	200 meters $\approx$ 656 feet
Minimum sensitivity	-65 dBm	-98 dBm
Antenna gain	Transmitter: 31 dB Receiver: 27 dB	39 dB
Antenna 3 dB beam-width	Transmitter: 4° Receiver: 6°	1°
Antenna type	Parabolic dish	Lens type
Polarization	Linear (horizontal)	Linear (horizontal)
Side lobe level	Transmitter: < -18 dB Receiver: < -15 dB	< -26 dB
Side lobe angle	Transmitter: 1st: 6.0° 2nd: 12.5° Receiver: 1st: 8.2° 2nd: 18.6°	1st: 2.1° 2nd: 3.1°
Scan rate	Manual	45°/sec, vertical 45°/sec, horizontal

curacy of measurement by the Juno dose-rate meter. The lateral exposure distribution exhibited a fairly sharp boundary and agreed well with geometric considerations. Reduction to a spherical coordinate system of the data taken indicates that for constant radii, the exposure distribution dropped to one-half of the maximum value at 2.2° from the reference axis.

IV. WEATHER CONDITIONS

The experiment was conducted during two periods, from 10:00 a.m. to 12:00 noon and from 1:00 to 3:00 p.m. Weather observations for the period of the experiment are shown in Table 37. In the morning and also in the first part of the afternoon, the winds were light, but during the latter portion of the experiment, the wind shifted from the southwest quadrant to slightly east of north and increased to moderate speeds. The

air was quite dry as seen by a comparison of the ambient air temperatures and dewpoint temperatures. Nearly maximum sunshine was present throughout the day since only a few high, thin cirrus clouds were present.

V. EXPERIMENTAL TECHNIQUES AND RESULTS

A. Data obtained by the AN/MPQ-33 radar set

During the morning, the AN/MPQ-33 radar provided oscilloscope photographs based on vertical scans of the ionized beams at a number of azimuth positions. The fuel rod was rotated to a number of angular positions ranging from the vertical to an angle of 70° with respect to the vertical.

In the afternoon, with the fuel rod in a vertical position, a number of horizontal scans was made for different elevation angles of the AN/MPQ-33 radar antenna. During these experiments, the fuel rod was at the bottom of the container.

The last test consisted of raising the fuel rod halfway up the container. This increased the radiation field at the opening to 4,000-5,000 R/hr. Horizontal scans for different elevation angles of the antenna were made again.

B. Data Obtained by the AN/APS-4

Initially, data were taken with the fuel rod in a vertical position and the transmitter directed at a point approximately 90 ft above the CP-5 fuel element. The receiving antenna then scanned the column in azimuth and elevation until a maximum signal was observed on the oscilloscope display. From the azimuth angle and elevation of the receiving antenna, it was determined that the common volume of the antenna beams contained the ionized column. As the fuel rod was tilted from its vertical position, the direction of the maximum response changed and again occurred in the common volume. No attempt was made to define the maximum elevation angle at which the phenomenon could be ob-

TABLE 36. RELATIVE ABUNDANCE OF ENERGY RANGES FOR CP-5 FUEL ELEMENT AFTER OPERATION FOR 270 DAYS AT 4.5 MW

Gamma groups	Energy (MeV)	Relative abundance ⁽¹⁾	
		12 Days after shutdown	18 Days after shutdown
1	0.1-0.4	400	300
2	0.4-0.9	1400	1000
3	0.9-1.35	600	520
4	1.35-1.8	1600	1200
5	1.8-2.2	17	10
6	2.2-2.6	150	100
7	2.6	6	5

FIG. 61. Shielded fuel-element container on transport vehicle

served, since the manual scanning technique was very time consuming. Such data were obtained with the AN/MPQ-33 radar.

C. Experimental Results

Although the film obtained from the AN/MPQ-33 oscilloscope has not yet been analyzed, the results ob-

served visually from a second oscilloscope of this radar set indicated the following:

1. The return signal on the radar "A" scope, which shows the magnitude of the return signal as a function of range distance, was well defined, i.e., the signal-to-noise ratio was many times greater than one. The possibility that only side lobes provided a return of the metal

TABLE 37. ARGONNE METEOROLOGY STATION
Weather Conditions April 30, 1965

Time (CDT)	Wind				Temper- ature 5.5 ft (°F)	Dew- point 4.7 ft (°F)	Solar ra- diation on a horizontal surface (Langleys during hour ending at indicated time)
	19 ft		150 ft				
	Speed (mph)	Dir. (deg)	Speed (mph)	Dir. (deg)			
0900	6.5	270	7.6	270	60.1	46.7	38.1
1000	4.9	270	6.4	280	64.2	48.2	51.9
1100	2.3	260	3.0	250	67.6	50.2	66.2
1200	3.4	210	4.2	220	71.4	49.9	73.8
1300	3.0	240	3.2	220	73.6	52.0	77.5
1400	10.7	010	12.1	010	72.3	49.9	75.5
1500	10.5	030	12.3	020	68.9	46.1	69.9
1600	10.5	030	12.3	030	68.2	45.8	58.1

cylindrical shield containing the fuel element was eliminated when the signal return disappeared upon rotating the fuel rod, thus removing the ionized column from the radar radiation beam.

2. When the fuel element was raised halfway up the cylindrical container, thus reducing the collimation, the beam was seen to diverge as expected.

3. During the latter part of the afternoon, when the winds were approximately 12 miles per hour, there was a deviation from a symmetrical pattern representing the ionized column. This, it seems, was due to wind motions. The direction of the wind relative to the line of sight may be seen from an examination of Table 37 and Figure 60.

VI. FUTURE WORK

The magnitude of the signal return as observed by both radar sets is greater than was expected on the basis of classical reflection intensity from ions. The reason for this is unclear at the present time. It is, therefore, necessary that a theoretical study be conducted to explain the mechanism which produced the magnitude of the power return observed.

There exist radar sets which are two or three orders of magnitude more sensitive than the AN/MPQ-33. It is also possible to obtain fuel elements which have substantially greater activity. It is, therefore, hoped that an experiment may be conducted with a more powerful radar and a cluster of more active fuel elements to provide an ionized beam which may be detected up to several thousand feet above ground. These tests would necessitate the use of a pulsed-radiation beam which can be achieved by means of a rotating shutter. The use of a Doppler radar for these experiments would also be desirable.

If such an experiment were carried out and wind data were obtained every few seconds over a layer of several thousand feet above the ground, it would then be feasible to obtain measurements of the turbulence spectrum throughout this layer. Such data are of importance for understanding atmospheric diffusion mechanisms. No such data exist at the present time.

Using a reactor fuel rod for this experiment was first suggested by L. D. Marinelli. His helpful suggestions and discussions have materially aided this experiment. The assistance provided in carrying out these experiments by the following Argonne personnel is gratefully acknowledged: James E. Carson, Frederick H. Martens, Carol D. Hampleman, R. B. Holzworth, Gunther A. Zerbe, Donald L. Rippon, Billie G. Oltman, John R. Novak, and Thomas A. Steele. Illinois State Water Survey personnel to whom thanks are due are: Ronald K. Tibbetts and Ronald E. Rinehart. In addition to the above, thanks are due to the following Argonne Groups without whose help this experiment could not have been carried out: Electronics Division, Reactor Operations Division, Industrial Hygiene and Safety Division, Graphic Arts Department, Motion Picture Production Unit, Plant Services and Site Administration.

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RADON-222 CONCENTRATION-HEIGHT-TIME RELATIONSHIPS

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1. INTRODUCTION

All topsoil contains trace amounts of uranium-238, a radioactive element. One of the daughters which results

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from its decay is radon-222. This gas of 3.8-day half-life is, therefore, also present in the soil and escapes to the atmosphere as a result of several processes including diffusion, evaporation of soil moisture in which radon is dissolved, and exhalation due to temperature or pressure changes. It is the purpose of this study to look into the

distribution of radon with height and time in the atmosphere.

Several studies of this type have been conducted at the Argonne National Laboratory.^(1, 2) This study extends the previous work since it is based on more data, 650 observations made in eight 24-hour periods, and carries out several new types of analyses. The rate of injection of radon is believed to be somewhat more uniform than that for pollen,⁽³⁾ auto exhaust, domestic heating, or industrial release. For this reason, the variation of atmospheric radon concentration is influenced to a greater extent by meteorological parameters.

While the data provide an insight regarding the relationship of the variables, it should be recognized that the information is limited by (1) the small number of samples, (2) the use of only one geographical location, (3) the collection of samples during a limited time period—the late spring and summer, and (4) the smallness of the atmospheric layer above the earth.

2. EXPERIMENTAL METHOD

The data were collected during 24-hour periods on the following days: 20–21 May, 1958; 16–17 July, 1958; 27–28 August, 1958; 8–9, 15–16, 23–24 June, 1960; 28–29 July, 1960; 4–5 August, 1960. The first observation of a calendar day was made at 0100 CST; the remainder at 1½-hour intervals thereafter. The few observations not made at the reported times were taken within 30 minutes of the time in all cases. The time se-

quence used provides 16 observations during a 24-hour period. Elevations at which samples were collected include one between the surface and 1 cm above the surface, and 0.5, 1.0, 4.0, and 16.0 meters above the ground.

Radon-222 concentrations were determined using the method described by Lucas.⁽⁴⁾ Briefly, the method includes collection of radon-222 by adsorption on activated coconut charcoal chilled in a dry-ice solution. The charcoal trap containing the sample was brought to the laboratory, where the radon sample was desorbed by heating the charcoal to 500° C. The trap was flushed several times, aged helium being used as a carrier, and the radon-helium mixture was pumped into an evacuated counting bottle, covered at one end by a quartz glass window and lined with a silver-activated zinc sulfide scintillation material. After transfer, the sealed bottle was allowed to stand about two hours during which short-lived radon decay products approached equilibrium with the parent radon-222. The radon content was determined by placing the counter bottle window in contact with the window of a photomultiplier tube, covering the assembly with a light-tight shield, and counting alpha-scintillations for a measured period of time. Corrections for radon decay during the intervals between collection, transfer, and counting were made.

3. DISCUSSION

Eight 24-hour periods of data represent a rather limited number of samples. However, the eight period

FIG. 62. Radon-222 concentration (in 10^{-12} curies liter⁻¹) variation with elevation and time for 28–29 July, 1960, a period with scattered to overcast clouds during daylight and clear skies, light winds, and inversion at night.

present a variety of normally-occurring meteorological regimes. At one extreme are cloudless conditions with strong incoming radiation during the day and pronounced outgoing radiation at night producing a marked inversion, while at the other is an overcast situation with greatly attenuated incoming radiation during the day with strong winds, good vertical mixing, and weak or no inversion conditions at night. It is expected that a majority of the conditions observed during most years are between these extremes.

A. Distribution of Radon under the Two Different Meteorological Regimes

The cloudless situation is represented by the data for 28-29 July, 1960, shown in Figures 62 and 63 while the cloudy regime with strong winds is illustrated by the data for 23-24 June, 1960, in Figures 64 and 65. Figures 62 and 64 show radon concentrations on a height-time plane while Figures 63 and 65 show the associated meteorological conditions.

The two radon concentration diagrams, Figures 62

FIG. 63. Radon-222 concentrations and related meteorological variables for 28-29 July, 1960

FIG. 64. Radon-222 concentration (in 10^{-12} curies liter $^{-1}$) variation with elevation and time for 23-24 June, 1960, a period with overcast skies during daylight and relatively high wind speeds with a weak inversion at night.

and 64, have several common characteristics. Highest concentrations are observed next to the ground, the source. Maximum concentrations occur during the night and minimum concentrations during the day. Late morning radon concentration profiles show little variation with height, but in the early evening concentrations increase more rapidly near the ground than above as shown by the slanting isopleths.

Figure 62 exhibits greater concentrations at all times and elevations than does Figure 64. In Figure 62 the maximum concentration at the ground was observed at 0230 CST while the maximum at 16 meters occurred three hours later, shortly after sunrise. This illustrates the inverse fumigation condition.⁽¹⁾ The weakest concentrations were observed at about 1300 CST. While the weak concentrations observed in Figure 64 may be attributed in part to the strong winds with pronounced mechanical turbulence and good vertical mixing of materials in the lower atmosphere, they may also be due to a reduced rate of emanation of radon-222 from the soil due to the presence of soil moisture. Rain fell on three days preceding this test. On the morning of June 20th, 0.05 in. fell. In the early afternoon of June 21st, another 0.05 in. of rain was added, while on the 22nd steady rain from 0900 to 1500 CST provided an additional 0.20 in. It is possible that sufficient moisture was present in the upper layers of soil to inhibit the release of radon to the atmosphere. In Champaign County,

Illinois, approximately 120 miles to the south, the same soil when moist, 0.17 to 0.18 air void fraction, releases about one third the emanation that it does when dry, 0.35 to 0.45 air void fraction.⁽⁶⁾ It has been suggested, also that rising atmospheric pressure will inhibit release of radon.⁽⁶⁾ Figure 65 shows this to be occurring during the June test. Maximum concentration reached near the surface on the 23-24 June test was 0.732×10^{-12} curies liter $^{-1}$ compared to the 3.78×10^{-12} curies liter $^{-1}$ of the 28-29 July test. Also the daylight minimum of the June test occurring at 0700 CST was less than half the minimum for the other test occurring near 1430 CST.

B. Average Time-Height Relationships to Radon Concentration

In Section A, the data taken in two individual series are presented, while in this section averages of eight sets of samples, each taken over about 24 hours, are used. These data are analyzed to provide a picture of the average variation of radon concentration with height and time. Since three variables are involved, radon concentration, height, and time, any two of these may be used as coordinates and the third represented by isopleths. All three presentations are given since each one brings into sharper focus different features of the distribution of radon concentrations.

In Figure 66, isopleths of radon concentration are

FIG. 65. Radon-222 concentrations and related meteorological variables for 23-24 June, 1960

shown in a height-time space. Each point represents the average of approximately 8 measurements, each taken on different days of which 5 were like the one presented in Figures 62 and 63, i.e., high incoming radiation during the day and high outgoing radiation at night, and three were similar to those shown in Figures 64 and 65, where high wind conditions and cloudiness resulted in distributions of relatively low radon concentrations.

The essential features of Figure 66 are quite similar to those of Figure 62, with the high buildups in the early morning hours near the ground, the inverse fumigation just after sunrise, and the vertical lines representing weak vertical concentration gradients or very good mixing during the morning hours, the minimum concentrations around noon or shortly thereafter, and in the evening the lag in the buildup in the upper levels

Fig. 66. Radon-222 concentration (in 10^{-12} curies liter $^{-1}$) variation with elevation and time; average for eight 24-hour periods

Fig. 67. Mean concentrations of radon-222 variation with elevation and time for eight 24-hour periods and average 24-hour concentrations.

after it has occurred near the ground, resulting in sloping isopleths as may be seen in the right side of Figure 66.

Figure 67 represents the same data but the average

radon concentration is presented as the ordinate and the time as the abscissa. The isopleths are lines of constant elevation. Figure 67 points out strikingly the time rate of change of the radon concentration at various

Fig. 68. Average Radon-222 concentration variation with time and elevation and mean concentration variation with elevation for all times. All times central standard.

Fig. 69. Individual radon concentrations measured at various elevations at 0230 and 1430 CST and a mean curve for the times indicated.

times of the day—more so than Figure 66. Also plotted on this figure are the average values for each level based on all of the data available. It is clear from this diagram that the average radon concentrations at the breathing level, i.e., about 5 feet, if measured during the daytime, would provide values that were appreciably lower than those for the total 24-hour period or for the night hours.

In Figure 68 is presented the radon concentration as a function of height for selected hours. Only half of the

observations were used to avoid confusing clutter. The extreme values are not included here but appear in Figure 69. The dark line represents the average of all the data for each level and, therefore, represents an average profile of radon concentration. Besides showing the vertical gradient, this chart shows quite markedly that the diurnal spread in values of radon concentration is large in the lower levels and converges to a substantially smaller range at 16 meters. Thus, Figures 66, 67, and 68 emphasize different features of the radon time-height distributions and, taken together, provide a more complete picture of the interrelationships involved.

Figure 69 presents the vertical distribution of radon concentration for two specific times—1430, a time when the radon concentration is at a minimum and 0230, when concentrations are relatively high. Figure 69 differs from Figure 68 in that in Figure 68 each point represented the average of 8 observations whereas in Figure 69 each point represents a single measurement at the time indicated. This figure indicates the dispersion of the points which went into the construction of Figure 68. It is clear that during daylight hours the variation from one date to another is appreciably smaller than during the nighttime.

C. Frequency Distributions of Radon Concentrations at Various Heights

To illustrate further how radon varies with height, frequency distributions of the observations for the daylight hours, 0500 to 1830 CST, and the nighttime hours, 1830 to 0500 CST, are presented in Figures 70 and 71, respectively. These figures show the large variability of

Fig. 70. Frequency distributions of nighttime radon-222 concentrations: 1830-0500 CST.

radon concentrations near the surface as compared with those at 4 or 16 meters. Also the values of radon concentrations at the mode decreases with height. Values of the standard deviation for each level for daytime and nighttime values are shown in Table 38. As is evident from the data, the standard deviation decreases with height both during day and night but the daytime values are considerably smaller. Table 38 also summarizes the measurements by giving values for the absolute maximum, average of the maxima for the 8 values, the average of all the data, average minima for the 8 series of observations, and the absolute minimum for each of the levels of measurement. Of course, during the day with solar heating, vertical motions are intense to provide mixing over a relatively thick layer. During the night with the presence of inversions, this mixing is suppressed, allowing the radon or any material emanating from the ground to become concentrated in the lower layers. The buildup in the lower layers is shown quantitatively by these data.

Admittedly, the information provided in this report is far less than necessary to provide a complete picture. Nevertheless, conditions representing high diffusion

FIG. 71. Frequency distributions of daytime radon-222 concentrations: 0530 1830 CST.

rates and the low diffusion rates discussed here bracket the majority of weather conditions which may occur. Thus, this analysis may be used as a guide line for distributions of radon as well as those of other contaminants, such as pollens or auto exhausts, which may be injected into the atmosphere. The same atmospheric processes operate in all of these cases.

4. RADON-222 IN THE ENVIRONMENT

Although this paper has emphasized the behavior of radon-222 in the lower atmosphere under varying atmospheric conditions, it also provides information regarding concentrations of this material and the consequent exposure of plants and animals residing in the bottom 16 meters of the atmosphere. The soil emission rate at the Argonne National Laboratory site is comparable to many others studied; likewise, the emanating radium-226 content of the soil at this site has been shown to be within 10 to 15 per cent of that for other locations in central United States.⁽⁵⁾ As radon is supplied to the atmosphere at a very nominal rate, concentrations observed at the breathing level for humans provide a guide to exposure to this radioactive material. The data in Table 38 show that the variation of concentration in picocuries per liter ranges from 0.032 to 1.400 at 1 meter and 0.018 to 1.170 at 4 meters, while the mean for 1 meter is 0.301 and the mean for 4 meters is 0.259. A comparison of daytime with nighttime means at these elevations also can be made from data in the table.

High values of radon concentration measured near the ground at Argonne included one at 3.93 and one at 3.78 picocuries per liter. Emanation rates approximately three orders of magnitude higher have been observed at the ground surface in New Mexico at a location where uranium-bearing strata of rock outcrop at soil surface.⁽⁵⁾ This suggests that a promising subject for future research would be an investigation of atmospheric con-

TABLE 38. RADON CONCENTRATIONS (IN PICOCURIES PER LITER) AT VARIOUS ELEVATIONS AT ARGONNE NATIONAL LABORATORY IN LATE SPRING AND SUMMER 1958 AND 1960

	Elevation of observation (meters)				
	Surface to 0.01	0.5	1.0	4.0	16.0
Maximum observed	3.930	2.429	1.400	1.170	0.908
Average maximum	1.732	0.957	0.764	0.570	0.449
Over-all average	0.705	0.407	0.301	0.259	0.204
Average minimum	0.177	0.101	0.084	0.090	0.078
Minimum observed	0.103	0.067	0.032	0.018	0.019
Daytime mean and standard deviation	0.385 ± 0.214	0.234 ± 0.168	0.181 ± 0.153	0.179 ± 0.197	0.164 ± 0.164
Nighttime mean and standard deviation	0.674 ± 0.255	0.481 ± 0.321	0.435 ± 0.270	0.339 ± 0.243	0.261 ± 0.154

centrations in the New Mexico region because of the implications regarding human exposure.

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METEOROLOGICAL INSTRUMENTS FOR AIR POLLUTION SURVEYS*

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In order to understand the movement and diffusion of materials in the atmosphere, an air pollution survey should include measurement of meteorological parameters. A program limited in scope should include observations of wind direction and speed; stability, as indicated by temperature variation with elevation; and precipitation. For more extensive programs, additional

measurements should be made, including ambient temperature, solar radiation, net all-wave radiation flux, atmospheric moisture, and the temperature of the soil surface or the upper layers of soil.

Principles of operation of sensing devices for measuring each of the above are explained. For each sensor an indicator or a recording device is required, and merits of each are discussed. Requirements of the various devices for calibration and routine maintenance are listed. The importance of appropriate averaging times is emphasized, and the problems of data handling and analysis are discussed.

Other agencies such as the U. S. Weather Bureau provide meteorological information and services, which are available to air pollution surveys. Reference materials, which are more extensive than this report in the details provided, are listed.

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THE CONTRIBUTION OF PLANTS TO ATMOSPHERIC RADON-222

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1. INTRODUCTION

The 20° C water-air phase distribution ratio of 0.25⁽¹⁾ and the 100 to 1000 times greater concentration of

radon-222 in soil air as compared to the atmosphere above these soils^(2, 3) suggests that soil water would be relatively rich in dissolved radon. From these two conditions, the hypothesis may be forwarded that plant roots acquiring the radon-222-rich soil water subsequently transports both water and dissolved radon to above-ground plant parts, where both are released to

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the atmosphere. A simple experiment was performed to test this hypothesis.

2. MATERIALS AND METHODS

This experiment, using greenhouse-grown tobacco (*Nicotiana tabacum* L. cv. Maryland Mammoth) and castor bean plants (*Ricinus communis* L.), was initiated in the winter of 1964-65. Plants were grown in potting soil (1:1:1, loam: peat: sand) in glazed, 30-gallon earthenware crocks. When plants were in the early flowering stage, leaf radon emission was assayed with a system similar to that used to measure soil radon emanation (Figure 72).⁽⁴⁾ Radon thus collected on chilled coconut charcoal was transferred to alpha-scintillation counting bottles, and the activity was determined.⁽⁵⁾ This collection system was not optimal for sample collection from leaves because water vapor, carbon dioxide, and light were excluded from the leaf surface during sample collection. Each of these exclu-

sions is capable of modifying water evaporation from leaf surfaces by inducing changes in stomatal openings.

3. RESULTS

Despite the cited inadequacies of the sampling system for measurement of leaf surface emanations which render the absolute quantitative value of these data questionable, the data clearly show that measurable quantities of radon-222 were released from leaf surfaces (Table 39). The marked decrease in rate of radon emission with length of sampling period, which was particularly evident on the lower leaf surfaces of tobacco, indicates that the inadequacies of the sampling system employed materially decreased stomatal opening and transpiration rates. Differences between upper and lower leaf surfaces, when the shorter sampling time was employed, are wholly consonant with stomatal distribution on these surfaces.⁽⁶⁾

Considering that fully open stomates constitute only about 0.4-1.0% of the leaf surface area, calculated on a basis of one surface,⁽⁷⁾ the radon contribution measured is exceedingly high with respect to active leaf area. Also, in view of the fact that the single surface leaf area to soil surface area ratio may exceed 10:1, even with cultivated crops,⁽⁸⁾ the contributions of radon to the atmosphere by leaves appears to be of importance when compared with the other source, the soil. The emanation measured from the moist potting soils, 67.3 and 76.5×10^{-18} curies $\text{cm}^{-2} \text{sec}^{-1}$, compares favorably with the 56.8×10^{-18} curies $\text{cm}^{-2} \text{sec}^{-1}$ emanation measured over undisturbed natural soil at this laboratory on July 16, 1963, following 1.75 in. of early morning rain.

4. FUTURE GOALS

We propose to modify the existing sampling system so that leaf radon emissions under more nearly natural conditions can be determined. These sampling modifications would provide for simulation within the collecting

FIG. 72. Schematic representation of the system used for collecting radon-222 released from leaf surface.

TABLE 39. EMANATION OF RADON-222 FROM LEAVES OF PLANTS ON APRIL 21, 1965

Leaf surface measured	Type of measurement	Tobacco		Castor bean 1-hr sample
		20-min sample	1-hr sample	
Upper	flux density ^(a)	$13.9 \pm (2.1)^{(b)}$	$7.53 \pm (1.56)$	$6.22 \pm (1.08)$
	total emanation ^(c)	$0.267 \pm (0.040)$	$0.437 \pm (0.090)$	$0.359 \pm (0.062)$
Lower	flux density	$28.0 \pm (4.8)$	$9.86 \pm (1.14)$	$8.56 \pm (1.43)$
	total emanation	$0.540 \pm (0.093)$	$0.569 \pm (0.066)$	$0.494 \pm (0.083)$
20-min soil samples	flux density	$67.3 \pm (7.4)$		$76.5 \pm (9.7)$

^(a) Flux density in 10^{-18} curies $\text{cm}^{-2} \text{sec}^{-1}$.

^(b) Bracketed values are standard errors associated with counting.

^(c) Total emanation in 10^{-12} curies.

device of nearly normal light intensities, as well as movement of air with near normal concentrations of water-vapor and carbon-dioxide content. These sampling system modifications will enable more quantitative assessment of the evidently important role plants play in modifying atmospheric radon concentrations.

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DETERMINATION OF THE VERTICAL HEAT FLUX IN THE ATMOSPHERE BY VARIANCE REDUCTION ANALYSIS

Paul Frenzen

INTRODUCTION

In a previous report, the author presented a general method for examining certain properties of stationary time series, a method henceforth to be termed variance reduction analysis or "Varedan."^(1, 2) The earlier discussion pointed out that when the form of the autocorrelation function appropriate to a time series is known, Varedan makes it possible to compute additional information concerning the properties of the field from which the data have been drawn. That particular report applied the method to wind records supplied by three-cup anemometers and showed that this exercise gave an expression for the rate at which energy is consumed by turbulent circulations working against viscosity, the so-called rate of kinetic energy dissipation. It was indicated further that such estimates of energy dissipation could be combined with measures of the vertical shear of the horizontal wind to evaluate the horizontal stress exerted by the wind upon the surface of the earth, a quantity important to meteorology, since near the ground it is equivalent to the vertical flux of momentum and represents the magnitude of a principal sink for atmospheric kinetic energy. In analogous fashion, the present note derives an expression for the rate at which small-scale, atmospheric temperature fluctuations are smoothed out by (molecular) thermal conductivity, this being the so-called rate of thermal fluctuation dissipation. It is then shown that by combining values of this parameter with measures of the vertical temperature gradient, one can determine the vertical flux of sensible

heat, this last representing an important source of energy for the atmospheric circulation.

THEORETICAL DISCUSSION

For any stationary time series, $X(t)$, one can write a variance function, $\beta(t)$, expressing the percentage variance retained by the series after it has been smoothed by running means over an interval, T (cf. References 1–4):

$$\beta(T) \equiv \frac{\overline{X_T^2}}{\overline{X^2}} = \frac{2}{T^2} \int_0^T \int_0^t R(\xi) d\xi dt \quad (1)$$

In this notation, $X_T(t)$ would represent the smoothed series; therefore, $\overline{X_T^2}$ in equation (1) designates the reduced variance effected by smoothing over T . The term $R(\xi)$ represents the autocorrelation function derived from the original, unsmoothed series. For the present application, consider $X(t)$ to represent an Eulerian record of relatively high-frequency temperature fluctuations whose spectral distribution contains an appreciable portion of the low-frequency end of the inertial subrange.* Adopting more standard temperature nota-

* An organized regime of high-frequency, isotropic turbulent fluctuations originally predicted for conditions of very high Reynolds number by the Kolmogoroff universal equilibrium hypothesis and now generally accepted as a model providing an adequate statistical description of small-scale atmospheric turbulence near the ground for frequencies in excess of $\bar{U}/z$, the ratio of the mean wind speed to the height above ground.

tion, let $X(t)$ be replaced by

$$\theta(t) \equiv \Theta(t) - \bar{\Theta}, \quad (2)$$

where $\Theta(t)$ represents the instantaneous (potential*) temperature at a fixed point and $\bar{\Theta}$ is the ten- or fifteen-minute mean; it follows that the time series, $\theta(t)$, represents a record of instantaneous departures or fluctuations of the local temperature from the longer-term mean.

Now, through dimensional considerations it has been shown theoretically⁽⁵⁻⁷⁾ and verified by experimental observation that the mean square temperature difference between two sufficiently close points in space takes the form

$$D_\theta(r) \equiv [\overline{\theta(r_0) - \theta(r_0 + r)}]^2 = c\epsilon^{-1/3}Nr^{2/3}. \quad (3)$$

Here $D_\theta(r)$ represents one member of a family of similar mean square relations known as structure functions, ϵ is the rate of kinetic energy dissipation, N is the rate of thermal fluctuation dissipation, r is the distance between points of observation, and c is a numerical constant. The specification "sufficiently close" insures that the temperature differences observed are those due to the relatively small-scale turbulent eddies of the inertial subrange.

To obtain the foregoing relation, it is necessary to assume that turbulent temperature fluctuations of small scale act in the nature of "passive additives" to the velocity field (cf. Reference 7). In other words, inertial subrange temperature fluctuations are considered to approximate the role of neutral density tracers added to the flow, tracers whose presence does not affect the dynamics of the velocity field in any way. Of course, because of buoyancy, this cannot be entirely true. On the other hand, in view of the fact that measurements in the inertial subrange of the atmospheric temperature spectrum by Krechmer⁽⁸⁾ and Tsvang⁽⁹⁾ seem to follow the form predicted for the structure function, it would appear that the relatively small buoyant accelerations associated with the higher-frequency temperature fluctuations do not have sufficient time to significantly change the velocity field.

Structure-function expressions can be seen to be analytical equivalents of Eulerian space correlations

* Strictly speaking, in a compressible atmosphere it is necessary to specify temperatures of moving parcels in terms of the "potential" values each would exhibit if the parcel were moved adiabatically to some standard pressure level; however, pressure variations experienced by parcels of air moving within small-scale turbulent fields near the ground are quite small, and, therefore, the difference between actual and potential temperature values in the present discussion is negligible.

through the identity

$$R(r) \equiv 1 - \frac{D_\theta(r)}{2\bar{\theta}^2}. \quad (4)$$

What is more, an Eulerian *space* correlation can be converted to the desired *time* correlation form by assuming that, in so far as Eulerian statistical representations are concerned, fields of turbulence are simply swept past fixed points of observation with the speed of the mean flow, this constituting the widely accepted Taylor "frozen-turbulence" hypothesis. It follows that substitution of equation (3) in equation (4) and transformation of the independent variable according to $r = \bar{U}\xi$ results in an autocorrelation function in terms of a time lag, ξ , that is appropriate to the time series, $\theta(t)$:

$$R(\xi) = 1 - \frac{cN\bar{U}^{2/3}\xi^{2/3}}{2\bar{\theta}^2\epsilon^{1/3}}. \quad (5)$$

At this point it is useful to examine the meaning of the thermal fluctuation dissipation, N . For the present purpose, it is sufficient to tabulate certain properties of N alongside similar characteristics of its closely analogous and physically more familiar counterpart, the kinetic energy dissipation, ϵ . More complete discussions of these parameters can be found in appropriate reference works.^(7, 10)

In Table 40, note that the index of mechanical turbulent energy, specified in the familiar form of a velocity squared (in this case the square of the turbulent fluctuation velocity), has an analogous counterpart in an index of thermal fluctuation intensity expressed simply as the square of the fluctuation temperature. In each case, the dissipation rate is defined as a change in the appropriate index per unit time. Similarly, as may be seen in the last column, the flux-gradient expressions for the two kinds of dissipation have parallel terms. For mechanical energy, the first relation states the well-known physical principle that the rate at which work is done (or energy expended) equals stress multiplied by rate of strain; in meteorological terms, the kinetic energy dis-

TABLE 40. COMPARISON OF KINETIC ENERGY AND THERMAL DISSIPATION FUNCTIONS

τ represents the surface stress, ρ is the density, H is the vertical heat flux, and c_p is the specific heat of air at constant pressure

Dissipation	Units	Dissipation = flux × gradient
ϵ	$\frac{\text{KE}}{\text{time}} = \left(\frac{\text{cm}}{\text{sec}}\right)^2 \text{sec}^{-1}$	$\epsilon = \frac{\tau}{\rho} \times \frac{d\bar{u}}{dz}$
N	$\frac{\text{temp}^2}{\text{time}} = (\text{deg})^2 \text{sec}^{-1}$	$N = \frac{H}{\rho c_p} \times \left(-\frac{d\bar{\theta}}{dz}\right)$

sipation rate per unit mass, ϵ , equals the surface stress per unit mass, τ/ρ , (equivalent to the vertical flux of momentum near the ground) multiplied by the vertical gradient of the mean horizontal wind. In analogous fashion, the second flux-gradient relation expresses the rate of thermal fluctuation dissipation per unit mass, N , as the product of the vertical heat flux per unit mass, $H/\rho c_p$, and the adverse vertical gradient of mean temperature, $-d\theta/dz$.

With this last relation, one can write the autocorrelation in terms of the meteorological variable of principal interest, the vertical heat flux, by substituting for N in equation (5):

$$R(\xi) = 1 - \frac{c\bar{U}^{2/3}\gamma}{2\bar{\theta}^2\epsilon^{1/3}} \frac{H}{\rho c_p} \xi^{2/3}. \quad (6)$$

Here $\gamma \equiv -(d\theta/dz)$ has been introduced for the adverse vertical gradient or "lapse rate" of temperature. Substituting this form into the variance function of (1) and carrying out the indicated integrations we obtain:

$$\frac{\bar{\theta}_T^2}{\bar{\theta}^2} = 1 - \frac{9c\bar{U}^{2/3}\gamma}{40\bar{\theta}^2\epsilon^{1/3}} \frac{H}{\rho c_p} T^{2/3}. \quad (7)$$

Multiplying through by the denominator on the left determines that

$$\bar{\theta}^2 - \bar{\theta}_T^2 \propto T^{2/3}, \quad (8)$$

which is to say, the variance of an Eulerian record of temperature fluctuations in the inertial subrange falls off with the 2/3 power of the equivalent averaging time of a lagged thermometer. As in the case of anemometer records, one evidently could correct for losses of variance in the records of a less than perfectly responsive thermometer, provided one both knew the averaging characteristics of the instrument and was assured that the device had recorded at least the low-frequency end of the inertial subrange without appreciable distortion. It is, however, unnecessary to reconstruct the complete or unsmoothed variance for Varedan applications. Instead, as in the earlier treatment of wind fluctuations, equation (8) can be written for two different averaging times and the complete variance eliminated between the two equations by subtraction. The result is an expression for the additional reduction in variance effected by increasing the averaging interval from T_j to T_k :

$$\bar{\theta}_{T_j}^2 - \bar{\theta}_{T_k}^2 = \frac{9c\bar{U}^{2/3}\gamma}{40\epsilon^{1/3}} \frac{H}{\rho c_p} (T_k^{2/3} - T_j^{2/3}). \quad (9)$$

Solving for the heat flux we obtain:

$$H = \frac{40}{9c} \frac{\rho c_p \epsilon^{1/3}}{\gamma \bar{U}^{2/3}} \left[\frac{\bar{\theta}_{T_j}^2 - \bar{\theta}_{T_k}^2}{T_k^{2/3} - T_j^{2/3}} \right]. \quad (10)$$

This form would be suitable for the determination of H

from temperature-fluctuation data when one has an estimate of ϵ based upon wind profile measurements. However, when velocity fluctuation data in the inertial subrange are also available, one can write

$$\epsilon^{1/3} = \left(\frac{A}{\bar{U}} \right)^{1/3} \left[\frac{\bar{U}_{T_j}^2 - \bar{U}_{T_k}^2}{T_k^{2/3} - T_j^{2/3}} \right]^{1/2} \quad (11)$$

from the expression obtained in the Varedan analysis previously reported in Reference 1, equation (7). Substituting this relation in (10), we obtain a combined expression suitable for data collected by a system that simultaneously records both wind and temperature fluctuations smoothed over identical averaging intervals:

$$H = \frac{B\rho c_p}{\bar{U}\gamma} \frac{(\bar{U}_{T_j}^2 - \bar{U}_{T_k}^2)^{1/2} (\bar{\theta}_{T_j}^2 - \bar{\theta}_{T_k}^2)}{(T_k^{2/3} - T_j^{2/3})^{3/2}}. \quad (12)$$

Here the numerical constants have been collected as $B \equiv (40 A^{1/3}/9c)$. Since $A \sim 3.3$, $B \sim 20/3c$, where c , it will be recalled, is the constant in the structure function for temperature, equation (3).

PRELIMINARY COMPARISONS WITH EXPERIMENT

To test the foregoing result, one requires high-frequency temperature fluctuation data that have been collected over a uniform site in a field experiment during which independent measures of the vertical fluxes of both momentum and heat have been recorded simultaneously. Each of these measurements represents an application of highly specialized micrometeorological technique; hence, it was considered quite fortunate when a set of such data not specifically collected for the present investigation was found. During a recent (1964) micrometeorological field expedition carried out at Hay, New South Wales by members of the Division of Meteorological Physics, C.S.I.R.O., Melbourne, Australia, rapid temperature fluctuations were recorded at three elevations in unstable conditions.* Simultaneous measures of vertical heat flux were made in two ways, the first using an eddy-correlation technique,⁽¹¹⁾ while the second utilized the energy-balance method. Values of ϵ were derived from the wind speed at the half-meter level and a measure of the equivalent surface drag coefficient of the experimental site determined from wind profile measurements.

The Hay temperature records (initially in the form of successive, instantaneous values at 1/16-sec intervals) were subjected to smoothing by running means over a

*Data as yet unpublished, supplied through the courtesy of W. C. Swinbank, Associate Director of the Division of Meteorological Physics, Commonwealth Scientific and Industrial Research Organization, Melbourne, whose continued interest and encouragement in this program is gratefully acknowledged.

INSTRUMENTATION FOR ATMOSPHERIC TURBULENCE STUDIES

Paul Frenzen

Figure 73 presents a schematic representation of the "Varedan" system for the measurement of micrometeorological variables in the field and subsequent analysis in the laboratory of the data obtained. This equipment constitutes the principal facility to be used in a continuing investigation of the structure of atmospheric turbulence and the energy exchange at the earth's surface along the lines developed in the preceding contribution to this report. All components shown in solid lines in the block diagram are complete at the present writing, while those outlined in dashed lines are either under construction or on order. The sensors and recording equipment grouped together in the upper part of the diagram have been combined in a portable field unit mounted in a small cargo trailer. Also included in the field equipment but not shown in the diagram are several lightweight towers, equipment to measure and record vertical gradients of both the mean horizontal wind and the mean temperature, a shielded net-radiometer, and an array of soil heat-flux plates. Note that the field equipment can operate either from 115-Vac lines or from a self-contained, but somewhat limited, power supply.

Of the several data input sources indicated, the LIHT anemometer equipment is currently fully operational. As described in the previous annual report, this "low-inertia, high-torque" instrument has a response length under one-half meter, a characteristic which enables it to record a significant portion of the more rapid fluctuations in the atmospheric turbulence field.^(1, 2) Of additional value in this regard is the unusually high resolution of this device; it delivers pulses to the recorder at the rate of 1 for each 2 cm of wind passing the instrument.

As indicated by the dashed block lines, the fast response thermometer is currently in preparation. The sensing element will be a single crystal, silicon carbide thermistor of a type recently developed by the Carborundum Company. This miniature device features stable sensitivity and fast response in addition to the large temperature coefficient of resistance associated with semiconductors. Mounted in one arm of a bridge circuit, the crystal thermistor will be arranged to supply 2 millivolts for each 1 deg C departure from a longer-term mean temperature represented by either a fixed, preset resistance or a heavily lagged resistance thermometer in the other arm of the bridge. The resultant voltage analog of the turbulent temperature fluctuations will then be fed into a voltage to frequency

converter; here each 2-MV change in voltage will become a frequency change of 200 cycles per second relative to a central value of 1 kc arranged by suitable bias circuits to represent the mean temperature. When integrated over an averaging time of 0.5 second, the signal received by the recorder from the temperature bridge will thus correspond to 1 pulse for each 0.01 deg of temperature deviation from the mean.

As indicated in the upper left of the block diagram, the Varedan system affords a completely general capability for analyzing fluctuating, analog voltages from any source. Maximum inputs can range from 0.1 to 100 volts; but during any minimal fluctuation, the voltage must not fall so low as to generate frequencies below the audio range, since these cannot be recorded by the tape equipment. The latter is a stereo-recorder of standard manufacture with two heads recording on the first and third tracks of half-inch, audio tape. At some future date it will be possible to add two more heads in order to simultaneously record data on the second and fourth tracks as well. Such a requirement is anticipated for experiments in which the fluxes of both momentum and heat will be recorded at two levels at the same time, this requiring both a second LIHT anemometer and a second fast thermometer.

The key component of the Varedan System is the Alternating Channel Scaler,* a device that replaces a previous use of the TMC 400-channel analyzer to convert the pulse signals to consecutive, digital means. The new unit has been designed to incorporate two major advantages over the capabilities of the TMC, namely a fully adjustable averaging time over a wide range (0.1 to 99.9 sec) and virtually unlimited total sampling time. The Alternating Channel Scaler counts input pulses for pre-selected intervals in one of a pair of four-decade scalars. At the end of the averaging period, the input signal is automatically switched to the second scaler, and the contents of the first are read out through a data punch. Upon completion of each succeeding averaging interval, the scaler-switch and read-out cycle is repeated, a process which can be continued for a total sampling time limited only by the paper-tape capacity of the data punch. Ordinarily, the data-reduction operation of MACS† will be carried out in the laboratory some time after the completion of the field experiment, using the tape recordings of pulsed signals. However, MACS

* Designed by the Electronics Division and assembled by Richard L. Hart of the Radiological Physics Division.

† Meteorology's Alternating Channel Scaler.

number of successively larger averaging times using the Varedan computer program previously developed for wind analyses. Reductions in variance effected by each increase in averaging time were then plotted against the difference of the $2/3$ powers of the corresponding averaging intervals [numerator versus denominator of terms in brackets in equation (10)] in the manner described in detail for Figure 87 of the earlier report⁽¹⁾. However the results obtained were inconclusive. In the nine cases obtained from Australia (three different days at 1-, 4-, and 16-meter heights), the expected change in the slope of the plot (associated with changes in averaging times from intervals shorter than to intervals longer than the period of the largest eddies in the inertial subrange) did not always appear. What is more, in those cases in which marked slope changes were evident, substitution of the observed ratios for the bracketed terms in equation (10) (along with appropriate values of H and ϵ) resulted in values of the constant, c , which were neither internally consistent with those obtained in other runs nor in agreement with values previously reported by Russian workers.

The difficulty may lie in the fact that the Hay temperature records were each little more than one minute in length, which may have been too short to establish stable statistical results. Tsvang⁽⁹⁾ found that stable estimates of the structure function constant, c , required fluctuation records of 10 minutes' duration. Thus, an adequate test of the present heat-flux relation must await the development and subsequent operation of suitable equipment at this Laboratory. However, the preliminary results obtained with the Australian data are considered promising. If one eliminates the 1-meter cases from the data (these probably representing conditions under which the inertial subrange terminated at frequencies too high for the thermometric equipment to record without distortion), there is some tendency for the remaining runs to agree upon a single value of c , a value, however, differing from that reported in the Russian literature.

A portable observation system designed to collect the combined observations required for equation (12) is now being constructed. This unit will combine in a lightweight cargo trailer both the previously developed LIHT anemometer apparatus⁽¹²⁾ and a new, high-frequency temperature-fluctuation recording system. For independent measures of heat flux through the energy balance, a shielded net-radiometer and a set of soil heat flux plates, both of CSIRO design, have been placed on order. In addition, equipment for measuring

the mean vertical temperature gradient is being assembled. The latter will provide independent estimates of H , for Dyer⁽¹¹⁾ has shown that H varies with the $3/2$ power of the temperature difference between 1 and 4 meters, a simple empirical relation giving the heat flux from such gradient measurements to within 10 per cent of values determined by more complex methods.

Eventually equipment to measure the vertical moisture gradient will be added to this portable system. By using vertical diffusion coefficients for moisture inferred from measurements of the other fluxes, it should then be possible to determine the vertical flux of latent heat, that is, the rate of evaporation. Thus, the complete system would be able to measure virtually all components of the atmospheric energy balance at the interface between the earth and the atmosphere, the exception being that portion of incoming solar energy involved in photosynthesis.

SUMMARY

Using the method of variance reduction analysis, it is shown that the vertical flux of sensible heat H , can be determined from a record of high-frequency temperature fluctuations taken by a single, fast-response instrument. This theoretical result, combined with a previously obtained relation for the rate of kinetic energy dissipation, leads to an expression for H utilizing concurrent records of wind and temperature fluctuations. A portable field system designed to record such data for the simultaneous measurement of the vertical fluxes of momentum and heat is briefly discussed.

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FIG. 73. The Varedan system for micrometeorological measurement, data reduction, and analysis

can be fed directly from a pulse source, an optional experimental procedure which provides a direct, digital readout in the field, but for one data channel only.

Digital data recorded on paper tape in this way constitute smoothed time series, for each original signal consisting of a train of pulses of more or less rapidly fluctuating frequency has been counted and collected in a set of consecutive, running sums (or means), totaled (or averaged) over constant time intervals. Thus the MACS output forms the input to the Varedan computer program which applies the method of time series analysis previously described.⁽³⁾

The output of the CDC 3600 is received in two forms.

Graphical presentations of the original time series input are delivered on 35-mm film; these are used to evaluate qualitatively the statistical steadiness of each field run. They make it possible to spot undesired systematic trends in mean values or erratic unsteady periods in the history of the input variable. One then has the option of either deleting such unsteady runs entirely or editing them so as to eliminate the undesired departures from homogeneity. The principal analytic outputs of the Varedan computer program are in the form of tabulations of the variance reductions effected by averaging over successively larger and larger intervals. These are converted into rates of kinetic energy dissipation, in the

case of the LIHT anemometer data in the manner previously described [cf. Reference 3, p. 245, equation (7)]. In similar fashion, data from the fast thermometer will be converted into rates of thermal fluctuation dissipation and measures of the vertical flux of heat as described in equation (12) of the preceding contribution to this report.

The computer also calculates autocorrelation functions and power spectra from the original time series. These supply an estimate of the true extent of the inertial subrange of the turbulence spectrum, that re-

gime upon whose statistical characteristics the validity of conclusions drawn from the associated theoretical analysis depends.

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