Toxicity Profiles

Formal Toxicity Summary for STRONTIUM-90

NOTE: Although the toxicity values presented in these toxicity profiles were correct at the time they were produced, these values are subject to change. Users should always refer to the Toxicity Value Database for the current toxicity values.

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EXECUTIVE SUMMARY

Strontium-90 is a radioactive isotope of strontium that is produced in nuclear fission. It is a low energy emitter with a physical half-life of approximately 28 years. In the environment, it is accompanied by its decay product, yttrium-90, also a emitter (NCRP, 1991).

Metabolically, strontium is an analog of calcium. Strontium-90 is rapidly absorbed from the gastrointestinal tract or the lung into the bloodstream and is subsequently deposited in bone (Hobbs and McClellan, 1986). Retention in the bone is long-term, with yearly loss of the existing burden in adults of 7.5% from cortical bone and 30% from trabecular bone (Papworth and Vennart, 1984).

Oral intake at high levels of activity results in irradiation of target organs and nearby tissues. At high exposures, death results from radiation-induced hemorrhagic syndrome; at lower exposures, death results from destruction of the bone marrow. As survival times increase at lower administered activities, these effects are accompanied by neoplasms. Oral administration to miniature swine at 115 x 10^6 Bq/day resulted in radiation-induced hemorrhagic syndrome and death within 4 months. Lower intakes, 4.62 x 10^6 to 0.037 x 10^6 Bq/day induced effects on the hematopoietic system ranging from pancytopenia to neutropenia. Mean survival times were decreased in all exposure groups (NCRP, 1991). Subchronic exposures (5.6 x 10^4 to 133 x 10^4 Bq/day) also resulted in cytopenias in beagle

dogs (NCRP, 1991). Median survival times were reduced, particularly at the two highest exposures. Doses in the latter study were estimated at 22.5 to 107 Gy. In a three-generation study of miniature swine, no effects were noted on litter size, the percentage of stillborn, or birth weight when dams received life-shortening exposures (Clarke et al., 1972). The EPA has not calculated subchronic or chronic oral reference doses (RfD) for radionuclides.

Inhalation of soluble forms of strontium-90 at high activity levels resulted in early death of beagle dogs from bone marrow hypoplasia, panleukocytopenia, terminal hemorrhage, and bacterial infection (Gillett et al., 1987; NCRP, 1991). Long-term bone burdens of 17×10^6 to 41×10^6 Bq were calculated. Acute pulmonary effects observed in mice exposed to high activity levels of insoluble strontium-90 were radiation pneumonitis and pulmonary fibrosis (Scott et al., 1987). The dose lethal to 50% of animals was 370 Gy. The EPA has not calculated subchronic or chronic inhalation reference concentrations (RfC) for radionuclides.

The primary effect in animals surviving acute effects of strontium-90 exposure is neoplasia of bone and bone-related tissues. Soft tissue carcinomas in tissues near the bone were also observed above control levels. Chronic ingestion in beagle dogs and miniature swine also produced a high incidence of myeloproliferative disease, including frank leukemia (Hobbs and McClellan, 1986). Orally administered activity levels of 0.1×10^4 to 133×10^4 Bq/day to beagle dogs, beginning in utero and continuing to 540 days of age induced primary bone sarcomas and myeloproliferative disorders at activity levels of $\geq 5.6 \times 10^4$ Bq/day (Pool et al., 1973; NCRP, 1991). Bone sarcomas and hematopoietic neoplasms were induced in F_1 and F_2 generations of miniature swine that chronically ingested 4.62×10^6 Bq/day or 23.1×10^6 Bq/day (Clarke et al., 1972; NCRP, 1991). These generations were exposed in utero and gradually raised to the treatment level by 6 months of age. At higher exposure activities, mean survival time was drastically reduced (to less than tumor induction time); at lower exposure activities, 0.037×10^6 to 0.925×10^6 Bq/day, no bone sarcomas were observed, and survival times were increased to approximately that of controls.

The primary effect in adult beagle dogs administered strontium-90 in a single inhalation exposure and surviving more than 2 years was an excess of bone tumors (McClellan et al., 1973; NCRP, 1991). This effect was induced in dogs with long-term retained bone burdens of $\geq 1.0 \times 10^6$ Bq/kg.

Bone tumors were induced in 2 of 7 adult monkeys administered strontium-90 by gavage (NCRP, 1991), in adult beagle dogs administered strontium-90 by intravenous injection (Mays and Finkel, 1980), and in mice administered strontium-90 by intraperitoneal injection (Nilsson and Ronnback, 1973). Soft tissue sarcomas in tissues near the bone were observed in the beagle dogs (Mays and Finkel, 1980). No tumors were observed over a 20-year period in young and adult Rhesus monkeys administered a single injection at activity levels of 0.13×10^6 to 6.21×10^6 Bq (NCRP, 1991).

The EPA has classified all radionuclides as Group A carcinogens based on their property of emitting ionizing radiation and on the weight of evidence provided by epidemiological studies of radiation-induced tumors in humans (EPA, 1994). A slope factor of 8.9E-10 (risk/Bq) was calculated for oral ingestion. The combined oral slope factor for strontium-90 and yttrium-90 is 9.7E-10 (risk/Bq). For inhalation exposure, the slope factor for strontium-90 is 1.5E-09 (risk/Bq); the combined inhalation slope factor for strontium-90 plus yttrium-90 is 1.7E-09 (risk/Bq). Because of their low penetration ability, external exposures (risk/yr per Bq/g soil) for strontium-90 and strontium-90 plus yttrium-90 are both 0.0E+00.

1. INTRODUCTION

Strontium-90 (CAS Reg. No. 10098-97-2) is one of 11 radioisotopes of strontium that are produced in nuclear fission. Strontium-90 is a low-energy beta () emitter (0.02 MeV) that decays to its radioactive daughter, yttrium-90, with a relatively long physical half-life of approximately 28 years. Yttrium-90 has a shorter half-life (2.7 days) and a higher energy beta emission (maximum, 2.3 MeV) than strontium-90 (NCRP, 1991). Because of radioactive decay, yttrium-90 is always present in the environment with strontium-90. Strontium-90 may be released to the environment from normal operation of nuclear power plants and reactors,

nuclear plant accidents, past nuclear weapons testing, and leakage from radioactive waste sites (NCRP, 1991).

Strontium is an alkaline earth metal belonging to Group IIA of the periodic table. No information on the physical and chemical properties of strontium-90 was located, but the chemical behavior of a radionuclide is essentially the same as that of the stable element (stable strontium or strontium-88) and is similar to that of other elements in the same chemical group such as calcium.

Radionuclide uptake is expressed in units of activity [Curies (Ci) or Bequerels (Bq)] rather than mass.[(1)] Absorbed dose is expressed in terms of rads or Grays (Gy); dose equivalent (the relative biological effectiveness of the type of radiation) is expressed in terms of rems or Sieverts (Sv).[(2)] Many of the studies discussed in this profile were reviewed and summarized with activity units converted from Ci to Bq by the National Council on Radiation Protection and Measurements (NCRP, 1991).

2. METABOLISM AND DISPOSITION

The gastrointestinal tract absorption factor for strontium-90 is 30% (EPA, 1994); the lung clearance classification recommended by the International Commission on Radiological Protection is defined in terms of days, indicating minimal retention in the lung (EPA, 1994). Ingested and soluble inhaled forms of strontium-90 such as $^{90}SrCl_2$, are rapidly absorbed into the bloodstream and translocated primarily to the skeleton where retention is longterm (McClellan et al., 1972; Hobbs and McClellan, 1986). Strontium-90 delivered to the lung within an insoluble fused aluminosilicate particle matrix has a long retention period in the lung (Scott et al., 1987).

In biological systems, the behavior of stable and radioactive strontium is similar to and partially governed by that of calcium (NCRP, 1991). However, living organisms generally discriminate against strontium in favor of calcium. Following absorption, strontium is (1) distributed in an exchangeable pool consisting of the plasma, soft tissues, and exchangeable bone, (2) deposited in the bone, and (3) removed from the body by urinary and fecal excretion. Deposition and turnover of calcium (and strontium) in the bone is dynamic and long-term deposition depends on the age of the exposed individual. Because of de novo formation of bone in the young compared to the adult, ingestion of the same amount of strontium-90 on a body weight basis will result in a greater deposition of strontium in the bone of the young. Analyses of human bones for strontium-90 between the years 1956 and 1970 showed peak values of strontium-90 in children aged 1 to 2 years (Bryant et al., 1964; Papworth and Vennart, 1984).

Radioautographs of the femurs of five week old rats injected intraperitoneally with strontium-90 showed even deposition of strontium throughout the mineral part of the bone and deposition in the calcifying trabeculae beneath the epiphyseal plate (Hamilton, 1947).

Based on the concentrations of strontium-90 in human bone and human diet in the United Kingdom, Papworth and Vennart (1984) estimated uptake and turnover in the skeleton. In adults, approximately 7.5% of the existing burden of strontium-90 is lost each year from cortical bone; the rate of loss from trabecular bone is 30%. Approximately 4.5% of the dietary intake of strontium-90 reaches the skeleton, half going to cortical bone and half to trabecular bone.

The retention of strontium-90 following ingestion of food contaminated as a result of radioactive fallout was studied in a human volunteer (Hardy et al., 1965). The daily intake level over a 7-day period, measured above background levels, was 640 pCi/day (24 Bq/day). Most of the strontium-90 was unabsorbed. Almost 50% of the dose was excreted in the feces by 10 days after the ingestion period, whereas only 2.5% was eliminated in the urine. Both fecal and urinary excretion fell sharply by 10 days after the ingestion period and dropped to pretreatment levels by 180 days. The retention curve was best represented by a series of exponentials that leveled off after 140 days and approached a value of 25%.

3. NONCARCINOGENIC HEALTH EFFECTS

3.1. ORAL EXPOSURES

3.1.1. Acute Toxicity

In general, acute toxicity of radionuclides is of less concern than for nonradioactive chemicals because the levels required to cause adverse effects are extremely large and are not commonly encountered in the environment. Chronic exposure to low levels of radioactive contaminants is the most common exposure situation (EPA, 1989).

3.1.1.1. Human

Information on the acute oral toxicity of strontium-90 in humans was not available. Stable strontium is considered relatively nontoxic to humans (EPA, 1988).

3.1.1.2 Animal

Information on the acute oral toxicity of strontium-90 in animals was not available. Soluble stable strontium compounds are of a low order of acute toxicity with LD_{50} values for several species ranging from 1826 mg/kg [$Sr(NO_3)_2$, mouse] to 7500 mg/kg ($SrCl_2$, rabbit) (EPA, 1988).

Miniature swine administered strontium-90 at a level of 115 x 10^6 Bq/day in the diet beginning at 9 months of age died of radiation-induced hemorrhagic syndrome within 4 months (NCRP, 1991).

3.1.2. Subchronic Toxicity

3.1.2.1. Human

Information on the subchronic oral toxicity of strontium-90 in humans was not available.

3.1.2.2. Animal

Subchronic exposures to high levels of strontium-90 result in irradiation of the bone marrow producing effects on the hematopoietic system and subsequent death. There was an increased incidence (statistical data not given) of myelolymphoproliferative syndrome (bone marrow dyscrasias ranging from aplastic anemia to myeloid leukemia) in beagle dogs ingesting strontium-90 ($^{90}SrCl_2$) at levels of 1.5, 3, 12, or 36 Ci/day (5.6 x 10^4, 11.1 x 10^4, 44.4 x 10^4, or 133 x 10^4 Bq/day). Exposures lasted from the onset of fetal calcification in utero to the end of the growth period at 540 days of age. Average doses to the bone were estimated at 22.5, 50.4, 80.2, and 107 Gy (Pool et al., 1973; Raabe et al., 1981; data summarized in NCRP, 1991). A distinction between cytopenias and leukemia was not made.

3.1.3. Chronic Toxicity

3.1.3.1. Human

Information on the chronic oral toxicity of strontium-90 in humans was not available.

3.1.3.2. Animal

Strontium-90 ingestion in female miniature swine, beginning at 9 months of age, resulted in effects on the hematopoietic system (neutropenia, lymphopenia, thrombocytopenia, and myeloproliferative disorders with myeloid and histiocyte infiltration of tissues of the kidney, heart, testes, and lung) (Clarke et al., 1972; NCRP, 1991). At a feeding level of 115 x 10^6 Bq/day, all animals died of radiation-induced hemorrhagic syndrome within 4 months. Females fed 23.1 x 10^6 Bq/day survived to produce a second generation, but the second

generation, exposed in utero and gradually raised to the treatment level by 6 months of age, had a mean life span of 3 months; observed effects in the young were pancytopenia-hemorrhagic crisis and myeloid metaplasia (bone marrow aplasia). At 4.62 x 10^6 Bq/day, neoplasms accompanied by pancytopenia were induced; the lifespan was shortened to 3.5 years for the combined F_1 and F_2 generations. At lower exposure activities, 0.925 x 10^6, 0.185 x 10^6, and 0.037 x 10^6 Bq/day, neutropenia, with some neoplastic effects at the 0.925 dose level, was the primary observed effect. At these latter activities, mean survival times of 10-11 years were close to the mean survival time of 11 years in a control group. Doses to the bone were not calculated.

3.1.4. Developmental and Reproductive Toxicity

3.1.4.1. Human

Information on the developmental and reproductive toxicity of strontium-90 in humans was not available.

3.1.4.2. Animal

In a summary of their studies on the effects of strontium-90 in three generations of miniature swine, Clarke et al. (1972) noted no significant differences in the litter size, the percentage of stillborn, or in birth weight between control animals and animals ingesting up to 625 Ci/day (23.1 x 10^6 Bq/day). Sows ingesting 3100 Ci/day (115 x 10^6 Bq/day) did not survive the gestation period.

3.1.5. Reference Dose

The EPA (1994) has not calculated subchronic or chronic oral reference doses (RfD) for radionuclides.

3.2. INHALATION EXPOSURES

3.2.1. Acute Toxicity

3.2.1.1. Human

Information on the acute toxicity of strontium-90 in humans following inhalation exposure were not available.

3.2.1.2. Animal

The D_{50} (LD_{50}) for the rat from inhalation of strontium-90 in fused aluminosilicate particles corresponds to 1200 kBq/g lung or a 900 day dose of 370 Gy (37,000 rad) (Scott et al., 1987). The cause of death was radiation pneumonitis.

Administration of strontium-90 ($^{90}SrCl_2$) to beagle dogs by a single inhalation exposure resulted in early deaths (6 of 66 dogs within 32 days) which were attributed to acute bone marrow destruction manifest by a profound pancytopenia (Gillett et al., 1987; NCRP, 1991). Septicemia, secondary to leukopenia, was the immediate cause of death; hemorrhaging was a contributing factor. The authors calculated "long-term body burdens" of 17 x 10^6 to 41 x 10^6 Bq (1.7 x 10^6 to 4.1 x 10^6 Bq/kg body weight).

3.2.2. Subchronic Toxicity

Information on the subchronic toxicity of strontium-90 in humans or animals following inhalation exposure was not available.

3.2.3. Chronic Toxicity

3.2.3.1. Human

Information on the chronic toxicity of strontium-90 in humans or animals following inhalation exposure was not available.

3.2.3.2. Animal

In a study of the early effects of inhaled radionuclides, a total of 280 male and female F344/CRL rats were exposed by inhalation to strontium-90 in equilibrium with its daughter radionuclide, yttrium-90 (Scott et al., 1987). The radionuclides were delivered within an insoluble fused aluminosilicate particle matrix that has a long retention period in the lung. There were three exposure groups (low, medium, and high) and one control group; initial lung burdens ranged from 0 to 3000 kBq/g of lung. Subgroups within each group were monitored 1.5 years postexposure for body weight, mortality (40 animals/treatment group), hematological measurements (10 animals/treatment group), and pulmonary function (20 animals/treatment group). Reductions in weight gain did not occur in groups where a majority of animals survived. The major cause of death was radiation pneumonitis and pulmonary fibrosis with a peak in the distribution of deaths between 140 and 180 days after exposure. The dose lethal to 50% of animals succumbing to radiation pneumonitis was 370 Gy. Total lymphocyte counts were reduced in exposed animals (data not given). Nonlethal doses as low as 65% of the median lethal dose of 370 Gy caused impaired pulmonary function observable as late as 1.5 years after exposure.

3.2.4. Developmental and Reproductive Toxicity

Information on the developmental and reproductive toxicity of strontium-90 in humans or animals following inhalation exposure was not available.

3.2.5. Reference Concentration

The EPA (1994) has not calculated subchronic or chronic inhalation reference concentrations (RfC) for radionuclides.

3.3. OTHER ROUTES OF EXPOSURE

No data on noncarcinogenic effects following administration by other routes of exposure were available.

3.4. TARGET ORGANS/CRITICAL EFFECTS

Noncarcinogenic effects were noted on target organs following administration of life-shortening doses.

3.4.1. Oral Exposures

GI tract: Oral administration at high doses resulted in death from radiation-induced hemorrhagic syndrome in miniature swine.

Bone: Translocation to the bone leads to damage to the hematopoietic system (from chronic irradiation of the bone) resulting in early deaths (at high doses) from bone marrow hypoplasia (aplastic anemia) among other bone marrow dyscrasias.

3.4.2 Inhalation Exposures

Lung: Administration of insoluble strontium-90 compounds to rats by the inhalation route results in radiation pneumonitis and lung fibrosis.

Bone: Translocation to the bone leads to destruction of the marrow cellular elements.

4. CARCINOGENICITY

The carcinogenicity of strontium-90 has been studied in mice, rats, beagle dogs, miniature swine, and monkeys. Single oral, inhalation, or intravenous administration results in high incidences of neoplasia of bone and bone-related tissues. The most frequently observed neoplasms have been osteosarcomas, hemangiosarcomas, fibrosarcomas, and epidermoid carcinomas. Chronic ingestion in beagle dogs and miniature swine produced a high incidence of myeloproliferative disease, including frank leukemia (Hobbs and McClellan, 1986). Target organs for strontium-90 are the red bone marrow because of its relevance to the induction of leukemia and the endosteal bone surfaces because of their relevance to the induction of bone cancer.

In some of the following studies, doses were not calculated from exposure activities. For humans, estimates of the average risk of fatal cancer from low linear energy transfer radiation range from approximately 0.007 to 0.07 fatal cancers/Sv (EPA, 1989). Doses above 1 Sv are not normally associated with radioactive contamination in the environment.

4.1. ORAL EXPOSURES

Primary bone sarcomas and myelolymphoproliferative syndrome developed in beagle dogs that were administered strontium-90 in the diet from the onset of fetal calcification in utero to the end of the growth period at 540 days of age (Pool et al., 1973; updated summary data in NCRP, 1991). Average daily intake activities were 0.0, 0.03, 0.08, 0.5, 1.5, 3, 12, or 36 Ci/day (0.0, 0.1 x 10^4, 0.3 x 10^4, 1.9 x 10^4, 5.6 x 10^4, 11.1 x 10^4, 44.4 x 10^4, or 133 x 10^4 Bq/day). Average doses to the bone were estimated at 0, 0.38, 1.15, 6.70, 22.5, 50.4, 80.2, and 107 Gy, respectively. Deaths occurred in tumor-bearing animals at 1.5-3 years of age in the highest dose group and at 6-8 years in the groups administered 44.4 x 10^4 and 11.1 x 10^4 Bq/day (compared with 14.6 yr in the control group). Incidences of tumors in the control to highest dose groups were 2.5% (2 of 80 dogs), 0.0% (0 of 75 dogs), 2.5% (1 of 40 dogs), 0.0% (0 of 66 dogs), 5.7% (4 of 69 dogs), 15.9% (10 of 63 dogs), 27% (17 of 63 dogs), and 53% (10 of 19 dogs), respectively. Irradiation of the bone marrow following ingestion of 5.6 x 10^4 to 133 x 10^4 Bq/day produced effects on the hematopoietic system, including myeloproliferative disorders; soft tissue carcinomas in tissues near the bone were also observed above control levels in these groups. Statistical analyses were not performed.

Chronic strontium-90 ingestion in miniature swine resulted in effects on the hematopoietic system (Clarke et al., 1972; NCRP, 1991). Experiments involving the ingestion of 0, 1, 5, 25, 125, 625, or 3100 Ci per day (0.0, 0.037 x 10^6, 0.185 x 10^6, 0.925 x 10^6, 4.62 x 10^6, 23.1 x 10^6, or 115 x 10^6 Bq/day) by 773 female miniature swine extending over three generations were conducted. Treatment for the P_1 generation was initiated at 9 months of age, but treatment in the second and third generations began in utero. Female offspring in the F_1 and F_2 generations were gradually raised to the treatment level of respective dams by 6 months of age. As noted in Subsect. 3.1.3.2, the parental generation and their offspring administered 115 x 10^6 Bq/day did not survive to tumor induction time. Bone sarcomas, primarily in the skull, occurred in the groups receiving 23.1 x 10^6 Bq/day and 4.62 x 10^6 Bq/day of the combined F_1 and F_2 generations but not in groups administered lower doses. The incidence in the group fed 4.62 x 10^6 Bq/day was 25%, but the incidence in the group fed 23.1 x 10^6 Bq/day was unclear due to deaths and discontinued feeding regimes. There appeared to be a slight increase in soft-tissue carcinomas in groups fed $\leq$4.62 x 10^6 Bq/day, but statistical analyses were not performed. The primary effects from administration of 4.62 x 10^6 Bq/day were pancytopenia, hematopoietic neoplasms and bone tumors; the mean survival time was 3.5 years. Administration of 0.037 x 10^6 Bq/day to 0.925 x 10^6 Bq/day resulted in a mean survival time of 10-11 years compared to 11 years in the control group; the primary effect was neutropenia.

4.2. INHALATION EXPOSURES

At 12 to 14 months of age, 66 beagle dogs (weight 10 kg) of both sexes were administered a single exposure of a $^{90}SrCl_2$ aerosol and observed over their lifespan (McClellan et al., 1973; data summarized in NCRP, 1991). Initial body burdens ranged from 3.59 x 10^4 to 703 x 10^4 Bq/kg and long-term retained burdens (bone burdens) ranged from 1 to 120 Ci/kg (0.036 x 10^6 to 4.4 x 10^6 Bq/kg). The primary effect among long-term survivors was an excess of bone tumors, occurring in 30 surviving dogs that received a long-term retained burden of approximately 1.0 x 10^6 Bq/kg or greater. Survival times in dogs with bone tumors ranged from 2.2 to 9.5 years post exposure, whereas those in the 0. 0.037, 0.125, and 0.185 Bq/kg dose groups survived 11 years (mean survival of the controls was estimated by the authors at >12 yr). Two myelomonocytic leukemias and three malignancies of tissues in the oral cavity and nasopharynx were also observed at long-term retained burdens of $\leq$1.3 x 10^6 Bq/kg.

4.3. OTHER ROUTES OF EXPOSURE

Forty male and female Rhesus monkeys aged 2 to 12 years and weighing 2.6 to 9.4 kg were administered a single injection of strontium-90 (form not given) at a level of 0.13 x 10^6 to 6.21 x 10^6 Bq (0.018 x 10^6 to 0.14 x 10^6 Bq/kg) (NCRP, 1991). Strontium retention was followed over a 20-year period. No biological effects attributable to strontium-90 administration were observed. No further details were available.

Seven adult monkeys were administered 1.85 x 10^6 or 3.7 x 10^6 of strontium-90 (form not given) by gavage in a single exposure (NCRP, 1991). Two monkeys developed bone sarcoma, one occurring at 36 months (chondrosarcoma) and one occurring at 45 months (osteosarcoma) after administration. For the animal dying at 45 months with osteosarcoma, the skeletal dose at the start of tumor growth was calculated to be 25 Gy, and the skeletal dose at death was calculated to be 34 Gy.

Eighty-seven young adult beagle dogs, in groups of 12-14 animals, were administered a single intravenous injection of strontium-90 at activity levels of 0, 2.11 x 10^4, 6.36 x 10^4, 12.8 x 10^4, 40.0 x 10^4, 121 x 10^4, 235 x 10^4, or 362 x 10^4 Bq/kg (Mays and Finkel, 1980; revised dosimetry in NCRP, 1991). The control population consisted of 125 beagles of which 57 were sham injected. The most prominent effect in the treated animals was bone sarcoma (neoplasia of the soft tissues near bone in the oronasopharynx and paranasal sinuses). Bone marrow dysplasia was observed at lower but significant incidences ($p<0.05$). Bone sarcomas were not observed in animals receiving doses of 12.8 x 10^4 Bq or lower (average skeletal dose one year before death of 6 Gy or lower). Incidences in the 40.0 x 10^4, 121 x 10^4, 235 x 10^4, and 365 x 10^4 dose groups were 8.3, 16.7, 66.7, and 57.1%, respectively; absorbed doses were estimated by the authors to be 21.7, 60.2, 71.4, and 85.2 Gy, respectively. Blood dysplasia was observed in 5 dogs in the four highest dose groups; malignant soft tissue tumors were observed in the three highest dose groups. Soft-tissue neoplasia was observed at lower doses. Average times to death were shortened in the three highest dose groups, 10, 5.8, and 3.4 years, respectively, compared with an average life span in the control group of 11.5 years. The average times to death in the four lower dose groups ranged from 11 to 13 years.

Groups of male and female CBA mice were administered a single intraperitoneal injection of 0.8 Ci (3 x 10^4 Bq) (males) or 0.4 Ci (1.5 x 10^4 Bq) (females) strontium-90 in the form of $^{90}Sr(NO_3)_2$ (Nilsson and Ronnback, 1973). Bone tumors were recorded but not classified histologically. Among male mice that survived to development of the first tumor, there was a mean number of 2.3 bone tumors per mouse with a mean induction time of 316 days. Tumor incidence in males was 88% (99/113 animals). Among female mice that survived to the development of the first tumor, there was a mean number of 2.0 bone tumors per mouse with a mean induction time of 379 days. Tumor incidence in females was 80% (75/94

animals). Treatment with estrogenic hormones increased the incidence of bone tumors in both male and female mice. No tumors were present in mice treated with only estrogen.

4.4. EPA WEIGHT-OF-EVIDENCE

The EPA classifies all radionuclides as Group A carcinogens based on their property of emitting ionizing radiation and on the weight of evidence provided by epidemiological studies of radiation-induced tumors in humans (EPA, 1994).

The EPA has set the National Interim Primary Drinking Water Regulations for radioactivity due to beta particle and photon emitters in community water systems at 4 mrem/year (56FR 33050; July 18, 1991).

4.5. CARCINOGENICITY SLOPE FACTORS

The EPA (1994) has calculated slope factors for strontium-90 for lifetime excess total cancer risk per unit intake of exposure for ingestion, inhalation, and external exposure:

Ingestion (risk/Bq): 8.9E-10

Inhalation (risk/Bq): 1.5E-09

External exposure (risk/yr per Bq/g soil): 0.0E+00

The combined slope factors (risk) from strontium-90 plus its decay product, yttrium-90, have also been calculated:

Ingestion (risk/Bq): 9.7E-10

Inhalation (risk/Bq): 1.7E-09

External exposure (risk/yr per Bq/g soil): 0.0E+00

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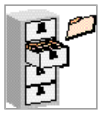
1. A Curie is defined as 3.7×10^{10} nuclear disintegrations per second; 1 Ci = 3.7×10^{10} Bq. A Bequerel is defined as one nuclear disintegration per second; 1 Bq = 2.7×10^{-11} Ci or 27 pCi.

2. A radiation absorbed dose of one Gray = 100 rad; a dose equivalent of one Sievert = 100 rem.  **Retrieve Toxicity Profiles**  **Condensed Version**

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