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USE OF AERIN CODE FOR DETERMINING INTERNAL DOSES OF TRANSURANIC ISOTOPES

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USE OF AERIN CODE FOR DETERMINING INTERNAL DOSES OF TRANSURANIC ISOTOPES*

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ABSTRACT

The AERIN computer code is a mathematical expression of the ICRP Lung Model. The code was developed at the Lawrence Livermore National Laboratory to compute the body organ burdens and absorbed radiation doses resulting from the inhalation of transuranic isotopes and to predict the amount of activity excreted in the urine and feces as a function of time.

Over forty cases of internal exposure have been studied using the AERIN code. The code, as modified, has proven to be extremely versatile. The case studies presented demonstrate the excellent correlation that can be obtained between code predictions and observed bioassay data. In one case study a discrepancy was observed between an in vivo count of the whole body and the application of the code using urine and fecal data as input. The discrepancy was resolved by in vivo skull counts that showed the code had predicted the correct skeletal burden.

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INTRODUCTION

The AERIN code[1] is a mathematical expression of the ICRP Lung Model.[2] The code computes the organ burdens and the absorbed doses resulting from an acute, a chronic, or a series of acute inhalation exposures. In addition, the code predicts the amount of activity that is excreted daily in the urine and feces. Particle size of the inhaled material can be selected by the health physicist from a data bank of 13 diameters, ranging from 0.01 to 50.0 μm AMAD (activity median aerodynamic diameter), or the option is available to alter the values if he chooses. Also ICRP solubility class D, W, or Y may be selected to represent the inhaled material.

The code has been revised to permit the summing of organ burdens and absorbed doses resulting from exposure to a mixture of isotopes. Also, a pathway of absorption from the GI tract to the bloodstream has been included. Figure 1 is a schematic representation of the AERIN model, and Table 1 shows the fractions and biological half-lives given in ICRP 19 for various compartments of the AERIN model.

We have used the code, since its development, to review past internal exposures of employees to transuranic isotopes. Several of these persons who received intakes in the late 1940's and the early 1950's still have measurable activity in their bodies.

In this paper I report our experience in applying the AERIN code to several case studies. Also, several interesting observations made during this study are included. All of our internal exposures resulted from accidental intakes and thus are considered to be acute exposures.

To protect the identity of the individuals involved, I have normalized the data to arbitrary values so that identification of individual doses and body burdens are protected.

CASE STUDY 1: AN INHALATION EXPOSURE TO Am-241

Three employees were accidently exposed to airborne Am-241. Employee A and Employee B, who was standing beside A, inhaled a detectable amount of the americium. Employee C was standing several meters away from them and did not receive a significant intake.

Employees A and B have been monitored periodically since the accident by means of urine and fecal radioactivity counts and in vivo counts of the lung.

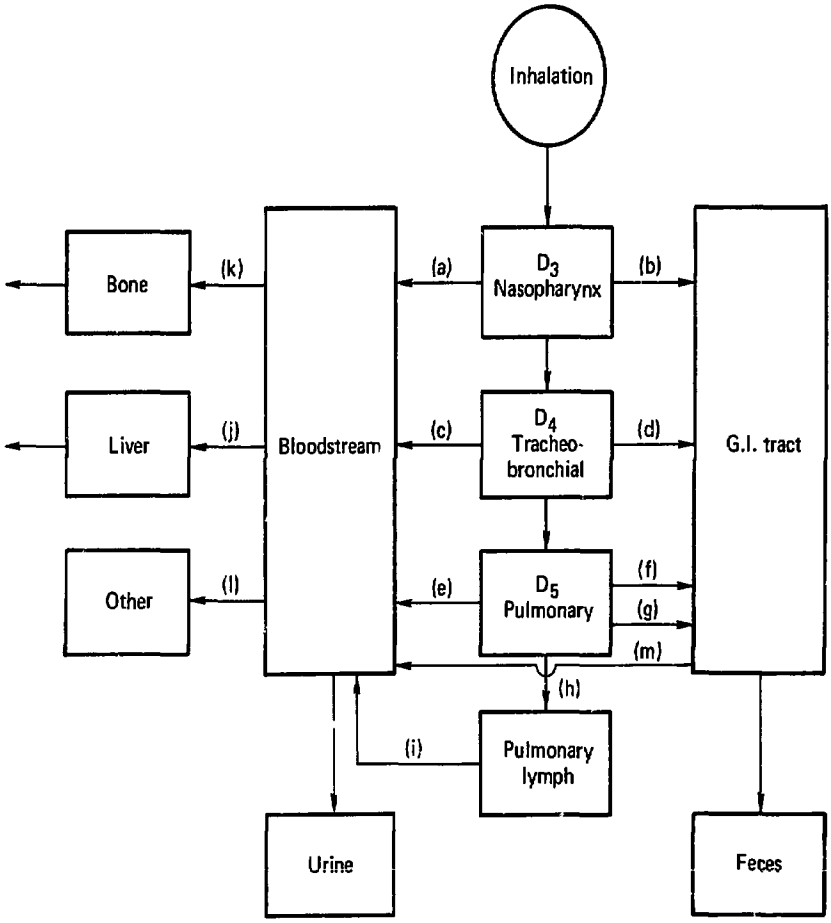

FIG. 1. Schematic representation of AERIN code model. Pathways (see Table 1) are shown in parentheses above the arrows. The deposit fractions are numbered D_3 to D_5.

TABLE 1. ICRP-19 values used in AERIN model.[a]

W Class		Y Class	
F (a) = 0.1	T (a) = 0.01 d	F (a) = 0.01	T (a) = 0.01 d
F (b) = 0.9	T (b) = 0.4 d	F (b) = 0.99	T (b) = 0.4 d
F (c) = 0.5	T (c) = 0.01 d	F (c) = 0.01	T (c) = 0.01 d
F (d) = 0.5	T (d) = 0.02 d	F (d) = 0.99	T (d) = 0.2 d
F (e) = 0.15	T (e) = 50 d	F (e) = 0.05	T (e) = 500 d
F (f) = 0.4	T (f) = 1 d	F (f) = 0.4	T (f) = 1 d
F (g) = 0.4	T (g) = 50 d	F (g) = 0.4	T (g) = 500 d
F (h) = 0.05	T (h) = 50 d	F (h) = 0.15	T (h) = 500 d
F (i) = 1.0	T (i) = 50 d	F (i) = 0.90	T (i) = 1000 d
F (j) = 0.45	T (j) = 0 d	F (j) = 0.45	T (j) = 0 d
F (k) = 0.45	T (k) = 0 d	F (k) = 0.45	T (k) = 0 d
F (l) = 0.20	T (l) = 0 d	F (l) = 0.20	T (l) = 0 d
F (m) = 0.00	T (m) = 0 d	F (m) = 0.00	T (m) = 0 d

$$U = 0.002\ t^{-0.74}$$

[a] F = fraction, T = biological half-life, and U = urine. Letters in parentheses refer to pathways.

Between these two individuals, both translocation and elimination patterns have been essentially the same.

Figure 2 displays the Am-241 activity observed in the lungs of Employee A. The error bars represent one standard deviation in the observed counts. Note that the rate curve for elimination of the activity from the lungs exhibits two components. I designated the short half-life component the "W" solubility class component. It has a pulmonary half-residency-time of 50 days. The other component, which I designated the "Y" class component, has a half-residency-time of 650 days. I have observed this dual solubility pattern in many cases of transuranic oxide inhalation.

In Fig. 2, the AERIN code prediction for Am-241 in the pulmonary region includes the americium in the lung, in the pulmonary lymph, and that incorporated in the bones of the chest region. From the code printout, I obtain the annual absorbed dose and the dose commitment to the lung, bone, and

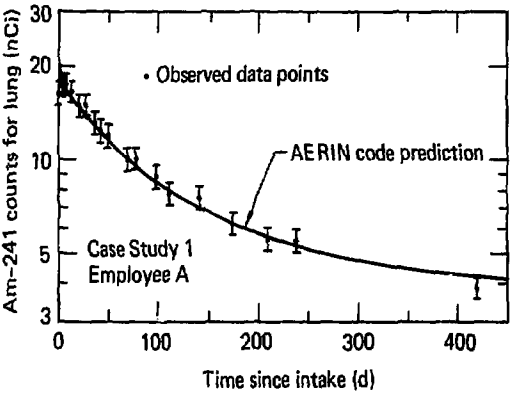

FIG. 2. The Am-241 activity in the lungs of Employee A as a function of time.

liver. I generally calculate the dose commitment to the various body organs out to 70 years of age.

I also compare the annual absorbed dose during the year of maximum deposition to the maximum allowable annual dose permitted under current, Federal, radiation-protection guides; this gives the fraction of permissible organ burden. I also compare the dose commitment at age 70 years to the commitment that could be received under the present guides.

In Case 1, the lung dose equivalent for Employee A for the first year after intake was 4.5 rem. Since 15 rem is the maximum permitted annual dose equivalent, Employee A, therefore, had a lung burden of 4.5/15 or 0.30 of the maximum permitted organ burden.

Employee A was 37 years of age at the time of the intake. His calculated dose commitment to age 70 is taken from the computer printout as 17.8 rem. Since there are 33 years remaining until this employee reaches age 70, his maximum permissible dose commitment to the lung is 33 years X 15 rem/year or 495 rem. The fraction of the maximum permissible dose commitment this employee now has is 17.8/495 or 0.036.

As the americium moves into the bloodstream, 45% is assumed to be incorporated in the bone, the value suggested in ICRP 19.[2] Depending on the quantity of initial intake and the solubility of the material inhaled, one would expect by making counts of the skull or knee, to observe the translocation of the americium to the bone. The AERIN code predicted that Employee A would have 0.24 nCi of Am-241 in the skull 420 days after the date

of intake. When we made counts of his skull on day 419, we found 0.23 nCi. This remarkable agreement helps confirm the validity of the model.

The maximum deposit in the bone, as projected by the code will occur between 10 and 11 years after the date of intake. The absorbed dose to the bone during the year of maximum deposition will be 0.043 rad. Using a quality factor of 10 for americium alpha particles and a nonuniform distribution factor of 5, I find the dose equivalent during the year of maximum deposition will be 2.17 rem. This represents 7.2% of the maximum permissible dose equivalent under the current radiation protection guides. The age-70-dose commitment to the bone for this employee, as given by the code, is 67 rem. The dose commitment permitted under current guides is 30 rem/year times 33 years or 990 rem. This exposure, therefore, represents 6.8% of the maximum permissible dose commitment.

Urine and fecal samples were also analyzed during the first few months following the accident. Figure 3 shows the urine data along with the AERIN code prediction. What is interesting about these data is that the activity in the urine began at a low value and then continued to rise until it peaked about 20 days following intake. Pathway A (see Fig. 1) from the nasopharnyx to the blood and Pathway C from the tracheobronchial compartment to the blood are, therefore, not evident in this case. This is not unusual, however, as other cases I have reviewed showed similar patterns.

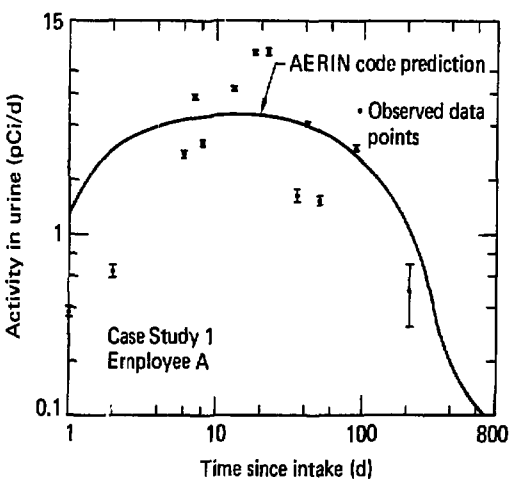

FIG. 3. The Am-241 activity in the urine of Employee A as a function of time.

Another interesting observation noted in using the AERIN model is that a good indication of the particle size of the inhaled material can be obtained by comparing the fecal activity with the urine activity. For large particles of the "W" and "Y" class (see Fig. 1), the fecal activity counts will be high compared to those of the urine, because more radioactive material will be deposited in the nasopharynx and tracheobronchial regions.

If the particle sizes are small, more of the radioactive material will be deposited in the pulmonary compartment, and the ratio of fecal activity to urine activity will be smaller. With experience in using the model, the health physicist will be able to select a proper particle size with few iterations of the code runs.

CASE STUDY 2: LARGE INTAKE OF Am-241 MORE THAN 25 YEARS AGO

When Employee D hired on at our Laboratory he already was carrying an internal burden of Am-241 but did not know about it. Several years later, he was assigned to a job that required routine urine analysis for alpha activity. His first sample showed a large alpha count, which we first thought resulted from a faulty analysis. However, a follow-up investigation of urine- and fecal-sample counts along with several whole-body counts verified that he indeed had an internal deposit of activity, which was identified as Am-241. The initial estimates of body burden made from the whole-body counts were in the range of 1.6 to 10.3 μCi, extremely high values. A review of this employee's work history indicated his intake must have occurred in 1952 or 1953.

Applying the AERIN model to the study of this exposure, I found the observed urine and fecal data did not support a body burden as high as that indicated by the whole-body count but rather one on the order of 100 to 200 times less. This discrepancy needed to be resolved.

A lung count made on this individual approximately 20 years after the estimated date of intake showed 12.2 ± 1.0 nCi of activity. I assumed that any activity detected in the lung after 20 years was due to the Am-241 deposited in the bones in the chest (i.e., ribs, sternum, clavicles, scapulae, and the thoracic vertebrae). Under this assumption, I knew from the data that the amount in the skeleton was probably no less than 37 nCi and could be as high as 309 nCi.

In 1977 we obtained two human skulls from New York University. The skulls had been coated with Am-241 and were used to calibrate our counters. We then made a skull count on Employee D and found the activity in the skull was 9.7 ± 0.14 nCi, which would indicate a burden of 73.9 ± 1.1 nCi in the skeleton. This value was compatible with the value determined by urine and fecal analyses.

By comparing the skull count with the lung count and assuming the lung count represented the activity deposited in the bones of the chest, we determined that a lung count detects approximately 15% of the skeletal burden. Table 2 is a chronological summary of the observations made in this case.

CASE STUDY 3: INHALATION OF Pu-239 IN 1959

Employee E inhaled weapons-grade plutonium in 1959 while working at another facility. When he hired on at our Laboratory, his urine still was registering plutonium activity. We continued to follow the elimination pattern until the levels fell below our minimum detection level. Figure 4 shows the plutonium activity in the urine as a function of time after the acute inhalation exposure. The solid curve represents the AERIN code predictions for the daily activity.

TABLE 2. Results for Employee D (Case Study 2).

Year of observation	Analysis	Activity (nCi)	Organ of reference
1962	Urine analyses	103	Whole body
1962	Whole body scan	1,650 to 10,300	Skeleton
1972	Lung count	12.2 ± 1.0	Bones in chest
1978	Urine analyses, using AERIN code	40 to 200	Whole body
1978	Skull count	73.9 ± 1.1	Skeleton
1978	Lung count of 1972	81 ± 7	Skeleton

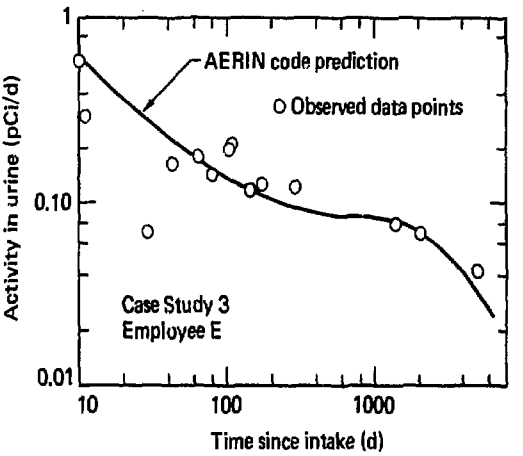

FIG. 4. The plutonium activity in the urine of Employee E as a function of time.

I will explain how we fit the AERIN code values to the observed urine data. By use of another code, I find the least-squares polynomial equation that best represents the data. I plot the curve of this equation along with the observed data. I then make iterative runs of the AERIN code selecting the parameters in the order shown in Fig. 5 until the curve generated by the code is forced to overlay as close as possible the curve of the polynomial equation. Once this is accomplished, a code run is made with the selected parameters and for the time interval extending to 70 years of age. The absorbed dose and dose commitments for the various organs are obtained from the code printouts.

Table 3 shows the various parameters used in this case study to obtain the best fit to the urine data. Table 4 is a comparison of in vivo counts of the lung and the code prediction. Again we assumed that some of the activity observed in the lung count comes from the deposits in the bones of the chest. Table 5 shows the maximum annual dose equivalents to the lung, bone, and liver with the age-70 dose commitment for this case.

1. Select solubility class D, W, Y, or a combination of two.
2. Select a particle size, using the activity data for feces and urine.
3. Select the fraction of activity that is deposited in each compartment of the model.
4. Select the biological half-life value for the material in each compartment.
5. Select the constants (f and m) in the urine elimination equation,

$$U(24) = f \cdot S_o \cdot t^{-m}$$

6. Select the intake quantity that will give the observed level of urine activity.

FIG. 5. Parameters used for fitting AERIN code values to observed data.

TABLE 3. Parameters used in Case Study 3 to fit AERIN code values to observed urine data. [a]

F(a) = 0.01	T(a) = 0.02 d
F(b) = 0.99	T(b) = 0.40 d
F(c) = 0.01	T(c) = 0.01 d
F(d) = 0.99	T(d) = 0.20 d
F(e) = 0.05	T(e) = 500 d
F(f) = 0.40	T(f) = 1 d
F(g) = 0.40	T(g) = 500 d
F(h) = 0.15	T(h) = 500 d
F(i) = 0.90	T(i) = 1,000 d
F(j) = 0.45	T(1) = 14,600 d
F(k) = 0.45	T(2) = 36,500 d
F(l) = 0.02	
F(m) = 0.00	

[a] See footnotes to Table 1 and refer to Fig 1.

TABLE 4. Comparison of *in vivo* counts of the lung with code prediction (Case Study 3).

	Lung Activity	
Date	Observed	Code
Jan. 1978	0.63 ± 0.26 nCi	0.76 nCi
May 1979	1.26 ± 0.52 nCi	0.74 nCi

TABLE 5. Maximum annual dose equivalents and dose commitments to lung, bone, and liver (Case Study 3, Employee E).

Organ	Annual dose (rem)	Fraction of maximum permissible	Age-70-dose commitment (rem)	Fraction of maximum permissible
Lung	11.3	0.75	46.4	0.0072
Bone	2.3	0.077	90.1	0.070
Liver	1.2	0.080	43.7	0.068

CASE 4: APPLICATION OF THE CODE TO A PLUTONIUM-CONTAMINATED WOUND

The AERIN code can also be used to calculate the organ burdens and the absorbed dose resulting from contamination of a wound. In this case, Employee F jabbed a plutonium-contaminated screwdriver into the fleshy part of his palm. When the wound was cleaned and treated by our Laboratory physician, 99.3% of the activity was removed. A series of counts made of the plutonium activity remaining at the wound site after the treatment are plotted in Fig. 6.

Figure 7 shows the equation that describes the residual activity in the wound with time. Because the movement of the material from the site of initial deposit into the bloodstream indicated materials with three very different half-lives, I modified the AERIN model to represent a

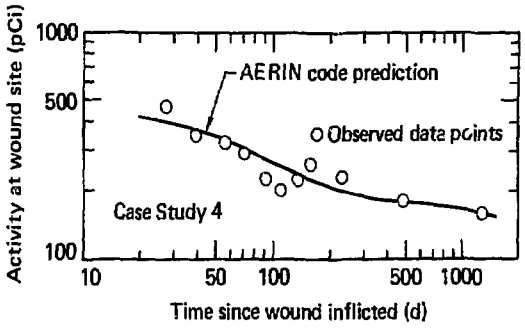

FIG. 6. The plutonium activity remaining at the wound site (Employee F) as a function of time.

three-compartment deposit, all compartments having pathways to the blood. (see Fig. 8). The values for the fraction and for the half-life of the material in each compartment were those given in the equation (see Fig. 7).

The activity counts of the urine for Employee F are shown in Fig. 9 along with the AERIN code prediction. The absorbed dose and dose commitments to the bone and liver are given in Table 6.

$$A = 0.22e^{-69.3t} + 0.29e^{-0.0141t} + 0.19e^{-0.000158t}$$

$T_{1/2}$: 14.4 min 49 d 4400 d

FIG. 7. Equation for describing residual plutonium activity in a contaminated wound.

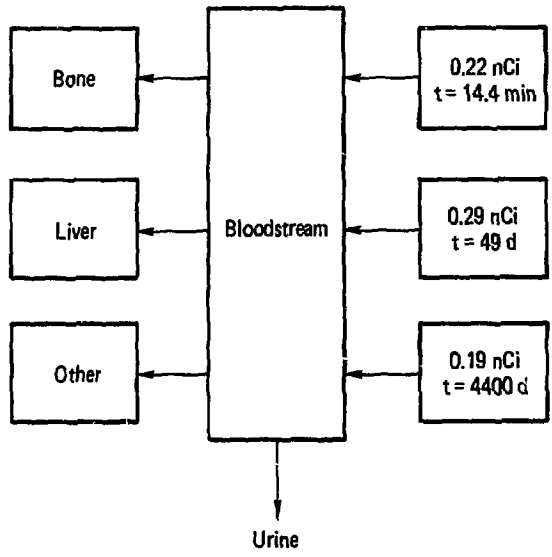

FIG. 8. AERIN code model modified to represent a three-compartment deposit.

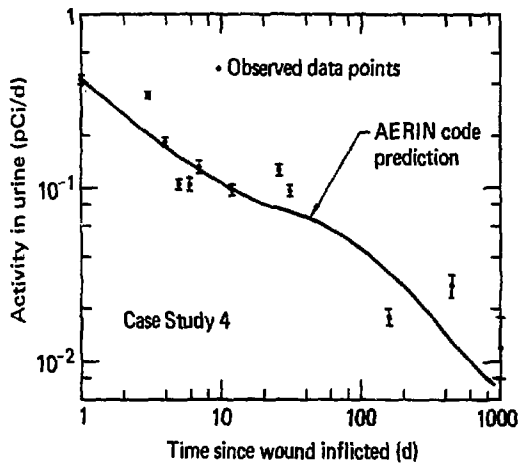

FIG. 9. The plutonium activity in the urine of Employee F as a function of time.

TABLE 6. Maximum annual dose equivalents and dose commitments to bone and liver for Employee F with plutonium contaminated wound (Case Study 4).

Organ	Annual dose (rem)	Fraction of maximum permissible	Age-70-dose commitment (rem)	Fraction of maximum permissible
Bone	0.25	0.008	7.57	0.008
Liver	0.13	0.009	3.85	0.009

SUMMARY

The cases presented here are typical of more than 40 that I have reviewed using the AERIN code. The ability to change the fractional distributions and the biological half-lives of the material in the various compartments makes the code extremely versatile, and the model may be adapted to almost any case of internal deposition one may wish to study.

At our Laboratory the code has been an effective tool for assessing internal doses. Used in connection with in vivo whole-body counting and urine and fecal analyses, the code accurately predicts dose commitments for exposed employees having internal deposits.

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2. International Commission on Radiological Protection, The Metabolism of Compounds of Plutonium and Other Actinides, ICRP Publication 19 (1972).

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