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CONSIDERATION OF THE EFFECT OF
LYMPH-NODE DEPOSITION UPON THE MEASUREMENT OF
PLUTONIUM AND AMERICIUM IN THE LUNGS

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Health Sciences

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U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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SUBJECT DESCRIPTORS

Body Counter
Lung Burdens
Lymph Nodes

ROCKWELL INTERNATIONAL
ATOMICS INTERNATIONAL DIVISION
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CONSIDERATION OF THE EFFECT OF LYMPH-NODE DEPOSITION UPON THE MEASUREMENT OF PLUTONIUM AND AMERICIUM IN THE LUNGS

Roger B. Falk and Clayton R. Lagerquist

Abstract. Measurement of an inhaled radionuclide by external photon counting includes quantities which may be contained in lymph nodes, as well as quantities in the lungs. An overestimate of the lung burden can result, if a portion of the radionuclide were present in the lymph nodes. This problem is analyzed with respect to the measurement of inhaled plutonium containing plutonium-241 and americium-241, when americium-241 has been used as a tracer for the plutonium.

Equations are derived which yield the amounts of americium and of plutonium in the lungs and in the lymph nodes as a function of time after exposure and for various translocation and retention parameters. Count histories (count profiles) of actual exposure cases are compared with calculated count profiles in order to gain insight into possible values of the translocation and retention parameters. Comparison is also made with calculated count profiles using values of translocation and retention parameters recommended by the International Commission on Radiological Protection (ICRP) for use with the Task Group Lung Model. The magnitude of the possible overestimate (error factor) was calculated for combinations of parameters which yielded matches to the observed count histories.

In only one of ten cases did the values recommended by the ICRP yield an adequate match to the observed count history. Significant retention was indicated, but the site of retention was not established. Duplicate matches to the observed count profile could be obtained by considering retention in the lungs or in the lymph nodes, or both. A variety of combinations of values of the translocation and retention parameters exists to match each count history, but no common set of values was evident which would yield an adequate match for all cases considered in the study.

Error factors can be high for no retention in the lungs and for retention in the lymph nodes, but approach unity (no error) for retention in the lungs. Because the actual values of the translocation and retention parameters could not be established, the actual error factor could not be determined.

INTRODUCTION

The measurement of inhaled plutonium is made at the Rocky Flats Plant by external counting with sodium iodide (thallium-activated) [NaI(Tl)] detectors placed over the surface of the chest. Counts are made of the 60 kiloelectron volt (keV) gamma emitted by americium-241 (^{241}Am), which is present in plutonium mixtures as the daughter product from the decay of plutonium-241 (^{241}Pu).

The count obtained by the detectors reflects the total amount of americium in the chest cavity and does not discriminate between counts from americium in the lungs and counts from americium in the lymph nodes. An overestimate of the lung burden would therefore result, if a portion of the americium and plutonium were in the lymph nodes.

This report will consider the problem of translocation of plutonium and americium to the lymph nodes and the effect of lymph-node deposition upon the value of the calculated lung burden. Equations will be derived which express the amount of americium in the lymph nodes relative to the amount in the lungs, as a function of time after exposure. Actual exposure cases will be analyzed in order to obtain possible values of translocation and retention parameters for the lungs and lymph nodes.

BIOLOGICAL REVIEW

Prior to the derivation of equations representing the translocation and retention of americium and

plutonium in the lungs and lymph nodes, the anatomy and histology of the lungs and lymph nodes will be reviewed with regard to retention and clearance mechanisms.

Retention of inhaled particles occurs in the deep lung regions of the respiratory bronchioles and the alveoli. Those particles deposited in the trachea and the bronchial tree are rapidly removed by means of the mucous blanket on the ciliated surface of the bronchioles and the trachea. The surface of the alveoli is nonciliated, but rather consists of a layer of squamous cells capable of detaching and engulfing the particles (phagocytosis). The purpose of phagocytosis is, according to Hatch and Gross (1964):¹

- “1. To render dust particles incapable of irritating or otherwise injuring the alveolar surface epithelium.
2. To prevent the penetration of dust particles into the lung interstitium.
3. To facilitate the removal of the dust by the alveolar clearance mechanisms.”

The lung interstitium is the loose connective tissue under surface membranes. The interstitial space between alveoli walls is restricted, but the interstitium for alveoli adjacent to bronchioles is broad and rich with lymphatic vessels. The lymphatic vessels lie along the bronchioles and pulmonary vessels, but do not extend to the alveoli, which are surrounded by dense networks of capillaries. The flow of cytoplasm in the interstitium is to the lymphatic vessels, which lead to the lymph nodes. In the region of the lungs are lymph nodes called the tracheobronchial lymph nodes. According to Gray (1948),² the tracheobronchial lymph nodes consist of four groups:

- “a. tracheal, on either side of the trachea;
- b. bronchial, in the angles between the lower part of the trachea and bronchi and in the angle between the two bronchi;

- c. bronchopulmonary, in the hilum of each lung; and
- d. pulmonary, in the lung substance, on the larger branches of the bronchi.”

The lymph nodes act as filters of the lymphatic system and retain the particulate matter until the particles dissolve or the node ulcerates or ruptures.

The portion of the initial deposition of particles not rapidly cleared (in the first few days) from the lung can be considered to have been deposited in the alveolar regions of the lung. According to Hatch and Gross:³ “The subsequent fate of a dust particle settling upon the alveolar surface may be one of four possibilities. It may be:

- “1. Transported to the mucous blanket of the tracheobronchial mucosa,
2. Transported to the satellite lymph nodes draining the lungs,
3. Sequestered within the lung by a tissue reaction (pneumoconiosis),
4. Dissolved and transferred in solution to the blood stream or become bound to the tissue substance in the lungs.”

For the first three possibilities the initial occurrence is the phagocytosis of the particle. For cytotoxic materials, such as plutonium and americium, the phagocytic cells may be killed and subsequently disintegrate and the particles be released, followed by rephagocytosis. Aggregates, plaques, and nodules tend to form “where limited dust clearance and alveolar stasis are likely to occur, namely, in alveoli attached to relatively rigid structures such as bronchi, vessels, scars, and thickened plura.” (See Hatch and Gross.) These aggregates form the major constituents of the long-term lung burden.

Long-term clearance from the lung of the particles held in the aggregates results when the deposits are mobilized. “If the ingested dust kills the cell, the particulates will be redispersed as a result of cellular disintegration, or the sequestered dust may be mobilized by focal or localized edema, or from causes at present unknown.” (See Hatch and Gross.) A portion of the newly released particles may be

¹T. F. Hatch and P. Gross. *Pulmonary Deposition and Retention of Inhaled Aerosols*. Academic Press, New York. 1964.

²H. Gray. *Anatomy of the Human Body*. C. M. Goss, Editor. Lea and Febiger, Philadelphia, Pennsylvania. 1948.

³*Op. cit.*

rephagocytized and transported (passively) to the tracheobronchial mucous blanket.

Bair *et al.* (1974)⁴ suggest that translocation and clearance from the lung can also occur from dissolution of plutonium particles and absorption into the blood. "It seems certain that dissolution of plutonium particles and aggregates does occur in the lung, although at low rates, and accounts for at least some of the mobility of plutonium in the lung as well as clearance from the lung."

Particles can be cleared from the alveoli by way of the lymphatic system, but must first penetrate the alveolar membrane and gain access to the interstitium. According to Hatch and Gross: "A greater portion [of particles in lymph nodes] appears to have originated from the alveolar dust plaques or nodules. Particles within such depots are already within the interstitium because . . . a nodule developing upon an alveolar wall causes the latter to lose not only its capillary but also its basement membranes. In a characteristic perivascular or peribronchial position, the dust is therefore no longer walled off from the interstitium by basement membranes. As the cells disintegrate and release the dust particles, the latter can now be carried into the interstitium by tissue fluid which normally flows toward the lymphatics." Particles released from disintegrated phagocytic cells, however, may still be retained in a matrix of fibrous tissue and thereby be impeded from translocating from the retention site.

Particles which reach the interstitium are transported by the lymphatic system to the pulmonary lymph nodes, located along the bronchial tree and along the pulmonary vessels. Some deposition may also occur in the other tracheobronchial lymph nodes. According to Bair *et al.*,⁵ the plutonium particles in the lymph nodes "eventually appear sequestered in 'hot spots' of scar tissue and do not appear to be mobile. The residence time for plutonium in lymph nodes appears to be very long; there is no direct evidence for clearance of inhaled plutonium particles from thoracic lymph nodes . . ."

⁴W. J. Bair, C. R. Richmond, and B. W. Wachholz. *A Radiobiological Assessment of the Spatial Distribution of Radiation Dose from Inhaled Plutonium*. Report WASH-1320. U. S. Atomic Energy Commission, Washington, D. C. 1974.

⁵*Ibid.*

The Task Group of the International Commission on Radiological Protection (ICRP), on Lung Dynamics (Morrow *et al.* 1966)⁶ developed a deposition and clearance model in an attempt to define and quantify deposition and clearance parameters for dust particles in the lung. This model is called the *Task Group Lung Model* or TGLM.

The TGLM classifies inorganic compounds according to the degree of retention in the lung. Class-D compounds are characterized by minimal retention and rapid clearance (days); Class-W compounds by moderate retention and intermediate clearance rates (weeks); and Class-Y compounds by avid retention with slow clearance (years). The oxides and fluorides of plutonium and americium are considered to be Class-Y compounds, while the nitrates and halides (except the fluorides) of plutonium and americium are considered to be Class-W compounds. The TGLM considered that for Class-Y compounds 40% of the total initial amount deposited in the pulmonary regions of the lung is removed rapidly with a biological half-life of one day. The remainder is removed with a half-life of 360 days with 8.33% of that amount being dissolved and removed by the blood, 66.67% removed by phagocytosis and the muco-ciliary transport via the tracheo-bronchial system to the gastrointestinal tract, and 25% cleared by the lymphatic system. Of the amount cleared to the lymph nodes, 90% was considered to be permanently retained in the lymph nodes and 10% cleared from the lymph nodes with a half-life of 360 days.

The Task Group (ICRP, 1972)⁷ has subsequently amended some of these values, increasing the biological half-life for the retained portion from 360 days to 500 days and favoring less avid retention in the lymph nodes. The fraction permanently retained in the lymph nodes was changed to 10% with 90% subject to clearance from the lymph nodes with a 1000-day half-life.

⁶P. E. Morrow, D. V. Bates, B. R. Fish, T. F. Hatch, and T. T. Mercer. "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract." *Health Physics* 12:173. 1966.

⁷*International Commission on Radiological Protection*. "The Metabolism of Compounds of Plutonium and Other Actinides. A Report prepared by a Task Group of Committee 2 of the International Commission on Radiological Protection." ICRP Publication 19. Pergamon Press, Oxford, England. 1972.

THEORY

The count from the detectors over the surface of the chest is from americium in the chest cavity, both in the lungs and in the lymph nodes. The americium is subject to translocation and retention mechanisms in both the lung and the lymph nodes. The americium is also produced from the decay of ^{241}Pu and is transformed by its own physical decay. The amount of americium in the lymph nodes relative to the amount in the lungs, as a function of time after exposure, is governed by the rate of movement of both Am and Pu from the lung, the fraction of each which translocates to the lymph nodes, and the rate of removal from the lymph nodes. Also included in the considerations are the possibility of permanent retention in the lungs or lymph nodes or both of a portion of the Am and Pu, the physical ingrowth of ^{241}Am from ^{241}Pu at the residence site of the Pu, and the physical decay of both Am and Pu.

To develop an equation to give the amount of americium in the lymph nodes as a function of time after exposure (not including the rapidly-removed component), assume that, as in the TGLM, removal of Am and Pu from the lungs and from the lymph nodes is exponential. The differential equation expressing the rate of accumulation of americium in the lymph nodes is:

$$\frac{dA_{LN}}{dt} = \lambda_1 N_1 - \lambda_A A_{LN} + f_{AL} \lambda_{TAL} A_L - \lambda_{TA} A_{LN} \quad (1)$$

Where, A_{LN} = amount of americium-241 (^{241}Am) in the lymph nodes at time t after exposure

(lambda) λ_1 = decay constant of plutonium-241 (^{241}Pu)

N_1 = amount of ^{241}Pu in the lymph nodes at time t after exposure

λ_A = decay constant of ^{241}Am

f_{AL} = fraction of ^{241}Am in the lungs which translocates to the lymph nodes

λ_{TAL} = biological removal constant of ^{241}Am from the lungs = $\ln 2 / T_{TAL}$

T_{TAL} = translocation half-life of ^{241}Am from the lungs

A_L = amount of ^{241}Am in the lungs at time t after exposure

λ_{TA} = biological removal constant of ^{241}Am from the lymph nodes = $\ln 2 / T_{TA}$

T_{TA} = translocation half-life of ^{241}Am from the lymph nodes

The term $(\lambda_1 N_1)$ represents the growth of ^{241}Am from the decay of ^{241}Pu ; the term $(\lambda_A A_{LN})$ represents the physical decay of ^{241}Am ; the term $(f_{AL} \lambda_{TAL} A_L)$ represents the Am coming to the lymph nodes from translocation from the lungs; and $(\lambda_{TA} A_{LN})$ represents the loss of Am from the lymph nodes by biological removal.

Both N_1 and A_L vary as a function of time, and equations must be developed for these quantities before Equation 1 can be solved. The rate of accumulation of ^{241}Pu in the lymph nodes is given by:

$$\frac{dN_1}{dt} = f_{PL} \lambda_{T1L} N_{1L} - \lambda_1 N_1 - \lambda_{T1} N_1 \quad (2)$$

Where, f_{PL} = fraction of ^{241}Pu in the lungs which translocates to the lymph nodes

λ_{T1L} = biological removal constant of ^{241}Pu from the lungs = $\ln 2 / T_{T1L}$

T_{T1L} = translocation half-life of plutonium from the lungs

N_{1L} = amount of ^{241}Pu in the lungs at time t after exposure

λ_{T1} = biological removal constant of ^{241}Pu from the lymph nodes = $\ln 2/T_{T1}$

T_{T1} = translocation half-life of plutonium from the lymph nodes

The term $(f_{PL}\lambda_{T1L}N_{1L})$ represents the amount of ^{241}Pu coming to the lymph nodes from the lungs, and the terms $(\lambda_1 N_{1L})$ and $(\lambda_{T1} N_{1L})$ represent the rate of decrease of ^{241}Pu in the lymph nodes from physical decay and biological removal, respectively.

The quantity, N_{1L} , also varies as a function of time after exposure, and an equation for N_{1L} must be developed before Equation 2 can be solved. The amount of ^{241}Pu in the lung as a function of time after exposure, N_{1L} , is obtained by solving the equation:

$$\frac{dN_{1L}}{dt} = -\lambda_1 N_{1L} - \lambda_{T1L} N_{1L} \quad (3)$$

Equation 3 indicates that the rate of loss of ^{241}Pu from the lung is governed by the rate of physical decay $(\lambda_1 N_{1L})$ and the rate of translocation from the lung $(\lambda_{T1L} N_{1L})$.

Solution of Equation 3 yields:

$$N_{1L} = N_{0L} \exp \left[-(\lambda_1 + \lambda_{T1L})t \right] \quad (4)$$

Where, N_{0L} = amount of ^{241}Pu in the lungs at $t = 0$ (not including the rapidly cleared component).

Substituting the equation for N_{1L} into Equation 2 and solving for N_1 yields:

$$N_1 = \frac{f_{PL}\lambda_{T1L}N_{0L}}{\lambda_{T1} - \lambda_{T1L}} \left\{ \exp \left[-(\lambda_1 + \lambda_{T1L})t \right] - \exp \left[-(\lambda_1 + \lambda_{T1})t \right] \right\} \quad (5)$$

The amount of ^{241}Am in the lungs at time t after exposure, A_L , is obtained by solving the equation:

$$\frac{dA_{LN}}{dt} = \lambda_1 N_{1L} - \lambda_A A_L - \lambda_{TAL} A_L \quad (6)$$

Equation 6 indicates that the rate of change of the amount of ^{241}Am in the lung is governed by the production of ^{241}Am from the decay of ^{241}Pu $(\lambda_1 N_{1L})$ and by the loss of ^{241}Am by physical decay $(\lambda_A A_L)$ and by biological removal $(\lambda_{TAL} A_L)$.

Substituting the equation for N_1 and solving for A_L yields:

$$A_L = \frac{\lambda_1 N_{0L}}{\lambda_A + \lambda_{TAL} - \lambda_1 - \lambda_{T1L}} \cdot \left\{ \exp \left[-(\lambda_1 + \lambda_{T1L})t \right] - \exp \left[-(\lambda_A + \lambda_{TAL})t \right] \right\} + A_{0L} \exp \left[-(\lambda_A + \lambda_{TAL})t \right] \quad (7)$$

Where A_{0L} = amount of ^{241}Am in the lungs at time $t = 0$ (not including the rapidly cleared component).

Substituting the expression of N_1 (Equation 5) and A_L (Equation 7) into Equation 1 and solving yield the equation for the amount of ^{241}Am in the lymph nodes as a function of time after exposure:

$$\begin{aligned}
A_{LN} = & \frac{f_{PL} \lambda_1 \lambda_{T1L} N_{OL}}{(\lambda_{T1} - \lambda_{T1L}) (\lambda_A + \lambda_{TA} - \lambda_1 - \lambda_{T1L})} \left\{ \exp[-(\lambda_1 + \lambda_{T1L})t] - \exp[-(\lambda_A + \lambda_{TA})t] \right\} \\
& - \frac{f_{PL} \lambda_1 \lambda_{T1L} N_{OL}}{(\lambda_{T1} - \lambda_{T1L}) (\lambda_A + \lambda_{TA} - \lambda_1 - \lambda_{T1})} \left\{ \exp[-(\lambda_1 + \lambda_{T1})t] \right. \\
& \quad \left. - \exp[-(\lambda_A + \lambda_{TA})t] \right\} \\
& + \frac{f_{AL} \lambda_1 \lambda_{TAL} N_{OL}}{(\lambda_A + \lambda_{TAL} - \lambda_1 - \lambda_{T1L}) (\lambda_A + \lambda_{TA} - \lambda_1 - \lambda_{T1L})} \left\{ \exp[-(\lambda_1 + \lambda_{T1L})t] \right. \\
& \quad \left. - \exp[-(\lambda_A + \lambda_{TA})t] \right\} \\
& + \frac{f_{AL} \lambda_1 \lambda_{TAL} N_{OL}}{(\lambda_A + \lambda_{TAL} - \lambda_1 - \lambda_{T1L}) (\lambda_{TAL} - \lambda_{TA})} \left\{ \exp[-(\lambda_A + \lambda_{TAL})t] \right. \\
& \quad \left. - \exp[-(\lambda_A + \lambda_{TA})t] \right\} \\
& + \frac{f_{AL} \lambda_{TAL} A_{OL}}{\lambda_{TA} - \lambda_{TAL}} \left\{ \exp[-(\lambda_A + \lambda_{TAL})t] - \exp[-(\lambda_A + \lambda_{TA})t] \right\} \quad (8)
\end{aligned}$$

The first four terms in Equation 8 pertain to the movement of the ^{241}Pu , the production of the ^{241}Am from the decay of ^{241}Pu , and the translocation of the ^{241}Am which originated from the decay of the ^{241}Pu . The fifth term describes the translocation and loss by physical decay of the original ^{241}Am . In general, Equation 8 describes the amount in the lymph nodes of a daughter radionuclide in the presence of its parent. If one were dealing with a radionuclide which did not involve the parent, the accumulation of that radionuclide in the lymph nodes would be given by only the fifth term in Equation 8.

For the case where more than one component might exist in the lymph nodes, governed by different biological removal constants, the total amount of americium accumulated in the lymph nodes, A_{LN} , is the sum of the values of A_{LN} calculated for each component weighted by the fraction f of the americium subject to that translocation half-life:

$$A_{LN} = f_1 (A_{LN})_1 + f_2 (A_{LN})_2 + \dots \quad (9)$$

If one component were considered to be permanently retained, a long removal half-life could be assigned to that component for calculation purposes.

Similarly, if there is more than one component of the americium or plutonium, or both in the lung, component values of A_{LN} would be calculated separately, weighted to reflect the fraction subject to that retention half-life, and summed to give the total value of A_{LN} . This procedure would also apply to the determination of the total value of A_L .

The sum of A_L and A_{LN} gives the total amount of americium in the chest cavity. If one assumes the counting geometry for americium in the chest cavity does not depend on the relative amounts in the lungs and lymph nodes, the count obtained by detectors placed over the surface of the chest would be directly proportional to the sum of A_L and A_{LN} .

The ratio $A_L/(A_L + A_{LN})$ is then the fraction of the total count coming from the americium in the lungs. A calculation of the lung burden based on the total count would yield a value of the lung burden which would be higher than the actual lung burden (independently of other sources of error) by a factor equal to $(A_L + A_{LN})/A_L$, since the lymph-node burden is considered to be separate from the lung burden. This factor will be called the error factor.

Figure 1 shows calculated error factors for selected values of translocation parameters for Pu and Am for a two-component retention. The solid curves represent the error factor when 90% of the plutonium and americium in the lymph nodes is subject to the shorter retention and the remaining 10% translocates with a half-life of 100 years. The dashed curves represent the error factor when 10% is subject to the shorter retention and 90% is retained indefinitely (half-life = 100 years for calculation purposes). The fraction of the Pu and Am in the lung which is subject to clearance via the lymph nodes (symbolized $f_{L \rightarrow LN}$) is taken as 0.25. Values of A_{0L} and N_{01} used in the calculation are 1000 and 5000, respectively. It is seen that error factors can be quite large, especially for values of translocation half-lives from the lung which are one year or less.

The values of translocation parameters recommended by the International Commission on Radiological Protection (ICRP) for Class-Y compounds for use with the TGLM Clearance Model are:

$$T_{TAL} = T_{T1L} = 500 \text{ days}$$

$$T_{TA} = T_{T1} = 1000 \text{ days}$$

$$f_{L \rightarrow LN} = 0.25 \text{ (of the 500-day fraction)}$$

$$\text{Fraction in lymph nodes subject to 1000-day clearance} = 0.9$$

The error factor calculated for these values as a function of time after exposure is presented in Figure 2 (solid line). The dashed line represents the error factor if the fraction in the lymph node subject to the shorter clearance time were 0.1, and

0.9 were retained *permanently* (100-year half-life). For the ICRP values, an error factor of 2 would

FIGURE 1. Error Factors for Sets of Selected Values of Translocation Half-Lives.

Légend

$$T_{TAL} = T_{TIL} = 500 \text{ days}$$

$$T_{TA} = T_{T1} = 1000 \text{ days}$$

$$f_{L \rightarrow LN} = 0.25$$

- 0.9 of lymph-node burden clears with half-life of 1000 days
- - - 0.1 of lymph-node burden clears with half-life of 1000 days

(The remainder clears with half-life of 100 years)

FIGURE 2. Error Factor as a Function of Time after Exposure for Task Group Lung Model Amended Constants (Class-Y Compounds).

result four years after exposure, and a factor of 4, seven years after exposure. The value of the error factor is independent of the value of the initial parts per million (ppm) Am, whenever the translocation half-lives of Pu and Am are equal.

For Class-W compounds the recommended values for use with the TGLM Clearance Model are:

$$T_{TAL} = T_{TIL} = 50 \text{ days}$$

$$T_{TA} = T_{T1} = 50 \text{ days}$$

$$f_{L \rightarrow LN} = 0.083 \text{ (of the 50-day fraction)}$$

Fraction in the lymph nodes subject to the 50-day clearance = 1.0

For times after exposure greater than two years, the amounts remaining in both the lungs and the lymphs are negligible for these values. Since no retention occurs in the lymph nodes for Class-W compounds, the error factor is not significant for the TGLM recommended constants for Class-W compounds.

ANALYSIS OF EXPOSURE CASES

A series of counts over a period of time for an individual with a positive amount of americium in his chest cavity yields a count history for that person. The net count divided by the *initial* count as a function of the time after exposure gives a count profile. This count profile can be compared with a calculated count profile, obtained from $(A_L + A_{LN})/A_{0L}$ as a function of time. The *initial* count does not include the component which is rapidly cleared (in the first several days) from the lungs, but rather is obtained by extrapolating the count history for the remaining component to the time of the exposure. Count profiles for ten persons are analyzed by matching with calculated count profiles in order to obtain insight into possible values for the retention and translocation parameters.

Case A:

Case A was exposed to plutonium oxide containing 52 ppm ^{241}Am and 0.5% ^{241}Pu . The counts were made with the detectors placed at the sides of the chest. The count profile for Case A is presented in Figure 3 along with several calculated profile matches. The combinations of values of the translocation parameters which yield these matches are

Legend

Curve	T_{TAL}	T_{TIL}	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA}	T_{TI}
A	0.2	0.3	0.84	0.25	1.0	1.5
B	0.4	0.6	0.68	0.3	0.6	1.0
C	0.6	1.0	0.50	0.4	1.0	1.5
D	1.0	1.0	0.34	0.5	1.5	2.0
E	1.5	1.5	0.14	0.9	2.0	2.5
F	2.0	2.0	0	—	—	—
TGLM	1.37	1.37	0.25	0.1	2.74	2.74

$A_{OL} = 52$

TGLM = Task Group Lung Model

---●--- = Typical error limits (one standard deviation)

Translocation half-lives in units of years

FIGURE 3. Case-A Count Profile and Selected Matches.

presented in Table I. The half-life for translocation of the americium from the lungs for these matches ranges from 0.2 to 2.0 years. The higher values of the half-lives correspond to lower values of the fraction translocating to the lymph nodes and to higher values of the fraction retained in the lymph nodes. For comparison, the TGLM combination of values for Class-Y compounds is also presented in Table I.

The possibility exists that a fraction of the initial (long-term) amount in the lungs may be retained in the lungs and not be subject to translocation. For calculation purposes, this fraction will be considered to translocate from the lungs with a half-life of 100 years for both the plutonium and the americium.

Analysis of the count profile with this consideration yields the result that each of the profile matches (except Match F) for the parameters in Table I can be duplicated within $\pm 1\%$ for values of the fraction retained in the lungs ranging from zero to the values listed in Table II. The values listed in Table II also correspond to zero-long retention in the lymph nodes.

The values in Table II indicate that for Case A the maximum fraction that could be retained in the lungs is approximately 0.2 of the initial (long-term) lung burden for a wide range of possible translocation half-lives. The fraction retained in the lungs can be any value between zero and this maximum factor and still yield duplicate matches. This feature is illustrated by the values in Table III

TABLE I. Values of Translocation Parameters which Yield Similar Profile Matches for Case A.

Match	T_{TAL} (years)	T_{TIL} (years)	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{TI} (years)	Error Factor (time = 4 years)
A	0.2	0.3	0.84	0.25	1.0	1.5	>100
B	0.4	0.6	0.68	0.30	0.6	1.0	66
C	0.6	1.0	0.50	0.40	1.0	1.5	10.4
D	1.0	1.0	0.34	0.50	1.5	2.0	4.4
E	1.5	1.5	0.14	0.90	2.0	2.5	1.7
F	2.0	2.0	0	—	—	—	1.0
	1.37	1.37	0.25	0.10	2.74	2.74	Tash Group Lung Model values for Class-Y Compounds (revised constants)

Legend

- T_{TAL} = translocation half-life of americium-241 from the lungs
 T_{TIL} = translocation half-life of plutonium from the lungs
 $f_{L \rightarrow LN}$ = fraction of plutonium and americium in the lung which is subject to clearance via the lymph nodes
 T_{TA} = translocation half-life of americium-241 from the lymph nodes
 T_{TI} = translocation half-life of plutonium from the lymph nodes

giving values which duplicate Match D within $\pm 1\%$ as a function of the fraction retained in the lungs.

The calculated error factor is presented in Tables I, II, and III for each set of values. The error factor ranges from unity (for no translocation to the lymph nodes) to a value greater than 100 (when the

translocation from the lungs is rapid and none is retained in the lungs). Retention in the lungs of a fraction of the initial amount has the effect of lowering the error factor toward unity (no error).

Case B:

Case B was exposed to plutonium oxide containing 275 ppm ^{241}Am and 0.5% ^{241}Pu . The Case B counts were obtained with the detectors at the sides of the chest. The count profile is presented in Figure 4 along with selected calculated profile matches. The values of the translocation parameters which yielded these matches are presented in Table IV.

TABLE II. Values of Translocation Parameters with Yield Duplicate Profile Matches to Corresponding Matches from Table I for Retention in the Lungs and Zero Retention in the Lymph Nodes.

Match	Fraction Retained in Lungs	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	Error Factor (time = 4 years)
A	0.211	0.796	0	1.38
B	0.209	0.594	0	1.36
C	0.201	0.379	0	1.28
D	0.184	0.177	0	1.20
E	0.126	0.022	0	1.03

TABLE III. Values of Translocation Parameters which Duplicate Match D for Various Values of the Fraction Retained in the Lungs.

Fraction Retained in lungs	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	Error Factor (time = 4 years)
0	0.34	0.50	4.35
0.05	0.30	0.45	2.55
0.10	0.26	0.33	1.78
0.15	0.22	0.15	1.38
0.184	0.177	0	1.20

Curve A in Figure 4 matches the initial drop, which may or may not be real, in the profile and indicates a rising count after one year from the ingrowth of americium from the plutonium retained in the lymph nodes. Curves B and C indicate a flatter profile. Translocation half-lives from the lungs of greater than one year would result in a calculated profile with an initial rise in the curve. Small values for the fraction retained in the lymph nodes would result in a calculated profile which decreases significantly several years after exposure. The actual count profile exhibits neither of these two features. For the larger values of the fraction retained in the lymph nodes, the values used for used for the half-lives of the fraction translocation from the lymph nodes are not significant.

Curve A can be duplicated within 1% by considering that up to 27% of the initial (long-term) amount in the lungs is retained in the lungs. Table V presents selected combinations of parameters which yield the duplication of Curve A.

Duplicate matches can be obtained for Curves B and C for up to 22.6 and 19.1% retained in lungs, respectively. As for Case A, the same count profile can be obtained whether the material is retained in the lymph nodes, in the lungs, or partially in both. In both cases, A and B, the retention is greater than predicted by the TGLM values.

FIGURE 4. Case-B Count Profile and Selected Matches.

TABLE IV. Values of Translocation Parameters which Yield Profile Matches for Case B.

Match	T_{TAL} (years)	T_{T1L} (years)	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{T1} (years)	Error Factor (time = 4 years)
A	0.2	0.4	0.30	0.90	0.6	1.0	>100
B	0.4	0.8	0.32	0.70	1.0	1.5	36
C	0.6	1.0	0.21	0.90	1.5	2.0	8.9

TABLE V. Combinations of Parameters which Duplicate Curve A in Figure 4 for Selected Values of the Fraction Retained in the Lungs.

Fraction Retained in Lungs	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	Error Factor (time = 4 years)
0	0.30	0.90	>100
0.05	0.27	0.86	5.5
0.10	0.23	0.83	2.8
0.20	0.13	0.72	1.38
0.25	0.08	0.41	1.11
0.271	0.041	0	1.00

The match obtained with the parameters presented in Table VI can be duplicated within 1%, if one considers that a fraction of the initial lung burden is retained in the lung indefinitely. This fraction can range from 0 to 0.13 when considered a part of the longer-term component in the lung. The higher the value of this fraction, the lower is the value of the fraction translocating from the lungs to the lymph nodes to obtain the duplication of the calculated profile. Table VII indicates the relationships of these parameters.

In relating the exposure of Case C to the TGLM, the exposure material can be considered to be a combination of Class-W and Class-Y compounds. The calculated TGLM match does not adequately match the observed count profile, no matter what fraction is attributed to the Class-W component or to the Class-Y component. The initial decrease in the count profile is more rapid than predicted for Class-W compounds, and the gradual increase in the profile after two years reflects more retention than reflected by the TGLM.

Case C:

Case C was exposed to plutonium containing 480 ppm ^{241}Am and 0.5% ^{241}Pu . The plutonium involved in this exposure was a mixture of plutonium oxide and plutonium chloride. The chelating agent, diethylenetriamine-pentaacidic acid (DTPA), was administered to Case C, both by injection and by inhalation, during the first 0.71 of a year after the exposure. The count profile is presented in Figure 5. The calculated profile match was obtained by considering two separate components in the lungs, one component subject to short translocation half-lives and the other component subject to longer half-lives.

This type of analysis could apply to a situation where one component is more soluble than the other. Each component was considered to translocate independently of the other. The calculated profile match, presented in Figure 5, was obtained using the values of the translocation parameters presented in Table VI. The shorter term component matches the initial drop in the count profile during the first 0.1 of a year after the exposure.

Case D:

Case D was exposed to plutonium oxide containing 1000 ppm ^{241}Am and 0.5% ^{241}Pu and received DTPA treatment by injection during the first year after exposure. The count profile for Case D, presented in Figure 6, is essentially flat over a period of more than five years. Values of translocation parameters for selected matches to the count profile are presented in Table VIII.

Values for half-lives of translocation from the lungs range from 0.5 to 4.0 years. The shorter half-lives are associated with higher values of the fraction translocating from the lungs to the lymph nodes and with lower values for the fraction retained in the lymph nodes. The high error factors for Matches A and B reflect the small amounts remaining in the lungs compared to the amount in the lymph nodes after several half-lives.

Matches A through E can be duplicated within 1% if one considers that retention occurs in the lungs

Legend							
	Component Fraction	T_{TAL} (years)	T_{T1L} (years)	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{T1} (years)
Profile Match	0.55	0.05	0.10	0.30	0.40	0.10	0.20
	0.45	1.0	1.5	0.30	0.90	2.0	3.0

$$A_{0I} = 480$$

Task Group Lung Model — Class-W Component = 0.55

— Class-Y Component = 0.45

$\pm$ — Typical error limits (one standard deviation)

DTPA = Diethylenetriamine-pentaacetic acid

FIGURE 5. Case-C Count Profile and Calculated Match.

TABLE VI. Values of Translocation Parameters which Yield the Profile Match for Case C.

Fraction in the Component	T_{TAL} (years)	T_{T1L} (years)	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{T1} (years)
0.55	0.05	0.10	0.30	0.40	0.10	0.20
0.45	1.0	1.5	0.30	0.90	2.0	3.0

Legend

Curve	T_{TAL}	T_{TIL}	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA}	T_{T1}
A	0.5	0.5	0.98	0.45	1.0	1.0
B	1.0	1.5	0.70	0.50	2.0	3.0
C	1.7	2.0	0.50	0.60	3.0	4.0
D	2.5	3.0	0.32	0.90	3.0	4.0
E	4.0	4.0	0.15	0.90	5.0	5.0
TGLM	1.37	1.37	0.25	0.10	2.74	2.74

$A_{OL} = 1000$

Translocation half-lives in units of years

= Typical error limits (one standard deviation)

DTPA = Diethylenetriamine-pentaacetic acid

TGLM = Task Group Lung Model

FIGURE 6. Case-D Count Profile and Selected Matches.

TABLE VII. Combinations of Parameters which Yield Duplication of Calculated Profile Match for Case C Considering Long-term Retention in the Lungs.

Fraction Retained in Lungs	Fraction Subject to Slower Rate of Translocation	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	Error Factor (time = 3 years)
0	0.45	0.30	0.9	3.43
0.05	0.40	0.21	0.9	2.15
0.10	0.35	0.09	0.9	1.59
0.13	0.32	0	0	1.51

TABLE VIII. Values of Translocation Parameters which Yield Profile Matches for Case D.

Match	T_{TAL} (years)	T_{T1L} (years)	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{T1} (years)	Error Factor (time = 5 years)
A	0.5	0.5	0.98	0.45	1.0	1.0	>100
B	1.0	1.5	0.70	0.50	2.0	3.0	7.8
C	1.7	2.0	0.50	0.60	3.0	4.0	2.20
D	2.5	3.0	0.32	0.90	3.0	4.0	1.83
E	4.0	4.0	0.15	0.90	5.0	5.0	1.18

TABLE IX. Translocation Parameters which Yield Duplication of Matches A through E for Case D for Zero Retention in the Lymph Nodes.

Match	Fraction Retained in Lungs	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes
A	0.443	0.967	0
B	0.355	0.540	0
C	0.306	0.287	0
D	0.296	0.045	0
E	0.142	0.015	0

TABLE X. Values of Translocation Parameter which Yield Duplication of Match A for Case D for Selected Values of the Fraction Retained in the Lungs and the Calculated Error Factors.

Fraction Retained in Lungs	$f_{L \rightarrow LN}$	Fraction Retained in Lymph Nodes	Error Factor (time = 5 years)
0.00	0.98	0.45	>100
0.10	0.977	0.390	4.74
0.20	0.975	0.311	2.37
0.30	0.973	0.209	1.59
0.40	0.970	0.073	1.19
0.443	0.967	0.000	1.09

as well as, or instead of, in the lymph nodes. Table IX presents the values of the translocation parameters which yield duplication for zero retention in the lymph nodes.

For retention both in lungs and lymph nodes the values of the translocation parameters will range between those listed in Table VIII and the corresponding values listed in Table IX.

Retention in the lungs has the effect of lowering the error factor. This is illustrated for Case D by considering the duplication of Match A as a function of the fraction retained in the lungs. These values are presented in Table X.

Cases E through J:

Cases E through J were exposed to plutonium oxide with 1830 ppm ^{241}Am and 0.5% ^{241}Pu from a plutonium fire. These count profiles are presented as a composite in Figure 7 and cover a period of nine years. The general profile of the composite is matched by considering translocation of americium and plutonium from the lungs with respective half-lives of 0.2 and 0.4 years with 30 to 44% translocation to the lymph nodes where 90% of that amount is retained in the lymph nodes. Profile matches, represented by Curves A and B in Figure 7 and Table XI, can be duplicated within less than 1% by considering that a fraction of the initial americium and plutonium in the lungs is retained there indefinitely.

TABLE XI. Values of Translocation Parameters which Duplicate the Calculated Profile Matches A and B for Cases E through J for Selected Values of the Fraction Retained in the Lungs.

Curve	T_{TAL} (years)	T_{T1L} (years)	Fraction Retained in Lungs	$f_{\text{L} \rightarrow \text{LN}}$	Fraction Retained in Lymph Nodes	T_{TA} (years)	T_{T1} (years)	Error Factor (time = 10 years)
A	0.2	0.4	0	0.44	0.90	1.0	1.5	>100
			0.05	0.41	0.89			7.96
			0.10	0.38	0.87			3.99
			0.20	0.30	0.82			1.99
			0.30	0.20	0.69			1.32
			0.35	0.08	0.09			1.01
			0.397	0.072	0.00			1.00
B	0.2	0.4	0	0.30	0.90	1.0	1.5	>100
			0.05	0.26	0.89			5.41
			0.10	0.22	0.86			2.71
			0.20	0.12	0.74			1.36
			0.25	0.065	0.43			1.08
			0.27	0.042	0.00			1.00

FIGURE 7. Count Profiles of Cases E, F, G, H, I, and J and Two Calculated Matches. →

FIGURE 7. (continued)

To achieve duplication, values of translocation to and retention in the lymph nodes decrease as the fraction considered to be retained in the lungs increases. Values of the parameters which yield duplication of Curves A and B are presented in Table XI for selected values of the fraction retained in the lungs.

The error factor at 10 years is also presented in Table XI. When no long-term retention occurs in the lungs, the error factor is high because little plutonium or americium remains in the lungs after 10 years for relatively short translocation half-lives. If the retention occurs in the lungs instead of the lymph nodes, the error factor approaches unity (no error).

DISCUSSION

Equations were derived which allow calculation of the count profiles for values of retention and translocation parameters for americium and plutonium in the lungs and lymph nodes. The error factor for combinations of values of these parameters can also be calculated.

Application of these equations depends upon knowing the appropriate values of the translocation and retention parameters. Some guidance in the choice of the appropriate values of the parameters is given by the TGLM. Further insight into the possible values was sought by examining the actual count profiles for ten exposure cases and matching calculated profiles to the observed profiles.

A number of combinations of values were found to yield an adequate match to the observed profile. It was also observed that for most of the cases, the combination of values recommended by the TGLM did not yield a match to the observed count profiles. The shape of the count profiles indicates that retention of a significant fraction of the initial amount does occur, but the site of that retention is not established.

Duplicate matches of each calculated profile can be obtained by considering retention in the lungs instead of, or in addition to, retention in the lymph nodes. A number of combinations of values of translocation and retention parameters exist to match each observed profile, but no common set of values was apparent which would yield an adequate match for all cases.

The count profile represents the amount of americium in the chest cavity as a function of time after exposure. The profile is affected by the plutonium only to the extent of being the source of ingrowth of additional americium, which becomes significant only for cases with low initial ppm americium or for long times after exposure. Hence, the values of translocation parameters, obtained from calculated matches to the count profiles, are less well-established for plutonium as compared to those for the americium.

With no retention in the lungs and with retention in the lymph nodes, the amount in the lymph nodes becomes significantly larger than the amount in the lungs for times after exposure of several multiples of the half-life of translocation from the lungs, and the error factor becomes large. After seven half-lives of translocation from the lung, the amount remaining in the lungs is less than 1% of the initial amount, and the count would reflect the lymph node burden instead of the lung burden. The error factor is significantly lowered if only 5 or 10% of the initial lung burden were retained in the lungs.

The actual values of the translocation and retention parameters were not established. For this reason, the actual error factor can not be determined. To be able to determine the actual error factor requires further insight into the actual values of the translocation and retention parameters for plutonium and americium for man. Even then, differences in exposure conditions and individual physiology may limit the applicability of such values for actual exposure cases.