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SOME ASPECTS OF STRONTIUM RADIOBIOLOGY

Recommendations of the
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PROTECTION AND MEASUREMENTS

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Preface

This report, which provides information on several aspects of strontium radiobiology, was prepared by Scientific Committee 57-12. In preparing the report, the committee was able to utilize unpublished material prepared some years ago by Scientific Committee 23 on Radiation Hazards Resulting from the Release of Radionuclides into the Environment. Howard L. Andrews, who served as a member of Scientific Committee 23, assisted Scientific Committee 57-12 during the preparation of this report and his help is gratefully acknowledged. C.W. Mays, now deceased, as well as others, also provided important information throughout.

The report reviews pertinent information on the metabolism and dosimetry of radiostrontium. Effects of radiostrontium are described briefly, especially as revealed in a series of long-term animal experiments. The possible extrapolation of these results to man is considered.

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Contents

1. Purpose and Plan

This report provides: (a) a review of some aspects of the radiobiology of radiostrontium, especially strontium-90; (b) a review of the pertinent information on the metabolism and dosimetry of radiostrontium; (c) a brief description of the effects of radiostrontium, especially as revealed in a series of long-term animal experiments (on mice, dogs, swine, and monkeys) and their possible extrapolation to man; and (d) estimates of risk to humans from the internal deposition of ^{90}Sr.

While the information reviewed in this report is sufficient to support first order estimates of risk to humans from internally deposited radiostrontium, the report does not recommend any changes in the radiation protection standards for strontium radionuclides. This is partly because the current data do not indicate a need for major changes from current standards and partly because the reanalysis of the risk factors for radiation derived from the revised Japanese exposure data may influence future radiation protection standards. Thus, this report should be regarded as an important and necessary update but not a final interpretation for the purposes of standard setting.

2. Background

Strontium-90 is a radioactive isotope of strontium that is produced in nuclear fission with a relatively high yield of 3 to 4 percent (Glasstone and Dolan, 1977). It has a physical half-life of about 29 years and emits a beta particle of fairly low average energy (0.2 MeV). It is accompanied by a decay product, yttrium-90, which has a shorter half-life (64h) and a much more energetic beta particle (2.3 MeV maximum, 0.93 MeV average). Because of its moderately long half-life, the energy of its radiation, its relatively high yield in the fission process, and its mobility under most circumstances, strontium-90 was early considered among the potentially most hazardous of the products of nuclear fission. Strontium-89 with a half-life of 50.5d and average beta energy of 0.58 MeV is also produced in nuclear fission along with several shorter-lived isotopes of strontium.

The possible hazard of ^{90}Sr, with its relatively long physical half-life and its chemical similarity to Ca, was recognized in the work with atomic energy carried out as part of the Manhattan District efforts. Experiments were undertaken very early to delineate the hazard more explicitly. These were necessarily at relatively high dose levels and of short term, because answers, even partial answers, were needed immediately. Much of this work was the basis for the recommendations given in NCRP Report No. 11 (NCRP, 1953). The interested reader is referred to that Report and to its bibliography as well as to NCRP Report No. 22 (NCRP, 1959), to ICRP Publication No. 2 (ICRP, 1959) and to the recently published history by Stannard (1988).

Initially, concern was for ^{90}Sr in fallout from atmospheric tests of nuclear weapons. By the mid-1970s concern had shifted to potential accidents with the ^{90}Sr inventory in power reactors, at fuel reprocessing plants and in high-level waste, and the underlying concern for the potential consequences of nuclear weapons use. The primary interest was in the induction of bone cancer by the beta radiations from radiostrontium, but the problems of fallout from nuclear weapons testing stimulated wide-ranging investigations of not only its effects but also its behavior in the environment, especially in food and food chains and in aqueous media and in a variety of organisms.

The radiobiology literature concerning the radioisotopes of strontium is enormous. Nevertheless, for many years, little was known

about its biological effects at doses low enough to be pertinent to the direct development of radiation protection standards. Much analysis had to be done to establish relative effectiveness ratios in animals between strontium and radium whose long term effects in man at low doses had been well-established. Some of this work was summarized in an unpublished report drafted by NCRP Scientific Committee 23 which was used in preparing this report. As these long term experiments developed, many progress reports were issued. These include reports from symposia held at Sun Valley (Mays *et al.*, 1969a), at Battelle Pacific Northwest Laboratories (Sikov and Mahlum, 1969; Clarke *et al.*, 1970a), at the University of California at Davis (Goldman and Bustad, 1972) and at Glasgow and Strontian, Scotland (Lenihan, 1972). Also, as will become evident in the following text, the documents of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and of the U.S. National Academy of Sciences-National Research Council Committee on the Biological Effects of Ionizing Radiation (BEIR) contain considerable information on the behavior and potential effects of radiostrontium. Annual reports and occasional special documents from the several laboratories gave detailed reports in tabular form of the status of each animal in each experiment.

All of these sources provided useful information for the deliberations of governmental agencies and national and international bodies concerned with radiation protection. Nevertheless, the slow progression of the long-term animal experiments always lent a degree of tentativeness to the conclusions that were possible. It is against this background that the present report has been assembled. While there are still some areas of uncertainty, it was considered useful to review the radiobiology of stontium without delay and to develop risk estimates for man.

3. Metabolism of Radiostrontium

Data on metabolism[1] of radiostrontium (as well as stable strontium) have much intrinsic scientific interest and are, of course, essential for the calculation of radiation doses. Since information on this aspect could be obtained much sooner than information on long-term effects, much of the earlier literature concentrated on metabolic behavior, but the long-term experiments also gathered information on metabolism, particularly the kinetics of retention over long periods.

The metabolic behavior of ^{90}Sr in mammals can be described in general terms as follows: after radiostrontium is ingested, a fairly substantial part is absorbed from the gastrointestinal tract, and a part is excreted unabsorbed in the feces. That which is absorbed is: (a) deposited in the bone volume; (b) distributed in an exchangeable pool which can be considered to be comprised of the plasma, extracellular fluid, soft-tissue and bone surfaces; or (c) removed from the body by urinary and fecal excretion. Absorption of ingested strontium from the gastrointestinal (GI) tract by adult man averages between 20% and 30% (Spencer *et al.*, 1960; Dolphin and Eve, 1963; Marshall *et al.*, 1973; Likhtarev *et al.*, 1975; Muth and Globel, 1983).

In biological systems, the behavior of stable strontium, and therefore of radioactive strontium that enters such systems, is qualitatively similar to and is governed partially by the behavior of calcium. Because of homeostatic control, there is a remarkable constancy of calcium concentration in most tissues and fluids (*e.g.*, bone, blood and milk). Thus, it was proposed that within normal dietary ranges and under steady-state conditions, the radiostrontium-to-calcium ratio in the body tissues or secretions is a function of the ratio that exists in the diet (Comar and Wasserman, 1964; Comar, 1965, 1967; Comar *et al.*, 1955). For this reason, the concentration of radiostrontium in biological materials was studied and reported by many investigators as a Sr/Ca ratio (usually picocuries of ^{90}Sr per gram of Ca).

[1]"Metabolism" means the behavior of the radionuclide in the organism; its absorption, distribution, localization in cells and the tissues and its excretion.

This ratio was termed the "strontium unit" or "Sunshine unit" in the early years of work on fallout from nuclear weapons tests.

However, living organisms generally utilize and retain strontium less effectively than calcium (Shvedov, 1978). The term "discrimination" has been used to describe the ratio of concentrations in, for example, the organism and its diet, and to denote the contributions of individual physiological processes responsible for it. The overall discrimination was designated as the "Strontium Calcium Observed Ratio" (OR) (Comar *et al.* 1956):

$$OR_{sample/precursor} = \frac{Sr/Ca\ of\ sample}{Sr/Ca\ of\ precursor}\ (dimensionless) \qquad (3.1)$$

This concept was used for many years and was a central feature in predicting behavior of radiostrontium in organisms and in the environment (Comar and Wasserman, 1960; Stannard, 1988). However, the behavior of strontium may also be considered directly without reference to calcium (Palmer *et al.*, 1958a, 1958b; Palmer and Thompson, 1961, 1964; Thompson and Palmer, 1960; Thompson, 1963).

To calculate the radiation dose to various parts of bone tissue from internally deposited radionuclides, one needs to know the pattern of uptake and retention of the radioactive material within the skeletal system. Appropriate data for man are scarce, so that existing estimates of the dose within bone from the alkaline earth elements have been based on the skeletal distribution of fallout ^{90}Sr, calcium distribution in the human skeleton and results of animal experiments. One study, published by the ICRP (ICRP, 1972, also published as Marshall *et al.*, 1973), has considered the subject in detail and used accumulated knowledge of the mechanisms of skeletal metabolism and the retention of radionuclides (Marshall, 1969) to construct a quantitative metabolic model for the alkaline earth series. It is reproduced in summary form in NCRP Report 84 (NCRP, 1985). This model (known as the ICRP or Marshall Model) deals with radionuclides that distribute throughout the *volume* of mineralized bone, primarily the alkaline earths, calcium, strontium, barium and radium. Obviously it cannot be applied to other chemical groups. Data on the retention of both ^{90}Sr and ^{226}Ra in dogs from the experiments to be described presently at Utah, at the Laboratory for Health Related Research (LEHR), at the Inhalation Toxicology Research Institute (ITRI) and at Argonne National Laboratory (ANL) were used in the construction of this model. These data were generally described by exponential or modified exponential (power) retention functions (see below).

The ICRP model has been extended to younger ages, modified or criticized by Papworth and Vennart (1973), Bennett and Harley (1973), Newton *et al.* (1977), Marcus and Becker (1980), Matsubara *et al.*, (1981), Harrison (1981), Schlenker *et al.* (1982), Johnson (1983), Holtzman *et al.* (1983), Leggett *et al.* (1982, 1984), and Crawford-Brown (1984), with additional published data by Likhtarev *et al.* (1975), Wenger and Soukas (1975), Ilyin *et al.* (1975), and Erre *et al.* (1980).

Single dosage experiments in beagle dogs at ANL have given some indication that the young animal excretes less of its ^{90}Sr than the adult. It appears that a factor of 3 or 4 is sufficient to span the results (Decker *et al.*, 1964, Finkel *et al.*, 1972). This is in concurrence with the findings of the continuous feeding experiments at LEHR and PNL and with studies using injected ^{85}Sr in beagles at Utah (Glad *et al.*, 1960). The influence of age on strontium metabolism (greater retention in younger individuals) has also been investigated by McClellan (1962), Speckman and Norris (1964), Della Rosa *et al.* (1965), Forbes and Reina (1972), Kahn *et al.* (1969), Papworth and Vennart (1973) and Leggett *et al.* (1982, 1984).

Perhaps the most extensive data on the behavior of ^{90}Sr in children, both in span of time and in the number of subjects studied, have been collected through the effort begun at the Health and Safety Laboratory (HASL) (now the Environmental Measurements Laboratory), New York City, under the late Joseph Rivera, continued in subsequent years by Burton Bennett and developed into the Rivera Model (Rivera, 1969; Rivera and Harley, 1965). This is an empirical model based on measurements of fallout ^{90}Sr in the diet and in bone from individuals of different ages. It is formulated as a simple description of the gain and loss of calcium and the associated ^{90}Sr. Data of Mitchell (Mitchell *et al.*, 1949) were used for the calcium content, and measurements of the concentrations of ^{90}Sr in bone and diet covering a considerable period of years were the basis for the ^{90}Sr data in their study (Radiological Health Data and Reports, 1960-1971).

A comprehensive review of information on the uptake and excretion of ^{90}Sr by infants was published by Durbin *et al.* (1970). Their analysis used data derived from the skeletal weight, Ca accretion and uptake, and the value of the observed ratio (OR) during the first year of life. This was supplemented by values derived from Bedford *et al.* (1960), Mitchell *et al.* (1949) and data of Beninson *et al.* (1969) as well as data from the HASL studies (*e. g.* HASL,1964). The dose commitment to red bone marrow was calculated by Durbin *et al.* (1970) for the individual assumed to be always ingesting 37 kBq of ^{90}Sr, and uptake from GI tract to blood was estimated by use of

combined data of Durbin *et al.* (1970) and Beninson *et al.* (1969). The dosimetric significance of some of the empirical models will be considered in Section 4.

Qualitatively, the results of both the Rivera model and its revision, the Bennett model, are much the same, and they also agree qualitatively with results obtained by other models, particularly those of Mays and Lloyd (1966), whose work predated ICRP Publication 20 (ICRP, 1972) and those of Papworth and Vennart (1973). All these models indicate than an infant ingesting 37 kBq of ^{90}Sr will receive a higher dose than an adult ingesting the same amount, and that the doses to the infant may be higher by a factor of as much as eight compared with the adult. In fallout studies, a smaller factor of increase, about 2-3, has been observed, but this is to be expected since the higher uptake at an earlier age would tend to be "diluted" or averaged out with lower uptake at later ages.

An important feature of the studies of the metabolism of radiostrontium is the measurement of retention. This is presented in Section 4 since it bears directly on dosimetry.

4. Dosimetry of ^{90}Sr

For purposes of this report, the concepts adopted by the ICRP (1977, 1979) will be utilized in the main. A succinct summary of the dosage formulations, their use, and cautions regarding their use is contained in NCRP Report No. 84 (NCRP, 1985). This includes detailed extracts from ICRP documents concerning the dosimetry of bone. These will not be repeated here.

Essential to all calculations of dose for long-lived radionuclides deposited in tissue is knowledge of the kinetics of retention because the rate of elimination frequently has as much or more influence on dose as does the physical half-life. For purposes of this report, it will be assumed that the retention models, risk estimates, etc. apply at doses and dose-rates sufficiently low to exclude acute radiation effects.

Table 34 of Marshall *et al.*, (1973) gives time integrals of the effective retention of ^{89}Sr and ^{90}Sr. Part of this table is reproduced here as Table 4.1.[2] The integral values are mean residence times in 10^4 Bq-days following the introduction of one unit of radiostrontium into the blood whether by injection, by inhalation, or following ingestion. For an intake to blood of 1 Bq, the time integral of activity will be in units of Bq-days.

The metabolic model of ICRP Publication 20 (ICRP, 1972; Marshall *et al.*, 1973) enables one to estimate the behavior of ^{90}Sr following an intake by an adult. By far the greatest residence (time integrated activity) is in bone, and the model gives separate estimates for retention in compact and in cancellous bone. This is of importance because the active marrow is more closely associated with and would receive most of its dose from the $^{90}Sr + {}^{90}Y$ retained in cancellous bone. The model predicts (Table 4.1), for 37 kBq of ^{90}Sr entering the blood of an adult, a residence of 1474×10^4 Bq-days for the compact bone

[2]It will be noted that this Table gives integration times for only one year and 50 years and infinity. Frequently, intermediate times may be useful in dose calculations. A table showing microcurie-days accumulated in cancellous and cortical bone and in soft tissue for 2, 7, 30, 60, 180, 365, 1,825, 3,650, 7,300, 10,950, 14,600 and 18,250 days after intake of one microcurie of three strontium isotopes and of barium-140 is given in the Reactor Safety Study, WASH-1400, Appendix VI (NRC, 1975). The data were supplied by Marshall. This table, with the data converted to SI units, is reproduced as Appendix "A" to this report.

TABLE 4.1—*Time integrals of the retention functions in 10^4 Bq days for 1 year, 50 years and infinity after injection of 3.7 × 10^4 Bq including the effect of radioactive decay*[a]

Isotope	Time After Intake Year	Blood	Total Body	Bone[b]	Soft Tissue	Bone Surface
^{90}Sr	1	0.906	260	211	49.2	6.07
	50	1.02	2116	2048	68.1	6.88
	∞	1.02	2209	2141	68.1	6.88
^{89}Sr	1	0.792	69.9	46.3	23.6	5.07
	50	0.792	70.3	46.6	23.7	5.07

		BONE VOLUME				TOTAL SKELETON[c]	
Isotope	Time, Yr	New Compact	Old Compact	New Cancellous Bone	Old Cancellous Bone	Cancellous Bone	Compact Bone
^{90}Sr	1	53	64.8	51.4	40.4	94.0	121
	50	662	807	325	253	582	1474
	∞	699	855	326	253	582	1558
^{89}Sr	1	10.2	12.5	10.1	7.84	20.5	25.3
	50	10.3	12.6	10.2	7.88	20.6	25.5

[a]Adapted from Table 34 of Marshall, *et al.*, 1973. For consideration of other times of integration see footnote 2 and Appendix A.
[b]Total body minus soft tissue.
[c]The total adult skeleton of Reference Man contains 5 kg of mineralized bone, 4 kg as compact bone and 1 kg as cancellous bone.

and 582 x 10^4 Bq-days in cancellous bone for the *50-year period* post exposure (numerical values taken directly from Marshall, *et al.*, 1973, and converted to SI units). The residence times corresponding to *infinite residence* of 1558 $\times$ 10^4 and 582 $\times$ 10^4 Bq-days, respectively, are quite close to these values, and consequently, little additional dose would be received even though the person did live beyond the 50-year period post intake. In soft tissues, the residences are quite small in comparison to the total mass of such tissues, and because there is no known concentration factor, except possibly for cartilage (Snyder and Cook, 1964), the dose to these tissues can be estimated as an average.

The model of Papworth and Vennart (1973) extended the ICRP 20 (Marshall) model (ICRP, 1972) to children to yield separately the retention in compact bone and in cancellous bone. Their estimates show the infant to have the largest dose commitment per unit of intake, but still within the range of values obtained by other models.

Each of the long-term animal experiments, which will be described in more detail in the next section, provided information on retention in the skeleton. These could be described by a retention function of the form:

$$R(\%) = A_1 e^{-k_1 t} + A_2 e^{-k_2 t} + A_3 e^{-k_3 t} \qquad (4.1)$$

where R = percentage retention, k_1, k_2 and k_3 and A_1, A_2 and A_3 are determined from experimental data. These were used to compute the doses associated with given times and effects that are presented in the Tables of Section 5. Details of the numerical values of the retention functions in the several exponents can be found in Appendix B (derived for this report). Relative magnitudes of corresponding values in Appendix B provide an important comparison of the retention of administered ^{90}Sr among the various lifespan studies, because data from each laboratory were supplied to a single investigator (NJP) who performed the calculations with a single program. This approach should eliminate differences that might arise from different fitting routines used at various laboratories or the selection of animals at differing skeletal dose-rates. For animals that were exposed to ^{90}Sr by injection or inhalation, the calculated values of the parameters were roughly similar.

In the long-term experiment with monkeys carried out at the University of California, Berkeley, and presented in more detail along with the other long-term experiments in Section 5, the kinetics of retention were worked out in depth. The time involved was over 20 years.

Total body retention in this work was described by Durbin *et al.*, (1974) with an exponential equation of 6 terms, viz:

$$R = A_1e^{-c_1t} + A_2e^{-c_2t} + A_3e^{-c_3t} + A_4e^{-c_4t} + A_5e^{-c_5t} + A_6e^{-c_6t} \quad (4.2)$$

Values of the A's and c's given by Durbin *et al.* (1974) are displayed in Table 4.2. Correlates of this experiment will be evident in the discussion of dosimetry and derivation of risk.

The values for uptake to blood from the GI tract or lung (0.3 with a range of 0.2 to 0.5) used in ICRP Publication 30 (ICRP, 1979),and other metabolic "constants" contained therein, appear entirely appropriate for adults. For subjects exposed at younger ages, the necessary recent modifications of the model for uptake, retention, etc. (Papworth and Vennart,1973; Johnson, 1983; Leggett *et al.*, 1982, 1984; Crawford-Brown, 1984) should be used.

For isotopes that emit beta particles of long-range in tissue, such as ^{90}Sr + ^{90}Y, it is probably sufficient to use the total residence times for either compact or cancellous bone, respectively, in order to calculate the doses to bone marrow or to endosteal surfaces rather than new or old compact/cancellous bone because the spatial distribution of radiation dose is quite uniform. Thus, the columns labeled COMPACT BONE or CANCELLOUS BONE in Table 4.1 (Table 34 of Marshall, *et al.*, 1973) should be used for ^{90}Sr rather than the columns NEW BONE or OLD BONE or BONE SURFACES. The rationale for this procedure is that when the particle range is large, the exact location of the activity within a given type of bone should not have an important effect upon the corresponding distribution of dose.

In contrast to the long-range beta emitters such as ^{90}Sr + ^{90}Y, for the acute intake of radionuclides that emit either alpha particles or beta particles of short range (<100 μm), one should take into account the effect of redistribution of the initially deposited material (hotspot burial). This greatly reduces the dose to bone surface or bone marrow from the NEW BONE component of the activity (*e.g.*, the method of Marshall, 1962). When intake is by continuous exposure beginning at very young ages, bone surfaces are labeled continuously, and hotspot burial is not important. The diffuse component of OLD BONE is more significant for isotopes of long half-life (*i.e.*, months to years), and BONE SURFACE is more significant for isotopes of short half-life (*i.e.*, days).

The differences in deposition and retention that occur with time assumed special importance when an ICRP Task Group identified endosteal tissue lying within 10 μm of bone surfaces as the tissue at risk for bone malignancies (ICRP, 1968). Factors, D_O, necessary to convert average skeletal doses to the corresponding doses to small

TABLE 4.2—*Parameter values for ^{90}Sr retention in monkeys*[a,b]

Term (Equation 4.2)	Young		Adolescent		Adult	
	A	c	A	c	A	c
1	0.11	1.39	0.23	1.82	0.28	1.69
2	0.10	0.330	0.18	0.347	0.24	0.315
3	0.11	0.0408	0.17	0.0693	0.24	0.0990
4	0.20	0.0105	0.14	0.00693	0.092	0.0315
5	0.26	0.00231	0.17	0.00139	0.088	0.00126
6	0.21	0.000128	0.11	0.000124	0.060	0.000165

[a]From Durbin, *et al.*, 1974.

[b]The units of the parameters, "c", are days^{-1}.

soft-tissue cavities within bone have been estimated for deriving dose to marrow or to endosteal tissue by Spiers (1968), by Spiers and Whitwell (1972), by Spiers *et al.* (1972), by Whitwell and Spiers (1976) and by Beddoe and Spiers (1979). It is recommended that ratios of the endosteal dose or marrow dose to average skeletal dose, D_O, be used if such a calculation is to be made. Dose to other specific components of the skeleton, such as the exterior surface, can be calculated by means of an appropriate ratio (see Figure 1 of Beddoe and Spiers, 1979). However, data of Lloyd and Henning (1983) indicate that the location of the cells at risk for bone sarcoma induction cannot be identified as a single layer within 1–10 μm of bone surfaces. This suggests that it may be premature to calculate local dose to cells at risk until their identity and location can be defined more adequately. Furthermore, there is not yet general agreement as to the proper way to determine dose to the critical cells for bone sarcoma induction (Jee, 1984). Fortunately, the problem is trivial for $^{90}Sr + ^{90}Y$ because of the range of the beta particles emitted. So long as risk coefficients to be compared are expressed in consistent units, e.g., bone sarcomas/10^4 Gy average skeletal dose, these nuances of dose parameters make little difference for strontium-90.

We can turn briefly to the mechanics of a dose calculation for radiostrontium. The mineralized bone of reference man has a mass of 5000 g, and the masses of compact and cancellous bone are taken as 4000 g and 1000 g, respectively (ICRP, 1975). The dose, D, to these portions of bone (assuming complete absorption of the beta energy) is given by

$$D = 1.38 \times 10^{-5} \times 1.075 \times U \times E \text{ (Gy)} \qquad (4.3)$$

where 1.38×10^{-5} represents (86400 s/day) (1000 g/kg) (1.602×10^{-13} J/MeV), 1.075 is a factor representing the greater dose within a small soft tissue cavity compared with the dose to surrounding bone (Spiers, 1968) and can be included or not depending on which dose is to be estimated, U represents Bq-days per gram of bone and E is the average energy released in Mev per disintegration of ^{90}Sr. Because ^{90}Y has a decay half-time of only about 2.7 days, it is assumed to be in equilibrium with its parent. While this assumption may not be strictly accurate, it is conservative and is not a significant factor in the case of bone (Arnold *et al.*, 1955). There is some evidence that the dose to active bone marrow and to endosteal cells per unit concentration (Bq ^{90}Sr/g Ca or Bq/g of tissue) should vary with age. It may be higher for the newborn than for the adult human by about 25% because the marrow spaces are smaller in infants and children. The factor becomes less as the marrow spaces approach adult size (Spiers and Whitwell, 1972; Beddoe and Spiers, 1979). If the marrow

dose rate is about half that to the skeleton (Mays and Lloyd, 1972c), the active marrow would receive a dose commitment of about 1.6 μGy/Bq of intake for the newborn, and most of the resulting dose commitment would be received within the first year post intake. This would be the dose commitment the infant would receive only if the ^{90}Sr were ingested during the first month or so of life. In succeeding months the dose commitment per unit intake would decrease rather rapidly, being about a third of the value for intake at 0–1 month of age if the ^{90}Sr is taken at 1 year of age. The average dose commitment to endosteal cells (an average over the distance 1–10 μm of the bone surface) would be approximately twice that received by the bone marrow.

A factor of 0.2 was used in the ICRP model to represent the absorption from the gastrointestinal tract to blood (Table 27, ICRP, 1972). This value is consistent with the data used in developing the retention model as well as with data on ^{90}Sr retention in fallout even though it differs from the one used in ICRP Publication 30 (viz: 0.3, ICRP 1979).

We will consider the skeletal dosimetry of ^{90}Sr in the monkey. The calculated average skeletal dose-rate, dD/dt, in an adult monkey having 150 g of skeleton per kg body is

$$\mathrm{dD}/dt = 1.38 \times 10^{-5} \frac{(g\ dis\ Gy)}{Bq\ MeV\ day} \frac{I\ Bq/kg}{150 g/kg} (1.13\ MeV/dis)\ F\ R \quad (4.4)$$

$$= 1.04 \times 10^{-7}\ \mathrm{IRF}\ Gy/day$$

for an average beta particle energy of 1.13 MeV per disintegration (dis) and where F is the fractional absorption of ^{90}Sr + ^{90}Y beta-particle energy by the skeleton (0.7, 0.75 or 0.8) for a typical 3.3 kg juvenile, 4.6 kg adolescent or 7 kg adult monkey, (Parmley *et al.*, 1962), I is the intake and R is the fractional ^{90}Sr retention in the skeleton.

Cumulative average skeletal dose D can be calculated as

$$D = 1.04 \times 10^{-7}\ IF \int_0^t R\ dt \quad (Gy). \quad (4.5)$$

For an adult monkey living 12 years after the intake of 1 MBq ^{90}Sr, D is about 36 Gy.

5. Effects of ^{90}Sr as Seen in the Long-Term Animal Studies

In this section we consider the biological effects of internally deposited strontium-90 in beagles studied at the University of Utah, mice at Argonne National Laboratory (ANL), miniature swine at Battelle Pacific Northwest Laboratory (PNL), beagles fed ^{90}Sr at the Laboratory for Energy Related Health Research (LEHR) at the University of California, Davis (UCD), beagles exposed by inhalation at the Lovelace Inhalation Toxicology Research Institute (ITRI), and a review of long-term experiments with ^{90}Sr in monkeys as studied at the University of California, Berkeley, and briefly at the University of Rochester.

In each case, the summary tables and descriptive text represent an enormous consolidation and extraction of the essence of what were large, long, difficult and expensive experiments. Glimpses of the true scope of the efforts can be seen in the occasional reports and publications referenced as appropriate.[3]

5.1 Studies with Mice at Argonne National Laboratory

During World War II, long-term studies on strontium were carried out with mice at the Metallurgical Laboratory of the Manhattan District. These were published post-war from the Argonne National

[3]Recently the proceedings of a major symposium entitled "Life-Span Radiation Effects Studies in Animals: What Can They Tell Us?" held at Richland, Washington, in October 1983 have been published (Thompson and Mahaffey, 1986). This includes individual reviews of the life-span studies with strontium at the University of California at Davis, at the Lovelace Inhalation Toxicology Research Institute (ITRI), and at the Radiobiology Laboratory, University of Utah. These reviews serve to update a portion of the information used in depth for the preparation of this report. However, the publication of the symposium proceedings came after completion of the major effort for this report. These later summaries did not result in major revision of the conclusions already drawn, since the bulk of the data had already been gathered and considered.

Laboratory by M. P. Finkel and her colleagues. The results were useful, even during World War II, via the use of in-house reports, for the establishment of the early maximum permissible exposures to radiostrontium.

The results have been summarized many times in the open literature and provided the original input for the toxicity ratio approach to setting the maximum permissible burdens (and derived figures) for many bone-seeking elements. (A toxicity ratio is the ratio of doses from two different radionuclides that produce the same level of effect in the same kind of animal model.) The reader is referred to publications by M. P. Finkel (1956), Finkel and Biskis (1959 and 1968) and a review by Mays and Finkel (1980). These data will be used in this report largely for comparison purposes.

5.2 Beagles Injected at the University of Utah

This ^{90}Sr experiment was conceived in the early 1950s, it was begun in 1955, animals were injected until 1966, and the study is just now reaching final data analysis.

The total of 87 young adult dogs were each given a single intravenous injection of ^{90}Sr at dose-levels ranging from 2.1×10^4 to 362×10^4 Bq/kg and retained for life-span observation. A companion study using single injections of 0.027×10^4 to 38.5×10^4 Bq/kg of ^{226}Ra in 120 young adult beagles was also conducted at the same laboratory.[4] There were 125 control beagles including 57 that were sham injected during the same time interval as the dogs given ^{226}Ra and ^{90}Sr. Veterinary care, preparation of the injection solutions, injection procedure, animal selection, experimental design, radionuclide retention and dosimetry have been described in earlier publications (Dougherty *et al.*, 1962; Lloyd *et al.*, 1976). All of the animals given ^{90}Sr have now died, mainly from causes unrelated to radiation, particularly at levels below 121×10^4 Bq/kg. In addition, all of the young adult dogs given ^{226}Ra have died. The most prominent ^{90}Sr-induced endpoint was bone sarcoma. Neoplasia of the soft tissues near bone in the oronasopharynx and paranasal sinuses, and bone marrow dysplasia were observed in excess of the incidence in the control population ($P<0.05$) but in lower incidences than bone sarcoma.

[4]The dosage levels were chosen in relation to the bench mark level of the maximum permissible body burden of radium in man. The key level (Level 1) for ^{226}Ra was equivalent to ten times the maximum permissible body content. Other levels (8 total) extended from 1/9 to 162 times Level 1.

Leukemia was not observed, and the incidence of myelolymphoproliferative disease was not elevated. Analysis of the dose-response relationships for both ^{90}Sr and ^{226}Ra for bone sarcoma induction have been reported (Mays and Finkel, 1980). Table 5.1 summarizes the results of these experiments in updated and consolidated form. Incidence of bone sarcoma as a function of calculated radiation dose is given in Figure 5.1 for both ^{90}Sr and ^{226}Ra in the Utah studies, omitting, for clarity, the data points beyond the region where the effect is maximized for ^{226}Ra (100%) and the lowest three zero incidence points for ^{90}Sr.

The studies of ^{90}Sr and ^{226}Ra effects at the University of Utah can be compared with corresponding experiments by Miriam Finkel and her colleagues at Argonne National Laboratory, already mentioned (Section 5.1) (Mays and Finkel, 1980).[5] Both of these studies indicate that the effectiveness (toxicity) ratio of ^{226}Ra relative to ^{90}Sr (1) may approach unity at high doses, (2) increases markedly as the skeletal dose is reduced, (3) approaches a value of about 25 for the lowest doses at which definite effects from ^{90}Sr were seen (see Table 5.2 and Figure 5.2), and (4) may be extrapolated to even more than 25 at extremely low levels of skeletal dose and dose-rate such as might be expected in the human population from normal peacetime environmental exposure to ^{90}Sr. Results of more recent experiments reported by Reif and Triest (1982) with ^{90}Sr in C57BL/6J female mice indicate that for injection levels between 118×10^4 and 1180×10^4 Bq/kg, tumor incidence is roughly comparable to that found at corresponding levels for the female CF1 mice at Argonne (Mays and Finkel, 1980). This analysis provides clear evidence that the strontium + yttrium-90 beta particles are much more effective per Gy at high doses and dose rates than at low doses and low dose rates.

The time from injection to death with osteosarcoma ranged between about 2.6 and 13.3 years. There were no other major late effects induced by ^{90}Sr that were as important as bone malignancy. For the two groups with the lowest dose-rate at which a bone sarcoma was seen, the survival of the animals with osteosarcoma was similar to the respective mean.

5.3 Beagles fed ^{90}Sr at the Laboratory for Energy Related Health Research (LEHR), University of California at Davis

A total of 389 beagles at the University of California, Davis (LEHR), were exposed to ^{90}Sr by feeding from the onset of fetal

[5]This is a retrospective analysis of the most cogent data from this large series of experiments and cites many of its original papers.

TABLE 5.1—*Bone sarcomas in beagles at the University of Utah given ^{90}Sr or ^{226}Ra*[a]

Nuclide	Inj. 10^4 Bq/kg	Av. Yr Inj. to Death	No. of Dogs	Sarcoma Dogs[c]	Incidence (%)	Av. Skel. Gy 1 Year Before Death[c]
^{226}Ra	38.5	2.86	10	9	90.0	101.5
	11.9	4.13	13	12	92.3	43.3
	3.96	6.12	12	11	91.7	19.1
	1.25	10.05	13	5	38.5	8.95
	0.614	9.40	14	2	14.3	3.57
	0.229	10.76	23	2	8.7	1.66
	0.081	12.07	25	2[b]	8.0	0.80
	0.027	10.93	10	0	0	0.28
	0	11.97	44	0	0	0
^{90}Sr	362	3.40	14	8	57.1	85.2
	235	5.82	12	8	66.7	71.4
	121	9.98	12	2	16.7	60.2
	40.0	12.27	12	1[d]	8.3[d]	21.7
	12.8	10.79	12	0	0	5.97
	6.36	11.31	13	0	0	3.35
	2.11	12.93	12	0	0	1.10
	0	11.49	13	0	0	0

[a]Adapted from Mays and Finkel, 1980, but with revised dosimetry (Wrenn, 1984) updated, 1987.

[b]Including one recently diagnosed ameloblastoma (skeletal malignancy).

[c]There were also observed among the ^{226}Ra-injected dogs 1 fatal case of blood dysplasia in the 38.5 × 10^4Bq/kg group (at 1288 days), 1 case of fatal malignant tumor of the tympanic bulla in the 1.25 × 10^4Bq/kg group (at 4615 days) and 3 fatal cases of soft tissue neoplasia (non-melanoma) of the oral cavity (0.164 × 10^4, 0.229 × 10^4 and 0.081 × 10^4Bq/kg groups at 3254, 4003 and 3848 days respectively). Among the ^{90}Sr-injected dogs, there were 5 animals that died with blood dysplasia (2 at 362 × 10^4Bq/kg at 990 and 1021 days, 1 each at 235 × 10^4, 121 × 10^4 and 40 × 10^4Bq/kg at 1493, 2114, and 1285 days), 4 with malignant tumors of soft-tissue in the nasopharynx (1 at 362 × 10^4, 2 at 235 × 10^4 and 1 at 121 × 10^4Bq/kg at 1982, 2066, 2813 and 4226 days, respectively) and 4 with soft tissue neoplasia (non-melanoma) of the oral cavity (2 at 121 × 10^4, 1 each at 40 × 10^4 and 2.11 × 10^4Bq/kg at 2093, 4844, 2898 and 5363 days after injection, respectively). Among 125 control dogs in the entire colony, there was one fatal case of blood dysplasia (leukemia, 3971 days), and 1 case of soft-tissue malignancy of the nasopharynx (5203 days). According to Fisher's exact Test for Independence (Sokal and Rohlf, 1969), there was no significant difference in occurrence of these soft-tissue malignancies and blood dysplasias between the control animals and the dogs given ^{226}Ra, but there was a clear excess ($P < 0.05$) of blood dysplasias and of soft tissue malignancies (non-melanoma) of the oronasopharynx in the dogs given ^{90}Sr as compared to the control group. For all other soft-tissue tumors, the difference between the occurrence among the ^{90}Sr or ^{226}Ra groups and the group of 125 control dogs was not significant ($P > 0.05$) except for introcular melanoma in dogs given Ra.

[d]Tumor was discovered in 1987 re-analysis of slides.

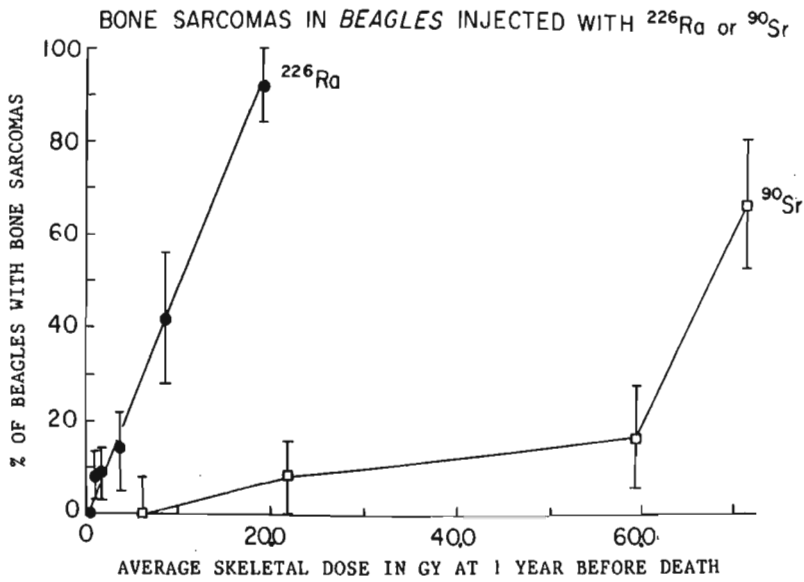

Fig. 5.1 Bone sarcoma incidence as a function of average skeletal dose from ^{90}Sr (open squares) or ^{226}Ra (closed circles). This updates to 1987 the data contained in Table 5.1. No bone sarcomas were induced by ^{90}Sr in dose groups below about 20 Gy, while bone sarcomas were induced by ^{226}Ra in a group averaging 0.85 Gy.

TABLE 5.2—*Relative effectiveness for bone sarcoma induction of ^{226}Ra and ^{90}Sr in beagles and mice[a] as a function of average skeletal dose*

Cumulative Incidence (%)	^{90}Sr β-particles (Gy)	^{226}Ra α-particles (Gy)	Relative Effectiveness, (α vs β)
Utah Beagles			
66.7	93.6	19.0[b]	5
38.5	86.0[b]	11.0	8
16.7	79.4	4.8[b]	17
8.7	29.4	2.1	14
8.0	22.1[b]	0.85	26
Argonne Mice			
86.4	65	64.2	1
81.0	63	44.0[b]	1.4
79.1	62	36.4	2
62.2	55	20.4	3
43.3	46	11.9	4
21.2	37	6.1	6
23.4	38	4.8	8
18.7	35	3.8	9
13.6	33	2.8[b]	12
11.7	31	2.4	13
7.7	27	1.1	25

[a]From Mays and Finkel (1980).
[b]Values interpolated from updated Figures 1 and 2 of Mays and Finkel (1980).

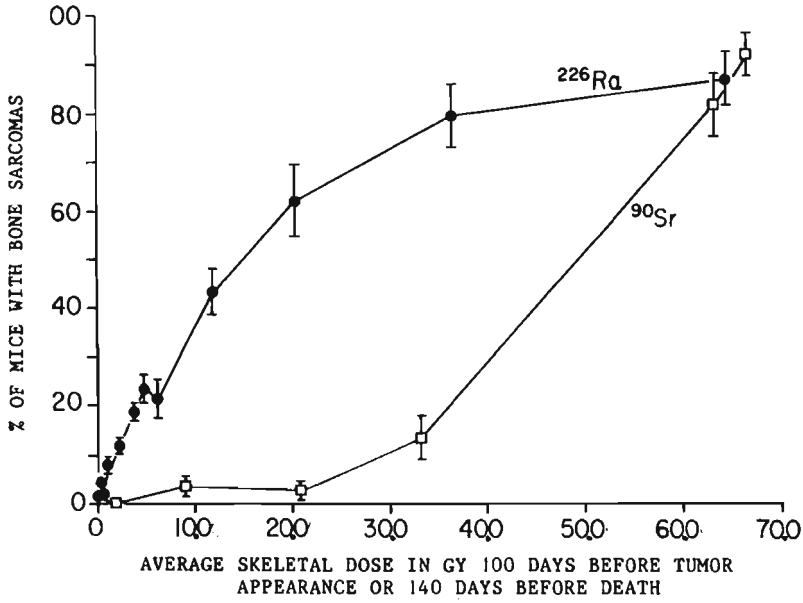

Fig. 5.2 Bone sarcoma incidence as a function of average skeletal dose from ^{90}Sr (open squares) or ^{226}Ra (solid circles) in female mice studied at Argonne National Laboratory (Mays and Finkel, 1980). The shape of the dose response curve for ^{90}Sr in mice resembles that for ^{90}Sr in beagles (Figure 5.1) and is much different from the curve for ^{226}Ra in mice or beagles.

calcification *in utero* to 540 days of age at seven levels ranging from 0.026×10^4 to 37×10^4 Bq/gram of dietary calcium (Table 5.3a). The ^{90}Sr was uniformly mixed into the diet fed each day. There were also 80 control beagles that were introduced into the experiment during the same period. An additional 46 beagles were each given a single intravenous injection of 13.7×10^4 or 122×10^4 Bq ^{90}Sr/kg at 540 days of age (Table 5.3a). In a companion experiment, 251 beagles were each given a series of 8 semi-monthly injections of ^{226}Ra beginning at 435 days of age (Table 5.3b). Six dosage levels were employed, ranging from 0.089×10^4 to 37 x 10^4 Bq/kg. There were also 84 controls introduced during the same period. Experimental design, preparation of the injection solutions, choice of dosage levels, veterinary care, animal selection, radionuclide retention and dosimetry have been described previously (Book, 1980; Raabe *et al.*, 1981a). The tables give the incidence of effects in both bone and soft tissue.

Hematopoietic effects, including myeloproliferative disorders (Dungworth, *et al.*, 1969), were seen mainly at the three or four highest levels of ^{90}Sr ingestion (average skeletal doses of about 20

Gy and above, but with one observed at 6.28 Gy and two in control dogs 15.4 and 16.4 years old) and one at 6.24 Gy among dogs injected with ^{90}Sr. At later times post-exposure, bone sarcoma, head sinus carcinoma and squamous cell carcinoma of the tissues in the mouth appeared at lower levels of exposure in clear excess of their occurrence in the control dogs (Book *et al.*, 1981, Pool, *et al.*, 1972 updated by Raabe 1990). Similarly, carcinomas of soft tissues overlying bone in ^{90}Sr contaminated rabbits were reported by Vaughan and Williamson (1969).

Comparison of bone sarcoma incidence vs dose in beagles given ^{90}Sr or ^{226}Ra (Tables 5.3a and 5.3b) indicate that their relative effectiveness (toxicity ratio) is similar at high doses, but at lower levels, the relative effectiveness of ^{90}Sr is decreased, reaching a value of about 1/12 that of radium at the lowest level at which ^{90}Sr induced tumors have appeared (Raabe *et al.*, 1981a).

5.4 Beagles Exposed to Airborne ^{90}Sr at Inhalation Toxicology Research Institute (ITRI)

Studies of ^{90}Sr effects in beagles exposed by inhalation (McClellan et al., 1973) have been completed at the Lovelace Inhalation Toxicology Research Institute (ITRI) in Albuquerque, NM (Tables 5.4a and 5.4b). Sixty six adult beagles of both sexes were exposed to $^{90}SrCl_2$ by inhalation, resulting in initial body burdens ranging from 3.59 $\times$ 10^4 to 703 $\times$ 10^4 Bq/kg. All of these dogs are now dead. Animal selection, veterinary care, experimental design, aerosol preparation, method of exposure, radionuclide retention and dosimetry have been reported (McClellan, *et al.*, 1972). Tissue distribution, resulting radiation doses, and biological effects in the skeleton have been found to be similar in dogs exposed by inhalation to those in dogs exposed by injection.

The ^{90}Sr inhaled as the chloride was rapidly translocated from lung to skeleton (McClellan, *et al.*, 1972). It appears that once ^{90}Sr as the chloride reaches the blood it is handled as though it were given intravenously. Thus, the authors reported the observed biological effects in terms of the long-term retained burden of ^{90}Sr.

The most prominent early effect was a dose-related pancytopenia (Gillett, *et al.*, 1987a). The major finding among the long-term survivors was an excess of bone tumors (Gillett, *et al*, 1987b). Most of the dogs with long-term retained burdens of 1.0 MBq/kg or greater died with a bone tumor. There were three nasal tissue tumors, and two dogs died of myelomonocytic leukemia (for more detail see McClellan, *et al.*, 1983).

TABLE 5.3a—*Beagles given ^{90}Sr at LEHR. Data are as of January 1, 1988 (no dogs alive). Shown are the number of dogs with bone sarcoma, myelolymphoproliferative syndrome (MPS), and malignant tumors of soft tissues near bone (mainly squamous cell carcinomas of tissues in the mouth) for dogs dying or terminated from the experiment.*

Group	No. of Dogs	Group Avg. Max. Body Content (kBq/kg)	Group Median Years to Death or Term (± S.E.)	Group Avg. Skel. Dose, Gy	Tumors		
					Bone Sar	MPS	Soft Tissue Tumors Near Bone
Exposed by ingestion							
D00	80	0	14.6 ± 0.4	0	2	2	3
D05	75	1.12 ± 0.32	14.4 ± 0.4	0.38 ± 0.16	0	0	4
D10	40	3.54 ± 0.57	13.4 ± 0.5	1.15 ± 0.25	1	0	4
D20	66	19.4 ± 3.0	14.2 ± 0.2	6.70 ± 2.04	0	1	4
D30	69	61.3 ± 10.9	13.9 ± 0.3	22.5 ± 5.7	4	4	10
D40	63	168 ± 29	11.8 ± 0.5	50.4 ± 18.0	10	7	14
D50	63	482 ± 88	5.3 ± 0.6	80.2 ± 35.2	17	26	11
D60	19	1469 ± 335	2.2 ± 0.2	107 ± 32	10	4	1
Exposed by injection							
S20	19	48.3 ± 12.1	12.5 ± 0.6	6.65 ± 2.28	1	1	0
S40	24	407 ± 87	11.0 ± 0.4	54.3 ± 18.1	6	0	3

TABLE 5.3b—*Beagles given ^{226}Ra at LEHR. Data are as of January 1, 1988 (no dogs alive).*

Group	No. of Dogs	Group Avg. Max. Body Content (10^6Bq/kg)	Group Median Years to Death or Term (± S.E.)	Group Avg. Skel. Dose, Gy	Tumors		
					Bone Sar.[a]	MPS	Soft Tissue Tumors Near Bone[a]
R00	79	0	13.2 ± 0.5	0	0	0	8
R05	46	0.30 ± 0.06	13.2 ± 0.5	0.94 ± 0.23	0	0	4
R10	38	0.94 ± 0.28	12.7 ± 0.3	2.96 ± 1.05	4	0	3
R20	41	5.19 ± 1.25	9.8 ± 0.5	13.9 ± 3.4	26	0	3
R30	39	16.9 ± 3.4	6.1 ± 0.4	31.6 ± 6.4	34	0	1
R40	41	56.2 ± 19.4	3.8 ± 0.1	77.6 ± 22.9	40	0	0
R50	41	158 ± 33	3.1 ± 0.2	167 ± 44	25	0	0

[a]Includes multiple primary tumors in same dog.

TABLE 5.4a—*Summary of individual body burdens and ^{90}Sr-related cause of death in 66 dogs that inhaled graded activity levels of $^{90}SrCl_2$ and were maintained for life-span observation (ITRI)*[a]

Animal No.	LTRB,MBq[b]	LTRB,MBq/kg[b]	Mode of Death[c]	Days post exposure at death	^{90}Sr-related death
164A	40.7	4.4	D	585	—
158E	44.4	4.4	E	927	Bone tumor
157E	44.4	4.4	E	759	Bone tumor
195C	36.6	4.1	D	21	Bone marrow hypoplasia
162F	44.4	3.7	E	886	Bone tumor
158B	35.5	3.7	E	31	Bone marrow hypoplasia
195B	40.7	3.7	D	28	Bone marrow hypoplasia
159B	35.5	3.6	E	18	Bone marrow hypoplasia
160B	34.0	3.6	E	864	Bone tumor
23C	27.8	3.1	E	1,099	Bone tumor
159A	31.1	2.7	D	29	Bone marrow hypoplasia
160C	26.6	2.6	E	1,142	Bone tumor
7B	18.9	2.5	E	927	Bone tumor
23B	17.4	2.2	E	1,787	Bone tumor
10A	20.4	2.0	E	1,168	Bone tumor
26F	14.8	1.9	E	1,938	Bone tumor
8A	14.8	1.9	E	1,362	Bone tumor
13A	15.9	1.9	D	1,361	—
162A	22.2	1.9	E	1,702	Bone tumor
12F	15.2	1.9	E	1,046	Bone tumor
9D	15.5	1.7	E	1,316	Bone tumor
11B	16.7	1.7	E	31	Bone marrow hypoplasia
22E	10.7	1.6	E	3,122	Bone tumor
10B	12.9	1.6	D	2,034	Bone tumor
26A	11.8	1.5	D	1,404	Bone tumor
19B	9.3	1.5	D	2,964	Bone tumor
9B	13.7	1.4	E	1,367	Bone tumor

9C	13.7	1.4	E	1,318	Bone tumor
6B	10	1.3	E	3,738	Nasal tumor
12E	11.1	1.3	E	2,380	Bone tumor
8B	10.7	1.3	E	2,264	Bone tumor
22F	11.1	1.3	E	1,540	Bone tumor
12B	12.2	1.1	E	2,768	Bone tumor
6D	8.1	1.1	E	2,782	Bone tumor
19C	8.1	1.0	D	3,237	Bone tumor[d]
22A	10.7	1.0	E	2,247	Bone tumor
12D	7.8	1.0	D	585	Myelomonocytic leukemia
19D	8.9	1.0	E	2,633	Bone tumor
6C	7.4	0.89	E	3,472	Bone tumor
9A	8.1	0.74	E	3,233	Bone tumor
4B	5.2	0.59	D	2,628	Skull carcinoma
12C	5.6	0.56	E	4,222	Nasal tumor
40E	2.2	0.36	E	3,994	—
28C	2.6	0.34	D	2,436	Myelomonocytic leukemia
39C	2.9	0.34	E	5,261	—
38E	2.1	0.33	E	5,678	—
30C	2.6	0.31	E	4,453	—
30B	2.4	0.29	D	4,795	—
42D	2.2	0.28	E	5,439	—
28B	1.9	0.26	E	3,077	Bone Tumor
22D	2.3	0.25	D	5,440	—
30D	2.1	0.24	E	3,874	—
42E	1.9	0.23	D	3,926	—
42F	1.5	0.21	D	5,064	—
26B	1.0	0.12	E	4,970	—
35E	0.6	0.085	D	4,584	—
30G	0.6	0.081	E	4,927	Nasal tumor
27D	0.9	0.081	E	4,744	—

TABLE 5.4a—*Continued*

Animal No.	LTRB,MBq[b]	LTRB,MBq/kg[b]	Mode of Death[c]	Days post exposure at death	^{90}Sr-related death
26G	0.5	0.070	E	5,079	—
27A	0.6	0.070	E	3,662	—
23E	0.5	0.063	D	2,247	—
24B	0.5	0.059	E	5,496	—
37F	0.3	0.041	E	4,117	—
24A	0.3	0.037	E	5,948	—
30E	0.3	0.037	D	3,033	—
30F	0.3	0.036	E	4,706	—

[a]From Gillett, *et al.*, 1987b, Inhalation Toxicology Research Institute, Albuquerque, NM
[b]LTRB = Long-Term Retained Burden.
[c]D = Died; E = euthanized.
[d]Immediate cause of death was pyometra.

TABLE 5.4b—*Summary of ^{90}Sr-exposed and control dogs dying of causes unrelated to the inhalation of ^{90}Sr*

Dog No.	Sex	Days after exposure to death	Age at death days	LTRB,MBq/kg	Primary cause of death: Neoplastic	Primary cause of death: Nonneoplastic
^{90}Sr-exposed dogs, neoplastic cause of death						
30E	M	3,033	3,441	0.037	Transitional cell carcinoma, bladder	
30D	M	3,874	4,269	0.24	Hemangiosarcoma, heart	
37F	F	4,117	4,517	0.041	Bronchoalveolar carcinoma, lung	
30C	M	4,453	4,848	0.31	Lymphosarcoma	
30F	F	4,706	5,114	0.036	Adenocarcinoma, mammary gland	
27D	F	4,744	5,134	0.081	Ependymoma, brain	
30B	M	4,795	5,190	0.29	Adenocarcinoma, lung	
26B	M	4,970	5,361	0.12	Transitional cell carcinoma, bladder	
26G	F	5,079	5,470	0.070	Adenocarcinoma, mammary gland	
39C	F	5,261	5,646	0.34	Mesothelioma, pleura	
^{90}Sr-exposed dogs, nonneoplastic cause of death						
164A	M	584	972	4.4		Epileptic seizures
13A	M	1,361	1,742	0.85		Hemorrhage, cerebellar
23E	M	2,247	2,663	0.063		Accidental death
27A	M	3,662	4,051	0.070		Peritonitis
42E	F	3,926	4,303	0.23		Malabsorption syndrome
40E	F	3,994	4,377	0.36		Hepatitis
35E	F	4,584	4,964	0.085		Congestive heart failure
42F	F	5,064	5,441	0.21		Hepatic degeneration
42D	F	5,439	5,816	0.28		Nephrosclerosis
22D	M	5,440	5,836	0.25		Congestive heart failure
24B	M	5,496	5,893	0.059		Nephrosclerosis
38E	F	5,678	6,069	0.33		Osteoarthritis, spine and stifles
24A	M	5,948	6,846	0.037		Nephrosclerosis

TABLE 5.4b—*Continued*

Dog No.	Sex	Days after exposure to death	Age at death days	LTRB,MBq/kg	Primary cause of death	
					Neoplastic	Nonneoplastic
Control dogs, neoplastic cause of death						
9E	F	2,638	3,037	0	Fibrosarcoma, thoracic wall	
30A	M	3,439	3,835	0	Epidermal cyst, skull	
40D	F	3,654	4,041	0	Adenocarcinoma, mammary gland	
10C	F	3,670	4,063	0	Adenocarcinoma, lung	
32A	M	4,236	4,630	0	Lymphosarcoma	
24E	F	4,508	4,901	0	Carcinoma, thyroid gland	
6A	M	4,738	5,152	0	Carcinoma, thyroid gland	
162E	F	4,767	5,201	0	Pituitary adenoma-Cushing's disease	
158A	M	5,008	5,446	0	Squamous cell carcinoma, tonsil	
13D	F	5,057	5,440	0	Adenocarcinoma, mammary gland	
33B	M	5,103	5,491	0	Lymphosarcoma	
160A	M	5,482	5,919	0	Squamous cell carcinoma, tonsil	
13B	M	2,615	2,998	0		Autoimmune hemolytic anemia
19A	M	2,740	3,146	0		Septicemia
35F	F	3,012	3,426	0		Accidental death
31A	M	3,023	3,423	0		Atherosclerosis, hypothyroidism
13C	M	3,310	3,693	0		Renal amyloidosis
21C	F	4,602	5,000	0		Congestive heart failure
12A	M	4,786	5,189	0		Nephrosclerosis-congestive heart failure
42C	F	5,136	5,516	0		Nephrosclerosis
26E	F	5,403	5,788	0		Aspiration pneumonia
28A	M	5,505	5,913	0		Congestive heart failure

Although a few animals at the highest dose levels died with hematological disorders, bone neoplasms were the most prominent radiation-induced endpoints at lower levels, occurring in 17 of the 48 lifespan dogs at between 1 and 10.36 MBq/kg initial body burden, but in just one dog below 1 MBq/kg. There were 13 animals with bone sarcoma among 24 other dogs at 1.59 to 5.55 MBq/kg initial body burden in a sacrifice study. Only two leukemias (myelomonocytic) were observed. There were also a total of 3 malignancies of tissues in the oral cavity and nasopharynx.

There were also experiments at ITRI in which ^{90}Sr was inhaled in insoluble form. No bone tumors occurred in these animals, although some neoplasms did occur in lung. This work is not included in this summary since it does not contribute to the objective of deriving risk estimates for bone cancer and leukemia. Details are contained in ITRI annual reports and publications.

5.5 Effects of ^{90}Sr Fed to Miniature Swine at Hanford (Battelle PNL)

This experiment was begun in 1959. About 800 Pitman-Moore miniature swine representing three generations were exposed to ^{90}Sr by chronic ingestion at feeding levels from 0.037 to 115 MBq per day.

Animals in the first generation were entered into the experiment at 9 months of age, but those in the second and third generations were exposed to ^{90}Sr beginning *in utero*. Sr was given each day in a "spiked" feed pellet. Following birth the animals were exposed to ^{90}Sr via the dam's milk (McClellan and Bustad, 1963; McClellan *et al.*, 1962; McClellan, 1964). At six weeks of age, the animals were weaned and began receiving ^{90}Sr daily in their diet at one-fourth that of their dam. At three months of age their dietary intake was increased to one-half the ^{90}Sr of their dam's diet and at six months to an amount equal to that of their dam.

Information bearing on the retention and dosimetry of ^{90}Sr in these swine has been published (Clarke *et al.*, 1969; Palmer *et al.*, 1970; Ragan *et al.*, 1972; Mays and Lloyd, 1972b; Krusemark *et al.*, 1974; McClellan, *et al.*, 1967; McClellan, 1965).

Hematopoietic effects from irradiation of bone marrow including neutropenia, lymphopenia, thrombocytopenia, and myeloproliferative disorders with myeloid and histiocyte infiltration of tissues such as kidney, heart, testes, and lung were observed among animals at

the highest feeding levels (Tables 5.5a and 5.5b), but these were not seen in excess of the control incidence in pigs at low doses and dose rates (Howard and Clarke, 1970, McClellan, *et al.*, 1963a; McClellan, 1966). Dental lesions, uterine pathology and arthritis were among the most common findings at death in both irradiated and control animals (Ragan *et al.*, 1972). Farrowing performance (litter size, stillbirth and birth weight) was not affected at ^{90}Sr intake levels of

TABLE 5.5a—*Summary of ^{90}Sr effects in miniature swine Studied at Battelle Pacific Northwest Laboratories (Richland, WA)*

Feeding Level (MBq/day)	Observed Effects	Mean Survival Time
23.1	Pancytopenia-Hemorrhagic crisis, Myeloid Metaplasia	3 months
4.62	Pancytopenia-Hematopoietic neoplasia, Bone Tumors	3.5 years
0.925	Neutropenia-Neoplasia	10 years
0.185	Neutropenia	11 years
0.037	Neutropenia	11 years

TABLE 5.5b—*Neoplasia in female miniature swine ingesting ^{90}Sr daily (combined f_1 and f_2 generation, exposure began in utero) Studied at Battelle PNL (Richland, WA)*

	^{90}Sr Dosage, MBq/day					
	23.1	4.62	0.925	0.185	0.037	0
Mean life span, y	0.25	3.5	10	11	11	11
Number of animals	24	40	47	29	52	74
Cum. skel. dose, Gy	11[a]	140	50	15	3	0
Bone sar.[a]	8[a]	10				
Myeloid	8[a]	38	9	3		4
Lymphoid		15	9	7	6	1
Liver tum.			23[b]	17	8	8
Intestinal			6		4	1
Ovarian[c]			9			1
Uterine		5	32[d]	48[e]	54[f]	38[g]
Misc.		3	15[h]	3	10	5

[a]Two removed from ^{90}Sr feeding at 3 months of age developed bone tumors and leukemia at 3 and 4 years of age; remaining animals not removed from ^{90}Sr died at about 3 months of age from bone marrow aplasia.

[b]Two of these tumors were malignant.

[c]All ovarian tumors were malignant.

[d]Four of these tumors were malignant.

[e]Seven of these tumors were malignant.

[f]Four of these tumors were malignant.

[g]No malignancies

[h]Six of these tumors were malignant.

23 MBq/day and lower. It was concluded that feeding levels of ^{90}Sr high enough to affect fetal or neonatal mortality in this species will not permit survival of the dam through gestation (Clarke *et al.*, 1970b; McClellan, *et al.* 1963b).

Bone tumors, classified as osteosarcomas or giant cell tumors, were found in the skeletons of many (see Table 5.5b) but not all of the ^{90}Sr treated animals. Most of these tumors occurred in the skull, including the mandible and maxilla. All of the giant cell tumors were found in the mandible (Howard *et al.*, 1969). A comparative study of the histopathologic effects in bone of injected ^{226}Ra and ^{90}Sr in the miniature pig (Clarke, 1962) verified that ^{226}Ra was more damaging than ^{90}Sr as measured by incidence of bone tumors at low doses. There appeared to be an increase in general soft-tissue cancer incidence among animals exposed to dietary ^{90}Sr; this was attributed in part to blood-borne ^{90}Sr (Palmer *et al.*, 1970). Note that this includes increases in liver neoplasia at the moderate doses, but only two liver tumors were malignant.

A summary of the primary effects and mean survival times in miniature swine at the several dosage levels is given in Table 5.5a. Additional details are given in Table 5.5b.

5.6 Strontium-90 Exposure Via Injection in Monkeys (University California, Berkeley, Supplemental Data from the University of Rochester)

Forty juvenile, adolescent and adult male and female Rhesus monkeys aged 2 to 12 years and weighing 2.6 to 9.4 kg were given 0.13 to 6.21 MBq by single injection (0.018 to 0.14 MBq ^{90}Sr/kg). In addition, 2 short-term animals were injected with 1.85 MBq/kg. Retention was determined by excreta collection and by periodic *in vivo* Bremsstrahlung counting. Animals were followed at the Lawrence Berkeley Laboratory (LBL), University of California at Berkeley, for up to about 20 years after entry into the experiment. The most pertinent metabolic parameters for radiostrontium in these animals are shown in Table 4.2.

No biological effects attributable to the ^{90}Sr exposure could be detected in this experiment, even over a twenty-year period. Nevertheless, the data currently available must be considered as still preliminary. The study can provide a useful upper limit on risk for bone sarcoma and leukemia in a primate species (see Section 8.1, footnote 8, for an example of this method).

In another experiment (Casarett *et al.*, 1962) that was done at the University of Rochester, 7 adult monkeys were given 1.85 or 3.7 MBq

^{90}Sr orally (by gavage, single dosage). There were 2 cases of bone sarcoma, occurring at 36 months (chondrosarcoma) and 45 months (osteosarcoma) after administration. Skeletal dose for the animal dying with osteosarcoma at 45 months has been calculated (Mays and Lloyd, 1972b) as 34 Gy at death and 25 Gy to the estimated start of tumor growth.

Details of life span and cause of death, where known, are embodied in Appendix C for the monkeys studied at LBL. Few, if any, of the causes could be reasonably associated with radiation exposure.

5.7 Summary and Discussion of Long-Term Animal Experiments With ^{90}Sr

The animal studies have shown that although the effects can occur with relatively high incidence at high levels of radiation dose from ^{90}Sr they occur at only a very low incidence, or not at all, at the lower levels of radiation dose from this deposited radionuclide (*i.e.*, no bone sarcomas were seen at individual average skeletal doses in the Utah beagle study between about 1 and 18 Gy). This is in contrast to the effects of radium (see next section). Clearly these "lower levels" of dose are well above those to be expected in humans from all normal peace-time operations. No striking differences from previous analyses of these experiments have been seen in this analysis, and it is unlikely that results from the few animals still alive (at the time this report was prepared) will alter the basic conclusions reached.

High doses to skeletal tissues from ^{89}Sr or ^{90}Sr have produced bone sarcomas, carcinomas of the nasopharynx and head sinuses, squamous cell carcinomas in tissues within the mouth, or hematopoietic neoplasia (leukemia) and dysplasia in the following experimental animals: mice (Finkel and Biskis, 1959; Nilsson, 1972; Ito *et al.*, 1969; Van Putten and DeVries, 1962; Brooks *et al.*, 1974); rats (Moskalev *et al.*, 1969; Casarett *et al.*, 1962; Jones *et al.*, 1970); cats (Ward *et al.*, 1972, Nelson *et al.*, 1973); rabbits (Vaughan and Williamson, 1969); monkeys (Casarett *et al.*, 1962; Durbin *et al.*, 1974); sheep (McClellan and Jones, 1969); dogs (Goldman *et al.*, 1969, 1972; McClellan *et al.*, 1972; Finkel *et al.*, 1972; Litvinov, 1962; Dougherty *et al.*, 1972; Mays *et al.*, 1969b; Raabe *et al.*, 1981b; Gillett *et al.*, 1987a, 1987b); and pigs (Clarke *et al.*, 1972; McClellan, 1964).

There is clear evidence in the preceeding references that the dosage pattern as well as the total dose can have a significant effect on the outcome of exposure. The same applies to the age at irradiation. For example, hematopoietic effects and soft-tissue malignancies (squa-

mous cell carcinoma) were important endpoints in dogs fed ^{90}Sr beginning in utero but much less significant among adult dogs that inhaled or were injected with ^{90}Sr even at comparable skeletal doses.

No effects attributable to ^{90}Sr have been observed in the monkeys at the Berkeley project presumably because of the low doses given. However, bone sarcomas have been induced by ^{90}Sr in other monkeys given much higher dosages (animals from University of Rochester transferred to Berkeley, Casarett *et al.*, 1962). Myeloproliferative disorders have been observed in both dogs and swine fed ^{90}Sr beginning as young animals, but no clear excess of these above control incidence has been detected in dogs that inhaled or were injected with ^{90}Sr as adults. Bone sarcomas have been induced by ^{90}Sr given by injection or in feed to swine and in dogs given ^{90}Sr by injection, by inhalation, or in feed. Malignancies of soft tissue near bone apparently have been induced in dogs given ^{90}Sr by injection and through the diet. Bone sarcoma induction and hematopoietic effects were also observed among cats given ^{89}Sr (Ward *et al.*, 1972; Nelson *et al.*, 1973). Because of these observations there is reason to expect similar effects (myeloproliferative disorders, bone sarcomas, cancer of soft tissue near bone) in humans receiving sufficient doses from ^{90}Sr + ^{90}Y or ^{89}Sr.

Only at the highest levels of ^{90}Sr exposure has there been a significant effect upon lifespan and, as already noted, fertility and fecundity seem to be unaffected below potentially lethal doses. This also contrasts markedly with the effects of radium on lifespan and bone sarcoma induction.

These data can be used to estimate the risk to humans from incorporated ^{90}Sr when appropriate results from animal experiments with ^{226}Ra and experience with ^{226}Ra in humans are included in the analysis. This is done in the following section.

The major ^{90}Sr-induced effects in these animal experiments were observed at times after exposure that were generally quite long at dose levels near the range of projected human exposures from normal peacetime operations. The time course of the appearance of these effects at low doses is less important than if ^{90}Sr-induced effects had appeared throughout the post exposure period.

6. Effects of ^{90}Sr Compared to ^{226}Ra

A comparison of bone sarcoma induction by the bone-seeking radionuclides, ^{226}Ra and ^{90}Sr, is important because a considerable body of data is available on exposure of man to ^{226}Ra; this includes information on more than two thousand cases of exposure to radium at a wide variety of levels. Moreover, these cases have been followed for many years, and extensive studies of the sequelae and of their frequency have been reported (Evans, 1966; Rowland *et al.*, 1971; Rowland and Stehney, 1977; Gustafsen and Stehney, 1983).

These studies with radium served as the principal support for the widely used limiting occupational body burden of 3.7 kBq ^{226}Ra which was recommended by the NCRP in 1941 (NCRP, 1941). Many of the extensive, long-term animal studies mentioned earlier in this report were based on the idea that a comparison of relative effectiveness of ^{90}Sr and ^{226}Ra in a variety of species would offer a basis for assessment of the hazard to man from ^{90}Sr. Generally, such comparisons were made by computing ratios of doses at which a common incidence of effect was seen in each of the various species studied.

Both the dosimetry and biological effects of ^{90}Sr and ^{226}Ra found from the study of mice at Argonne National Laboratory (ANL), Illinois, have been analyzed by Finkel and Biskis (1968), Marinelli (1969), Mays and Lloyd, (1972b) and Mays and Finkel (1980) in terms of these "toxicity ratios." They indicate that for an equal percent of bone sarcoma occurrence, ^{226}Ra is from 1 to 25 times as effective as ^{90}Sr on the basis of average skeletal dose (Table 5.2); the relative effectiveness is a function of dose. The studies of Finkel and Biskis (1968) in mice indicated that at least 200 times as much activity of ^{90}Sr as of ^{226}Ra must be injected to obtain about a 10 percent incidence of bone sarcomas. Analysis by Marinelli (1969) of the dosimetry applicable to the work of Finkel and Biskis (1968) indicated that the ratio of absorbed doses averaged over the skeleton is 8.8 or more (Marinelli, 1969). In the case of these mice, strontium and radium have essentially the same retention function, so the ratio of average skeletal doses is essentially independent of time. Below the 10 percent level of incidence, statistical difficulties obscure the interpretation of the data.

Similar results have been obtained with beagles studied at the University of Utah. The effectiveness of radium per Gy of absorbed dose at the lowest dose levels at which bone sarcoma occurred compared to Sr is about 26 (Mays and Finkel, 1980). That is, a given average skeletal dose from ^{226}Ra is about 26 times as effective in bone sarcoma induction as an equal dose from ^{90}Sr in this low dose region (Table 5.2). Some soft-tissue effects (including malignancies and blood dyscrasias) were detected in beagles given ^{90}Sr, but the identical effects were not seen with ^{226}Ra. These effects in dogs appear to be in conformity with the results in mice (Mays and Finkel, 1980). Bone sarcomas have been observed in the Utah beagles only at the higher exposure levels for ^{90}Sr but at much lower levels of ^{226}Ra (Figure 5.1). Corresponding conclusions can be drawn from the comparative toxicity studies of ^{90}Sr and ^{226}Ra in beagles at the University of California at Davis. These indicate that the doses of Sr required to produce an equivalent incidence of bone sarcoma are between a maximum of 10 and 20 times those required for radium at low levels of dose and effect (Raabe *et al.*, 1981b). Results for the induction of bone sarcomas in beagles at the University of California at Davis (LEHR) also correspond to those in mice at ANL and beagles at Utah (Mays and Finkel 1980) in that the effectiveness of ^{90}Sr relative to ^{226}Ra for bone sarcoma induction diminishes with decreasing dose and dose-rate (Raabe *et al.*, 1981b).

Thus it appears from the data available from both mice and dogs exposed to relatively low levels of ^{90}Sr and ^{226}Ra that absorbed dose to bone from ^{90}Sr is less effective by a factor of about 10 to 25 than an equal dose to bone from ^{226}Ra, both doses being averaged over the skeleton. If one uses the concept of dose equivalent, as is usual in radiation protection, the dose in gray or rad from the alpha emitter, ^{226}Ra, is multiplied by a quality factor (Q) of 20, whereas the dose in Gy or rad from the beta emitter, ^{90}Sr, is multiplied by a quality factor of one. In fact, the long-term studies on adult dogs and mice at low doses suggest that when a Q of 20 is used for dose from ^{226}Ra, the relative bone sarcoma effects per sievert are about the same for both emitters. In terms of activity levels administered, there is no question of the greater effectiveness of radium, especially at low doses. However, it should be emphasized that these considerations apply only for bone malignancies and thus are just a part of the hazard posed by ^{90}Sr.

Application of the toxicity ratio method to estimate the hazard to man from radiostrontium is relatively straightforward. For doses (D) that produce a common level of an effect, one investigates whether or not the ratio D_{Sr}/D_{Ra} is relatively constant for that level of injury among different species. Thus, if the hypothesis holds approximately, the following relation can be applied:

$$(D_{Sr}/D_{Ra})_{man} \approx (D_{Sr}/D_{Ra})_{animal} \quad (6.1)$$

The ratio on the right is evaluated by the animal studies, D_{Ra} in man is derived on the basis of the experience with radium, and D_{Sr} for the given level of incidence in man is calculated (Evans, 1966, see Eq. 3). Obviously, there are many difficulties involved, such as the dose to the target cells to be used, if this refinement seems appropriate, as well as the validity of the basic hypothesis. However, even if the ratio were not constant for different species, regardless of the dosimetric scheme employed, a study of its behavior in various animal models might provide a means of extrapolation to man. The hypothesis has been tested in a variety of species, and results of extensive studies directed toward that end which have been carried out appear to be internally consistent so long as comparable degrees of effect are considered. Indeed, the studies of Lisco *et al.* (1947) and of Finkel (1956) indicate that even the early approaches to the problem did indeed determine the ratio of doses to bone from ^{90}Sr and ^{226}Ra which would produce similar levels of effect.

Further development of the use of the ratio of effectiveness between strontium and radium (toxicity ratio) is included in Section 8 which treats the derivation of risk.

7. Genetic Effects of ^{90}Sr

Little attention was given in the earlier studies to the possibility of genetic effects from ^{90}Sr, presumably because of preoccupation with its role as a bone seeker. Later, interest was stimulated by limited experimentation and observations along the following lines: (a) incorporation of alkaline earth elements in chromosomes (Aberg and Gillner, 1966; Mueller, 1967), and (b) genetic effects of ^{90}Sr injected into male mice (Luning, *et al.*, 1963a, 1963b). In large animals, the gonadal dose is small from ^{90}Y and ^{90}Sr deposited in bone and from ^{90}Sr in the diet because of the distance between gonad and bone, but ^{90}Y (in equilibrium with ^{90}Sr) injected into the peritoneal cavity can move to the scrotal sac via the inguinal canal and irradiate the testes. It would be expected that the gonadal dose to humans would be only a small fraction of the skeletal dose in the absence of entry via the peritoneal cavity and is probably unimportant at levels to be expected from normal peacetime exposures. In addition, it was reported that a repetition of the genetic studies (Lindop and Rotblat, 1969) indicated less effect than reported originally. Frolen (1970) concluded that ^{90}Sr has not manifested dominant genetic effects detectable in later generations. In terms of comparative risk, it appears that somatic effects of ingested ^{90}Sr will be of far greater concern than genetic effects. Additional information on the genetic effects of internally deposited radionuclides is contained in NCRP Report No. 89 (NCRP, 1987a).

8. Estimated Risks to Humans from Internally Deposited ^{90}Sr

There have been no cases of human exposure to ^{90}Sr on record which would provide direct guidance concerning the kinds of effects to be expected or their frequency. Attempts to study effects due to ^{90}Sr present in fallout were beset by two difficulties:

(1) No criteria were known that would distinguish unambiguously the pathological effects due to ^{90}Sr from those occurring naturally. Thus, the identification of an effect could be established only by demonstrating a significantly higher incidence in an exposed group as compared with a suitable group at a lower level of exposure.

(2) The excess of incidence to be expected at world-wide fallout levels was so low that only studies on very large populations could even potentially yield a statistically significant result. Such studies have been attempted for humans, but careful evaluation of the statistics confirms the expectation that whatever excess of incidence may be present is masked by the variation in incidence among the population groups studied, differences in recording of data, and the normal statistical fluctuations of the data for such groups (Sagan, 1969; Harley, 1969; Lindop and Rotblat, 1969; Tompkins and Brown, 1969). Thus, no statistically significant excess of biological effects due to ^{90}Sr exposure at levels characteristic of world-wide fallout has been demonstrated.

Lacking direct data on humans with ^{90}Sr, one can attempt to estimate hazard on the basis of experience in man with other forms of radiation or on the basis of dose-effect relations seen in experimental animals exposed to ^{90}Sr. Either approach requires uncertain extrapolations.

As indicated previously, the risk of somatic effects induced by internally deposited ^{90}Sr is of far greater concern than the risk of genetic effects. Thus, attention will be directed here to the risk of bone cancer and the risk of leukemia.

In humans, the observations that bone sarcomas have been produced by skeletally-deposited radium (Evans *et al.*, 1972; Finkel *et al.*, 1969; Rowland *et al.*, 1970 and 1971; Spiess and Mays, 1972) and

that leukemias have been produced by exposure to x-rays (Mays and Lloyd, 1972c), and atom-bomb radiation (Ishimaru *et al.*, 1971; Beebe *et al.*, 1971; Jablon and Kato, 1972; Ohkita and Kamada, 1979; Preston and Pierce, 1988), suggest that significant skeletal doses from ^{90}Sr could also produce bone sarcomas and leukemias in people. Therefore, the risk estimates derived in this section for ^{90}Sr in man are based upon the extensive experiments with animals and experience with irradiated human populations. These involve very different dosage patterns ranging from the acute, high intensity, very brief burst of energy from the atomic bomb through the relatively high dose and dose-rate of therapeutic x-ray applications to the relatively low and prolonged dose from a deposited radionuclide. These differences are recognized in the risk derivations that follow.

Mays and Lloyd (1972c) have shown that in the human, for uniform concentrations of either ^{90}Sr or ^{226}Ra in the 5000 g of mineralized bone of reference man, the dose to the cells lining bone surfaces (a presumed site of origin for bone sarcomas) is roughly equal to the dose averaged over the total 10,000 g skeleton including marrow, and that the ^{90}Sr dose to the red marrow (the presumed site of induction for myeloid leukemia) is roughly 1/2 that of the ^{90}Sr average dose to the total skeleton. Beddoe (1978) derived a figure for the ratio of marrow dose to mineralized bone dose of about one-fourth, a value also used in ICRP Publication 30 (ICRP, 1979, see Table 7.2 page 40 of part 1). Because the dose averaged over 10 kg of total skeleton is about 1/2 of that averaged over 5 kg of mineralized bone, the value of Beddoe (1978) corresponds to a red marrow dose of about 1/2 of that averaged over the total skeleton, the same as that of Mays and Lloyd (1972c). Obviously the calculation of risk to the human from internally deposited ^{90}Sr has inherent uncertainties, among which are differences in size of the marrow space among animal species and humans, the changing value with decreasing dose of the relative effectiveness for bone sarcoma induction of beta vs. alpha radiation, and differences in methods of dose calculation among populations. At present, the reliability of risk estimates is limited by such factors as the uncompleted follow-up of irradiated subjects (some of whom are still alive), the uncertainty in tissue doses, and the lack of fundamental radiobiological knowledge on how malignant neoplasms are induced by irradiation. Therefore, it must be emphasized that the estimates of risk presented here are provisional and may require revision in the light of future information.

8.1 Risk of Bone Cancer

Ninety-two cases of skeletal cancer (61 bone sarcomas and 31 head sinus carcinomas) had occurred to 31 December 1982 among the 1700

radium-containing persons of known dose, excluding subjects of zero dose (these numbers were derived from data in Gustafsen and Stehney, 1983). A number of these subjects received part of their dose from ^{228}Ra but most of it from ^{226}Ra. It is important to note, however, that as of that date only 2 cases of bone sarcoma had occurred among the 1470 persons who received a dose to the marrow-free skeleton of less than 10 Gy, totaling 964 person Gy (these numbers were derived from data in Gustafsen and Stehney, 1983), or a ^{226}Ra equivalent of 1168 person Gy if 1 Gy from ^{228}Ra has the same biological effect as 2 Gy from ^{226}Ra (Lloyd, *et al.*, 1986 have shown that in beagles 1 Gy from ^{228}Ra has the same effect in bone sarcoma induction as 2 Gy from ^{226}Ra). The subjects tabulated, mostly female dial painters, were first exposed on the average about 60 to 70 years previously, when they were about 20 years of age. The naturally expected rate among American women, aged 20 to 80 years, of about 10 bone sarcomas per year per million (Doll *et al.*, 1966, 1970; Waterhouse *et al.*, 1976, 1982) corresponds to 0.9 cases naturally expected in 60 years among the 1,470 persons who received a dose below 10 Gy. Using the method of Mays and Lloyd[6] (1972a and 1972b), the fitted 60 year linear risk for induced bone sarcoma from a dose to the marrow-free skeleton from ^{226}Ra and ^{228}Ra below 10 Gy is 11.4 bone sarcomas/10^4 person Gy (if 1 Gy from ^{228}Ra is equivalent to 2 Gy from ^{226}Ra) or 9.4 bone sarcomas/10^4 person Gy if 1 Gy from ^{228}Ra is equivalent in effectiveness to 1 Gy from ^{226}Ra. Mays *et al.* (1985) calculated about 12 bone sarcomas/10^4 person Gy of bone dose for the radium subjects, using a somewhat different grouping of cases and different dosimetric assumptions. While the best linear estimate of risk to the radium subjects is about 9 to 11/10^4 person Gy, there were only 2 observed cases of bone sarcoma in the low dose realm.

From Poisson statistics (Molina, 1949), the observation of two or fewer cancers could have occurred with a 10 percent chance ($P = 0.1$) if 4.9 cancers (4.0 induced + 0.9 natural) were the correct expectation. The linear risk which predicts 4.0 induced cases is based upon 42 bone sarcomas/10^4 person Gy, and we regard this as a reasonable higher limit for the 60-year linear risk to the radium subjects whose doses were below 10 Gy. The lower limit of risk is taken as essentially 0 induced bone sarcomas/10^4 person Gy, since the probability that both of the observed cases at doses below 10 Gy might have occurred naturally with an expectation of 0.9 cases is about 50%.

[6]A linear dose-response relationship was fit through the data such that the predicted number of sarcoma cases matched exactly with the observed total (points beyond the region of peak incidence were excluded).

Rowland *et al.* (1970) showed that for the data then available for the radium subjects, the radiation-induced fractional incidence of the combined bone sarcomas plus sinus carcinomas could also be fitted over the entire dosage range by the dose squared exponential equation,

$$I = (5.24 \text{ cancers}/10^4 \text{ [person Gy]}^2)\, D^2\, e^{-D/48.5\ \text{Gy}}, \qquad (8.1)$$

where D is the dose to the marrow-free skeleton. The dose squared factor (D^2) could imply that the induction of these forms of cancer frequently requires two "hits" in the same "target," whereas the exponential factor could represent the net survival of potentially malignant cells (and irradiated persons). Other explanations are possible. The goodness of fit to the data suggests that the dose squared exponential equation might provide an alternative estimate of risk. The dose squared exponential equation predicted about 1.5 induced cancers in the 584 radium subjects among whom the nonzero dose was below 10 Gy, which with the 0.44 case naturally expected (calculated from Waterhouse *et al.*, 1982), gives a total prediction of about 2 cases, a result which was in reasonable agreement with the 1 case that had by then (1970) been observed.

Using the toxicity ratios developed from the animal experiments already described, the effectiveness of ^{90}Sr relative to radium can be given as 0.04 to 0.11 in mice (Marinelli, 1969; Mays and Finkel, 1980) and about 0.04 to 0.1 in beagles (Raabe, *et al.*, 1981b; Dougherty and Mays 1969, updated by new results from Mays and Finkel 1980). This is based on the average doses of ^{226}Ra or ^{90}Sr required to produce about 10 percent incidence of bone sarcomas. These relative effectiveness values may be considerably less at dose rates from deposited ^{90}Sr of less than about 0.016 Gy/day (Raabe, *et al*, 1981b; Book, *et al.*, 1981). This latter indicates a sigmoid dose-response relationship for ^{90}Sr in dogs, perhaps with a substantial quadratic term, in contrast to a linear relationship for radium in dogs. If a linear relationship for ^{90}Sr is assumed, however, it will probably not underpredict the effects and is useful for extrapolation.

Transferring the radium risk of about 10 bone sarcomas (0 to 42) per 10^4 person Gy from doses in a 7 kg bone marrow-free human skeleton to dose in a 10 kg total human skeleton and using an effectiveness for bone sarcoma induction of 0.1 for ^{90}Sr relative to ^{226}Ra (NCRP 1980; Brown *et al.*, 1968) (see Sections 8) one obtains for doses below 10 Gy and based on the toxicity ratio from animal experiments (mouse and beagle) the following estimates of 60-year risk from ^{90}Sr for average dose D to the total skeleton (including marrow):

Linear model:

$$Best\ estimate = \frac{(1\ bone\ sarcoma)}{10^4\ person\ Gy} D \tag{8.2}$$

$$Higher\ estimate = \frac{(6\ bone\ sarcomas)}{10^4\ person\ Gy} D \tag{8.3}$$

$$Lower\ estimate = \frac{(0\ bone\ sarcoma)}{10^4\ person\ Gy} D \tag{8.4}$$

Dose squared exponential model:

Alternative estimate (from Rowland *et al.*, 1970)

$$\frac{(11\ skeletal\ cancers)}{10^6\ person\ Gy^2} D^2\, e^{-D/340\ Gy} \tag{8.5}$$

From the preceding equations it appears that if 1,000,000 persons each received a dose from ^{90}Sr of 0.01 Gy averaged over the total skeleton, the predicted number of induced bone sarcomas during about the next 60 years would be a best linear estimate of 1, a higher linear estimate of 6 and a lower linear estimate of 0. An alternative based upon a dose squared exponential relationship gives an estimate of 0.001. These estimates, for bone sarcomas, tend to be slightly higher than, but are still in reasonable agreement with, the estimates made by Mays and Lloyd (1972b). Note that for a dose of 0.01 Gy, the estimated risk is 1000 times lower for the dose squared exponential model than for the linear model. Note also that, within the dose limits where it applies (0 to 10 Gy), the lower linear estimate of zero corresponds to a threshold model. It has been reported (Moskalev *et al.*, 1973) that the prolongation of ^{90}Sr administration decreases the occurrence of osteosarcoma for equal total amounts given. We note that no bone sarcomas have appeared among beagles injected with ^{90}Sr in the Utah project at below about 18 Gy average skeletal dose, among beagles exposed to ^{90}Sr by inhalation in the ITRI project at below about 35 Gy (potential dose to 5000 days), among monkeys fed ^{90}Sr at below about 20 Gy, and among miniature swine fed ^{90}Sr at below about 90 Gy. Among beagles fed or injected with ^{90}Sr in the LEHR project, a bone sarcoma occurred among the lowest level dogs at about 26 Gy while another (possibly naturally occurring) was seen at only 1.6 Gy average skeletal dose.

The best, higher, and lower estimates derived above for bone cancer induction from incorporated ^{90}Sr are quite similar to the estimates quoted by UNSCEAR (1977, p. 399) for bone tumor induction from external radiation of between 3 and 5×10^{-4} per Gy. Risk coefficients of 3.4 to 20 cases/yr/10^6/Gy, equal to about 2 to 11 cases/

10^4 Gy over 50 years, are quoted for external radiation exposure by Thorne and Vennart (1976). Table A-27 on page 417 of BEIR III (BEIR, 1980)[7] suggests a risk coefficient of about 1.4 per 10^4 person Gy of low LET radiation, such as ^{90}Sr, for bone sarcoma induction. ICRP Publication 26 (ICRP, 1977, page 11) gives a risk coefficient for radiation protection purposes of 5×10^{-4}/Sv.

Strictly speaking, the risk estimates derived here from the experience with ^{226}Ra apply to persons whose exposures to ^{90}Sr would begin as teen-agers or young adults (the starting ages of the radium dial painters), but these results should also apply approximately to children, since the efficiency per Gy for bone sarcoma induction by ^{224}Ra seems roughly comparable for adults and children (Spiess and Mays, 1972). Furthermore, the effectiveness per rad average skeletal dose of ^{90}Sr in producing bone sarcomas in mice was approximately equal (within a factor of 2) when the ^{90}Sr was given at either 3 or 20 weeks of age, at about equal skeletal doses (Van Putten, 1969). In the LEHR beagles the lowest average skeletal doses at death to the two individuals with a bone sarcoma whose ^{90}Sr intake extended from gestation to adulthood was 1.2 and 22.9 Gy. For other beagles injected at LEHR with ^{90}Sr as adults the lowest values were about 5 and 51 Gy (Goldman, 1982, updated by Raabe, 1990). The lowest average skeletal dose at death to an individual with a bone tumor was the same (90 Gy) in pigs fed ^{90}Sr throughout life and in a pig injected with ^{90}Sr at 6 months of age (Howard *et al.*, 1969). The foregoing studies suggest that within a factor of 2, children and adults may be equally radiosensitive to bone sarcoma induction from radionuclides in the skeleton.

There might be some interest in the estimated risk of bone sarcoma per kBq ^{90}Sr ingested. Using the time integral given in Table 4.1 of 20.48 MBq days per kBq intake into blood, 5000 g skeleton in the reference man, and about 1 MeV/^{90}Sr + ^{90}Y disintegration chain, the 50-year dose is about 1.5 mGy per kBq intake to blood. If the uptake to blood of ^{90}Sr in the GI tract is about 20%, then for every 37 kBq ingested, about 7.4 kBq would be transferred to blood, and the 50 year integral dose resulting therefrom would be about 0.01 Gy. Therefore, the estimated risk of bone sarcoma in a population of 1 million adult persons each ingesting 37 kBq ^{90}Sr might be calculated by a linear model as a preferred estimate of 1×10^{-6}, a higher estimate of 6×10^{-6}, and a lower estimate of 0. Since infants and

[7]A more recent report from the National Research Council, National Academy of Science (BEIR V) became available after this report was returned from Council review. However, no reference is made to BEIR V herein because of this and because BEIR V has not been evaluated by the NCRP.

children receive a higher dose per kBq intake than adults by about a factor of 3 to 8 (see above), corresponding risk estimates for juveniles could be calculated by the linear model to be about 5×10^{-6}, 3×10^{-5}, and 0 cases of bone sarcoma among 1 million individuals each ingesting 37 kBq as a best, higher and lower estimate, respectively.[8]

8.2 Risk of Leukemia

As part of its overall effort concerned with internal emitters, the NCRP is examining the general problems of leukemia risk from deposited radionuclides. Also, a recent report of the NCRP addresses the risk of leukemia from sources external to the body, such as gamma rays and neutrons (NCRP, 1987b). Therefore, the discussion here will consider primarily problems and estimates of the risk of leukemia from radiostrontium as they can be gleaned from the experimental data.

The risk estimates for radiation-induced leukemia given in BEIR III (BEIR, 1980) range between 0.25 and 55 per 10^4 person Gy of low-LET radiation. Mays and Lloyd (1972c) derived a risk coefficient for leukemia induction by x rays in humans of 21 cases/10^4 person Gy for doses averaged over total marrow. The 1988 UNSCEAR report (UNSCEAR, 1988) provided an estimate of about 95 cases/10^4 person Gy for high dose-rate radiation but did not estimate the attenuation of risks at lower dose rates except to state that they could be a factor of 2 to 10 lower. ICRP Publication 26 (ICRP, 1977, p. 10) gives a risk coefficient for radiation protection purposes of 2×10^{-3}/Sv, which is equivalent to 20 induced cases per 10^4 person Sv. Thorne and Vennart (1976) reviewed published risk estimates for radiation induced leukemia and chose 30 leukemias/10^4 person Gy as a representative value (with a range of 15 to 50 per 10^4 person Gy). Mays and Lloyd (1972c) derived a risk coefficient for leukemia induction of 26 per 10^4

[8]While the long-term experiment on monkeys at UC Berkeley did not produce any bone sarcomas, a speculative calculation can be made based on the dosimetry outline in Section 5. For 13 adult animals living more than 1 year after injection, the cumulative dose would be about 1742 monkey Gy. If there had been one additional monkey and it had developed a bone sarcoma, the monkey Gy might have been increased to (14/13) (1742) = 1876 and the linear risk coefficient would have been

$$\frac{1 \textit{ bone sarcoma}}{1876 \textit{ monkey Gy}} = 5 \textit{ bone sarcomas}/10^4 \textit{ monkey Gy},$$

so that an upper limit estimate of 5 bone sarcomas per 10^4 monkey Gy for low dose, low dose-rate exposure might be inferred from these data, surprisingly, even if coincidentally, close to the risk estimates derived above.

person Gy for the A-bomb survivors using the (T65D) dosimetry. Preston and Pierce (1988) have stated that the organ dose risk estimates for the new (DS86) dosimetry are about 1.2 times greater.

The risk of leukemia must be formulated from leukemia experience of irradiated humans, since the relative sensitivity for the induction of different effects (leukemia, bone sarcoma, tumors of soft-tissue near bone, etc.) is probably different in different species. Therefore, simple ratios of various effects at various exposure levels in experimental animals cannot be applied directly to man for leukemia induction, since there is a dearth of information about the induction of leukemia in man by internal irradiation.

Two mitigating conditions exist for leukemia induction by ^{90}Sr + ^{90}Y irradiation of the bone marrow in comparison to that from external sources. First, the marrow dose is about 1/2 of the average dose to the total skeleton (Mays and Lloyd, 1972c; Beddoe and Spiers, 1979; ICRP, 1979). Second, whereas the A-bomb survivors on which most of the leukemia risk estimates depend received nearly all of their dose in less than a minute during the exploding flash of the weapon, ^{90}Sr continues to irradiate the skeleton from the time of its deposition throughout the remaining lifespan. Strontium-90 and its decay product, ^{90}Y, emit beta particles, radiation of low LET. Low-LET radiation distributes its ionizations and excitations rather diffusely throughout tissue. Most of the damage from isolated ionizations and excitations appears to be repaired readily if sufficient time is available before additional radiation events are received locally. A wide variety of biological experiments suggests that for low LET radiation, the risk per Gy for most effects is about a factor of 2 to 10 less at low dose rates than at high dose rates. For general information on this topic see NCRP Report No. 64 (NCRP, 1980) and the proceedings edited by Brown *et al.* (1968).

The ratios of the relative effectiveness of irradiation at lower vs. higher dose rates, as determined in animal studies, and given in NCRP Report No. 64 (NCRP, 1980) are presented as values for lifespan shortening, bone sarcoma induction, and genetic mutations. The 8 tabulated effectiveness factors for lower dose rate vs. higher dose rate ranged from 0 to 0.47 and averaged 0.14. Tentatively, and subject to future revision, the dose-rate effectiveness factors for leukemia induction in humans for dose rates below 10^{-4} Gy/min relative to those above 10^{-1} Gy/min are taken to be 0.3 (best estimate, also used for the dose squared exponential alternative), 0.5 (higher estimate) and 0.1 (lower estimate). Qualitatively, the dose-rate effectiveness factor for induction of myeloid leukemia in RF mice at low vs. high dose rates of total-body, external irradiation seems reasonably close to the lower estimate of 0.1, although the published

crude incidences (Upton *et al.*, 1970), until properly corrected for competing causes of death, do not permit quantitative numerical evaluation of the dose-rate effectiveness factor for each individual type of neoplasm.

Assuming that the bone marrow dose is 1/2 of the average skeletal dose, using the indicated dose-rate effectiveness factors for ^{90}Sr doses below 10 Gy, and the risk coefficient of Mays and Lloyd (1972c) the following are calculated as lifetime risks:

Linear model:

$$Best\ estimate = \frac{(3\ leukemias)}{10^4\ person\ Gy} D \tag{8.6}$$

$$Higher\ estimate = \frac{(8\ leukemias)}{10^4\ person\ Gy} D \tag{8.7}$$

$$Lower\ estimate = \frac{(<1\ leukemia)}{10^4\ person\ Gy} D \tag{8.8}$$

(The original risk coefficients were multiplied by 0.3 for dose-rate effectiveness as well as 0.5 for ratio of marrow dose to skeletal dose.)

Dose squared exponential model

Alternative estimate (from Mays and Lloyd, 1972c):

$$\frac{(45\ leukemias)}{10^6\ (person\ Gy)^2} D^2\ e^{-D/33\ Gy} \tag{8.9}$$

From these leukemia risk equations, it can be seen that if one million persons in a general population each received 0.01 Gy from ^{90}Sr (averaged over the whole skeleton) the predicted number of leukemias induced during their remaining lifespans would be 3 (best linear), 8 (higher linear) and less than 1 (lower linear estimate). The dose-squared exponential estimate would be about 0.004.

It is interesting that the estimated risk to people from ^{90}Sr-induced leukemia may be higher than that from bone sarcoma, although smaller estimates for leukemia risk, approximately equal to those indicated for bone sarcoma, have been derived by Mays and Lloyd (1972c), assuming less effectiveness of low dose-rate on leukemia induction than those assumed in this report. Note also that for ^{90}Sr doses below 10 Gy, the exponential factors in the dose squared exponential relationships can be ignored, both for bone sarcoma and for leukemias, leaving a simple dose squared relationship.

It can be calculated from the foregoing that the ingestion of 37 kBq ^{90}Sr results in a marrow dose in 50 years of about 7.4 mGy. The corresponding lifetime leukemia risk values using a linear model

are a preferred estimate of 2.3, a higher estimate of 6 and a lower estimate of less than 1 leukemias/10^6 persons each ingesting 37 kBq.

Ginevan (1980) analyzed the available evidence regarding leukemia induction by low LET radiation and concluded that the contention is not supported that human leukemia is increased by exposure at low total doses of <0.2 Gy. Similarly, epidemiological studies by Dreyer and Friedlander (1982) indicated that for high dose-rate x rays, an excess leukemia risk to humans has not been demonstrated at doses less than about 0.3 Gy to the blood forming organs. Linos *et al.* (1980) reported that they could not identify any significant increase in the risks of developing leukemia for human exposure to low dose, low dose-rate x-ray exposures of up to 3 Gy, although their study was limited by a low number of human subjects. Therefore, a lower estimate for leukemia induction by ^{90}Sr exposure of humans at low dose-rates and low total doses could be taken as zero.

8.3 Summary: Risk of Malignancy from Internally Deposited ^{90}Sr

The following lifespan risks of fatal malignancies (bone sarcomas plus leukemias) induced by ^{90}Sr are estimated for doses below 10 Gy, summarized from the two preceding sections.

Linear model:

$$\textit{Best estimate} = \frac{(4\ \textit{malignancies})}{10^4\ \textit{person Gy}} D \tag{8.10}$$

$$\textit{Higher estimate} = \frac{(14\ \textit{malignancies})}{10^4\ \textit{person Gy}} D \tag{8.11}$$

$$\textit{Lower estimate} = \frac{(0\ \textit{malignancies})}{10^4\ \textit{person Gy}} D \tag{8.12}$$

Dose squared model:

$$\textit{Alternative estimate} = \frac{(56\ \textit{malignancies})}{10^6\ (\textit{person Gy})^2} D^2 \tag{8.13}$$

where D is the dose from ^{90}Sr averaged over the total skeleton (10 kg in a 70 kg reference man.)

While these risk estimates are considered to be among the best that can be offered at this time, the need for future revision must be emphasized. Many of the irradiated subjects forming the basis of the analysis are still alive, uncertainties remain in the tissue doses, and the value of the effectiveness ratio for leukemia induction of low vs.

high dose rates is not well known. Further, fundamental knowledge is lacking on how malignant neoplasms are induced by irradiation. It is hoped that the risk estimates can be improved in the future with the development of a better understanding of dose-rate effects and the dose-response relationship.

9. Conclusions

The metabolism of radiostrontium is similar but not identical to that of stable calcium. A metabolic model has been developed for strontium in the human by Marshall, *et al.* (1973), subsequently extended and modified, that seems to be adequate for purposes of dosimetry in man. Animal experiments indicate that bone sarcoma, hematopoietic dyscrasia and neoplasia, and tumors of soft tissue near bone may be important endpoints in the exposure of humans to radiostrontium at high doses. These same experiments suggest that lifespan, cancer incidence, reproductive performance and genetic effects are unlikely to be influenced at the low doses expected from normal peacetime conditions. The incidence of bone sarcoma and other malignant diseases at low doses and dose rates in animals has been remarkably low, and these effects have not been seen in excess of control incidence except at the highest dose levels (tens of grays average skeletal dose). The results indicate a curvilinear dose-response relationship, in contrast to the linear relationships seen in animal studies with some alpha-emitting bone seeking radioelements such as ^{239}Pu (Mays *et al.*, 1969b). In fact, the ^{90}Sr results are more similar to the experience with the nonlinear dose-response curve seen thus far in the radium dial painters. The dose-response relationships for ^{90}Sr-induced bone sarcomas in animal studies are in concordance with but do not prove the existence of a threshold. Therefore, there are important qualitative as well as quantitative radiobiological differences between ^{90}Sr and most of the bone-seeking alpha emitters. Although the investigation of fallout ^{90}Sr in humans and their food has supplied valuable information for construction of metabolic models on which dosimetric calculations can be based, it has been the animal experiments that have provided the information that has elucidated the unique interspecific type of dose-effect curve seen with ^{90}Sr in the skeleton, revealed the decreasing value of the relative effectiveness of ^{90}Sr/^{226}Ra with decreasing dose, and with the anchor points of human radiation exposure, allowed the calculation of risk estimates to human populations from possible exposures to ^{90}Sr. Comparison with ^{226}Ra effects in humans using relative effectiveness ratios of ^{90}Sr/^{226}Ra developed from animal studies for predicted bone sarcoma induction in humans and with external radi-

ation experience for leukemia induction in humans has yielded estimates of 1 bone sarcoma per 10^4 person Gy (with lower and higher limits of 0 and 6) and 3 leukemias per 10^4 person Gy (with lower and higher limits of 0 and 8) for populations exposed to radiostrontium at low doses and dose-rates.

APPENDIX A

Kilobecquerel-days Accumulated in Cancellous Bone, in Cortical Bone, and in Soft Tissue

APPENDIX A—*Kilobecquerel-Days Accumulated in Cancellous Bone, in Cortical Bone, and in Soft Tissue after Intake of 1 Kilobecquerel of the Indicated Radionuclide in Blood*[a,b,c,d]

(*t*) Days	Tissue	Strontium-89	Strontium-90	Strontium-91	Barium-140
2	Cancellous bone	0.004	0.004	0.0008	0.002
	Cortical bone	0.0044	0.0044	0.0008	0.0022
	Soft tissue	0.032	0.032	0.0111	0.0166
7	Cancellous bone	0.016	0.017	0.0008	0.0055
	Cortical bone	0.018	0.019	0.0009	0.006
	Soft tissue	0.060	0.062	0.0112	0.024
30	Cancellous bone	0.053	0.062	0.011	(c)
	Cortical bone	0.062	0.073	0.013	
	Soft tissue	0.110	0.124	0.037	
60	Cancellous bone	0.084	0.114	0.013	
	Cortical bone	0.100	0.137	0.015	
	Soft tissue	0.141	0.174	0.040	
180	Cancellous bone	0.140	0.346	0.013	
	Cortical bone	0.171	0.432	0.016	
	Soft tissue	0.172	0.286	0.041	
365	Cancellous bone	0.150	0.651	(c)	
	Cortical bone	0.185	0.835		
	Soft tissue	0.175	0.354		
1825	Cancellous bone	0.151	2.24		
	Cortical bone	0.187	3.24		
	Soft tissue	0.175	0.462		
3650	Cancellous bone	(c)	3.22		
	Cortical bone		5.41		
	Soft tissue		0.484		
7300	Cancellous bone		3.97		
	Cortical bone		7.89		
	Soft tissue		0.492		
10,950	Cancellous bone	(c)	4.14	(c)	(c)
	Cortical bone		9.38		
	Soft tissue		0.494		
14,600	Cancellous bone		4.24		
	Cortical bone		10.2		
	Soft tissue		0.494		
18,250	Cancellous bone		4.27		
	Cortical bone		10.6		
	Soft tissue		0.494		

[a]Data supplied by courtesy of Dr. John C. Marshall to the authors of NRC (1975).

[b]The entries indicated for a given time, *t*, represent the kilobecquerel-days accumulated for the period 0 to *t* days.

[c]Blank spaces indicate the data are the same as the last entry in the column.

[d]From NRC (1975).

APPENDIX B

Retention Functions for ^{90}Sr Retention in Skeletons

APPENDIX B—*Retention Functions for ^{90}Sr retention in skeletons of the general form:*

$$R\ (\%) = A_1\, e^{-k_1 t} + A_2\, e^{-k_2 t} + A_3\, e^{-k_3 t}.$$

(B.1a)—*Inhalation, age range 389 to 416 days, ITRI-beagles; data from 0 to 3600 days after exposure.*

Age at t_0 days	t_i	A_1	k_1	A2	k_2 $\times 10^{-3}$	A_3	k_3 $\times 10^{4}$	n	Max BB[c] (kBq)	Dog ID
416	0	52.77	1.49	20.04	16.46	27.31	4.20	86	925	23E
398	1	75.99	7.0[a]	13.21	6.62	10.80	3.33	87	1258	24A
398	0	69.33	1.03	14.60	9.18	16.41	2.73	87	1184	24B
391	0	60.99	0.38	13.03	10.40	17.39	3.96	89	814	26G
389	0	59.56	0.39	12.35	12.29	13.48	3.47	92	1332	27A
390	0	72.48	0.41	12.01	8.48	13.23	3.84	85	1591	27D
408	1	62.93	3.5	18.89	6.25	17.68	3.73	87	814	30E
408	0	65.49	2.72	20.23	6.65	14.29	3.50	86	999	30F
409	0	50.59	5.50	27.64	6.74	21.77	2.71	84	1184	30G
400	0	68.82	3.07	16.24	5.82	14.98	2.70	79	999	37F
MEAN ± SD[b]		63.90 8.20	1.59 (0.56–4.84)	16.82 4.93	8.41 (5.99–11.8)	16.73 4.78	3.38 (2.86–3.98)			

[a]This data set started at $t_i = 1$ instead of $t_0 = 0$; k_1 was arbitrarily set to a value which reduced the assumed 100% retention value at t_0 to the best fit % retention at $t = 1$.

[b]The geometric mean and asymetric standard deviation is given for the rate constant (k) values; the arithmetic mean and standard deviation is given for the coefficients (A).

[c]Maximum body burden.

(B.1b)—*Intravenous Injection of Strontium-90 at 540 days; LEHR:Davis–Beagles*

Age at t_0 days	t_i	A_1	k_1	A2	k_2 $\times 10^3$	A_3	k_3 $\times 10^4$	n	Max BB[c] (kBq)	Dog ID
540	30	—	—	14.80	4.51	11.34	1.80	28	1461	S20F01
540	24	—	—	13.33	4.19	8.57	2.32	26	1243	S20F06
540	20	—	—	18.03	5.42	13.49	1.76	28	1153	S20F12
540	19	—	—	14.05	4.86	11.96	2.46	21	1876	S20M22
540	19	—	—	13.58	4.78	11.10	2.22	28	1709	S20M24
540	19	—	—	14.99	7.03	9.13	2.41	25	1273	S20F26
540	24	—	—	10.56	7.06	9.31	2.38	27	1238	S20M33
540	24	—	—	14.51	4.69	10.42	1.89	24	1121	S20M35
540	21	—	—	19.83	8.50	14.33	2.53	25	1109	S20F37
540	21	—	—	18.22	5.53	17.61	2.14	25	1769	S20M39
MEAN ± SD[b]				15.19 2.75	5.51 (4.37–6.96)	11.73 2.78	2.17 (1.90–2.49)			

[b, c]See footnotes Table B.1a.

(B.1c)—*Injection range = 508 to 608 days; Utah—Beagles*

Age at t_0 days	t_i	A_1	k_1	A_2	k_2 × 10^3	A_3	k_3 × 10^4	n	Max BB[c] (kBq)	Dog ID
522	10	—	—	24.01	3.89	10.05	1.33	11	596	F4S1.7
549	709	—	—	—	—	17.24	1.74	9	599	F9S1.7
522	10	—	—	20.44	5.86	13.26	0.884	11	1221	F4S2
508	443	—	—	28.52	3.20	11.53	0.897	6	1321	M10S2
608	244	—	—	14.96	5.58	14.36	1.73	7	1499	M12S2
527	10	—	—	21.15	7.80	14.02	3.12	9	3596	F4S3
557	10	—	—	41.93	21.15	11.53	0.996	6	3326	M5S3
528	10	—	—	32.34	6.01	14.00	1.29	11	9786	F4S4
562	14	—	—	42.15	24.27	12.62	1.39	7	10926	M5S4
606	224	—	—	12.82	4.83	11.29	1.28	7	13028	M12S4
MEAN ± SD[b]				26.48 10.68	7.12 (3.52–14.4)	13.01 2.07	1.37 (0.938–1.98)			

[b, c]See footnotes Table B.1a.

(B.1.d)—*Ingestion*, in utero *to 540 days; LEHR Davis—Beagles*

Age at t_0 days	t_i	A_1	k_1	A_2	k_2 × 10^3	A_3	k_3 × 10^4	n	Max BB[c] (kBq)	Dog ID
540	59	—	—	21.63	2.92	76.91	1.42	31	526	D30F02
540	1	—	—	13.91	3.63	83.89	1.38	35	515	D30M10
540	3	—	—	25.94	3.30	75.38	1.25	45	609	D30M16
540	0	—	—	30.66	2.39	70.07	1.30	41	600	D30F19
540	0	—	—	31.85	1.70	67.15	1.21	40	477	D30F20
540	0	—	—	21.34	4.37	80.21	1.61	34	755	D30M22
540	4	—	—	30.43	3.27	69.53	1.98	31	407	D30F25
540	4	—	—	30.16	2.60	92.16	2.47	24	457	D30M27
540	4	—	—	23.14	1.65	72.70	1.26	35	877	D30M30
540	3	—	—	44.17	1.50	6.62	0.225	18	766	D30M31
MEAN ± SD[b]				24.57 11.19	3.30 (1.40–7.78)	74.46 9.78	1.24 (0.652–2.35)			

[b, c]See footnotes Table b.1a.

(B.1e)—*Injection; Young Adult Rhesus Monkeys; Berkeley. Data from 1800 to 3600 days (whole body count)*

Age at t_0 years	t_i	A_1	k_1	A_2	k_2 × 10^3	A_3	k_3 × 10^4	n	Max BB[c] (kBq)	Monkey ID
6	1820	—	—	—	—	24.29	2.74	9	2253	D43F
6	1820	—	—	—	—	13.92	2.90	9	5635	D50M
8	1820	—	—	—	—	12.03	1.90	9	5635	D64M
6	1820	—	—	—	—	13.95	2.59	9	2253	D27F
6	1820	—	—	—	—	17.07	2.01	9	5635	D62M
6	1820	—	—	—	—	24.70	3.26	6	2253	D29F
5.4	1850	—	—	—	—	3.93	1.66	9	1854	R38F
MEAN ± SD[b]						15.70 7.24	2.37 (1.85–3.05)			

[b, c] See footnotes Table B.1a.

(B.1f)—*Injection of Strontium-90; Young Adult Rhesus Monkeys; Berkeley. Data from excreta collection (0–3600 days) and a terminal whole body count (5000–5600 days)*

Age at t_0 years	t_i	A_1	k_1	A_2	k_2 × 10^3	A_3	k_3 × 10^4	n	Max BB[c] (kBq)	Monkey ID
5.4	0	74.67	0.955	17.00	18.02	7.91	3.90	17	1854	R38F
5.5	0	80.41	1.14	13.50	5.53	5.90	4.21	18	1854	R39F
6.7	0	64.57	0.168	19.94	2.99	8.89	2.48	13	4351	R61M
12	0	75.88	0.214	13.34	7.51	7.53	4.65	18	6227	R62M
MEAN ± SD[b]		73.88 6.68	0.445 (0.165–1.19)	15.95 3.15	6.88 (3.25–7.68)	7.55 1.24	3.71 (2.80–4.90)			

[b, c]See footnotes Table B.1a.

APPENDIX C

Injection, Retention and Cause of Death for ^{90}Sr Injected Monkeys, University of California, Berkeley

APPENDIX C—*Injection, Retention and Cause of Death for ^{90}Sr injected monkeys*
University of California, Berkeley

Injection and Biological Retention Date for ^{90}Sr Injected Monkeys.

		Injection Data					
Species[a], no., sex	Age (yr)	Weight (kg)	^{90}Sr (kBq)[b]	Injection date	Days to death	^{90}Sr in[c] body	Cause of Death or Reason for euthanasia[d]
Young Monkeys (2.1 to 3 yr old)							
R37F	2.6	4.4	473.6	2/15/60	1	46.7	
R36F	2.3	3.1	473.6	2/15/60	4	57.7	
R52F	2.5	2.8	4829	11/13/61	21	50.9	
R53F	2.7	2.6	4829	11/13/61	66	72.5	
R29F	3.0	3.3	1539	9/10/58	280	38.5	Positive TB Test
R51F	2.7	2.8	966	11/13/61	441	27.9	
R20F	2.7	3.8	1843	1/15/57	707	14.0	Amoebic dysentery
R50F	2.8	3.1	966	11/13/61	1212	24.9	
R34F	2.8	3.6	2079	2/21/58	1921	15.2	Accident
R35F(1)[e]	2.4	4.0	2079	2/21/58	2187	19.3	Reinjected by mistake
R28F	2.5	2.9	1539	9/10/58	2087	15.5	Accident
Adolescent Monkeys (3.1 to 5 yr old)							
R10F	3.3	3.4	2083	8/8/55	94	42.9	
R64F	4.3	4.5	1225	3/27/67	427	16.1	
R33F	3.1	3.8	2079	2/21/58	2278	7.6	Leptospirosis
R9M	3.8	9.1	1406	4/16/54	2519	(18.0)[f]	Cyst on neck
R31F	4.5	4.1	2261	10/27/59	2663	5.5	Intussusception
R27M	3.6	3.2	1539	9/10/58	3157	11.3	Cage paralysis
R63F	4.1	5.4	1735	1/9/67	3287	5.3	Strangulated bowel, endometriosis
R65F	4.4	4.5	1225	3/27/67	4427	4.2	
R21F	3.3	4.2	1843	1/15/57	6448	5.1	Respiratory infection
R32F	4.0	4.5	2261	10/27/59	7168	5.9	

APPENDIX C—*Continued*

Injection and Biological Retention Date for ^{90}Sr Injected Monkeys.

		Injection Data					
Species[a], no., sex	Age (yr)	Weight (kg)	^{90}Sr (kBq)[b]	Injection date	Days to death	^{90}Sr in[c] body	Cause of Death or Reason for euthanasia[d]
Adult Monkeys (> 5 yr old)							
R8M	6.8	8.9	163	9/9/69	2	35.5	
R161F	9.8	7.3	1480	1/4/82	8	(16.7)[g]	
R11M	~7	7.1	185	6/8/70	16	51.4	
R98F	9.3	5.6	130	10/28/69	35	17.0	
R40F	8.8	8.4	2605	1/9/67	99	6.6	Pneumonia
R35F(2)[e]	8.0	5.2	1854	9/23/63	147	(8)	
R7M	>6.5	4.2	1388	3/16/54	181	24.1	Cage paralysis
R160F	8.8	4.6	1480	1/4/82	204	(11)[g]	
R152F	13.4	6.4	1480	10/26/81	302	(13.1)[g]	
R153F	10.9	5.9	1480	10/26/81	668	(<17)[g]	
R154F	13.4	8.8	1524	10/26/81	936	(<12)[g]	
D60M	8	8.0	5635	6/17/63	2040	5.4	Sq. cell Ca of gingiva
D29F	6	7.4	2253	6/17/63	2813	9.8	Endometriosis
R23M	>7	5.4	1843	1/15/57	3175	7.4	Accident
R38F	5.4	3.6	1854	9/23/63	3411	2.3	Uterine tumor
R8F	~5	5.5	1476	4/1/54	3506	2.9	Leptospirosis
D27F	6	5.7	2253	6/17/63	3927	5.3	Strangulated hernia
D62M	8	12.5	5635	6/17/63	4599	9.0	Undetermined
D64M	8	13.8	5635	6/17/63	5232	4.9	Laryngeal tumor
R61M	6.7	6.8	4351	2/25/63	5373	3.2	Anesthesia accident
R39F	5.5	4.1	1854	9/23/63	5650	0.88	
D50M	6	11.3	5635	6/17/63	5860	3.7	
D43F	6	5.1	2253	6/17/63	5846	6.7	
R62M	12	9.4	6227	2/25/63	5853	1.2	

[a]All rhesus (R); M, male; F, female. Capital "D" precedes the numbers of monkey originally injected at the University of Rochester, housed until 1968 at the Delta Primate Center, and transferred to LBL in 1968.

[b]S.I. conversion: 3.7×10^{10} Bq = 1Ci.

[c]Radiochemical analysis of skeleton and soft tissues.

[d]Where no cause of death is shown, animals were killed to obtain ^{90}Sr distribution data.

[e]Monkey 35F was reinjected (by mistake) with ^{90}Sr 2037 d after her original injection. When she was killed 147 d after the second injection, the measured ^{90}Sr in excreta, bones and tissues was compatible with the approximate ^{90}Sr body contents shown.

[f]Values shown in parentheses are estimates; data are incomplete.

[g]Estimated from collected excreta through 302 days.

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SC 1 Basic Radiation Protection Criteria
- SC 1-1 Probability of Causation for Genetic and Developmental Effects
- SC 1-2 The Assessment of Risk for Radiation Protection Purposes
- SC 1-3 Collective Dose

SC 16 X-Ray Protection in Dental Offices
SC 40 Biological Aspects of Radiation Protection Criteria
SC 40-1 Atomic Bomb Survivor Dosimetry
SC 46 Operational Radiation Safety
SC 46-2 Uranium Mining and Milling—Radiation Safety Programs
SC 46-4 Calibration of Survey Instrumentation
SC 46-5 Maintaining Radiation Protection Records
SC 46-8 Radiation Protection Design Guidelines for Particle Accelerator Facilities
SC 46-9 ALARA at Nuclear Plants
SC 46-10 Assessment of Occupational Doses from Internal Emitters
SC 46-11 Radiation Protection During Special Medical Procedures
SC 57 Internal Emitter Standards
SC 57-2 Respiratory Tract Model
SC 57-6 Bone Problems
SC 57-8 Leukemia Risk
SC 57-9 Lung Cancer Risk
SC 57-10 Liver Cancer Risk
SC 57-14 Placental Transfer
SC 57-15 Uranium
SC 59 Human Population Exposure Experience
SC 63 Radiation Exposure Control in a Nuclear Emergency
SC 63-1 Public Knowledge About Radiation
SC 63-2 Criteria for Radiation Instruments for the Public
SC 64 Environmental Radioactivity and Waste Management
SC 64-6 Screening Models
SC 64-16 Uncertainties in Dose Assessment
SC 65 Quality Assurance and Accuracy in Radiation Protection Measurements
SC 66 Biological Effects and Exposure Criteria for Ultrasound
SC 67 Biological Effects of Magnetic Fields
SC 69 Efficacy of Radiographic Procedures
SC 71 Radiation Exposure and Potentially Related Injury
SC 75 Guidance on Radiation Received in Space Activities
SC 76 Effects of Radiation on the Embryo-Fetus
SC 77 Guidance on Occupational and Public Exposure Resulting from Diagnostic Nuclear Medicine Procedures
SC 78 Practical Guidance on the Evaluation of Human Exposures to Radiofrequency Radiation
SC 79 Extremely Low-Frequency Electric and Magnetic Fields
SC 80 Radiation Biology of the Skin (Beta-Ray Dosimetry)
SC 81 Assessment of Exposures from Therapy
SC 83 Identification of Research Needs
SC 84 Radionuclide Contamination
SC 84-1 Decontamination and Decommissioning of Facilities
SC 84-2 Contaminated Soil
SC 85 Risk of Lung Cancer from Radon
SC 86 Hot Particles in Eye, Ear and Lung
SC 87 Radioactive and Mixed Waste

Ad Hoc Committee on Comparison of Radiation Exposures
Ad Hoc Group on Nuclear Medicine Misadministration
Ad Hoc Group on Plutonium

Ad Hoc Group on Radon
Ad Hoc Group on Video Display Terminals
Study Group on Compartive Risk
Task Force on Occupational Exposure Levels

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations that are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements, and effects, or radiation protection may be admitted to collaborating status by the Council. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

American Academy of Dermatology
American Association of Physicists in Medicine
American College of Medical Physics
American College of Nuclear Physicians
American College of Radiology
American Dental Association
American Industrial Hygiene Association
American Institute of Ultrasound in Medicine
American Insurance Services Group
American Medical Association
American Nuclear Society
American Occupational Medical Association
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society of Radiologic Technologists
American Society for Therapeutic Radiology and Oncology
Association of University Radiologists
Bioelectromagnetics Society
College of American Pathologists
Conference of Radiation Control Program Directors
Electric Power Research Institute
Federal Communications Commission
Federal Emergency Management Agency
Genetics Society of America
Health Physics Society
Institute of Nuclear Power Operations
National Electrical Manufacturers Association
National Institute of Standards and Technology
Nuclear Management and Resources Council
Radiation Research Society
Radiological Society of North America
Society of Nuclear Medicine
United States Air Force

United States Army
United States Department of Energy
United States Department of Housing and Urban Development
United States Department of Labor
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Service

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

Another aspect of the cooperative efforts of the NCRP relates to the special liaison relationships established with various governmental organizations that have an interest in radiation protection and measurements. This liaison relationship provides: (1) an opportunity for participating organizations to designate an individual to provide liaison between the organization and the NCRP; (2) that the individual designated will receive copies of draft NCRP reports (at the time that these are submitted to the members of the Council) with an invitation to comment, but not vote; and (3) that new NCRP efforts might be discussed with liaison individuals as appropriate, so that they might have an opportunity to make suggestions on new studies and related matters. The following organizations participate in the special liaison program:

Australian Radiation Laboratory
Commissariat a l'Energie Atomique (France)
Commission of the European Communities
Defense Nuclear Agency
Federal Emergency Management Agency
Japan Radiation Council
National Institute of Standards and Technology
National Radiological Protection Board (United Kingdom)
National Research Council (Canada)
Office of Science and Technology Policy
Office of Technology Assessment
Ultrasonics Institute of Australia
United States Air Force
United States Army
United States Coast Guard
United States Department of Energy
United States Department of Health and Human Services
United States Department of Labor
United States Department of Transportation
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission

The NCRP values highly the participation of these organizations in the liaison program.

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American Dental Association
American Hospital Radiology Administrators
American Industrial Hygiene Association
American Insurance Services Group
American Medical Association
American Nuclear Society
American Occupational Medical Association
American Osteopathic College of Radiology
American Podiatric Medical Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society of Radiologic Technologists
American Society for Therapeutic Radiology and Oncology
American Veterinary Medical Association
American Veterinary Radiology Society
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To all of these organizations the Council expresses its profound appreciation for their support.

Initial funds for publication of NCRP reports were provided by a grant from the James Picker Foundation and for this the Council wishes to express its deep appreciation.

The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

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1	*Perceptions of Risk,* Proceedings of the Fifteenth Annual Meeting, Held on March 14–15, 1979 (Including Taylor Lecture No. 3) (1980)
2	*Quantitative Risk in Standards Setting,* Proceedings of the Sixteenth Annual Meeting, Held on April 2–3, 1980 (Including Taylor Lecture No. 4) (1981)
3	*Critical Issues in Setting Radiation Dose Limits,* Proceedings of the Seventeenth Annual Meeting, Held on April 8–9, 1981 (Including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Procedures,* Proceedings of the Eighteenth Annual Meeting, Held on April 6–7, 1982 (Including Taylor Lecture No. 6) (1983)
5	*Environmental Radioactivity,* Proceedings of the Nineteenth Annual Meeting, Held on April 6–7, 1983 (Including Taylor Lecture No. 7) (1984)
6	*Some Issues Important in Developing Basic Radiation Protection Recommendations,* Proceedings of the Twentieth Annual Meeting, Held on April 4–5, 1984 (Including Taylor Lecture No. 8) (1985)
7	*Radioactive Waste,* Proceedings of the Twenty-first Annual Meeting, Held on April 3–4, 1985 (Including Taylor Lecture No. 9) (1986)

8 *Nonionizing Electromagnetic Radiation and Ultrasound,* Proceedings of the Twenty-second Annual Meeting, Held on April 2–3, 1986 (Including Taylor Lecture No. 10) (1988)

9 *New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates,* Proceedings of the Twenty-third Annual Meeting, Held on April 5–6, 1987 (Including Taylor Lecture No. 11) (1988).

10 *Radon,* Proceedings of the Twenty-fourth Annual Meeting, Held on March 30–31, 1988 (Including Taylor Lecture No. 12) (1989).

11 *Radiation Protection Today—The NCRP at Sixty Years,* Proceedings of the Twenty-fifth Annual Meeting, Held on April 5–6, 1989 (Including Lecture No. 13) (1989).

12 *Health and Ecological Implications of Radioactively Contaminated Environments,* Proceedings of the Twenty-Sixth Annual Meeting of the National Council on Radiation Protection and Measurements, Held on April 4–5, 1990 (Including Taylor Lecture No. 14) (1991).

Symposium Proceedings

The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack, Proceedings of a Symposium held April 27–29, 1981 (1982)

Lauriston S. Taylor Lectures

No. Title and Author

1 *The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)

2 *Why be Quantitative About Radiation Risk Estimates?* by Sir Edward Pochin (1978)

3 *Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk,* see above]

4 *From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980) [Available also in *Quantitative Risks in Standards Setting,* see above]

5 *How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits,* see above]

6 *Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches,* see above]

7 *The Human Environment-Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity,* see above]

8 *Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations,* see above]

9 *Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste,* see above]

10 *Nonionizing Radiation Bioeffects: Cellular Properties and Interactions* by Herman P. Schwan (1986) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound,* see above]

11 *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1987) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates,* see above]

12 *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon,* see above]

13 *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today, see above].*

14 *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990)

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1 *Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)

2 *Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982)

3 *Screening Techniques for Determining Compliance with Environmental Standards* (1986), Rev. (1989)

4 *Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)

5 *A Review of the Publication, Living Without Landfills* (1989)

6 *Radon Exposure of the U.S. Population—Status of the Problem* (1991)

NCRP Reports

No.	Title
8	*Control and Removal of Radioactive Contamination in Laboratories* (1951)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons and Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
36	*Radiation Protection in Veterinary Medicine* (1970)
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41	*Specifications of Gamma-Ray Brachytherapy Sources* (1974)
42	*Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)
44	*Krypton-85 in the Atmosphere—Accumulation, Biological Significance, and Control Technology* (1975)
46	*Alpha-Emitting Particles in Lungs* (1975)
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49	*Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV* (1976)
50	*Environmental Radiation Measurement* (1976)
51	*Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities* (1977)

52 *Cesium-137 from the Environment to Man: Metabolism and Dose* (1977)
53 *Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally Exposed Women* (1977)
54 *Medical Radiation Exposure of Pregnant and Potentially Pregnant Women* (1977)
55 *Protection of the Thyroid Gland in the Event of Releases of Radioiodine* (1977)
57 *Instrumentation and Monitoring Methods for Radiation Protection* (1978)
58 *A Handbook of Radioactivity Measurements Procedures*, 2nd ed. (1985)
59 *Operational Radiation Safety Program* (1978)
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62 *Tritium in the Environment* (1979)
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Volume XIX. NCRP Reports Nos. 101, 102, 103, 104

(Titles of the individual reports contained in each volume are given above).

The following NCRP Reports are now superseded and/or out of print:

No.	Title
1	*X-Ray Protection* (1931). [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934). [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936). [Superseded by NCRP Report No. 6]
4	*Radium Protection* (1938). [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compounds* (1941). [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949). [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949). [Superseded by NCRP Report No. 30]
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951). [Out of Print]
10	*Radiological Monitoring Methods and Instruments* (1952). [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953). [Superseded by NCRP Report No. 22]
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953). [Superseded by NCRP Report No. 81]
13	*Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954). [Superseded by NCRP Report No. 24]
14	*Protection Against Betatron—Synchrotron Radiations Up to 100 Million Electron Volts* (1954). [Superseded by NCRP Report No. 51]

15 *Safe Handling of Cadavers Containing Radioactive Isotopes* (1953). [Superseded by NCRP Report No. 21]

16 *Radioactive Waste Disposal in the Ocean* (1954). [Out of Print]

17 *Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposure to Man, Addendum to National Bureau of Standards Handbook 59* (1958). [Superseded by NCRP Report No. 39]

18 *X-Ray Protection* (1955). [Superseded by NCRP Report No. 26]

19 *Regulation of Radiation Exposure by Legislative Means* (1955). [Out of Print]

20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957). [Superseded by NCRP Report No. 38]

21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958). [Superseded by NCRP Report No. 37]

24 *Protection Against Radiations from Sealed Gamma Sources* (1960). [Superseded by NCRP Report Nos. 33, 34, and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961). [Superseded by NCRP Report Nos. 33, 34, 35, and 36]

28 *A Manual of Radioactivity Procedures* (1961). [Superseded by NCRP Report No. 58]

29 *Exposure to Radiation in an Emergency* (1962). [Superseded by NCRP Report No. 42]

31 *Shielding for High Energy Electron Accelerator Installations* (1964). [Superseded by NCRP Report No. 51]

33 *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV*—Equipment Design and Use (1968). [Superseded by NCRP Report No. 102]

34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation* (1970). [Superseded by NCRP Report No. 49]

39 *Basic Radiation Protection Criteria* (1971). [Superseded by NCRP Report No. 91]

43 *Review of the Current State of Radiation Protection Philosophy* (1975). [Superseded by NCRP Report No. 91]

45 *Natural Background Radiation in the United States* (1975). [Superseded by NCRP Report No. 94]

48 *Radiation Protection for Medical and Allied Health Personnel.* [Superseded by NCRP Report No. 105]

56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977). [Superseded by NCRP Report No. 95]

58 *A Handbook on Radioactivity Measurement Procedures.* [Superseded by NCRP Report No. 58, 2nd ed.]

Other Documents

The following documents of the NCRP were published outside of the NCRP Reports and Commentaries series:

"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology 63, 428 (1954)

"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. 84, 152 (1960) and Radiology 75, 122 (1960)

Dose Effect Modifying Factors In Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service, Springfield, Virginia).

X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements (National Council on Radiation Protection and Measurements, Washington, 1968)

Specification of Units of Natural Uranium and Natural Thorium (National Council on Radiation Protection and Measurements, Washington, 1973)

NCRP Statement on Dose Limit for Neutrons (National Council on Radiation Protection and Measurements, Washington, 1980)

Control of Air Emissions of Radionuclides (National Council on Radiation Protection and Measurements, Bethesda, Maryland, 1984)

Copies of the statements published in journals may be consulted in libraries. A limited number of copies of the remaining documents listed above are available for distribution by NCRP Publications.

Index