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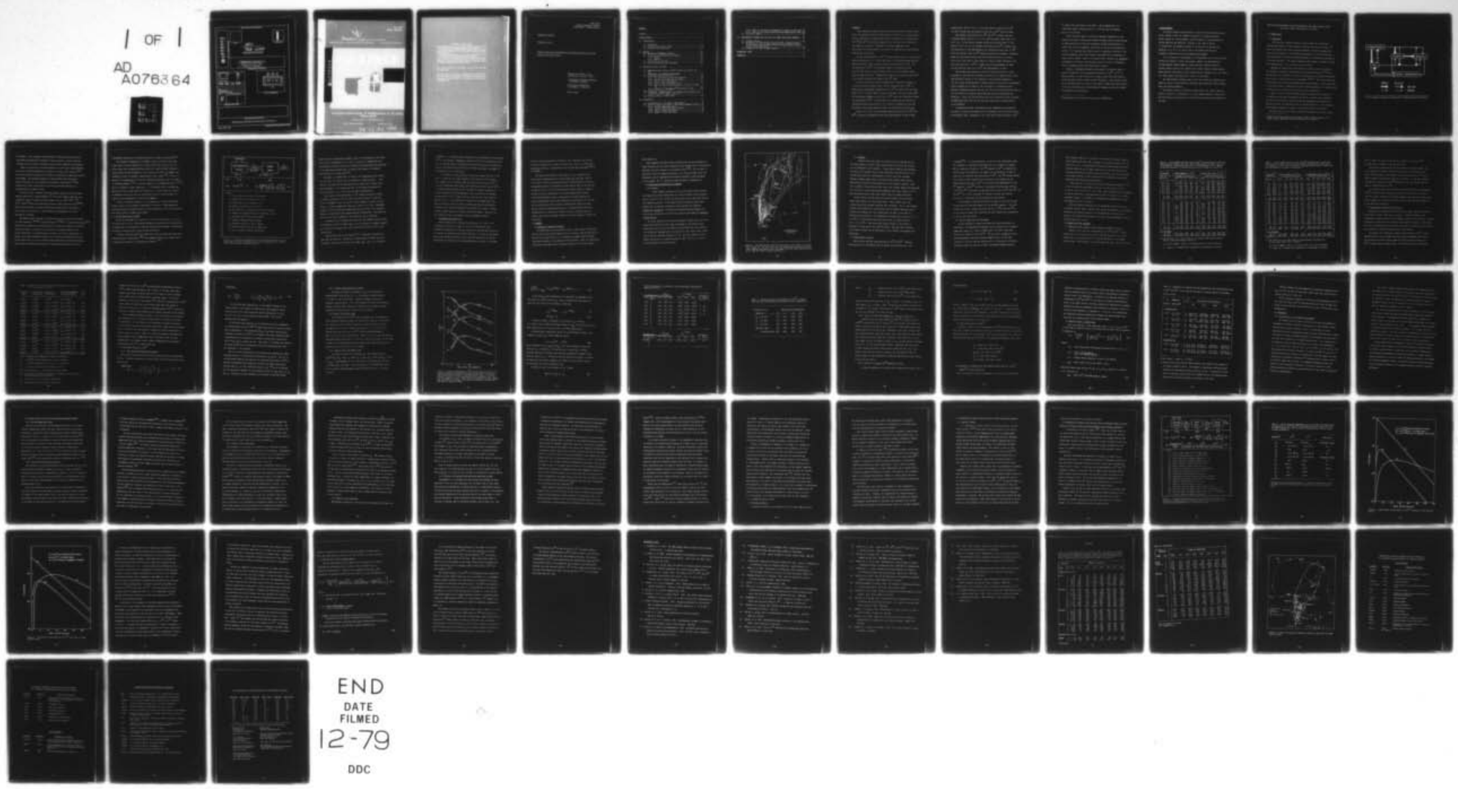

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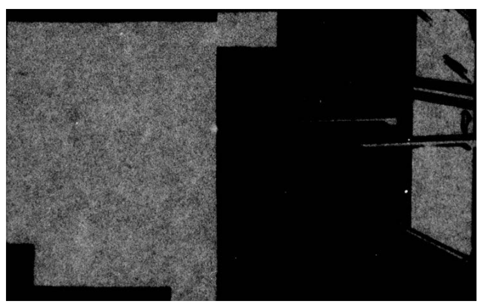

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PROJECT SEDAN

PROJECT 62.83

FOOD-CHAIN RELATIONSHIPS OF RADIOSTRONTIUM IN THE SEDAN FALLOUT FIELD

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Los Angeles, California

March 1965

69 p.

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ABSTRACT

Plant samples and rabbits were collected before and at various times after the detonation from 20 representative locations in the Sedan fallout field. Radiochemical analyses were made to determine the concentrations of Sr^{89} and Sr^{90} in dry plant samples and in the bone ash of rabbits at the times of collection. Estimates of initial gamma dose rates (R_o = mr/hr, 3 ft above ground, 24 hr after the detonation) were obtained from aerial survey data.

Average concentrations of Sr^{89} in plant samples and in the bone ash of rabbits collected on D + 5 (five days after the detonation) were approximately 100 times higher than the average concentrations of Sr^{90}. The concentrations of Sr^{90} in post-Sedan samples from locations where $R_o < 10$ mr/hr were not significantly higher than in pre-Sedan samples from the same locations. Consequently, most of our statistical and food-chain kinetic studies were based on the Sr^{89} data.

For the 20 stations at which samples were collected, the means of initial dose rate estimates (R_o), initial concentrations of Sr^{89} on plants (P_o), and maximum concentrations of Sr^{89} in rabbit bone ash (B_{30}) were 17.5 ± 5.2 mr/hr, 1800 ± 575 pc/g, and 2100 ± 625 pc/g respectively. The correlation between R_o and P_o was 0.76^{**} while the correlation between P_o and B_{30} was 0.70^{**}. In both cases, the correlation and regression coefficients were significant at the 1% level of probability; and the deviations from linear regression were not statistically significant.

From D + 5 to D + 30, the average effective half-lives of Sr^{89} and Sr^{90} on fallout-contaminated plants were approximately 18 and 28 days

respectively. From D + 30 to D + 60, the effective half-life of Sr^{89} was about 38 days and the effective half-life of Sr^{90} was > 100 days.

The average concentrations of Sr^{89} and Sr^{90} in rabbit bone ash increased rapidly from D + 5 to D + 15 and then more slowly from D + 15 to D + 30. In both cases, maximum levels were attained about D + 30. From D + 30 to D + 60, the average concentration of Sr^{89} in rabbit bone ash declined at a rate approximating the radioactive decay rate of Sr^{89} while the average level of Sr^{90} remained essentially unchanged. Estimates based on these data indicate that the biological half-life of radiostrontium in the bones of jack rabbits is about 33 days; therefore, the effective half-life of Sr^{89} in rabbit bone was approximately 20 days, and the effective half-life of Sr^{90} was approximately 33 days.

The average concentrations, build-up, and later decline of radiostrontium in the bone ash of rabbits collected in the Sedan fallout field were apparently related to the averages of the following parameters: (a) the initial concentrations of radiostrontium on the fallout-contaminated plants consumed by the rabbits, (b) the weight of contaminated plant material consumed per rabbit per day, (c) the weight of bone ash per rabbit, (d) the fraction of ingested radiostrontium which was assimilated and deposited in bone, (e) the effective half-life of radiostrontium on fallout-contaminated plants, and (f) the effective half-life of radiostrontium in the skeleton.

A mathematical model incorporating these parameters was formulated and found to function satisfactorily with parameter values derived from the radiochemical data. Estimates of the total doses (rad) delivered by Sr^{89}

to rabbit bone were based on the model. The estimated doses to individual rabbits ranged from 0.11 to 9.48 rad, and the average was 1.12 ± 0.36 rad.

While the model seems to provide an adequate explanation of the quantitative-kinetic relationship between average initial concentrations of radiostrontium on plants and subsequent average concentrations in rabbit bone ash, the parameter values used in fitting the hypothetical curves to the observed data points could be inaccurate; and even if the derived parameter values are accurate, they might not be applicable to other fallout fields. Some of the factors which influence the parameters considered in the model, and the major sources of error in estimating specific parameter values were discussed at length.

Finally, a mathematical model was proposed to provide at least a partial explanation of the quantitative-kinetics of Sr^{89} or I^{131} on pasture plants, in cow's milk, and in human tissues (bone and thyroid) following fallout from a single nuclear detonation. The potential value of the proposed model as an aid in the study of human food-chain kinetics or for the interpretation of radiochemical datawas illustrated by means of hypothetical calculations.

** Significant at the one per cent level of probability

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FOOD-CHAIN RELATIONSHIPS OF RADIOSTRONTIUM IN THE SEDAN FALLOUT FIELD*

William E. Martin and Frederick B. Turner

1.0 INTRODUCTION

1.1 Background

The biological hazards related to fallout have been classified, somewhat arbitrarily, as short-term or acute and long-term or chronic [7]. Short-term hazards have been attributed primarily to external gamma radiation and secondarily to the biological accumulation of internal emitters. Long-term hazards have been attributed primarily to internal and secondarily to external emitters. This report describes and attempts to explain certain short-term aspects of the internal emitter problem.

Mathematical models have been designed to explain and/or to predict the formation, dispersal, and deposition of fallout particles [1,28]; and models have been developed to describe and explain the worldwide distribution and cycling of radionuclides in the biosphere [16,21]. This report describes relationships and presents mathematical models which may be of practical value in explaining and/or predicting the early food-chain kinetics of radionuclides following close-in fallout from a single nuclear detonation.

Figure 1 shows the most probable routes of radionuclide transfers in a terrestrial ecosystem contaminated by fallout. Factors which determine the physical and chemical properties and the geographic distribution of fallout particles are operative prior to fallout deposition. The transfers and exchanges diagrammed in Figure 1 occur after fallout deposition.

Fallout results in the direct, external contamination of soils, plants

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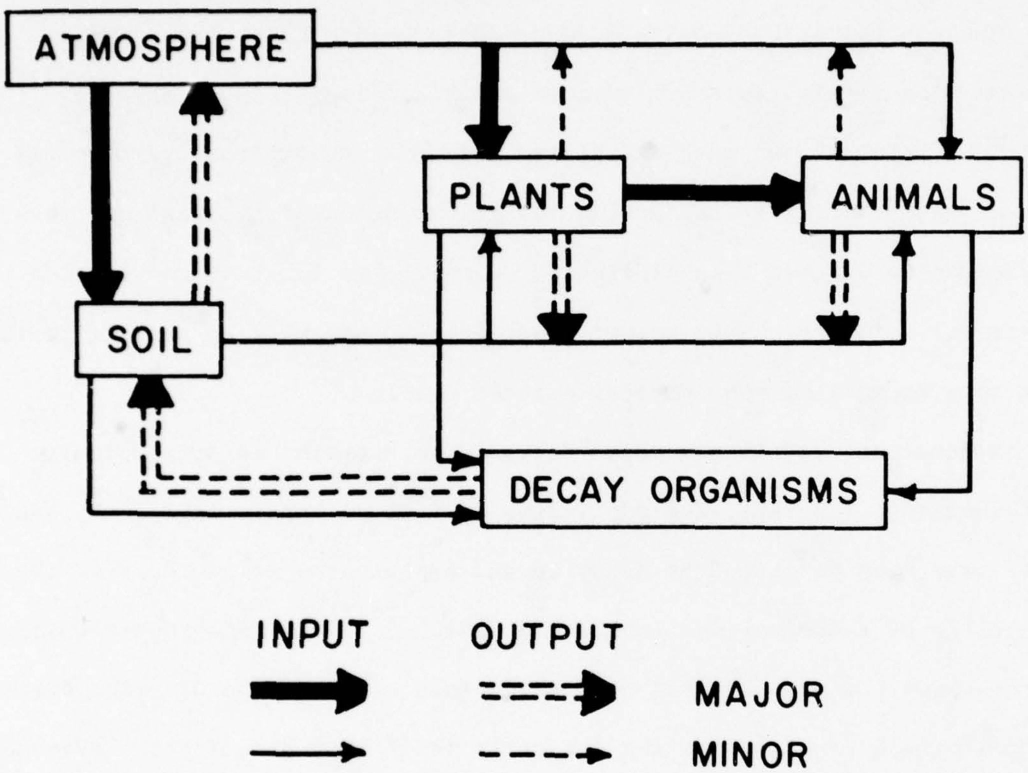


Figure 1. Major and minor routes of radionuclide transfer and exchange in a terrestrial ecosystem contaminated by radioactive fallout debris.

and animals. The subsequent redistribution of fallout particles, and of the various radionuclides contained in those particles, results from the interaction of the biotic and abiotic factors which comprise the ecosystem.

Some of the particles initially deposited on soil may be redistributed by wind or rain and redeposited on plants or on other soil surfaces [20]. Some of the fallout particles on soil may be accidentally ingested by burrowing animals. The downward movement of radionuclides from superficial fallout deposits is, in the absence of plowing, a slow process [31] and therefore of little significance in the early food-chain kinetics of radionuclides in a fallout field.

Particles < 50μ in diameter are more readily trapped on plant foliage than are particles of larger diameter [32] and these smaller particles are relatively richer in certain fission products (e. g., Sr^{89}, Sr^{90}, I^{131}, Cs^{137}, and Ba^{140})and relatively more soluble in water and dilute HCl [18,32]. Some of the particles initially intercepted by plants may be transferred to the soil by wind, rain, or other mechanical disturbances or by the dehiscence of foliage.

The radionuclides contained in fallout particles may enter plant tissue via root absorption [29,30], foliar absorption [27,34], or stem-base absorption [33]. Because these processes are relatively slow or because the amount of activity involved is small in relation to the activity of external deposits, the actual assimilation of radionuclides by plants is of little significance in regard to the early food-chain kinetics in a fallout-contaminated ecosystem. On the other hand, the loss of radionuclides from fallout-contaminated plants, which is due to radioactive decay and to mechanical disturbance, may be of considerable importance in limiting the rate of intake by herbivores[24].

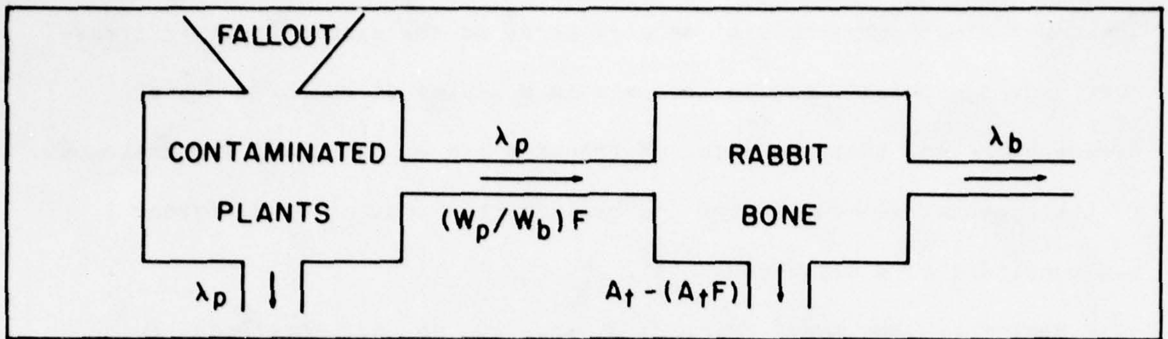
The external contamination of animals living in a fallout field may result from the direct deposition of fallout particles on their pelts or from contact with contaminated plants and soil. Radionuclides contained in fallout particles may accumulate in the tissues of herbivorous mammals via inhalation, which is probably insignificant in most cases [36]; via the ingestion of contaminated soil, which is probably significant only in relation to burrowing animals [10]; or via the ingestion of contaminated plants [24,37], which is probably of major importance. It is probably safe to assume that, during the first 60 days after the deposition of close-in fallout, fallout-contaminated plants are the only significant source of radionuclides for ingestion and assimilation by herbivorous mammals.

Finally, as shown in Figure 1, the decomposition of plant and animal bodies results in the release of materials to the soil. These materials, including long-lived radionuclides, are then available for re-cycling through the various plant to animal food-chains.

1.2 A Food-Chain Kinetics Model

The model diagrammed and formulated in Figure 2 was designed to explain the quantitative kinetic relationship between concentrations of radiostrontium on plants and in the bone ash of rabbits following environmental contamination by close-in fallout from a single nuclear detonation.

A nearly identical model has already been used to explain the early food-chain kinetics of radioiodine [38], and comparable models are commonly used to explain the kinetics of physiological tracers [35].



$t = 0$: $\quad P = P_0 \quad , \quad B = 0$

$t > 0$: $\quad P_t = P_0 e^{-\lambda_p t} \quad (1) \qquad B_t = \dfrac{P_0 \; W_p F}{W_b}\left[\dfrac{e^{-\lambda_p t}}{(\lambda_b - \lambda_p)} + \dfrac{e^{-\lambda_b t}}{(\lambda_p - \lambda_b)}\right] \quad (2)$

Where,

t = time, in days, after plant contamination

P_o = pcSr*/g (dry wt.) on plants at $t = 0$

P_t = pcSr*/g (dry wt.) on plants at $t > 0$

B_t = pcSr*/g in rabbit bone ash at $t > 0$

W_p = dry weight (g) of plants eaten per rabbit per day

F = fraction of ingested Sr* which is deposited in bone

W_b = dry weight (g) of bone ash per rabbit

$\lambda = 0.693/T$ = effective decay constant

T_p = effective half-life of Sr* on plants

T_b = effective half-life of Sr* in rabbit bone

e = 2.718 ... (base of natural logarithms)

Figure 2. A food-chain Kinetics model for radiostrontium (Sr*) on plants and in rabbit bone ash following enviro mental contamination by close-in fallout from a single nuclear detonation.

These and other compartmental models, based on the assumption that transfers from one compartment to the next in a series of compartments are irreversible and that the rates of transfer are exponential, are analagous to the exponential models used to explain the kinetics of different radionuclides in a decay-chain[12].

Basically, the model (Fig. 2) depicts two compartments each having one inlet and two outlets for the transfer of radiostrontium. Pre-fallout concentrations of radiostrontium on plants and in rabbit bone ash are assumed to be negligible; and the processes considered are those beginning at $t = 0$ (the time of plant contamination).

The initial concentration (P_o) of Sr^* (radiostrontium) on plants is probably related to the Sr^* content and distribution of particles $< 50\ \mu$ in diameter; and this may be closely related, at least in some cases, to initial gamma dose rates (R_o = mr/hr at H + 24). Subsequent losses of Sr^* from fallout-contaminated plants are due to the combined effects of radioactive decay and mechanical disturbances. The effective rate of loss (T_p) is assumed to be exponential ($\lambda_p = 0.693/T_p$).

The amount of Sr^* ingested per rabbit per day depends on the initial concentration of Sr^* on plants (P_o), on the dry weight of plants ingested per rabbit per day (W_p), and on the effective half-life of Sr^* on the plants (T_p).

Some fraction (F) of the ingested Sr^* is eventually deposited in the rabbit's skeleton. The weight of plants eaten per rabbit per day divided by the weight of bone ash per rabbit (W_p / W_b = 2.0 g/g/day) is assumed to be a constant which determines the concentration of assimilated Sr^* in the skeleton. Subsequent losses of Sr^* from the skeleton are due to the combined effects of radioactive decay and biological elimination, and the effective rate of Sr^* loss from rabbit bone (T_b) is assumed to be exponential ($\lambda_b = 0.693/ T_b$).

If the ratio of plant material ingested per rabbit per day to the weight of bone ash per rabbit (W_p/W_b), the fraction of Sr^* ingested which appears in the skeleton (F), the effective half-life of Sr^* on fallout-contaminated plants (T_p), and the effective half-life of Sr^* in the rabbits skeleton (T_b) are all constants (or nearly constant), it should be possible to solve Equation 2 and thus predict the average concentration of Sr^* in rabbit bone ash (B_t) for any given values of P_o and $t > 0$. If the relationship between initial gamma dose rates (R_o) and initial levels of plant contamination (P_o) is predictable, estimates of P_o can be obtained from estimates of R_o based on ground surveys, aerial surveys, or fallout prediction models. (See Sec. 4.2 for possible errors in estimating various parameter values.)

1.3 Procedure and Objectives

Project Sedan, which involved the detonation of a 100 ± 15 Kt thermonuclear device at a depth of 635 ft in alluvium and tuff, provided an opportunity to test the hypothesis outlined above (Sec.1.2) in relation to radioiodine and radiostrontium. To obtain the necessary data, plant samples and rabbits were collected before and at various times after the detonation, from representative locations in the Sedan fallout field and analyzed to determine their radioiodine and radiostrontium contents at the times of collection. Most of the data and conclusions relating to radioiodine have already been published [23,24, 37, 38,39].

The three-fold purpose of this paper is: (1) to describe the statistical interrelations of initial gamma dose rates (R_o = mr/hr at H + 24), initial concentrations (P_o) of radiostrontium on fallout-contaminated plants and subsequent concentrations (B_t) in the bone ash of rabbits, (2) to show how a mathematical model, Figure 2, seems to provide a partial explanation of the early quantitative-kinetic relationship between initial concentrations of radiostrontium on fallout-contaminated plants and subsequent concentrations in the bone ash of rabbits, and (3) to propose a mathematical model which may explain the early quantitative-kinetics of radiostrontium (or other radionuclides) in relation to close-in fallout intensity, pasture plants, cow's milk, and human skeletons (or other organs or tissues of reference).

2.0 <u>METHODS</u>

2.1 <u>Location of Sampling Stations</u>

The Sedan device was detonated on July 6, 1962, and the predicted fallout sector was from GZ (ground zero) to 150 mi. N 60° W and N 60° E. During the two weeks prior to the detonation, samples were collected from many locations in the predicted fallout field. After the detonation, collections were made only at stations located in the actual fallout field (Figure 3).

Plant samples and rabbits were collected more or less regularly at 5-day intervals for the first 30 days and then 60 days after the detonation from more than 30 locations in the fallout field [38]. For the sake of simplicity, only the samples collected 5, 15, 30 and 60 days after the detonation from 20 representative locations (Figure 3) are considered in this paper. (N. B. Additional data are given in Appendix A.)

2.2 Collection and Processing of Samples

2.2.1 Plants

Plant samples, weighing 0.5 to 1.0 kg (dry), were collected by clipping twigs and foliage from the crowns of desert shrubs growing within a radius of 150 ft from the metal posts used to mark and identify each sampling station. In the Groom Valley and Currant study areas (Figure 3), the species collected at most stations was sagebrush (*Artemisia tridentata*). In Penoyer and Railroad Valleys (Figure 3), the species collected at all but three stations was shadscale (*Atriplex confertifolia*).

The plant samples were stored and shipped in paper bags which were sealed with masking tape but often perforated to facilitate drying. After drying for 24 hrs at 20-22°C in a forced-draft oven and grinding in a Wiley mill equipped with a 4.0 mm screen, the coarse plant "flour" had an average moisture content of $\leq$ 5%. Two 50-g aliquots of each sample were placed in a muffle-furnace at 550° C for 12 hr, and the ash was analyzed for radiostrontium.

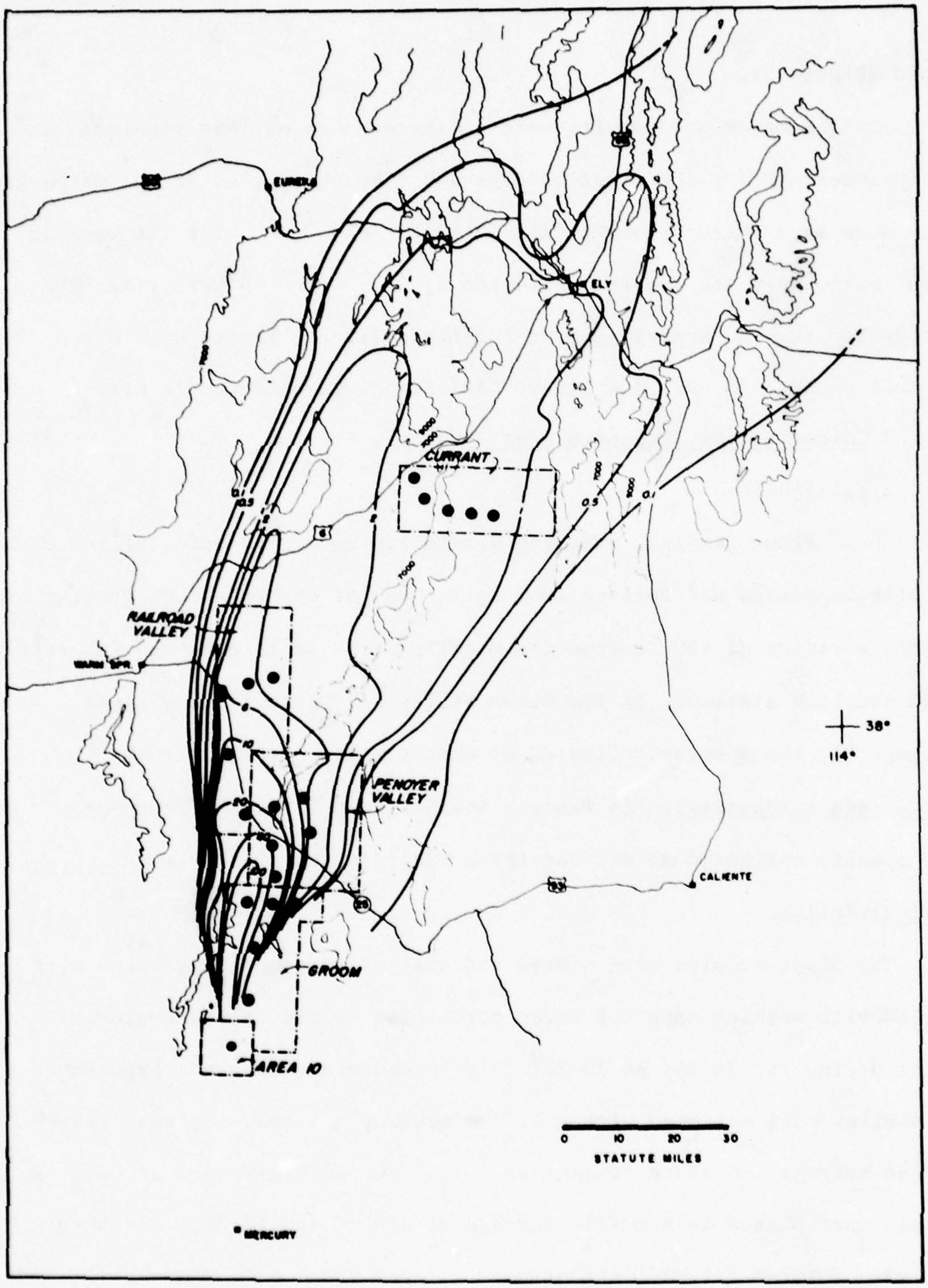


Figure 3. The Sedan Fallout Field: Ground zero is indicated by the black dot in Area 10. The other dots show the approximate locations at which plant samples and rabbits were collected. The dose rate contours (mr/hr at H + 24) are based on aerial surveys[13].

2.2.2 Rabbits

Rabbits were shot, mostly at night, with 0.22 caliber rifles, and then wrapped in plastic bags, quick-frozen on dry ice, and shipped to our Laboratory at Los Angeles. In most areas, rabbits were abundant, and most of the animals used in this study were collected within a few hundred yards from the station-marker to which they were assigned. However, animals taken within a one-mile radius from a given station-marker were accepted as representatives of that general location. Most of the animals collected were black-tailed jack rabbits (*Lepus californicus*), but cotton-tail rabbits (*Sylvilagus auduboni*) were taken, usually in the more mountainous areas where jack rabbits were not always available.

After thawing, rabbits were skinned and weighed, and the thyroid glands were removed for radioiodine assay. Skins, heads, feet, and viscera (except for stomach contents) were discarded. (N. B. The stomach contents were analyzed for radioiodine, but the samples remaining after aliquots were removed for this purpose were too small to be used for radiostrontium analyses.) The dismembered carcasses were dried for 24 hr at 100°C in a forced-draft oven and then placed in a muffle-furnace for 12 hr at 550°C. The residue was passed through a 2 mm screen to separate the finer muscle ash from the bones. The bones were returned to the muffle-furnace for an additional 12 hr at 900°C, then removed and pulverized.

2.3 Radiochemical Analyses

Plant ash and bone ash were analyzed for Sr^{89} and Sr^{90}. Detailed descriptions of the procedures used in making these analyses are given elsewhere[40]. In both procedures, the ash is first dissolved in HCl. The phosphate or carbonate precipitates are then treated with fuming HNO_3 to separate Sr from Ca. The Y^{90} daughter of Sr^{90} is separated by precipitation with NH_4OH and the samples are set aside for 18 days to allow for the regrowth and stabilization of Y^{90}. The Y^{90} produced during this period is also separated by precipitation with NH_4OH, and the disintegration rate due to Sr^{90} is calculated from measurements of the Y^{90} daughter. The Sr^{89} activity is calculated by subtracting the sum of Sr^{90} and Y^{90} c/m (counts per minute) from the sum of Sr^{90} and Sr^{89} c/m. The Sr^{89} c/m is then corrected for chemical recovery and counting efficiency to determine d/m (disintegrations per minute).

The radiometric data were processed by means of a special Fortran program devised by Richard Tenney for an IBM 7090 computer. The final results for a given sample were expressed as pc Sr^{89}/g and pc Sr^{90}/g at the time the sample was collected, and most samples were represented by two or more replicates.

2.4 Initial Gamma Dose Rate Estimates

Aerial radiometric surveys were made both before and after the detonation. The equipment and methods used in obtaining the estimated gamma dose rates (R_o = mr/hr at H+24) shown in Figure 3 have been described in detail by Guillou[13]. The four basic components of the Aerial Radiometric Monitoring System (ARMS II) are: (1) NaI (Th) crystals of various sizes and sensitivities in conjunction with photomultiplier tubes and sealers to detect and measure gamma radiation,

(2) a Doppler radar unit to monitor the aircraft's altitude, heading, ground speed, and drift, (3) a computer to integrate signals from the first two units, to compensate for deviations from the desired survey altitude (500 ft), and to make corrections for pre-determined cosmic background radiation, and (4) a printout recording unit which provides a continuous record of counts per second (c/s) already corrected for background and altitudinal fluctuations.

Count rates at the time of survey were corrected for decay ($t^{-1.2}$) to H + 24 and then converted to mr/hr at 3 ft ($5.0 \pm 2.5 \times 10^4$ c/s at 500 ft = 1.0 mr/hr at 3 ft at H + 24). Using roads and other landmarks as ground references, these data were plotted on a map (e. g., on USGS topographic maps, 1: 250,000 or 1:1,000,000); and isodose-rate lines were drawn as shown in Figure 3.

While the absolute accuracy of the measurement system and of the conversion factors used in making these surveys are doubtful, the relative positions and relative values of the iso-dose-rate contours shown in Figure 3 are sufficiently accurate to provide a useful delineation of the fallout pattern at H + 24.

3.0 RESULTS AND DATA ANALYSES

3.1 Radiostrontium Content of Plant Samples and Rabbit Bone Ash

Tables 1 and 2 show the concentrations of Sr^{89} and Sr^{90} in plant samples and in the bone ash of rabbits collected before and at various times after the detonation from 20 locations (Figure 3) in the Sedan fallout field. The estimates of initial gamma dose (R_o = mr/hr at H + 24)

Table 1. Initial gamma dose rates (R_o) and Sr^{89} concentrations in plant and rabbit bone ash samples collected, before (Bkgd) and after (D+5, D+15, etc.) the detonation, at different locations in the Sedan fallout field. (Decay corrections were made to indicate activities at the times of collection.)

LOCATION 1/		PLANT SAMPLES (pc Sr^{89}/g					RABBIT BONE ASH(pc Sr^{89}/g)				
(See Fig. 3)		(Times of Collection)					(Times of Collection)				
Station	R_o	Bkgd	D+5	D+15	D+30	D+60	Bkgd	D+5	D+15	D+30	D+60
G-6	75.0	43.3	6487	4445	1813	671	76.6	1400	12598	4395	1503
G-7	75.0	51.0	2528	1257	993	1175	23.6	1347	2332	8316	6804
G-8	35.0	9.5	4315	1882	601	295	--	3745	1061	7400	7235
P-1	35.0	--	2228	959	768	758	99.6	3396	4492	7441	1168
P-15	35.0	--	873	542	491	293	42.4	2686	1064	388	782
G-3	35.0	58.6	6722	5770	4261	1719	22.5	734	2234	4783	2114
R-2	15.0	12.6	602	250	151	121	140.0	714	2317	1663	3781
$\bar{x}$:	43.6	35.0	3394	2158	1297	791	67.4	2003	3728	4912	3341
$s\bar{x}$:	±20%	±28%	±28%	±37%	±41%	±30%	±28%	±24%	±49%	±23%	±30%
P-4	8.0	--	990	450	141	170	--	273	2995	280	448
R-3	8.0	--	352	223	122	114	21.0	180	226	310	425
G-4	5.0	10.1	344	224	50	80	69.7	69	15	99	251
R-4	5.0	33.8	298	405	96	13	75.0	195	123	876	212
P-5	3.0	31.0	261	212	103	95	49.0	308	409	293	188
P-7	3.0	--	386	187	157	99	--	152	1161	3012	172
R-6	3.0	10.8	397	221	171	133	75.6	224	211	871	1053
R-7	3.0	--	337	246	279	252	79.0	359	221	194	243
C-1	1.5	19.0	506	349	216	88	--	522	381	280	265
C-2	1.5	66.4	298	170	170	53	59.0	811	586	710	39
C-3	1.5	34.8	414	140	114	53	33.2	67	489	121	350
C-4	1.5	21.8	144	117	72	42	21.0	62	27	266	189
C-5	1.5	17.6	228	139	106	40	18.0	15	650	237	556
$\bar{x}$:	3.5	27.3	381	237	138	95	50.0	249	576	580	338
$s\bar{x}$:	±17%	±21%	±15%	±12%	±12%	±32%	±16%	±24%	±38%	±37%	±21%
ALL STATIONS:											
$\bar{x}$:	17.5	30.0	1436	909	544	313	56.5	863	1680	2097	1389
$s\bar{x}$:	±30%	±17%	±32%	±37%	±40%	±32%	±30%	±29%	±38%	±30%	±32%

1/ The letters G, P, R, and C refer to the Groom, Penoyer, Railroad, and Currant study areas shown in Figure 3.

R_o = (gross gamma) = mr/hr, 3 ft above ground, 24 hr post-detonation

$\bar{x}$ = mean, $s\bar{x}$ = standard error expressed as a percentage of the mean

Table 2. Initial gamma dose rates (R_o) and Sr^{90} concentrations in plant and rabbit bone ash samples collected, before (Bkgd) and after (D+5, D+15, etc.) the detonation, at different locations in the Sedan fallout field. (Activities are indicated for the times of collection.)

LOCATION[1/] (See Fig.3)		PLANT SAMPLES (pc Sr^{90}/g) (Times of Collection)					RABBIT BONE ASH (pc Sr^{90}/g) (Times of Collection)				
Station	R_o	Bkgd	D+5	D+15	D+30	D+60	Bkgd	D+5	D+15	D+30	D+60
G-6	75.0	1.4	47.3	37.5	11.3	11.2	6.1	22.4	113.8	81.1	72.5
G-7	75.0	9.8	28.4	22.8	18.6	19.4	30.8	14.2	22.0	123.2	95.0
G-8	35.0	1.0	33.9	16.2	8.0	5.8	--	34.0	12.5	72.0	111.8
P-1	35.0	--	17.9	8.9	9.5	12.5	21.2	27.7	45.1	74.7	17.2
P-15	35.0	--	7.3	5.0	5.0	5.8	3.9	33.1	12.6	6.7	18.3
G-3	35.0	3.0	84.7	60.8	49.6	28.9	4.6	10.1	24.0	52.9	40.9
R-2	15.0	1.5	4.9	3.3	3.0	3.0	8.9	8.4	28.3	6.3	55.1
$\bar{x}$:	43.6	3.3	32.0	22.0	15.0	12.4	12.6	21.4	36.9	59.6	58.7
$s\bar{x}$:	±20%	±51%	±32%	±36%	±33%	±27%	±39%	±19%	±37%	±27%	±24%
P-4	8.0	3.9	3.9	2.0	2.2	4.6	9.4	4.7	37.4	6.3	10.3
R-3	8.0	--	3.6	3.0	3.0	3.0	8.9	6.3	5.1	7.3	29.2
G-4	5.0	1.8	5.6	4.0	2.4	2.6	21.5	5.6	6.4	8.6	13.6
R-4	5.0	3.3	2.7	3.2	2.6	3.3	3.3	6.2	4.4	11.5	9.8
P-5	3.0	1.4	3.3	3.2	3.0	3.1	3.4	4.9	7.9	6.6	6.2
P-7	3.0	--	3.7	2.8	3.3	3.1	--	4.7	19.8	35.2	6.1
R-6	3.0	1.3	4.0	3.4	3.4	4.2	7.6	7.4	5.7	14.5	28.8
R-7	3.0	--	4.1	4.2	5.0	3.8	7.2	10.4	5.7	12.1	5.6
C-1	1.5	0.5	5.6	7.2	5.3	3.7	23.3	23.2	15.6	14.9	12.5
C-2	1.5	4.2	5.4	5.4	4.9	4.1	4.1	20.2	20.9	32.7	4.9
C-3	1.5	8.8	5.0	4.0	4.0	2.6	3.6	6.2	13.8	19.2	17.5
C-4	1.5	6.7	4.3	4.0	2.8	2.4	19.8	6.6	5.4	17.5	16.5
C-5	1.5	4.0	4.0	4.7	4.0	4.2	19.2	7.1	23.9	19.4	24.6
$\bar{x}$:	3.5	3.6	4.2	4.0	3.5	3.4	10.9	8.7	13.2	15.8	14.3
$s\bar{x}$:	±17%	±25%	±5%	±7%	±29%	±6%	±21%	±19%	±21%	±17%	±17%
ALL STATIONS:											
$\bar{x}$:	17.5	3.5	14.0	10.3	7.5	6.6	11.5	13.2	21.5	31.1	29.8
$s\bar{x}$:	±	±23%	±33%	±35%	±35%	±23%	±18%	±17%	±25%	±24%	±23%

1/ The letters G, P, R, and C refer to Groom, Penoyer, Railroad, and Currant study areas shown in Figure 3.

R_o = (gross gamma) = mr/hr, 3 ft above ground, 24 hr post-detonation

x = mean, sx = standard error expressed as a percentage of the mean given in these two tables are based on a tracing of Guillou's [13] original map (1:250,000) of the fallout field.

The average concentrations of radiostrontium in plant samples and in the bone ash of rabbits collected 5 days after the detonation was about 10 times higher in the samples from stations where $R_o > 10$ mr/hr than in samples from stations where $R_o < 10$ mr/hr. In the same samples, the average concentrations of Sr^{89} were about 100 times higher than the average concentrations of Sr^{90}.

At locations where $R_o < 10$ mr/hr, the average postshot concentrations of Sr^{90} on plants and in rabbit bone ash were not significantly higher than the preshot averages for the same general area. For this reason, most of the statistical and kinetic analyses which follow are based primarily on the Sr^{89} data in Table 1.

3.2 Correlation and Regression Analyses

Estimates of correlation (r) and regression (b_{xy}) coefficients based on the data in Table 1 are given in Table 3. Without exception, the correlations between arrays of plant samples collected from the same locations at different times after the detonation are highly significant. The slight decline in correlation with increasing time after the detonation may reflect the influence of fallout redistribution by wind action.

In general, the correlation between concentrations of Sr^{89} in plant samples (P_t) and initial gamma dose rates (R_o) is somewhat better than the correlation between initial gamma dose rates and concentrations of Sr^{89} in rabbit bone ash samples (B_t). The relatively poor correlations

Table 3. Estimates of correlation (r) and regression (b x y) based on the data given in Table 1.

Functions x(y)	Correlation Coefficients	Regression Coefficients	Regression Formulas $X = \bar{x} + bxy\ (y-\bar{y})$	$F^{(2)}$
$P_5(P_o)$	$1.000^{(1)}$	$0.796^{(1)}$	$P_5 = 0.796P_o$	-
$P_{15}(P_o)$	0.965^{**}	$0.570 \pm 0.134^{**}$	$P_{15} = 0.570P_o - 118$	1.04
$P_{30}(P_o)$	0.868^{**}	$0.329 \pm 0.078^{**}$	$P_{30} = 0.329P_o - 49$	1.50
$P_{60}(P_o)$	0.794^{**}	$0.137 \pm 0.032^{**}$	$P_{60} = 0.137P_o + 66$	1.65
$P_o(R_o)$	0.765^{**}	$83.75 \pm 16.65^{**}$	$P_o = 83.75R_o + 335$	2.00
$P_{15}(R_o)$	0.528^{*}	$43.56 \pm 11.47^{**}$	$P_{15} = 43.56R_o + 63$	3.39
$P_{30}(R_o)$	0.558^{*}	$23.17 \pm 8.12^{*}$	$P_{30} = 22.17R_o + 138$	1.93
$P_{60}(R_o)$	0.720^{**}	$13.64 \pm 3.10^{**}$	$P_{60} = 13.64R_o + 74$	1.73
$B_5(P_o)$	0.472^{*}	$0.205 \pm 0.094^{*}$	$B_5 = 0.205P_o + 495$	4.71^{*}
$B_{15}(P_o)$	0.689^{**}	$0.759 \pm 0.188^{**}$	$B_{15} = 0.759P_o + 315$	1.48
$B_{30}(P_o)$	0.698^{**}	$0.742 \pm 0.250^{**}$	$B_{30} = 0.742P_o + 761$	1.87
$B_{60}(P_o)$	0.484^{*}	$0.399 \pm 0.170^{*}$	$B_{60} = 0.399P_o + 671$	1.48
$B_5(R_o)$	0.586^{**}	$28.13 \pm 9.17^{**}$	$B_5 = 28.13R_o + 370$	2.57
$B_{15}(R_o)$	0.722^{**}	$87.14 \pm 19.68^{**}$	$B_{15} = 87.14R_o + 153$	3.25
$B_{30}(R_o)$	0.540^{*}	$63.97 \pm 23.65^{*}$	$B_{30} = 63.97R_o + 976$	3.38
$B_{60}(R_o)$	0.640^{**}	$57.98 \pm 16.37^{**}$	$B_{60} = 57.98R_o + 373$	1.82

x (y) = dependent and independent variables respectively

P_t = $pcSr^{89}/g$ of plant material at time of collection

B_t = $pcSr^{89}/g$ of rabbit bone ash at time of collection

R_o = estimated gamma dose rate (mr/hr) at H + 24

(1) By definition, $P_o = 1.256\ P_5$ and $1/1.256 = 0.796$

(2) F is based on analyses of variance to determine the significance of deviations from linear regression.

* significant at the 5% level of probability

** significant at the 1% level of probability between initial levels of Sr^{89} on plants (P_o) and subsequent levels of Sr^{89} in rabbit bone ash may be due, in part, to the fact that plant samples were always collected with a 150 ft radius of station markers while rabbits were collected within a one mile radius. It is also possible, as was true of radioiodine [23], that the concentrations of Sr^{89} on the plants collected at a given station may have been higher or lower by a factor of 2 or 3 than the concentrations of Sr^{89} in the plant materials actually being consumed by the rabbits representing the station.

In all comparisons made in Table 3, the coefficients of correlation and regression were statistically significant at or below the 5% level of probability. In all cases but one, analyses of variance indicated no significant deviations from linear regression. These results indicate that, in spite of the high degree of apparently inherent variability in the data given in Table 1, there is a close relationship, throughout the field, between initial gamma dose rates and initial levels of plant contamination and between initial plant contamination and subsequent concentrations of Sr^{89} in rabbit bone ash.

3.3 Food-Chain Kinetics of Sr^{89}

3.3.1 The Decay-Chain-Food-Chain Analogy

The analogy between decay-chain and food-chain kinetics was mentioned earlier. Comparable equations for decay-chain and food-chain kinetics,are given below.

Decay-Chain

$$N_1 = N_o \lambda_o \left(\frac{e^{-t\lambda_1} - e^{-t\lambda_0}}{\lambda_o - \lambda_1} \right) + N_1{}^o e^{-t\lambda_1} \quad (3)$$

Food-Chain

$$B_t = \frac{P_o W_p}{W_b} \qquad F \left(\frac{e^{-t\lambda_b} - e^{-t\lambda_p}}{\lambda_p - \lambda_b} \right) + B_o e^{-t\lambda_b} \qquad (4)$$

In the decay-chain equation, N_o is the number of atoms of the parent and N_1 is the number of atoms of the first daughter nuclide while λ_o and λ_1 are their respective decay constants and $\lambda_o > \lambda_1$. If, at $t = 0$, $N_1 = 0$, the correction factor $(N_1^o e^{-t\lambda_1})$ can be deleted from the equation.

In the food-chain equation, N_1 is replaced by B_t which represents the concentration (pc/g) of Sr^{89} in rabbit bone ash at a given time after plant contamination. The expression $(P_o W_p / W_b)$ which replaces $N_o\lambda_o$ represents the amount of Sr^{89} in the rabbit's first meal following plant contamination and is expressed as a number of picocuries ingested per gram of bone ash per rabbit per day. The factor F indicates the fraction of ingested Sr^{89} which is assimilated from the gastrointestinal tract and deposited in the skeleton.

The λ's in the bracketed part of the decay-chain equation are decay constants based on the radioactive half-lives of N_o and N_1. The λ's in the food-chain equation are based on the effective half-lives of Sr^{89} on fallout-contaminated plants (T_p) and in rabbit bone (T_b) respectively. Assuming that $B_o = 0$, the correction factor $(+ B_o e^{-t\lambda_b})$ can be omitted; and the quantities required to solve Equation 5 are: P_o, (W_p / W_b), F, T_p, and T_b. Estimates of these parameters can be made as indicated below.

3.3.2 Initial Concentrations on Plants

As shown in Figure 4, estimates of P_o can be obtained by extrapolation of P_5 and P_{15} (i. e., the average concentrations on D + 5 and D + 15) to zero time. Similar estimates of P_o can be obtained from R_o (mr/hr at H + 24) estimates by using the regression formula in Table 3 ($P_o = 83.75\ R_o + 335$), but this formula probably should not be used for $R_o < 5$ mr/hr or $R_o > 50$ mr/hr.

3.3.3 Rate of Loss from Plants

The average rates of Sr^{89} loss from plants and accumulation in rabbit bone ash (Figure 4) were not uniform with respect to time after the detonation, but the most significant changes in both P_t and B_t occurred prior to D + 30. During this period, D = 0 to D + 30, the average effective half-life of Sr^{89} on plants was approximately (0.7 x 15d + 0.3 x 20d =) 16.5 days. From D = 0 to D + 60, the average effective half-life was (0.6 x 15d + 0.25 x 20d + 0.15 x 38d =) 19.7 days. In order to give added weight to the earlier loss rates we shall use a value of T_p (= 16.5 + 19.7 / 2) = 18 days.

3.3.4 Rate of Loss from Rabbit Bone

As shown in Figure 4, the average (n = 20) observed values ($pcSr^{89}/g$) of B_t were: $B_5 = 863$, $B_{15} = 1680$, $B_{30} = 2097$, and $B_{60} = 1389$. At $t_{max.}$ (approximately 30 ± 2.5 days after the detonation) the rate of change in B_t was zero. This relationship can be expressed, where K is a constant representing the other parameters in Eq. 2, as shown in Eq. 6.

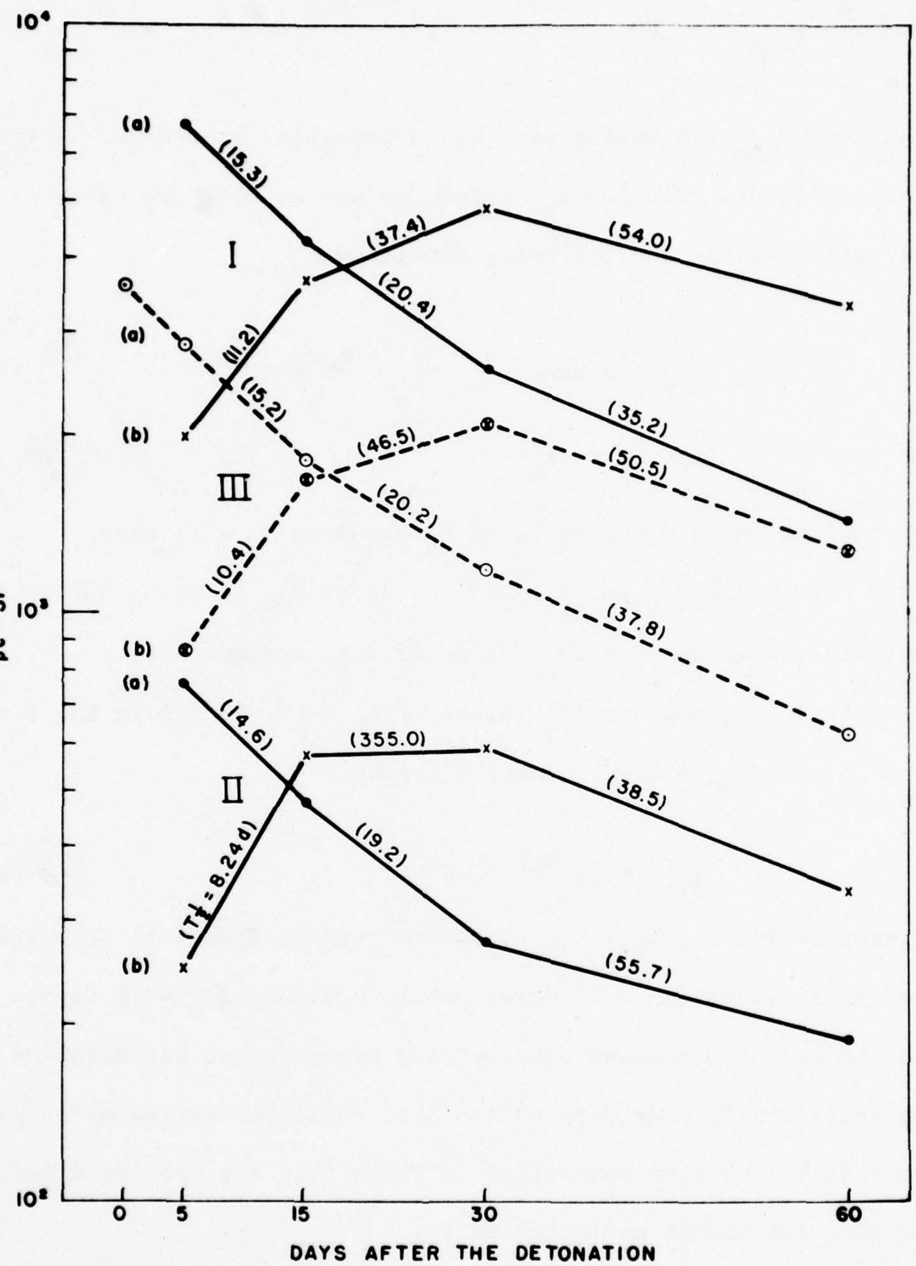


Figure 4. Average concentrations of Sr^{89} in plant samples (a) and in the bone ash of rabbits (b) collected at various times after the detonation from representative locations in the Sedan fallout field. I: Stations where $R_o > 10$ mr/hr (n = 7), II: Stations where $R_o < 10$ mr/hr (n = 13), III: All stations (n = 20). Values for (a) are $pcSr^{89}$/2g of plant material and (b) $pcSr^{89}$/g of bone ash. The numbers in parentheses indicate half-time rates of change (in days).

$$\left(\frac{dB_t}{dt}\right)_{t = t_{max}} = K\,(\lambda_p e^{-\lambda_p t_{max}} - \lambda_b e^{-\lambda_b t_{max}}) = 0 \qquad (6)$$

If λ_p and t_{max} are determined, it is possible, by systematic trial and error, to find a value of λ_b which, no matter what the value of K might be, will satisfy the following conditions:

$$\lambda_p e^{-\lambda_p t_{max.}} = \lambda_b e^{-\lambda_b t_{max.}} \qquad (7)$$

$$\text{and } \lambda_p \neq \lambda_b \qquad (7.1)$$

As shown in Table 4 estimates of λ_b based on $T_p = 18$ days, $\lambda_p = 0.693 / 18 = 0.0385$, and assumed values of $t_{max} = 27.5$, 30.0, or 32.5 days indicate values of $T_b = 20$, 23, or 29 days respectively.

By substituting appropriate values of λ_b ($= 0.693/T_b$) in Eq. 8 and finding K to make $B_{30} = 2100$, numerical values

$$B_t = K\,(e^{-\lambda_b t} - e^{-\lambda_p t}) \qquad (8)$$

were determined for B_5, B_{15}, and B_{60}. The results (Table 5) show that values of $\lambda_b = 0.0346$ ($T_b = 20$ days) and $\lambda_p = 0.0385$ ($T_p = 18$ days) provided the best fit between observed and hypothetical estimates of B_t. While we shall use $T_b = 20$ days as the best available estimate, it should be noted that the results summarized in Table 5 do not provide a basis for rejecting the higher estimates of T_b.

According to Eq. 9, an estimate of $T_b = 20$ days

$$Tbe = T_r \times T_b / \; T_r - T_b \qquad (9)$$

Table 4. Estimates of λ_b based on the relationships described by Equations 6 and 7.

Assumed Values of λ_b	t_{max}:	$e^{-\lambda_b t_{max.}}$ 27.5	30.0	32.5	$\lambda_b e^{-\lambda_b t_{max.}}$ 27.5	30.0	32.5	Estimate of T_b (days)
.020		.577	.548	.522	.0106	.0110	.0104	
.025		.503	.472	.444	.0126	.0118	.0111*	* 29
.030		.438	.406	.378	.0131	.0122*	.0113	* 23
.035		.382	.350	.321	.0134*	.0123	.0112	* 20
.040		.333	.301	.272	.0133	.0120	.0109	
.045		.290	.259	.232	.0131	.0117	.0104	
.050		.252	.223	.197	.0121	.0111	.0099	

Assumed Value of λ_p	$t_{max.}$	$e^{-\lambda_p t_{max.}}$ 27.5	30.0	32.5	$\lambda_p e^{-\lambda_p t_{max.}}$ 27.5	30.0	32.5	Estimate of T_p (days)
0.0385		.347	.316	.286	.0134	.0122	.0110	18

Table 5. Observed average concentrations of Sr^{89} in rabbit bone ash (B_t) and hypothetical estimates based on Equation 8.

Estimates of B_t Based on	Days After the Detonation 5	15	30	60
T_b = 29 days	770	1670	2100	1640
T_b = 23 days	815	1730	2100	1490
T_b = 20 days	860	1720	2100	1400
Observed: Mean	863	1680	2097	1389
± Standard Error	±250	±640	±630	±445

Where, T_{be} = biological half-life of Sr^{89} in jack rabbit bone

T_r = radioactive half-life of Sr^{89} (50.5 days)

T_b = effective half-life of Sr^{89} in jack rabbit bone

implies a biological half-life of T_{be} = 33 days. An estimate of T_b = 29 days implies T_{be} = 68 days. These relatively rapid rates of biological elimination (T_{be}) suggest that much of the Sr^{89} found in jack rabbit bone was not incorporated in the bone lattice.

3.3.5 Ratio of Daily Food Consumption to Weight of Bone Ash

French's work with jack rabbits in Idaho [9], Currie's work in Utah [6], and Arnold's work in Arizona [2], all indicate that adult jack rabbits consume approximately 100 g (dry wt.) of plant material per day. Unpublished data collected by this laboratory since 1951, indicate that the "standard" Nevada jack rabbit has a total body weight of about 2000 g and a skeleton weighing about 200 g (fresh). Since the ratio of fresh bone weight to bone ash weight is about 4 to 1, we have assumed an average of W_b = 50 g of bone ash per adult rabbit. Therefore, the dry weight of food consumed per gram of bone ash per rabbit per day is W_p / W_b = 100/50 = 2.0; and this ratio is likely to be less variable than the actual weights of food consumed per rabbit per day and the actual weights of bone ash per rabbit.

3.3.6 Fraction of Ingested Sr^{89} Deposited in Bone

As shown in Equation 6, I_o and F can be expressed, using $W_p / W_b = 2$, as shown below.

$$I_o = 2\ P_o\ F\ /\ (\lambda_p - \lambda_b) \tag{10}$$

$$F = I_o\ (\lambda_p - \lambda_b)\ /\ 2\ P_o \tag{11}$$

For $B_t = 2100$, $t = 30$, $T_p = 18$ days, and $T_b = 20$ days, Equation 9 gives $I_o = 5.38 \times 10^4$; and Equation 11 gives $F = 5.75 \times 10^{-2}$. This indicates that only 5.75% of the Sr^{89} ingested, if the Sr^{89} concentrations in plants eaten by rabbits were the same as in the plants collected for radiochemical analysis, was deposited in the skeleton.

3.4 Food Chain Kinetics of Sr^{90}

As shown in Table 2, the concentrations of Sr^{90} on plants and in the bone ash of rabbits from stations where $R_o < 10$ mr/hr were not significantly above background. We can, however, test the applicability of the model to those stations where $R_o > 10$ mr/hr. The appropriate parameter values are:

$P_o = (83.75\ R_o + 335) \div 100$

$F = 0.0575$ (the same as for Sr^{89})

$W_p / W_b = 2$ (the same as for Sr^{89})

$T_p = 23$ days (from Table 2)

$T_b = 33$ days (from Sec. 3.3.4)

3.5 Comparison of Hypothetical and Observed Concentrations of Sr^{89} and Sr^{90} in Rabbit Bone Ash

To be of practical value in explaining or predicting the food-chain kinetics of radionuclides in a fallout field, the model should be applicable to different parts of the fallout field corresponding to different initial levels of contamination. In Table 6, the observed average concentrations of Sr^{89} and Sr^{90} in the bone ash of rabbits from different parts of the Sedan fallout field are compared with hypothetical estimates obtained by using the parameter values described in Sections 3.3 and 3.4 to solve either Equation 2 or Equation 5. In 23 out of 28 comparisons, the difference between hypothetical estimates and observed means were less than the standard errors of the observed means.

3.6 Radiation Dose to Rabbit Bone

The total dose (D_t = rad) delivered, from t = 0 to t > 0, by Sr^{89} to the bones of rabbits living in the Sedan fallout field can be estimated by Equation 12.

$$D_t = \frac{K_r P_o W_p F}{W_{bf}} \left[\frac{(1 - e^{-\lambda_p t})}{\lambda_p (\lambda_b - \lambda_p)} + \frac{(1 - e^{-\lambda_b t})}{\lambda_b (\lambda_p - \lambda_b)} \right] \quad (12)$$

Where,

D_t = total dose (rad = 100 ergs/g) delivered from t = 0 to t > 0

$K_r = \dfrac{3.20 \times 10^3 \text{ dis/day/pc}}{6.24 \times 10^7 \text{ MeV/100 ergs/g}} \bar{E}$

$\bar{E}$ = average energy deposited in bone = 0.56 MeV/dis

W_{bf} = fresh weight of bone per rabbit = 200 g

Using the values given earlier for W_p, F, λ_p and λ_b, Equation 12 reduces, at t = infinity, to

$$D_{\infty} = 6.24 \times 10^{-4} \text{ (g/pc/100 ergs) } P_o \text{ (pc/g)} \quad (13)$$

Table 6. Comparison of observed (O) and hypothetical (H) concentrations (B_t) of Sr^{89} and Sr^{90} in the bone ash of rabbits in various parts of the Sedan fallout field.

R_o (mr/hr)	Sampling Stations 1/	B_t 2/	Days After the Detonation D+5	D+15	D+30	D+60
(STRONTIUM-89)						
43.6	G-6 to R-2 (n = 7)	O:	2003± 475	3728±1837	4912±1150	3341±1020
		H:	2018 (15)	4037 (309)	4920 (8)	3280 (61)
17.5	G-6 to C-5 (n = 20)	O:	863 ±252	1680 ±633	2097 ±625	1389 ±474
		H:	860 (3)	1720 (40)	2100 (3)	1400 (11)
4.75	P-4 to R-7 (n = 8)	O:	224 ±33	670 ±354	742 ±340	375 ±105
		H:	350 (126)*	700 (30)	855 (113)	570 (205)*
3.50	P-4 to C-5 (n = 13)	O:	249 ±61	576 ±219	580 ±215	333 ±70
		H:	300 (51)	600 (24)	732 (152)	488 (155)*
1.50	C-1 to C-5 (n = 5)	O:	295 ±158	427 ±109	323 ±100	280 ±86
		H:	220 (75)	440 (13)	536 (213)*	358 (78)
(STRONTIUM-90)						
43.6	G-6 to R-2 (n = 7)	O:	21.4 ± 4.0	36.9±13.6	59.6±15.9	58.7±12.9
		H:	20.0 (1.4)	47.0(11.9)	63.5 (3.5)	60.0 (1.3)
17.5	G-6 to C-5 (n = 20)	O:	13.2 ±3.0	21.5 ±5.6	31.1 ±5.2	29.8 ±6.9
		H:	9.0 (4.2)*	21.2 (0.3)	27.6 (3.5)	27.0 (2.8)

1/ See Figure 3, Table 1, and Table 2

2/ Values given for B_t (O) are observed means and standard errors based on the data in Tables 1 and 2. The numbers in parentheses following B_t(H) Indicate the differences between B_t(O) and B_t (H). An asterisk (*) indicates a difference greater than the standard error of the observed mean. The method of calculating B_t(H) is described in the text.

For $\bar{P}_o$ = 1800 ± 575 pc/g, Equation 13 indicates an average dose of $\bar{D}_{oo}$ = 1.12 ± 0.36 rad; but individual rabbits may have received doses ranging from 0.11 to 9.48 rad.

Other solutions of Equation 12 indicate that approximately 32% of the total dose (D_{oo}) would be delivered during the first 30 days, 64% during the first 60 days, and 93% during the first 120 days after plant contamination.

4.0 DISCUSSION

4.1 An Evaluation of the Model's Performance

The results given in Table 5 show that the model diagrammed and formulated in Figure 2 functions satisfactorily, with parameter values derived from the data in Tables 1 and 2, in explaining the early quantitative-kinetic relationship between initial concentrations of radiostrontium on fallout-contaminated plants and subsequent concentrations in the bone ash of rabbits in the Sedan fallout field. If we suppose that the specific values we have calculated for the basic input parameters (i. e. $P_o = 83.75\ R_o + 335$, $W_p\ /\ W_b = 2$, $F = 0.0575$, $T_p = 18$, and $T_b = 20$) are accurate and relatively constant, the model provides the basis for a prediction system which begins with estimates of initial gamma dose rates and ends with estimates of average Sr^{89} concentrations in rabbit bone ash at specific times after fallout. If comparable parameter values were known for other analogous situations, it should be possible to make similar predictions related to any radionuclide in any number of specified food-chain compartments.

The specific parameter values derived from our interpretation of observations in the Sedan fallout field, may or may not be applicable to the same problem in other fallout fields. On the basis of only one case, we can neither prove nor disprove the general validity of specific parameter values, but we can examine some of the possible sources of error in obtaining estimates of these values.

The inherent variability of our raw data (Tables 1 and 2) suggests that we are actually dealing with probabilistic rather than deterministic processes. The parameters we have treated as constants are known to vary, but the means of these variates exhibit some of the properties of true constants. Their treat t as constants permits a degree of simplification which is highly desirable. At the same time, this approach may permit us to make a variety of compensating errors which are quite difficult to detect because the parameter values are interrelated and the net results are more or less consistent with expectations.

We are convinced that deterministic models are valuable as research tools which help to explain the food-chain kinetics of radionuclides, but their practical value in predicting the biological consequences of environmental contamination by radioactive fallout is largely unknown. Before attempting to use such a model for making predictions, the methods of estimating parameter values, the possible errors in making estimates, and the probable accuracy of the estimates obtained should be carefully considered.

4.2 Possible Sources of Error in Estimating Parameter Values

4.2.1 Initial Gamma Dose Rates

The precise relationship between gamma dose rates at 3 ft above a fallout-contaminated surface and count rates at 500 ft has not been established. Conversion factors ranging from 25,000 to 75,000 counts per second at 500 ft = 1 mr/hr at 3 ft have been used in the past[13], and it is possible that different conversion factors are required for different parts of a fallout field, different atmospheric conditions at the time of survey, different kinds of devices, conditions of detonation, etc. Also, the use of $t^{-1.2}$ as a decay factor for the Sedan fallout field may be open to question because dosimetry studies in the crater area [25] have indicated an effective field-decay rate of $t^{-1.33}$.

4.2.2 Initial Concentrations on Plants

Our estimates of P_o were extrapolated from P_5 and based on $T_p = 15.2$ days which was obtained by comparing P_5 and P_{15}. Since T_p tended to increase with time after the detonation, T_p from D + 0 to D + 5 may have been < 15.2 days; and this error would result in an underestimate of P_o. Errors of this sort would probably be less than the standard errors of observed means for P_o.

While the correlation and regression of initial plant contamination (P_o) on estimates of initial gamma dose rates (R_o) were highly significant in relation to the Sedan fallout field, this may not always be the case. For example, previous studies have shown that plant contamination (assessed on the basis of gross beta activity) is correlated with the distribution of fallout particles < 50 μ in diameter[32]. Studies now in progress[26], show that nearly all the radioactive particles on the foliage of plants in the Sedan fallout field were < 50μ in diameter, and about half were < 20μ in diameter.

Previous studies have also shown that rabbit tissue burdens following fallout from above-ground nuclear detonations were poorly correlated with gamma dose rates but closely correlated with the distribution of particles < 50μ in diameter[18]. In several cases following tower-supported or balloon-supported detonations, it was found that the percentage of fallout activity attributable to particles < 50μ in diameter, the gross beta activity of plants, the thyroid activity, and bone ash activity of rabbits were higher at intermediate distances from ground zero (and hence at intermediate levels of initial gamma dose rate) than at either lesser or greater distances[20].

These considerations make it obvious that the unqualified use of aerial surveys to estimate R_o and of linear regression equations to estimate P_o could result in serious prediction errors. A more realistic method of predicting P_o might be based on a consideration of the following parameters: (a) the formation, dispersal and deposition of fallout particles < 50μ diameter[28], (b) the radionuclide deposition rate, e. g., picocuries per radionuclide per unit area in the < 50μ fraction of fallout deposited, (c) the vegetational interception rate, e. g., the percentage of particles < 50μ diameter intercepted per unit weight of plants by different kinds of vegetation, and (d) the weight of foliage (or other edible plant parts) per unit area of contaminated land surface.

For the Sedan test, at least, the regression of initial gamma dose on the initial plant contamination, $P_o(R_o)$, was highly significant. The same regression formula ($P_o = 83.75 R_o + 335$) might apply to another detonation of the same kind, but the evidence now available suggests that the linear regression of P_o on R_o following a surface or air burst may not be significant and hence could not be used to predict P_o.

4.2.3 Rates of Loss from Plants

Our estimates of T_p, based on the means of P_t, indicated a tendency for T_p to increase with increasing time after the detonation. Consequently, the treatment of T_p as a constant and the choice of $T_p = 18$ days were arbitrary decisions justified only by the fact that the most important changes observed in P_t and B_t occurred prior to D + 30.

The loss of radiostrontium from fallout-contaminated plants can be attributed partly to radioactive decay and partly to mechanical disturbances such as wind or rain which remove particles from foliage or foliage from plants [24]. During the earliest period after fallout, the number of radioactive particles removed by wind from foliage is probably greater than the number removed by wind from soil and redeposited on foliage. As the ratio of particles removed to particles redeposited approaches unity, T_p should approach T_r. Since $T_p < T_r$ during the earliest period after contamination, it seems reasonable to ignore the increasing value of T_p with increasing time after fallout. By the same token, it seems reasonable in relation to the formulation of exponential models, to treat the early average value of T_p as a constant which determines the average rate of radionuclide intake by animals feeding on contaminated plants.

Experimental studies have been made by Bartlett et al.[3] which provide estimates of the combined effects of wind and rain. Plants of various kinds (especially grasses) were sprayed with solutions of different radionuclides and then exposed to rain (as much as 1 inch per week) for 60 days or more. The average half-time rate of loss due to all causes (wind and rain) other than radioactive decay, was 14 days. Applying this "environmental half-life" to Sr^{89}, we find T_p (= 50 x 14/50 + 14) = ca 11 days. Therefore, our estimates of T_p (Sr^{89}) = 18 days and T_p(Sr^{90}) = 27 days are applicable only to plants in arid regions and lower values should be expected in more humid areas.

Other factors are also known to influence T_p. For example, rugose or pubescent surfaces are more efficient in trapping and retaining fallout particles than are smooth or waxy surfaces. Some radionuclides (e. g., I^{131}) may be lost by vaporization[23]. Rapid plant growth [22] may result in the dilution of radionuclide concentration and thus in an apparent decrease of T_p. Loss of foliage from deciduous plants could result in an abrupt decrease in P_t. In spite of these complexities, it seems reasonable, for most radionuclides, to estimate $T_p = T_r T_d / T_r + T_d$ where T_r is the radioactive half-life of a given radionuclide (in days) and T_d is the half-time rate of loss due to environmental disturbances. The value of T_d can be expected to range from 14 days or less in humid areas to 28 days or more in arid regions.

4.2.4 Rates of Loss from Bone

The methods discovered in this paper for estimating T_b (20 days) are logical but related to unforeseen variations in T_p and B_t in relation to time after fallout deposition. Any confidence we may have in the accuracy of these estimates is justified primarily by the results obtained (Table 5). Whenever possible estimates of biological and effective half-lives should be based on the results of feeding experiments.

4.2.5 Ratio of Daily Food Consumption to Weight of Bone Ash

Our estimate of W_p = 100 g is based on French's work with jack rabbits in Idaho [9], Currie's work in Utah [6], and Arnold's work in Arizona [2]. Our estimate of W_b = 50 g is based on unpublished data, accumulated by this laboratory since 1951, which indicate that the "standard" Nevada jack rabbit (adult) has a total body weight of ca. 2000 g of which ca. 200 g. is skeleton and that the ratio of fresh bone weight to bone ash weight is ca. 4 to 1.

Even if larger rabbits eat more and smaller rabbits eat less than 100 g (dry wt.) of plant material per day, we can still assume that the ratio, $W_p/W_b = 2$, is more or less constant in a population of jack rabbits.

4.2.6 Fraction of Ingested Radiostrontium Deposited in Bone

The parameter F is probably the most complex and perhaps the most important of all the input parameters for the model used in this study. The potential assimilability of radiostrontium in a heterogeneous mixture of fallout particles and plant material may vary in relation to the physical and chemical properties of the particles and of the plant matrix in which they are dispersed. Actual assimilation and metabolism may vary in relation to species, age of individual animals, time of year, etc. Our estimate of F = 0.0575 is a mathematically arbitrary value which provided a reasonable quantitative fit between the observed and the hypothetical data points of maximum interest. Its physiological significance is dubious, and it does not shed much light on the interaction of factors which determine the appropriate F-value.

There is some evidence that F-values may vary for a given species and a given radionuclide, in relation to the different designs of nuclear devices and the different conditions under which they may be detonated. Studies made during the Plumbob test series, for example, indicated marked differences between Smoky (700 ft tower) and Priscilla (700 ft balloon). While the fission yields of these two detonations were similar (ca. 40 kt), Smoky deposited 52 times more beta activity from H + 1 to H + 12 than did Priscilla, but the beta activity attributable to particles $< 50\mu$ was only 14 times as high in the Smoky fallout pattern as in the Priscilla pattern. Rabbits were collected at comparable times from comparable locations in both of these fallout fields, but the beta activity of the bone ash of rabbits collected in the Smoky fallout field was only 1.4 times as high as that of rabbits from the Priscilla fallout field, an order of magnitude less than might have been expected.[17]

These apparent disparities between levels of fallout deposition and expected levels of beta activity in the bone ash of rabbits are probably related to the relatively higher percentage of particles $< 50\mu$ in the Priscilla fallout debris and to the relatively higher water and dilute acid solubility of radiostrontium and radiobarium in the Priscilla fallout debris[18]. These and similar results have led Larson et al.[18] to suggest that a first approximation of the potential biological availability of a given radionuclide in a given fallout field could be obtained by determining its water (or 0.1 N HCl) solubility in contaminated plant material ($< 50\mu$ fraction), but this is not the F-value indicated in our model.

In the model outlined in Figure 2, the parameter F indicates only the fraction of radiostrontium ingested by a rabbit which is eventually deposited in the rabbit's skeleton. The model effectively ignores the unassimilable fraction which passes through the gastro-intestinal tract. It ignores the fraction which may be assimilated from the gastro-intestinal tract but not deposited in the skeleton, and it ignores the possibly reversible transfers between blood and bone. It ignores, in fact, everything about the rabbit's metabolism of radiostrontium except the amount presumably ingested with contaminated plants and the fraction of that amount which appears in the skeleton. Some of the factors not considered could have a marked influence on the actual value of F which is appropriate for the model.

French and van Middlesworth[11] found that F-values for I^{131} were approximately twice as high for wild jack rabbits (16%) as for Dutch rabbits (8%) maintained in the laboratory. Even larger apparent differences were indicated by our own feeding experiments and field observations[38]. French [9] found that F-values estimated during the winter months were nearly twice as high as comparable estimates obtained during the summer. Experimental estimates of F for radiostrontium could be expected to vary in a similar fashion; and differences related to dietary Ca (or stable Sr) levels, age, general health, and other physiological or environmental factors could also be expected. These ambiguities and uncertainties are of obvious significance because any disparity between estimates of F will be accompanied (Equation 2) by proportional disparities between estimates or predictions of B_t.

Within the mathematical framework of the model, our estimate of F is assumed to be valid for the estimated values (Tables 1 and 2) of P_o and B_t, but we have no assurance that the rabbits collected had actually been feeding on the plants collected for radiostrontium determinations. Indeed, there is some good evidence to the contrary. As mentioned earlier, the stomach contents of rabbits represented in Tables 1 and 2 were analyzed for radioiodine, but the samples remaining after aliquots were removed for this purpose were too small for reliable radiostrontium analyses. The radioiodine data [23] indicate that concentrations in plant samples were higher in the Groom and Currant study areas (Figure 3) but lower in the Penoyer and Railroad study areas than concentrations in stomach contents. If, as was true in regard to radioiodine, the average concentration of radiostrontium in all plant samples was 1.44 times as high as the average concentration in rabbit diets, the value of F would appear to be proportionally higher than we have estimated, i. e., 0.0828 instead of 0.0575.

4.3 Stochastic Models

As mentioned earlier, the variability of our data suggest that we are dealing with probabilistic rather than deterministic processes. Since the model we used for rabbits is deterministic, it provides only a partial explanation of the processes involved.

Also, from a health physics point-of-view, estimates of mean tissue burdens in populations exposed to fallout are of only limited value. In making realistic assessments of biological hazards, information concerning the probable frequency of very high tissue burdens may be more valuable than a single estimate of the mean or mode.

As shown in an earlier paper [39], deterministic models can be used to derive stochastic or probabilistic models. In essence, the stochastic model for I^{131} on desert plants and in the thyroids of jack rabbits [39] attempts to simulate the variable feeding experiences of individuals comprising hypothetical rabbit populations. This is done by allowing each of the input parameters to vary independently and at random within a specified range and frequency of values. The output of the stochastic model is a frequency distribution instead of a single value; and from this distribution, the statistical properties of hypothetical populations can be derived.

By permitting a more realistic treatment of input parameters, a stochastic model provides more information than can be obtained from a deterministic model. However, the computations are complex enough to require an electronic computer; and, at present, the methods of generating frequency distributions to represent input parameters are no more precise than the methods of estimating mean values for the same parameter.

5.0 DETERMINISTIC MODELS FOR THE STUDY OF HUMAN FOOD-CHAIN KINETICS

5.1 General Concept

The hypothesis on which this and our previous studies of food-chain kinetics [38,39] were based involves an analogy which can be stated as follows: If the effective half-lives of a given radionuclide in the different compartments of a food-chain are analogous to the radioactive half-lives of the different radionuclides in a fission product decay-chain, it follows that food-chain and decay-chain kinetics are also analogous. This analogy is more or less obvious in various treatments of physiological tracer kinetics [35], but our purpose here is to illustrate its potential application to the quantitative kinetics of radionuclides on pasture plants, in cow's milk, and in human tissues following a single fallout event.

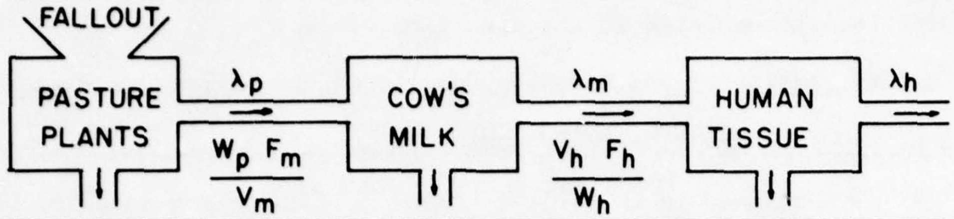
Suppose, for example, that a dairy farm is contaminated by fallout comparable to that produced by Project Sedan, the milk produced by cattle grazing in contaminated pastures is consumed by people living on the farm or in a nearby village. If we know the gamma dose rate at H + 24 or the initial concentration of Sr^{89} or I^{131} on pasture plants or the concentration of one or both of these radionuclides in milk produced within a few days after fallout, can we estimate the other parameters which must be considered in assessing the potential biological consequences to people? The sections which follow will present the bare outline of a deterministic model which might be useful either in future studies of this problem or as an aid in interpreting some of the data which have accumulated in the open literature.

5.2 Estimation of Radionuclide Concentrations on Pasture Plants in Cow's Milk, and in Human Tissues Following Fallout from a Single Detonation

As mentioned in an earlier paper [39], there are no dairy herds in the area contaminated by fallout from Project Sedan (Figure 3), and the few family milk cows in the area are maintained on irrigated pasture and stored feed instead of desert range. Since we have collected no data concerning the concentrations of radionuclides on pasture plants, in cow's milk, or in human tissues, our consideration of the problem is purely hypothetical.

The model diagrammed and formulated in Figure 5 is based on the analogy stated above. To illustrate the kinds of information required for and potentially available from such a model, we have used the parameter values listed in Table 7 to calculate the concentrations of Sr^{89} and I^{131} on pasture plants, in cow's milk, and in human tissues following fallout from a single nuclear detonation. The results of these calculations are given in Figures 6 and 7. (N. B. To avoid unwarranted inferences it should be remembered that the fallout, the pastures, the cows, and the people represented in Figures 6 and 7 are all hypothetical.)

Except for P_o and T_p, the input parameter values used in making these calculations (Table 7) are based on experimental results reported in the open literature. When more than one estimate was found for a given parameter, we usually selected the one which would result in a higher estimate of the concentrations in milk or human tissues.



$t = 0$: $\quad P = P_o \quad , \quad M = 0 \quad , \quad H = 0$

$t > 0$: $\quad P_t = P_o e^{-\lambda_p t} \quad (14) \qquad M_t = \frac{P_o W_p F_m}{V_m}\left[\frac{e^{-\lambda_p t}}{(\lambda_m - \lambda_p)} + \frac{e^{-\lambda_m t}}{(\lambda_p - \lambda_m)}\right] \quad (15)$

$$H_t = \frac{P_o W_p F_m V_h F_h}{V_m W_h}\left[\frac{e^{-\lambda_p t}}{(\lambda_m - \lambda_p)(\lambda_h - \lambda_p)} + \frac{e^{-\lambda_m t}}{(\lambda_p - \lambda_m)(\lambda_h - \lambda_m)} + \frac{e^{-\lambda_h t}}{(\lambda_p - \lambda_h)(\lambda_m - \lambda_h)}\right] \quad (16)$$

Where,

t = time, in days, after plant contamination
N_i = a given radionuclide (e. g., Sr^{89} or I^{131})
P_o = pcN_i/g (dry wt.) on pasture plants at $t = 0$
P_t = pcN_i/g (dry wt.) on pasture plants at $t > 0$
M_t = pcN_i/ml (fresh) in milk produced at $t > 0$
H_t = pcN_i/g (fresh) in human tissue at $t > 0$
W_p = dry wt. (g) of plants consumed per cow per day
F_m = fraction of ingested N_i secreted in milk
V_m = volume (ml.) of milk produced per cow
V_h = volume (ml.) of milk consumed per person per day
F_h = fraction of ingested N_i deposited in human tissue
W_h = fresh wt. (g) of human organ or tissue
λ = $0.693/T$ = effective decay constant
T_p = effective half-life (days) of N_i on pasture plants
T_m = effective half-life (days) of N_i in cow's milk production
T_h = effective half-life (days) of N_i in human tissue of reference
e = 2.718 ... (base of natural logarithms)

Figure 5. A food-chain Kinetics model for estimating radionuclide concentrations on pasture plants, in cow's milk, and in human tissues following environmental contamination by a single fallout event.

Table 7. Values of input parameters used to estimate the hypothetical concentration of Sr^{89} and S^{131} on pasture plants, in cows' milk, and in human tissues (bone and thyroid) following fallout from a single nuclear detonation.

Parameter*	Sr^{89}	I^{131}	References
P_o	100 pc/g	400 pc/g	arbitrary values
W_p	1.4×10^4 g	1.4×10^4 g	19
F_m	0.02	0.06	5.4
V_m	1.0×10^4 ml	1.0×10^4 ml	19
V_h	1.0×10^3 ml	1.0×10^3 ml	arbitrary values
F_n	0.21	0.30	14
W_h	700 g	20 g	14
T_p	18.0 d	5.5 d	24.23
T_m	2.5	2.0 d	5
T_R	50.4 d	7.5 d	14

*Parameters are described in Figure 5. Results of calculation based on these values and the equations in Figure 5 are given in Figures 6 and 7.

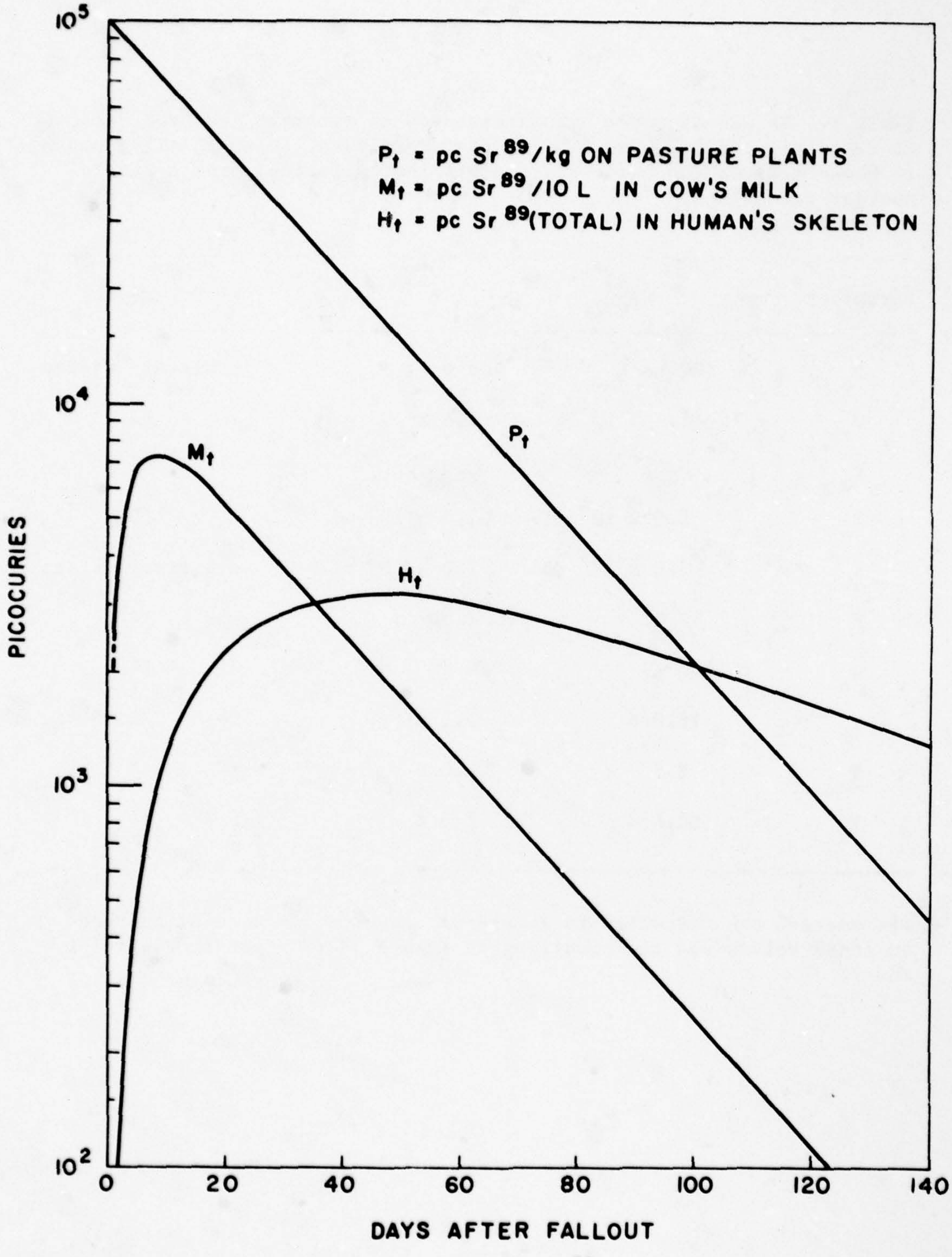


Figure 6. Hypothetical concentrations of Sr^{89} following a single fallout event.

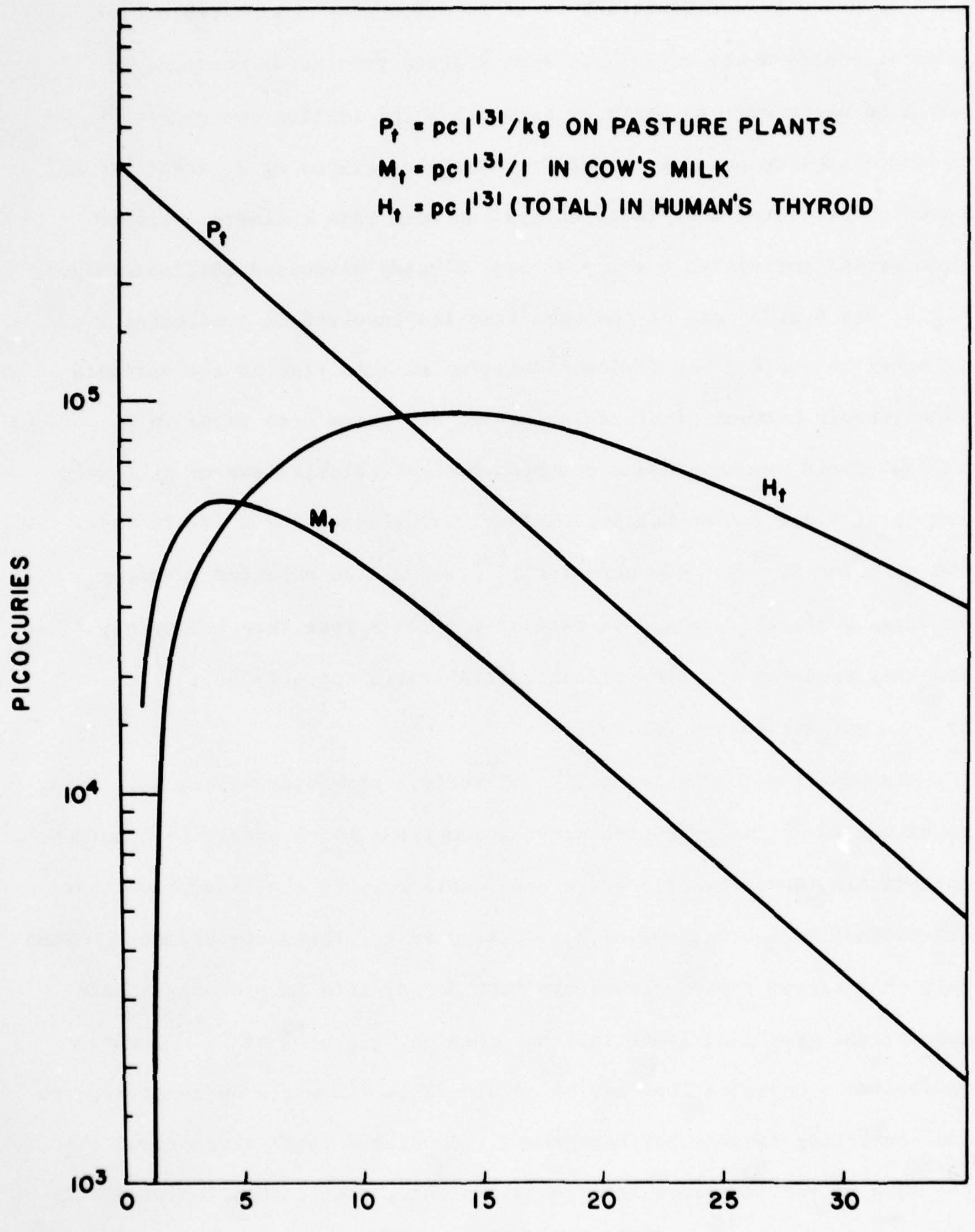


Figure 7. Hypothetical concentrations of I^{131} following a single fallout event.

In order to use Equations 14-17 in predicting the possible biological consequences of fallout from a given nucelar detonation, it would be necessary to begin by predicting the initial concentrations of radionuclides on pasture plants. These predictions of P_o might be based on predicted dose rates or else on dose rate estimates derived from aerial surveys on D + 1. We have already discussed (Sections 4.2.1, 4.2.2, and 4.2.3) some of the uncertainties involved in predicting P_o. In order to avoid a lengthy consideration at this time of the variable relationship between plant contamination and gamma dose rates in a fallout field, we have based our hypothetical calculations on arbitrary levels of plant contamination. The values selected for P_o (Table 7)-- 100 pc/g for Sr^{89} and 400 pc/g for I^{131} --could be expected to occur in areas where the gamma dose rate at H + 24 is less than 1.0 mr/hr; and they preserve the theoretical initial ratio (ca.4:1) of I^{131} to Sr^{89} in unfractionated fallout.

In addition to the assumption of various parameter values (Table 6), Equations 14-17 imply several other assumptions which should be considered. For example, these equations are applicable only to the assumption that pre-fallout concentrations of N_i are zero in all three compartments. When only short-lived radionuclides are considered, this is probably a safe assumption. For long-lived radionuclides (e. g., Sr^{90} or Cs^{137}) whose prefallout concentrations may be considerable, it would be necessary to add correction factors for background. Equations 14-17 also assume that the loss of radionuclides from pasture plants, the consumption of plants and production of milk by cows, and the consumption of milk by people are continuous processes. Since the practical time intervals for these processes are relatively short (Ca. 0.5 -1.0 day), the error introduced by treating them as continuous processes is probably small. Finally, the model assumes that radionuclide transfers from plant to cow, from cow to milk, and from milk to man are irreversible and occur at exponential rates.

Within the framework of these assumptions, the model outlined in Figure 5 could be used to study the plant-cow-human food-chain in much the same way as we have used similar models to study the desert shrub-jack rabbit food-chain. In the absence of field test and experimental data we cannot judge how well this model might function in explaining or predicting radionuclide concentrations in milk and human tissues following pasture contamination by fallout. Probably such predictions should not be undertaken until better methods have been developed for predicting initial radionuclide levels on fallout-contaminated pasture plants, and for estimating the other parameter values which are most appropriate in a given situation.

Even though such a model may not yet be useful for making predictions, it can still be useful as an aid in assessing the possible biological consequences of observed levels of radionuclides on plants or in cow's milk. James [15] for example, has derived some very similar equations in an attempt to explain the food-chain kinetics of I^{131}. By assuming various parameter values and calculating an integration constant, James has used the maximum observed concentrations of I^{131} in milk to estimate initial concentrations on pasture plants, subsequent concentrations in milk and human thyroids, and the total dose delivered to human thyroids.

5.3 Estimations of Dose to Human Tissue

The dose delivered by N_i to human tissue is related to the energy deposited per disintegration of N_i and to the area under the curve generated by Equation 16. Therefore, the cumulative dose (D_H = rem) implied by the parameter values listed in Table 6 is given by Equation 17.

$$D_H = K_r \frac{P_o W_p F_m V_h F_h}{V_m W_h}\left[\frac{(1 - e^{-\lambda_p t})}{\lambda_p(\lambda_m-\lambda_p)(\lambda_h-\lambda_p)} + \frac{(1-e^{-\lambda_m t})}{\lambda_m(\lambda_p-\lambda_m)(\lambda_h-\lambda_M)} + \frac{(1-e^{-\lambda_h t})}{\lambda_h(\lambda_p-\lambda_h)(\lambda_m-\lambda_h)}\right] \quad (17)$$

Where,

D_H = cumulative dose in rem (based on rem = rad x RBE, rad = 100 erg/g, and RBE = 1)

$$K_r = \frac{3.20 \times 10^3 \text{ dis/day/pc}}{6.24 \times 10^7 \text{ Mev/100 erg/g}} \times \bar{E}(\text{RBE})$$

E(RBE) = average energy (Mev/dis) deposited by N_i in tissue of reference multiplied by the relative biological effectiveness

By way of contrast, the annual dose (D_y) resulting from the ingestion of a given amount (A) of N_i each day is given by Equation 18.

$$D_y = 365 \text{ A } K_r F_H/\lambda_h W_h \quad (18)$$

In our hypothetical example (Figures 5-7 and Table 7) the total dose (D_{oo} = rem) delivered by Sr^{89} to the 700 g skeleton of a child would be 0.82 rem; and the total dose delivered by I^{131} to the 2.0 g thyroid of an infant would be 14.6 rem. These total doses, based on Equation 17, are equivalent to the annual doses, based on Equation 18, which would result from an average intake of 720 pc/day of Sr^{89} and 2100 pc/day of I^{131}.

The Federal Radiation Council[8] has recommended several Radiation Protection Guides (RPG's) which are said to represent "... a reasonable balance between biological risk and benefit to be derived from useful applications of radiation and atomic energy." The RPG's for human bone and thyroids are 1.5 rem per year "... for individuals in the general population ..." and 0.5 rem per year as an average "... to be applied to suitable samples of an exposed population group." An average annual intake of > 2000 pc/day of Sr^{89} or of > 100 pc/day of I^{131} (based on a 2 g thyroid)"... would be presumed to result in exposures exceeding the RPG... ".

Using Equation 18 and the parameter values given in Table 7, we find that an average annual intake of 2000 pc/day of Sr^{89} would result in a dose of 2.28 rem to a 700 g skeleton; and an average annual intake of 100 pc/day of I^{131} would result in a dose of 0.695 rem to a 2 g thyroid. Using Equation 17 and the parameter values given in Table 7, we find that similar doses could result, according to the model outlined in Figure 5, from a single fallout event producing initial contamination levels of about 280 pc/g of Sr^{89} or only 20 pc/g of I^{131} on pasture plants.

The initial concentration of Sr^{89} on desert shrubs in the vicinity of Currant, Nevada (Figure 3) was approximately 400 pc/g. The initial concentration of I^{131} on the same plants was approximately 1000 pc/g[(23)]. If equivalent levels of contamination had occurred in our hypothetical pasture, the total dose delivered by Sr^{89} to 700 g skeleton would have been 3.28 rem. The hypothetical total dose delivered by I^{131} to a 2 g thyroid would have been 36.5 rem.

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APPENDIX A

Table A. Concentrations (pc/g) of Sr^{89} and Sr^{90} in the bone ash of rabbits collected, before (BKGD) and at various times after (D+5, D+10, D+15, etc.) the detonation, at different locations (See Figure A) in the SEDAN fallout field. (Decay corrections were made to the times of collection.

LOCATION		TIMES OF COLLECTION							
AREA	STA.	BKGD	D+5	D+10	D+15	D+20	D+25	D+30	D+60
(STRONTIUM-89, pc/g)									
GROOM	1	SL	45	640	454	457	NS	166	330
	2	SL	26	55	118	187	259	97	51
	3	22.5	734	NS	2234	7332	3565	4783	2114
	4	69.7	69	473	15	243	62	99	251
	6	76.7	1400	SL	12598	22169	12127	4395	1503
	7	23.6	1347	573	2332	893	939	8316	6804
	8	NS	3745	932	1061	823	754	7400	7235
PENOYERS	1	99.6	3396	1736	4492	150	3630	7441	1168
	2	NS	NS	5620	7122	580	2729	4335	674
	4	SL	273	843	2995	2868	2141	280	448
	5	49.0	308	SL	409	3678	179	293	188
	7	NS	152	359	1161	214	247	3012	172
	9	NS	1623	403	21	2594	5170	3145	174
	10	NS	574	52	598	573	934	103	2386
	14	NS	NS	1112	4161	2993	729	468	3522
	15	42.4	2686	962	1064	5508	310	388	782
	16	NS	4071	315	356	244	326	593	1257
	20	NS	NS	1034	19559	611	783	8248	4859
RAILROAD	1	SL	2070	1013	1434	692	2412	NS	1590
	2	140.0	714	489	2317	2013	2050	1663	3781
	3	21.0	180	455	226	3566	NS	310	425
	4	75.0	195	619	123	172	161	876	212
	5	NS	161	1165	249	214	189	298	110
	6	75.6	224	341	211	3633	342	871	1053
	7	79.0	359	1196	221	NS	76	194	243
CURRANT	1	SL	522	669	381	414	625	280	265
	2	59.0	811	220	586	193	237	710	39
	3	33.2	67	73	489	424	357	121	350
	4	21.0	62	582	27	160	116	266	189
	5	18.0	15	307	650	478	514	237	556
(STRONTIUM-90, pc/g)									
GROOM	1	8.2	814	20.4	14.4	SL	NS	8.2	15.4
	2	6.4	3.8	6.5	14.5	12.5	10.6	9.7	6.4

(Continued)

Table A. (continued)

LOCATION		TIMES OF COLLECTION							
AREA	STA.	BKGD.	D+5	D+10	D+15	D+20	D+25	D+30	D+60
GROOM (cont.)	3	4.6	10.1	NS	24.0	SL	44.5	52.9	40.9
	4	21.5	5.6	20.3	6.4	9.9	7.0	8.6	13.6
	6	6.1	22.4	6.5	113.8	184.9	104.5	81.1	72.5
	7	30.8	14.2	12.2	22.0	11.5	13.8	123.2	95.0
	8	NS	34.0	11.7	12.5	8.6	10.4	72.0	111.8
PENOYER	1	21.2	27.7	69.3	45.1	6.9	35.8	74.7	17.2
	2	NS	NS	49.9	67.4	7.7	31.4	50.1	41.4
	4	9.4	4.7	23.3	37.4	37.6	27.2	6.3	10.3
	5	3.4	4.9	6.4	7.9	41.4	16.1	6.6	6.2
	7	NS	4.7	6.7	19.8	6.0	5.4	35.2	6.1
	9	NS	22.4	7.6	6.0	32.2	53.5	39.8	14.3
	10	NS	16.5	4.4	26.3	13.5	17.5	4.0	44.5
	14	NS	NS	16.7	39.7	32.3	8.0	9.7	48.2
	15	3.9	33.1	11.6	12.6	61.8	10.3	6.7	18.3
	16	NS	47.3	8.2	4.1	4.8	6.3	11.6	25.9
	20	NS	NS	12.1	161.4	8.0	12.0	78.4	72.3
RAILROAD	1	5.4	20.4	12.8	12.6	9.4	30.6	NS	28.5
	2	SL	8.4	6.7	28.3	44.3	22.4	6.3	55.1
	3	8.9	6.3	8.7	5.1	52.7	NS	7.3	29.2
	4	3.3	6.2	12.7	4.4	8.0	4.3	11.5	9.8
	5	NS	4.5	32.4	5.6	6.5	5.6	7.5	5.6
	6	7.6	7.4	8.3	5.7	47.8	7.8	14.5	28.8
	7	7.2	10.4	23.1	5.7	NS	2.4	12.1	5.6
CURRANT	1	23.3	23.2	20.3	15.6	15.0	16.7	14.9	12.5
	2	4.1	20.2	19.5	20.9	13.5	17.9	32.7	4.9
	3	3.6	6.2	6.4	14.8	16.6	19.3	19.2	17.5
	4	19.8	6.6	19.1	5.4	12.6	14.5	17.5	16.5
	5	19.2	7.1	19.9	23.9	21.9	21.1	19.4	24.6

NS = No sample collected
Sl = Sample lost

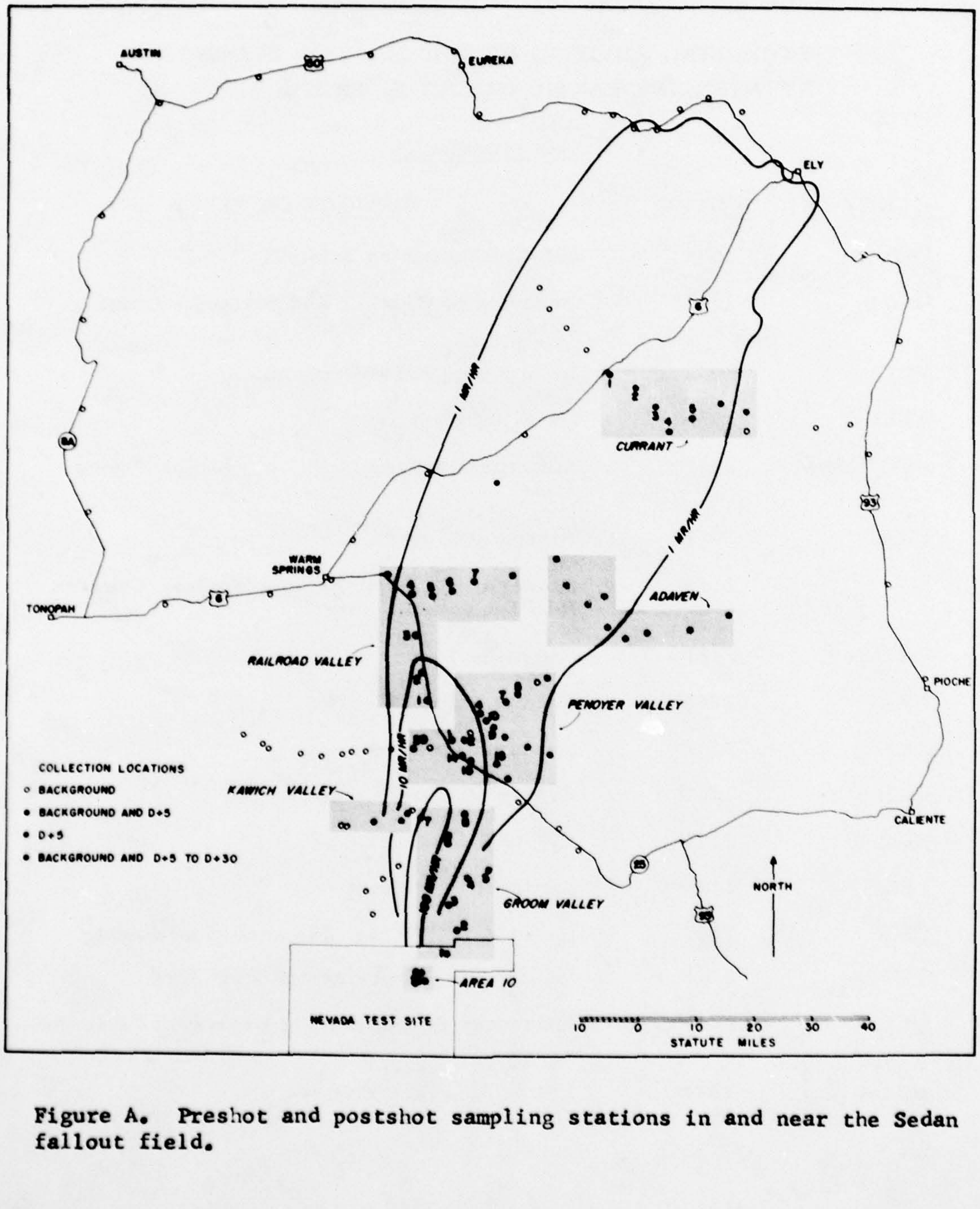

Figure A. Preshot and postshot sampling stations in and near the Sedan fallout field.

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ABBREVIATIONS FOR TECHNICAL AGENCIES

STL	Space Technology Laboratories, Inc., Redondo Beach, Calif.
SC	Sandia Corporation, Sandia Base, Albuquerque, New Mexico
USC&GS	U. S. Coast and Geodetic Survey, San Francisco, California
LRL	Lawrence Radiation Laboratory, Livermore, California
LRL-N	Lawrence Radiation Laboratory, Mercury, Nevada
Boeing	The Boeing Company, Aero-Space Division, Seattle 24, Washington
USGS	Geological Survey, Denver, Colorado, Menlo Park, Calif., and Vicksburg, Mississippi
WES	USA Corps of Engineers, Waterways Experiment Station, Jackson, Mississippi
EGG	Edgerton, Germeshausen, and Grier, Inc., Las Vegas, Nevada, Santa Barbara, Calif., and Boston, Massachusetts
BYU	Brigham Young University, Provo, Utah
UCLA	UCLA School of Medicine, Dept. of Biophysics and Nuclear Medicine, Los Angeles, Calif.
NRDL	Naval Radiological Defense Laboratory, Hunters Point, Calif.
USPHS	U. S. Public Health Service, Las Vegas, Nevada
USWB	U. S. Weather Bureau, Las Vegas, Nevada
USBM	U. S. Bureau of Mines, Washington, D. C.
FAA	Federal Aviation Agency, Salt Lake City, Utah
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