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Evaluation of Skin and Ingestion Exposure Pathways

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FOREWORD

After a nuclear accident when there has been a release of radionuclides into the atmosphere with consequential deposition on the ground, decisions are necessary on whether protective action guides should be implemented. In order to do this, several pathways for radiation exposure must be evaluated to determine the projected dose to individuals.

The objective of this study, conducted by Pacific Northwest Laboratories for the U.S. Environmental Protection Agency, is to provide background information on exposure pathways for use in the development of Protective Action Guides. The relative importance of three exposure pathways that are usually considered to be unimportant compared to other pathways expected to control relocation decisions following a nuclear power plant accident is evaluated. The three pathways are the skin dose from contact with radionuclides transferred from the ground, the skin dose from radionuclides on the ground surface, and ingestion of radionuclides transferred directly to the mouth from the hands or other contaminated surfaces. Ingestion of contaminated food is not included in this evaluation, except for situations where the food is contaminated as a result of actions by the person who consumes the food (e.g., transfer of contamination from hands to food).

Estimates of skin and ingestion doses are based on a source term with a radionuclide mix predicted for an SST2-type nuclear accident in an area where the first year reference whole-body dose equivalent from whole body external exposure to gamma radiation plus the committed effective dose equivalent from inhalation of resuspended radionuclides is 1 rem.

Appendixes have been included to allow the reader to examine dose factor calculations, source-term data, and quantification of contact and ingestion parameters in more detail.

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EVALUATION OF SKIN AND INGESTION EXPOSURE PATHWAYS

1. INTRODUCTION

Proposed Protective Action Guides (PAGs) for relocation are based on the whole-body dose equivalent from 1-yr external exposure to gamma radiation plus the committed effective dose equivalent from inhalation of resuspended airborne radioactive materials. The guides also include dose equivalent limits to the skin from 1-yr beta exposure. This study was conducted by Pacific Northwest Laboratory (PNL) for the U.S. Environmental Protection Agency (EPA) to determine the relative importance of three additional exposure pathways that are usually considered to be unimportant compared to other pathways expected to control relocation decisions following a nuclear power plant accident. The dose equivalent from each of the following exposure pathways was evaluated and compared with the total dose from the external gamma and inhalation exposure pathways:

Contact - from beta-emitting radionuclides transferred from the ground to the skin;

Surface (external) - from the beta emitters deposited on the ground; and

Ingestion - from the ingestion of radionuclides transferred directly to the mouth from the hands or other contaminated surfaces. Ingestion of contaminated food is not included in this study.

The dose calculations are based on the assumption of no protective actions beyond normal bathing, clothing, and partial occupancy in low or noncontaminated areas.

2. SUMMARY

The estimated dose equivalent to the skin from beta radiation and the committed effective dose equivalent from ingestion for the maximally exposed individual are given in Table 1. The estimated dose to the skin includes contributions from both contact and external sources; the committed effective dose equivalent from ingestion results from transfer of hand contamination to the mouth.

The doses in Table 1 are from the first-year exposure following an SST2-type reactor accident (Aldrich et al. 1983) of an individual who resides where the projected effective dose from external gamma radiation plus the committed effective dose from inhalation of resuspended materials is 1 rem[1]. That is, the doses are based on concentrations of radionuclides deposited per unit area on the ground that would yield a reference whole-body dose rate of 1 rem from first-year exposure, as calculated with the CRAC2 computer code (Ritchie et al. 1984). A first-year average source term, calculated with the radioactive decay and the weathering functions from WASH-1400, is used in CRAC2. For this study, the contamination layer is assumed to be incorporated in a 1-mm-thick surface layer of soil, or a 0.1-mm-thick layer of dust associated with a paved surface.

Contact and surface (external) beta doses are computed as rem to radiosensitive tissues at a depth of 70 μm (ICRP 1977). This depth was selected to correspond to assumptions used in calculation of doses supporting the selection of PAGs for skin.

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1 The integrated dose considering radioactive decay and weathering according to the WASH-1400 model (using the CRAC2 computer code) normalized to 1 rem for the first-year exposure is herein referred to as the "reference whole-body dose." Gamma exposure dominates this dose.

TABLE 1. Dose for the First-Year Exposure to Maximally Exposed(a) Individuals Residing in the 1-REM/Year "Reference Whole-Body Dose" Zone Following an SST2-Type Reactor Accident

Individual	Exposure Pathway	First-Year Dose (rem)(b)	
		Soil	Pavement(c)
Adult			
	Contact (skin) (d)	0.7	6.7
	Surface (skin) (e)	1.7	1.7
	TOTAL SKIN	2.4	8.4
	Ingestion (e)	0.01	0.1
Child			
	Contact (skin)	0.7	6.7
	Surface (skin)	7.4	7.4
	TOTAL SKIN	8.1	14
	Ingestion	0.05	0.5

(a) See Table 2 for average individuals.

(b) Skin dose is expressed as dose equivalent from the first-year exposure and ingestion dose is expressed as the 50-yr committed effective dose equivalent from the first-year exposure.

(c) Surface mixing: 1 mm for soil (160 mg/cm^2), 0.1 mm for pavement (16 mg/cm^2) .

(d) Contact assumed: contamination residing on the skin 4380 h/yr equivalent to 1.8 mg/cm^2, or 1.1 percent of ground concentration for soil, 11 percent of ground concentration for pavement.

(e) External (surface) dose based on 4380 h/yr at elevations of 1 m for adults and 30 cm for children.

(f) Based on ingestion of 100 mg/d for the adults; 500 mg/d for children.

2.1 CONTACT PATHWAY DOSE

Skin contact doses in Table 1 were calculated for maximally exposed individuals who spend much time outdoors, work in soil, and bathe infrequently. The critical group includes children playing in a yard or playground. Contact doses depend on the deposition of contaminated materials on the skin and duration of exposure to the skin, which in turn depends on bathing practices. The maximally exposed individual is assumed to have a dirt layer of 1.8 mg/cm^2 on the skin (1 to 11 percent of the ground surface concentration). This is based on a 50-μm layer of dust or dirt on the skin (Hawley 1985). Dose factors for contact doses are based on a skin depth of 70 μm.

For a given concentration of contaminants on the skin, the dose that is calculated is the same regardless of whether a large or small area is exposed. Although the skin is considered an organ, the dose to the skin is not averaged over the entire skin. The dose of interest is to the particular area of skin that receives irradiation from direct contact with contamination. The dose is calculated to unclothed skin only because this reflects the maximum dose rate. Contamination is assumed to be in contact with the skin for 4380 h (from cycles of contamination, bathing, and recontamination) for the first year after deposition of contaminants.

2.2 SURFACE PATHWAY

Doses resulting from the exposure of ground-deposited beta emitters are dependent on the amount of time the individual spends outdoors in a contaminated area. The maximally exposed individual is assumed to spend 8 h/d outdoors in the contaminated area. The first-year dose to the skin from external exposure to beta emitters 1 m above the contaminated ground is conservatively calculated to be 0.7 rem/yr, based on CRAC2 weathering, which is very conservative for beta exposure. The dose factors for external exposure are based on a skin depth of 70 μm, as are contact dose factors.

Dose factors at different distances are highly dependent on the beta spectra. A reference height of 30 cm above contaminated ground is used to estimate the potential dose to children. For the mix of radionuclides in the SST2 source term, the dose at 30 cm would be approximately four times greater than that at 1 m. The first-year beta dose at 30 cm corresponds to about 2 to 3 rem to the skin with no credit for shielding provided by clothing.

2.3 INGESTION PATHWAY

Ingestion doses evaluated here are only those resulting from exposure to contaminated surfaces and from poor hand-washing practices. For the ingestion pathway, the maximally exposed individual is a person with contamination on the hands who does not wash his/ her hands before eating. The critical group includes children playing outdoors and then not washing their hands before eating, or small children who put their hands or other objects in their mouths while playing in a contaminated area. The ingestion pathway may potentially be a significant route. The effective dose equivalent from the first-year intake by the maximally exposed child may equal the 1 rem/yr of the reference whole-body dose.

Maximally exposed adults include individuals who engage in frequent hand-to-mouth activity (smokers) and also engage in outdoor activities, such as construction workers or gardeners.

3. METHODS AND ASSUMPTIONS

3.1 SST2 SOURCE TERM

The source term used for this task is based on the initial mix of radionuclides predicted for an SST2-type reactor accident in sufficient quantity to produce a 1-rem first-year reference whole-body dose. In-growth of daughters as well as physical decay and weathering corrections are applied to the source term to yield first-year average radionuclide concentrations on surfaces. Doses from individual radionuclides are calculated and summed.

3.1.1 Source-Term Averaging

The first-year average ground concentration (C_i) for each radionuclide is determined as follows:

$$C_i = C_{oi} \frac{(1 - e^{-\lambda_i t})}{\lambda_i t}$$

where C_o = initial ground concentration (Ci/m^2) of each radionuclide

i = individual radionuclide

λ = effective decay constant (yr^{-1})
(ln 2/physical half-life) + (ln 2/weathering half-time)

t = time period (1 yr).

The contribution from daughter nuclides using simple decay chains is calculated as follows:

$$C_i' = C_i + C_j \left(\frac{(1 - e^{-\lambda_j t})}{\lambda_j t} - \frac{(1 - e^{-\lambda_i t})}{\lambda_i t} \right) \left(\frac{\lambda_i}{\lambda_i - \lambda_j} \right)$$

where C_i' = average ground concentration of daughter radionuclide i, including contribution from parent radionuclide j

C_j = initial concentration for the parent radionuclide

λ_i = decay constant of radionuclide i.

Source-term and chain-decay data used in the calculations are given in Appendix B, Source-Term Data.

The value of C_o is equal to the surface concentration of nuclides comprising the SST2 source term whose sum produces a 1-rem/yr reference whole-body dose from the gamma exposure pathway, plus the inhalation exposure pathway, as calculated with the CRAC2 computer code (Ritchie et al. 1984). The reference dose is mostly from external exposure to gamma-emitting radionuclides that are on the ground; inhalation contributes only a small fraction of the total. The relative quantity of each isotopeused to calculate skin and ingestion doses is directly proportional to the SST2 particulate material source term.

3.1.2 Weathering

The skin and ingestion doses are evaluated using the weathering model from WASH-1400 (USNRC 1975) that is used in the CRAC2 computer code (Ritchie et al. 1984). The basis for this weathering model is gamma dose rates from soils with ^{137}Cs contamination distributed on the surface. Weathering of paved areas such as sidewalks, driveways, and streets may be described by the WASH-1400 model; the model has been confirmed to some degree by field studies (Warming 1982, 1984).

This weathering model introduces extra conservatism into the calculation of beta dose rates. Dispersion of gamma emitters into a thin layer of soil would have a negligible effect on external exposure from gamma radiation, but it would serve as a barrier to beta emitters. For example, the range of a beta particle with a maximum energy of 1 MeV is about 3 mm in soil, indicating that most of the beta energy will be attenuated by a soil cover of a few millimeters. The dose rate from gamma radiation, however, is attenuated to 10 percent of its original value only with a thickness of about 30 cm of soil, or 100 times the range of a 1 MeV beta particle.

Assumptions concerning mixing of the surface layer, which are related to weathering, lead to important consequences in the calculation of contact doses. There is an effective 1600-fold concentration difference between contamination existing in surface dust layer of 10 g/m^2 and contamination dispersed in the top 1 cm of soil. Contamination that is not at the surface would still be available for direct skin contact during gardening or field work, but at a concentration that has been reduced by dilution with soil. For this study, the contamination layer is assumed to be incorporated in a 1-mm-thick (1600 g/m^2) surface layer of soil, or a 0.1-mm-thick (160 g/m^2) layer of dust associated with a paved surface. The conversion from mass to area is discussed in Appendix C.

Since leaching with rainwater could make a large difference in surface concentrations of contaminants, the WASH-1400 weathering model applied to beta emitters may best describe the surface conditions in a relatively dry, unirrigated area. In the studies by Warming, precipitation was sufficient to produce runoff only 3 percent of the time in which precipitation occurred. The dose reduction due to weathering could be greater in areas with heavier precipitation.

Experimental evidence shows that hosing of paved surfaces such as sidewalks, driveways, and streets decreases the (gamma) dose rate by only 15 to 25 percent (Warming 1982, 1984). In these experiments, old asphalt surfaces showed no significant weathering. It may be extremely conservative to apply dose rates based on gamma emitters to contact beta dose or ingestion because experiments show a marked decrease with time for the ability to decontaminate (transfer contamination from) these surfaces.

3.2 DOSE FACTORS

Dose factors for skin contact found in the literature included photons and electrons, and were not in the form required for this report. Therefore, contact dose factors were developed for this task. Dose factors for external exposure from beta radiation at 1 m were taken from the literature (Kocher 1981b). VARSKIN, a PNL-developed computer code (Traub et al. 1987), was used to estimate the ratio of dose factors at different distances above the ground and to provide factors for calculating doses at 30 cm above contaminated ground (see Appendix A for dose-factor data). Skin dose is expressed as dose equivalent, and ingestion dose is expressed as committed effective dose equivalent. The exposure period for both is one year. Dose factors for ingestion are based on ICRP 26 and ICRP 30 models (ICRP 1977, 1979).

3.2.1 Skin Contact

Radioactive material deposited directly on body surfaces is considered to be on an infinite, thin plane. This is valid for very thin, curved surface with a radius of curvature greater than the maximum beta-particle range. Skin contact dose factors for a skin thickness of 70 μm were computed using the Loevinger, Japha, and Brownell (1956) solution to the thin-plane problem. The dose equation was solved for each beta and electron energy level or group in the spectrum for each radionuclide of interest. Healy (1971) used the same formula to calculate allowable contamination levels, but used only the principal beta energies and included photon dose in the results. Considering these differences our calculated dose factors compared reasonably well with those by Healy.

Beta and electron spectra used in computations are those given by Kocher (1981a). A low-energy cutoff of 100 keV (maximum energy) for beta particles and 60 keV for electrons was assumed. Mono-energetic electrons were treated as betas for this analysis. Additional information, including equations and beta spectrum data used in SKINDOSE (developed for this study) to calculate the dose factors, is given in Appendix A.

3.2.2 <u>External</u>

External dose equivalent to skin from nearby beta radiation sources was calculated for radiosensitive tissue at a single depth of 70 μm (ICRP 1977). Dose factors are from Kocher (1981b), and estimates of dose factors based on distance of 1 ft above a surface are given in Appendix A, Table A.2.

3.2.3 <u>Ingestion</u>

Committed effective dose equivalents for ingestion are based on the concepts of ICRP 26 and ICRP 30 (USEPA 1988). The dose factors for ingestion are presented in Appendix A, Table A.1. Where two values of dose factors (committed effective dose equivalent) based on solubility were presented, the larger value was used in this analysis.

3.3 EXPOSURE ASSUMPTIONS

Dispersion of contaminants in soil and transfer of contaminants to skin and to the mouth are key parts of dose estimation.

3.3.1 Skin Contact

The dose resulting from contamination on the skin is a function of the concentration and duration of contaminants on skin. The concentration of contamination on the skin is estimated based on concentration of contaminants present on the ground over the first year after contamination and the amount of dust or dirt residing on the skin. For this study, the contamination layer is assumed to be incorporated in a surface layer of soil 1 mm thick (1600 g/m^2) or a layer of dust 0.1 mm thick (160 g/m^2) associated with a paved surface. Justification for the mixing layers is provided in Appendix C.

The maximally exposed individual is assumed to have a dirt layer of 1.8 mg/cm^2 on the skin (1 to 11 percent of the thickness of the contaminant ground layer). The average individual is assumed to have 1.0 mg of contaminated dust per cm^2 of skin (0.6 to 6 percent of the thickness of the contaminated layer). These estimates are based on interpretations of experiments involving contamination on skin surfaces (Hawley 1985, Shaum 1984). Conversion from mass to area is discussed in Appendix C.

The transfer of contaminants to the skin is assumed to be proportional to the concentration of contaminants on the ground. Because the contamination on the ground is assumed to be mixed in a 160- to 1600-g/m^2 dust layer, a dirt loading on the skin of 16 to 160 mg/cm^2 would be required to be equivalent to 100 percent of the concentration present on the ground.

Although weathering is considered in the radionuclide source term, the weathering model is conservative for beta emitters. Although dilution of contaminants on the ground surface (mixing contamination into a thin layer of soil) would have negligible effects on external exposure from gamma emitters, it could decrease the dose from beta emitters by a significant amount.

Despite the fact that most contamination would be on the hands and arms, other areas of the body may also be affected (e.g., children with legs uncovered sitting on a contaminated surface). Skin contact also applies to surfaces of the feet. Although contact may be considerable for someone with bare feet, the skin of the feet is 5 to 10 times thicker than skin on other areas of the body (Whitton 1973). Thus, beta doses to sensitive tissues of the feet will be considerably less than that estimated using a 70-μm depth.

The dose equivalent for a maximally exposed individual is calculated using the assumption that the affected skin area is contaminated for 4380 h (half the number of hours in a year) in the year following the contamination event. The average individual is assumed to have contamination on a portion of the skin area for 800 h/yr. These time periods, which are assigned arbitrarily, include many recontamination events in the course of a year.

3.3.2 External

External exposure is based on the number of hours per year the individual is exposed to the contaminated surface (outdoors). Dose factors for external exposure of the skin (beta radiation only) are based on a height of 1 m above the contaminated surface[2] (Kocher 1981b). Dose factors are greater closer to the ground. Factors for 30 cm above a contaminated surface were estimated using VARSKIN (Traub et al. 1987). A ratio of dose factors (which depends on the energy of the particle) was calculated by representing 30 cm and 1 m of air, plus tissue thickness of 0.007 cm with the equivalent thickness of unit density. Dose factors from Kocher (1981b) were multiplied by this ratio to yield an estimate of dose factors at 30 cm. To be conservative, no credit was taken for the protection afforded by clothing.

The maximally exposed individual is assumed to be exposed to external beta radiation for 4380 h/yr. This is equivalent to an occupational exposure for someone who works outdoors in the

[2] One meter is the standard height given in dose factor tables. Dose factors from beta radiation are functions of height above the ground and beta energy. For a height of 1 m in air, the minimum electron energy giving a non-zero dose-rate factor is about 320 keV; at ground level (0.01 m) the cutoff is about 75 keV (Kocher 1981b).

contaminated area 12 h/d, year-round. An average individual is assumed to spend 2080 h/yr outdoors, or 40 h/wk. The exposure times for the maximally exposed and average child are assumed to be equivalent to those for adults.

3.3.3 Ingestion

Ingestion of radioactive surface contamination can occur when radiocontaminants are transferred to the mouth via hands or foodstuffs. Recent developments in estimating the ingestion of soil and dust (LaGoy 1987) are used to estimate doses to individuals. A discussion of assumptions involved in ingestion calculations is given in Appendix C.

Because the source term for this study is given in terms of curies per unit area, and previous studies involving radiocontaminants have used concentrations per unit mass, ingestion of contaminants and contact with contaminants are expressed in terms of surface area as well as unit mass. For assessment of contact and ingestion doses by mass rather than effective surface area, a conversion factor of 160 to 1600 g/m^2 is used to describe the extent of the contaminated layer. Relationships between mass and surface area contamination for this assumption are discussed in detail in Appendix C.

Individuals are assumed to ingest radiocontaminants proportional to that found on a given surface area. The amounts are based on ingestion of contaminated soil and are compared with results from methods that were developed for occupational exposure to radiocontaminants. Data from LaGoy (1987) suggest ingestion rates of 100 mg/d for maximally exposed adults and 25 mg/d for the average adult who does not participate in much outdoor activity and does not smoke. Ingestion rates for children are taken as 500 mg for the maximally exposed child and 100 mg/d for the average child. Since the units of the SST2 source term are in Ci/unit area, the ingestion quantity must be converted from grams per day. This conversion makes the source term units compatible with the units of ingestion. These ingestion rates are equivalent to the total contaminated dust from 1.5 to 6.25 cm^2/d (based on pavement dust) for adults and 6.25 to 31 cm^2/d for children (see Appendix C).

The rate at which contamination is picked up from surfaces and ingested, given by Dunster (1962) and Gibson and Wrixon (1979), is 10 cm^2/d for occupational exposure (8 h/d). For exposure to the public, this value is multiplied by 16/8 (to correct to 16 h/d of exposure) to yield 20 cm^2/d. These ingestion rates correspond reasonably well with mass ingestion rates from LaGoy (1987) based on a thin dust layer on a paved surface.

Children old enough to play outdoors, but young enough not to have acquired good personal hygiene practices, are the critical group because ingestion of contaminated soil is estimated to be higher than that for the maximally exposed (adult) individual. According to LaGoy (1987), the average child of 1 to 6 yrs of age may ingest 100 mg of dust or soil per day, and the maximally exposed child of that age (excluding those with habitual pica) may ingest 500 mg of dust per day. Age-specific dose factors are not used in this analysis and are beyond the scope of this report.

4. RESULTS

Dose equivalents, based on residency in an area within the 1-rem first-year reference whole-body dose zone for the maximally exposed and average individuals, are summarized in Table 2. The radionuclide source term for exposures is a first-year average concentration based on the WASH-1400 weathering model. The two columns in Table 2 correspond to exposures based on soil (contamination mixed with the top 1 mm of soil) and pavement (contamination mixed with the top 0.1 mm of surface dust).

Based on the assumed conditions, the ingestion of surface contamination is a potentially significant exposure pathway. For the maximally exposed individual, ingestion may account for up to 10 percent of the reference whole-body dose for an adult or 50 percent for a child. In order of importance, the major contributors to effective dose equivalent from ingestion during the first year include ^{137}Cs (33 percent), ^{134}Cs (31 percent), ^{132}Te – ^{132}I (6 percent), ^{131}I (8 percent), and ^{144}Ce (7 percent). For the SST2 source term, these isotopes account for about 85 percent of the ingestion dose equivalent.

Contact doses are for exposure to the skin and are not directly comparable to the reference whole-body dose. The isotopes ^{132}Te-^{132}I (28 percent), ^{137}Cs (15 percent), ^{144}Ce (14 percent), and ^{134}Cs (7 percent) account for the major part of the dose to skin by direct contact for the first year after SST2 contamination. Doses to the average individual (based on 1.0 mg/cm^2 on skin for 800 h) are about 10 percent of those for the maximally exposed individual. The average individual would also have a smaller portion of contaminated skin area.

Exposure to beta emitters at 1 m for adults or 30 cm for children above a contaminated surface accounts for a small increment to the total dose. The surface (external) beta dose is equal to about a tenth of the dose from direct contact for the maximally exposed adult but about twice the contact amount for the average child. Estimates of external exposure to beta radiation depend only on the number of hours spent outdoors and not on personal cleanliness or other factors. The estimates of external beta dose are conservative; actually clothing would provide some protection from beta radiation. To be conservative, no credit is taken for shielding provided by clothing. The dominant contributor to external beta dose at 1 m is ^{132}I (daughter of ^{132}Te), which accounts for about 55 percent of the dose. Other contributors to external dose are ^{91}Y (17 percent) and ^{129M}Te (9 percent). The dose estimated at 30 cm is dominated by ^{132}I (39 percent), ^{134}Cs (17 percent), ^{91}Y(10 percent), and ^{127}Te (9 percent). A larger proportion of the dose is from radionuclides with softer betas.

5. DISCUSSION

Table 2 shows that dose equivalent to skin from beta emitters and committed effective dose equivalent from ingestion via contaminated hands may be significant compared with inhalation dose plus external dose from gamma radiation.

The contact dose is closely related to weathering of the surface layer of contaminants. Assumptions related to weathering have important consequences in the calculation of contact doses. An effective 1600-fold

TABLE 2. Dose for the Maximum and Average Individual Residing in the 1 REM/Year "Reference Whole-Body Dose" Zone Following an SST2-Type Reactor Accident

Individual	Exposure Pathway	First-Year Dose (rem)(a) Soil	Pavement(b)
Maximum Adult	Contact (skin) (c)	0.7	6.7
	Surface (skin) (d)	1.7	1.7
	TOTAL SKIN	2.4	8.4
	Ingestion (e)	0.01	0.1
Average Adult	Contact (skin) (c)	0.06	0.6
	Surface (skin) (d)	0.7	0.7
	TOTAL SKIN	0.8	1.3
	Ingestion (e)	0.002	0.02
Maximum Child	Contact (skin)(c)	0.7	6.7
	Surface (at 30 cm)(d)	7.4	7.4
	TOTAL SKIN	8.1	14
	Ingestion(e)	0.05	0.5
Average Child	Contact (skin)(c)	0.06	0.6
	Surface (at 30 cm)(d)	3.2	3.2
	TOTAL SKIN	3.3	3.8
	Ingestion (e)	0.01	0.1

(a) Skin dose is expressed as dose equivalent from the first-year exposure and ingestion dose is expressed as the 50-yr committed effective dose equivalent from the first-year exposure.

(b) Surface mixing: 1 mm for soil (160 mg/cm^2), 0.1 mm for pavement (16 mg/cm^2).

(c) Contact assumed: contamination residing on the skin 4380 h/yr equivalent to 1.8 mg/cm^2, for maximally exposed, 800 h/yr and 1.0 mg/cm^2 for average individuals.

(d) External (surface) dose based on 4380 h/yr for maximally exposed, 2080 for average individuals. 1 m for adult, and 30 cm for child.

(e) Based on ingestion of 100 mg/d for the maximally exposed adult, 25 mg/d for average adult; 500 mg/d for the maximally exposed child, 100 mg/d for average child.

concentration difference between contamination in the surface dust layer of 10 g/m^2 and contamination dispersed in the top 1 cm of soil exist). For this study, the contamination layer is assumed to be incorporated in a 100 g/m^2 surface layer of dust and soil. (Conversion from mass to area is discussed in Appendix C).

A depth of 70 μm is used for the calculation of skin dose (for both contact and external components) to correspond to assumptions used in dose calculations supporting the selection of PAGs for skin. A value of 40 μm has been suggested as the appropriate depth of the radiosensitive layer of skin (Whitton 1973). The use of dose factors calculated at the 40-μm depth would increase the resulting dose by about 40 percent. Although the skin of the hands is likely to come in contact with surface contamination, the skin thickness is greater, reducing the potential damage to the sensitive layer.

Absorption of contaminants through the skin is another potential pathway for internal exposure. A study of radioiodine determined an absorption rate for iodine through skin of 0.008 percent h/cm^2 (Harrison 1963). For the maximally exposed individual, assuming 3000 cm^2 of skin is contaminated for 3000 h, this would correspond to about 3.5 percent of the intake of iodine by ingestion of contaminants transferred from contaminated surfaces. This includes the assumption that the particulate iodine in the contaminants are absorbed as well as the aqueous solution used in the experimental procedure. A matrix of soil rather than solvent can affect the absorption by skin; experiments using TCDD (dioxin) showed that the soil matrix reduced the amount absorbed by 85 percent (Hawley 1985). The soil matrix may have a similar effect on absorption of iodine.

Many variables may affect doses to residents of a contaminated area. In some areas, the time of year an accident occurs could have a large effect. For example, residents are much more likely to come in contact with dirt in spring or summer. Also, the mix of radionuclides will change with time as the short-lived radionuclides decay.

Assumptions about the transfer from surfaces to skin and the residence time on skin are somewhat arbitrary and might be modified if additional data become available in the future.

REFERENCES

ALDRICH, D. C., J. L. Sprung, D. J. Alpert, K. Diegert, R. M. Ostmeyer, L. T. Ritchie, and D. R. Strip. Technical Guidance for Siting Criteria Development. NUREG/CR-2239, SAND81-1549, prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Washington, DC, 1983.

DUNSTER, H. J. Maximum Permissible Levels of Skin Contamination. AHSB(RP)R28, United Kingdom Atomic Energy Authority, Authority Health and Safety Branch Report, Harwell, Didcot, Berkshire, England, 1962.

GIBSON, J. A. B., and A. D. Wrixon. "Methods for the Calculation of Derived Working Limits for Surface Contamination by Low-Toxicity Radionuclides." Health Physics 36(3):311-321, 1979.

HARRISON, J. "The Fate of Radioiodine Applied to Human Skin." Health Physics 9:993-1000, 1963.

HAWLEY, J. K. "Assessment of Health Risk from Exposure to Contaminated Soil." Risk Analysis 5(4):289-302, 1985.

HEALY, J. W. Surface Contamination: Decision Levels. LA-4558-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 1971.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP). Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Pergamon Press, New York, 1977.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP). Limits for Intakes of Radionuclides by Workers, ICRP Publication 30, Pergamon Press, New York, 1979.

KOCHER, D. C. Radioactive Decay Data Tables. DOE/TIC-11026, U.S. Department of Energy, Washington, DC, 1981a.

KOCHER, D. C. Dose-Rate Conversion Factors for External Exposure to Photons and Electrons. NUREG/CR-1918, prepared by Oak Ridge National Laboratory for the U.S. Nuclear Regulatory Commission, Washington, DC, 1981b.

LAGOY, P. K. "Estimated Soil Ingestion Rates for Use in Risk Assessment". Risk Analysis 7(3):355-359, 1987.

LOEVINGER, R., E. M. Japha, and G. L. Brownell. "Discrete Radioisotopes Sources," Chapter 16. In Radiation Dosimetry, eds. G. H. Hine and G. L. Brownell, pp. 693-799, Academic Press, Inc., New York, 1956.

RITCHIE, L. T., D. J. Alpert, R. P. Burke, J. D. Johnson, R. M. Ostmeyer, D. C. Aldrich, and R. M. Blond. CRAC2 Model Description. NUREG/CR-2552, SAND82-0342, prepared by Sandia National Laboratories, Albuquerque, New Mexico and Livermore, California for the U.S. Nuclear Regulatory Commission, Washington, DC, 1984.

SCHAUM, T. Risk Analysis of TcDD Contaminated Soil. Prepared for EPA Office of Health and Environmental Assessment, Washington, DC, 1984.

TRAUB, R. J., W. D. Reece, R. I. Scherpelz, and L. A. Sigalla. Dose Calculation for Contamination of the Skin Using the Computer Code VARSKIN. NUREG/CR-4418, PNL-5610. prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, Washington, DC, 1987.

U.S. ENVIRONMENTAL PROTECTION AGENCY. Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion. EPA-520/1-88-020. U.S. Environmental Protection Agency, Office of Radiation Programs, 1988.

U.S. NUCLEAR REGULATORY COMMISSION. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. Appendix G: Calculation of Reactor Accident Consequences. WASH-1400 (NUREG 75/014). U.S. Nuclear Regulatory Commission, Office of Nuclear Research, Washington, D.C. 1975.

WARMING, L. Weathering and Decontamination of Radioactivity Deposited on Asphalt Surfaces. RISO-M-2273, Riso National Laboratory, DK-4000 Roskilde, Denmark, 1982.

WARMING, L. Weathering and Decontamination of Radioactivity Deposited on Concrete Surfaces. RISO-M-2473, Riso National Laboratory, DK-4000, Roskilde, Denmark, 1984.

WHITTON, J. T. "New Values for Epidermal Thickness and Their Importance." Health Physics 24:1-8, 1973.

APPENDIX A

DOSE FACTOR CALCULATIONS AND DATA

A.1 COMPUTATION OF SKIN DOSE FACTORS

Skin contact dose factors were calculated with the computer code SKINDOSE, developed for this task. An equation presented by Loevinger, Japha, and Brownell (1956) was used to estimate doses resulting from radioactive materials deposited directly on body surfaces. The equation is a function of the distance from a thin-plane source:

$$D(x) = (1.07)\nu(E_{avg})\alpha\sigma\{c[(1 + \ln(c/\nu x) - e^{(1 - \nu x/c)}] + e^{(1 - \nu x)}\}$$

given $[\ ] \equiv 0$ for $x \geq c/\nu$,

where $D(x)$ = dose rate (rad/h) at distance x (gm/cm^2)

ν = beta absorption coefficient (cm^2/g)

E_{avg} = average beta energy (MeV)

σ = surface activity ($\mu Ci/cm^2$)

α and c = functions of the maximum beta energy (E_{max}):

E_{max} (MeV)	α	c
0.17 – 0.5	0.260	2.0
0.5 – 1.5	0.297	1.5
1.5 – 3.0	0.333	1.0

Skin depth x is assumed to be 70 μm which equates to 7.8 E-3 gm/cm^2 for a skin density of 1.12 gm/cm^3. The equation is solved for D(x) for unit activity for each radionuclide of interest. The dose factor for a radionuclide is calculated from individual beta and electron energy levels of its beta spectrum weighted by frequency of occurrence. Dose factors for the components of the spectrum are summed giving a dose factor for the radionuclide.

A depth of 70 μm is used to calculate skin dose (for both contact and external components) to correspond to assumptions used in dose calculations supporting the selection of PAGs for skin. The use of a different depth would change the dose factors.

Beta energy levels and some electron energies are grouped to simplify calculations. Low-energy cutoffs were made for electrons that cannot penetrate through 70 μm of skin. In addition, contributions from short-lived (one hr or less) daughter decay products are included in dose factors for the parent radionuclides.

Dose conversion factors for each of the isotopes in the source term are given in Table A.1. This table gives dose factors for skin contact, external exposure (from 1 m and 30 cm; beta only), and ingestion. Dose factors for skin contact are from SKINDOSE, for external exposure at 1 m are from Kocher (1981b), and for external exposure at 30 cm are calculated using VARSKIN. The ingestion dose based on ICRP models is the 50-yr committed effective dose equivalent per unit of activity ingested (USEPA 1988).

A.2 BETA SPECTRA

The beta spectrum of a radionuclide may have many components. Each beta has two parameter energies, average (E_{avg}) and maximum (E_{max}), and a frequency (intensity) associated with this mode of decay. The two characteristic energies, E_{avg} and E_{max}, are used in calculating dose factors from beta spectra. Conversion and Auger electrons, however, have one characteristic energy rather than a range. To use the same techniques for calculating dose factors, average and maximum energies are

TABLE A.1. Summary of Dose Conversion Factors for Skin Contact, External Exposure to Beta and Electron Radiation and for Ingestion

Nuclide	DOSE FACTORS[(a)] Contact, rem/μCi per cm²/h	External, rem/μCi/m²/yr at 1 m	External, rem/μCi/m²/yr at 30 cm	Ingestion, rem/μCi ingestion
^{58}Co	1.20E+00	3.5E-04	8.76E-04	3.6E-03
^{60}Co	4.30E+00	0E+00	0E+00	2.7E-02
^{86}Rb	8.30E+00	8.99E-01	2.25E+00	9.4E-03
^{89}Sr	9.40E+00	7.88E-01	2.1E+00	9.3E-03
^{90}Sr	7.20E+00	1.61E-02	4.03E-02	1.4E-01
^{90}Y	8.50E+00	1.24E+00	3.11E+00	1.1E-02
^{91}Y	8.20E+00	8.21E-01	2.09E+00	9.5E-03
^{95}Zr	5.10E+00	2.54E-03	6.35E-03	3.8E-03
^{95}Nb	8.40E-01	1.75E-03	4.37E-03	2.6E-03
^{99}Mo	8.30E+00	4.18E-01	1.05E+00	5.0E-03
^{99M}Tc	5.80E-01	5.62E-04	1.41E-03	6.2E-05
^{103}Ru	2.60E+00	4.4E-03	1.1E-02	3.0E-03
^{106}Ru	8.50E+00	0E+00	0E+00	2.7E-02
^{105}Rh	5.60E+00	9.58E-03	2.4E-02	1.5E-03
^{127}Sb	7.80E+00	2.34E-01	1.37E+00	6.7E-03
^{127}Te	7.00E+00	6.03E-02	4.16E+00	6.9E-04
^{127M}Te	2.20E+00	2.14E-03	5.36E-03	8.3E-03
^{129}Te	9.20E+00	6.59E-01	1.93E+00	2.0E-04
^{129M}Te	5.30E+00	2.83E-01	7.2E-01	1.1E-02
^{131M}Te	7.60E+00	5.77E-02	1.44E-01	9.1E-03
^{132}Te	3.00E+00	0E+00	0E+00	9.4E-03
^{131}I	9.40E+00	2.13E-02	1.47E+00	5.3E-02
^{132}I	8.10E+00	5.59E-01	1.69E+00	6.7E-04
^{134}Cs	5.00E+00	3.81E-02	9.53E-02	7.3E-02
^{136}Cs	5.40E+00	6.25E-03	1.56E-02	1.1E-02
^{137}Cs	6.90E+00	2.75E-02	6.86E-02	5.0E-02
^{140}Ba	7.40E+00	1.98E-01	4.96E-01	9.5E-03
^{140}La	8.60E+00	6.59E-01	1.94E+00	8.4E-03
^{141}Ce	6.80E+00	4.55E-03	1.14E-02	2.9E-03
^{143}Ce	8.40E+00	4.33E-01	1.08E+00	4.6E-03
^{144}Ce	1.20E+01	0E+00	0E+00	2.1E-02
^{143}Pr	7.80E+00	2.33E-01	1.47E+00	4.7E-03
^{147}Nd	7.20E+00	1.05E-01	2.64E-01	4.4E-03
^{239}Np	8.70E+00	2.52E-03	6.3E-03	3.3E-03
^{238}Pu	0E+00	0E+00	0E+00	3.2E+00
^{239}Pu	0E+00	0E+00	0E+00	3.5E+00
^{240}Pu	0E+00	0E+00	0E+00	3.5E+00
^{241}Pu	0E+00	0E+00	0E+00	6.8E-02
^{241}Am	2.10E-01	0E+00	0E+00	3.6E+00
^{242}Cm	0E+00	0E+00	0E+00	1.1E-01
^{244}Cm	0E+00	0E+00	0E+00	2.0E+00

(a) The contact dose factor is for beta emitters residing directly on the skin; the external dose factor is based on irradiation from contaminated ground. Both are based on dose at a 70-μm skin depth. The ingestion dose factor is based on ICRP dosimetry.

hypothesized. Beta and electron spectra used in the computations were from Kocher (1981a). A low-energy cutoff of 100 keV (E_{max}) for beta particles and 60 keV for electrons was used. Mono-energetic electrons are treated as betas for this assessment. Some energy levels are grouped for simplicity. An example of how data from Kocher for ^{127}Sb is interpreted for determining skin dose factors is given in Table A.2.

Mono-energetic electrons were assumed to behave as if they were beta particles, with a maximum energy (E_{max}) corresponding to that expected for a beta particle with the same average energy. This assumption led to reasonable results, based on comparisons of tabulated mean energy emitted per unit of accumulated activity (column 4 in Table A.2) in units of rad/h per μCi/g. Resulting dose factors from beta particles and electrons were compared with mean energy emitted. They correlated well.

Table A.2. Example Application Using Data for ^{127}SB From Kocher (1981a) as Input to Skindose

Radiation Type	Energy (keV)	Intensity (percent)	Delta (rad/hr per μCi/g)	SKINDOSE Input	
				Average	Maximum
Auger-L	3.19	3.9	0.0003	Below Threshold	
Auger-K	22.7	0.53	0.0003	Below Threshold	
ce-K- 1	22.29	3.47	0.0022		
ce-L- 1	56.16	0.45	0.0005		
ce-K- 6	220.6	0.43	0.0020	221	660
ce-K- 19	441.19	0.220	0.0021	441	1240
cd-K- 30	653.4	0.212	0.0017	653	1740
Beta-1	max 258 avg 72.7	0.110	0.0002	81	285
Beta-2	max 291 avg 82.9	0.610	0.0011		
Beta-3	max 425 avg 127.5	0.8	0.0022	130	435
Beta-4	max 441 avg 132.8	1.25	0.0035		
Beta-5	max 504 avg 155.1	5.22	0.0172	504	155.1
Beta-6	max 657 avg 211.1	1.25	0.0056	657	211.1

Kocher (1981b) assessed doses from mono-energetic electrons by a more rigorous method. The equation for mono-energetic sources included a term for the specific absorption fraction. The value of this quantity is evaluated by interpolation of tabulated values obtained using Monte Carlo techniques. For this analysis, the more rigorous approach was not required.

A.3 DOSE FACTORS FOR EXTERNAL EXPOSURE

Dose factors used for external exposure of skin to a depth of 70 μm from electrons (betas and electrons, as distinguished from photons) are from Kocher 1981b (given in $Sv/Bq/cm^2$). These factors are for 1 yr of chronic exposure of skin to beta emitters at 1 m above a contaminated surface and are given in Table A.1.

Dose factors for a distance of 30 cm above contaminated ground were estimated using VARSKIN (Traub et al. 1987). A ratio of dose factors was calculated by representing 30 cm and 1 m of air plus the tissue thickness of 0.007 cm by the equivalent thickness of unit density. Dose factors from Kocher (1981b) were multiplied by this ratio to yield an estimate of the dose factor 30 cm above contaminated ground.

The dose factors for the nuclides of interest averaged about four times greater at 30 cm than for 1 m above contaminated ground. These factors may be appropriate to assess external exposure from surface contamination to children. However, the potential dose from exposure to beta radiation from contaminated surfaces is less than the potential dose from the contact pathway.

A.4 DOSE FACTORS FOR INGESTION

Dose factors for ingestion are 50-yr effective committed dose following 1 yr of chronic uptake based on ICRP 26 and ICRP 30 models (USEPA 1988). Ingestion dose factors for radionuclides of interest, in units of rem/μCi ingested, are given in Table A.1. In cases where there were dose factors for different chemical forms, the larger factor was selected.

REFERENCES

KOCHER, D. C. Radioactive Decay Data Tables. DOE/TIC-11026, Technical Information Center, U.S. Department of Energy, Washington, DC, 1981a.

KOCHER, D. C. Dose-Rate Conversion Factors for External Exposure to Photons and Electrons. NUREG/CR-1918, prepared by the Oak Ridge National Laboratory for the U.S. Nuclear Regulatory Commission, Washington, DC, 1981b.

LOEVINGER, R., E. M. Japha, and G. L. Brownell. "Discrete Radio-isotope Sources," Chapter 16. In Radiation Dosimetry, eds. G. H. Hine and G. L. Brownell, pp. 693-799, Academic Press, Inc., New York, 1956.

TRAUB, R. J., W. D. Reece, R. I. Scherpelz, and L. A. Sigalla. Dose Calculation for Contamination of the Skin Using the Computer Code VARSKIN. NUREG/CR-4418, PNL-5610, prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, Washington, DC, 1987.

U.S. ENVIRONMENTAL PROTECTION AGENCY. Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion. EPA-520/1-88-020. U.S. Environmental Protection Agency, Office of Radiation Programs, 1988.

APPENDIX B

SOURCE-TERM DATA

B.1 SST2 SOURCE TERM

The source term used for this report is based on the initial mix of radionuclides predicted for an SST2-type reactor accident in sufficient quantity to produce a 1-rem first-year reference whole-body dose.

In-growth of daughters as well as physical decay and weathering corrections are applied to the source term to yield first-year average radionuclide concentrations on the ground surfaces. Decay chains and the effect of weathering options are described in this appendix.

B.2 DECAY CHAINS

Table B.1 lists radionuclides in the source term and shows the parent radionuclides used in simple decay chain calculations.

B.3 WEATHERING

Average ground concentrations of radionuclides listed in Table B.2 are first-year average concentrations calculated with CRAC2 weathering (Ritchie et al. 1984), a two-step exponential weathering model from WASH-1400 (USNRC 1975).

TABLE B.1. Radionuclides and Decay Chains in SST2 Source Term

Nuclide	Half-Life, days	Parent
^{58}Co	7.130E+01	
^{60}Co	1.921E+03	
^{86}Rb	1.865E+01	
^{89}Sr	5.200E+01	
^{90}Sr	1.026E+04	
^{90}Y	2.670E+00	^{90}Sr
^{91}Y	5.880E+01	^{91}Sr
^{95}Zr	6.550E+01	
^{95}Nb	3.510E+01	^{95}Zr
^{99}Mo	2.751E+00	
^{99m}Tc	2.508E-01	^{99}Mo
^{103}Ru	3.959E+01	
^{106}Ru	3.690E+02	
^{105}Rh	1.479E+00	^{105}Ru
^{127}Sb	3.800E+00	
^{127}Te	3.896E-01	^{127}Sb
^{127m}Te	1.090E+02	
^{129}Te	4.861E-02	^{129}Sb
^{129m}Te	3.340E+01	
^{131m}Te	1.250E+00	
^{132}Te	3.250E+00	
^{131}I	8.040E+00	^{131m}Te
^{132}I	9.521E-02	^{132}Te
^{134}Cs	7.524E+02	
^{136}Cs	1.300E+01	
^{137}Cs	1.099E+04	
^{140}Ba	1.279E+01	
^{140}La	1.676E+00	^{140}Ba
^{141}Ce	3.253E+01	
^{143}Ce	1.375E+00	
^{144}Ce	2.844E+02	
^{143}Pr	1.358E+01	^{143}Ce
^{147}Nd	1.099E+01	
^{239}Np	2.350E+00	
^{242}Cm	1.630E+02	
^{238}Pu	3.251E+04	^{242}Cm
^{239}Pu	8.912E+06	^{239}Np
^{244}Cm	6.611E+03	
^{240}Pu	2.469E+06	^{244}Cm
^{241}Pu	5.333E+03	
^{241}Am	1.581E+05	^{241}Pu

TABLE B.2. Initial Deposition and First-Year Average Concentration Calculated with CRAC2 (WASH-1400) Weathering Model.

Nuclide	Initial, Ci/m^2	Average Concentration: Decay Only, Ci/m^2	Average Concentration: CRAC2, Ci/m^2
^{58}Co	1.4E-08	3.8E-09	3.2E-09
^{60}Co	1.0E-08	9.3E-09	7.0E-09
^{86}Rb	4.3E-08	3.2E-09	3.0E-09
^{89}Sr	6.5E-07	1.3E-07	1.2E-07
^{90}Sr	3.2E-08	3.1E-08	2.3E-08
^{90}Y	1.4E-07	3.3E-08	2.5E-08
^{91}Y	3.3E-06	7.6E-07	6.6E-07
^{95}Zr	4.3E-06	1.1E-06	9.5E-07
^{95}Nb	4.3E-06	1.7E-06	1.4E-06
^{99}Mo	2.1E-06	2.3E-08	2.2E-08
^{99M}Tc	2.0E-06	2.4E-08	2.4E-08
^{103}Ru	1.6E-06	2.6E-07	2.3E-07
^{106}Ru	3.7E-07	2.7E-07	2.0E-07
^{105}Rh	9.4E-07	6.0E-09	5.9E-09
^{127}Sb	1.7E-05	2.5E-07	2.5E-07
^{127}Te	1.7E-05	2.8E-07	2.8E-07
^{127M}Te	2.2E-06	8.5E-07	7.0E-07
^{129}Te	4.1E-05	3.1E-08	3.1E-08
^{129M}Te	7.8E-6	1.0E-06	9.5E-07
^{131M}Te	2.3E-05	1.1E-07	1.1E-07
^{132}Te	2.4E-04	3.1E-06	3.1E-06
^{131}I	1.7E-05	6.6E-07	6.4E-07
^{132}I	3.5E-05	3.1E-06	3.1E-06
^{134}Cs	2.6E-06	2.2E-06	1.7E-06
^{136}Cs	1.4E-06	7.4E-08	7.1E-08
^{137}Cs	3.6E-06	3.6E-06	2.7E-06
^{140}Ba	1.1E-06	5.3E-08	5.1E-08
^{140}La	4.3E-06	8.2E-08	7.9E-08
^{141}Ce	4.0E-06	5.2E-07	4.8E-07
^{143}Ce	3.6E-06	1.9E-08	1.9E-08
^{144}Ce	2.7E-06	1.8E-06	1.4E-06
^{143}Pr	3.7E-06	2.2E-07	2.1E-07
^{147}Nd	1.6E-06	6.8E-08	6.6E-08
^{239}Np	4.2E-05	3.9E-07	3.9E-07
^{242}Cm	1.7E-08	8.4E-09	6.8E-09
^{238}Pu	1.0E-09	1.1E-09	7.9E-10
^{239}Pu	8.9E-10	9.0E-10	6.7E-10
^{244}Cm	1.2E-10	1.2E-10	8.7E-11
^{240}Pu	8.6E-10	8.6E-10	6.4E-10
^{241}Pu	1.6E-07	1.6E-07	1.2E-07
^{241}Am	1.1E-10	2.4E-10	1.7E-10

The average concentration for CRAC2 weathering is calculated by the following algorithm:

$$C_i = C_{oi}\left[0.63\left(\frac{(1 - e^{-R1_i})}{R1_i}\right) + 0.37\left(\frac{(1 - e^{-R2_i})}{R2_i}\right)\right]$$

where $R1_i = (1.13 + \lambda_i)t$

$R2_i = (0.0075 + \lambda_i)t,$

t = years

The correction for in-growth of a daughter product from parent j is as follows:

$$C_i' = C_i + C_j\left(\frac{\lambda_i}{\lambda_i - \lambda_j}\right)\left[0.63\left(\frac{(1 - e^{-R1_j})}{R1_j} - \frac{(1 - e^{-R1_i})}{R1_i}\right) + 0.37\left(\frac{(1 - e^{-R2_j})}{R2_j} - \frac{(1 - e^{-R2_i})}{R2_i}\right)\right]$$

where λ_i and λ_j are the decay constants of nuclides i and j.

REFERENCES

RITCHIE. L. T., D. J. Alpert, R. P. Burke, J. D. Johnson, R. M. Ostmeyer, D. C. Aldrich, and R. M. Blond. 1984. CRAC2 Model Description. NUREG/CR-2552, SAND82-0342, prepared by Sandia National Laboratories.

U.S. NUCLEAR REGULATORY COMMISSION. Reactor Safety Study; An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. Appendix 6: Calculation of Reactor Accident Consequences. WASH-1400 (NUREG 75/014). U.S. Nuclear Regulatory Commission, Office of Nuclear Research, Washington, D.C., 1975

APPENDIX C

QUANTIFICATION OF CONTACT AND INGESTION PARAMETERS

C.1 SURFACE CONTAMINATION/MIXING ASSUMPTIONS

Exposure to two types of surfaces with differing contaminant concentrations is hypothesized. The first is a hard surface (paved) on which a very thin layer of dust is present; the second surface is soil, which has a thicker mixing layer.

For the hard surface, the amount of dust in which contamination is mixed is assumed to be 160 g/m^2. This corresponds to a dust layer 0.1 mm thick, based on a density of 1.6 g/cm^3, or approximately 1 year of dustfall in a moderately dusty area (Hawley 1985). Hawley gives dustfall for the community of Niagara Falls as 1.2 mg/cm^2 per 30 days, or 400 $mg/m^2/d$, which is described as moderate dustfall. A dust layer of 160 g/m^2 is 1 year of dustfall accumulating at a rate 10 percent higher than the rate for Niagara Falls.

For comparison, the mass of a dust layer was calculated using mass and concentration data for lead. Using lead in dust measurements reported by Gallacher et al (1984) and lead concentration data from Duggan and Williams (1977) or Lepow et al (1975) results in an estimate of the mass of the dust layer on paved surfaces that is much lower than the 160 g/m^2 given above. The quantity of lead in dust per unit area from a study in Wales (Gallacher et al 1984) was given as 8.5 mg/m^2 for paved areas adjacent to houses on roads with heavy traffic and 2.7 mg/m^2 for similar areas on cul-de-sacs. Typical lead concentrations in street dust measured in 5 residential areas in greater

London range from 920 to 1840 ppm (Duggan and Williams 1977); A U.S. study (Lepow et al 1975) reported mean lead levels in street dirt of 1200 ppm. Assuming concentration of lead in dust in the range of 500 to 2000 μg/g, the mass of dust would be only 1.3 to 17 g/m^2. This corresponds to a thickness of 0.01 mm or less. This estimate of the dust layer seemed unreasonably thin and was not comparable with measured dustfall.

The choice of dust thickness is rather arbitrary due to the large number of variables affecting dust deposition and accumulation. Some of the variables include roughness of surface, wind frequency and velocity, and amount and intensity of rainfall. The value of 160 g/m^2 was chosen as the mixing layer for paved surfaces. A smaller value comparable to the estimates based on lead deposition may be more appropriate for some circumstances, but this assumption will be offset, to some degree, by assumptions for the amount of dust transferred to skin from paved surfaces (see Section 2.0).

For a nonpaved surface, a mixing layer of 1 mm, or 1600 g/m^2 was used. The 1 mm thickness is used in an attempt to describe a surface that is mixed by forces other than cultivation. A relatively thin layer was used to provide conservatism (i.e., to bias the dose calculation on the high side, if at all). Concentrations may be calculated with a greater mixing depth, but this would provide additional dilution, thus be less conservative.

C.2 DUST/DIRT RESIDING ON SKIN SURFACES

The amount of dust or dirt that may reside on the skin of a maximally exposed individual is assumed to be 1.8 mg/cm^2. The dirt loading on the skin of an average individual is assumed to be 1 mg/cm^2. These values may be high (conservative) for paved surfaces where the relative roughness of the surface tends to reduce the amount of dust transferred to the skin. The quantities are based on estimates by Schaum (1984) and Hawley (1985), and studies by Lepow (1975) and Roels (1980). The range of 0.5 to 1.5 mg/cm^2 was assumed by Schaum (1984) to represent an average value for the entire exposed area of the body.

Hawley (1985) estimates the dirt loading on the skin of an adult equivalent to 1.8 mg per cm^2, which is based on a 50-μm layer of dust with density of 0.7 g/cm^3 (to account for the voids between dust particles, however, an effective density of 0.35 g/cm^3 was used).

The Lepow (1975) study deals with ingestion of lead from dirt on the hands of children. Preweighed self-adhesive labels were used to sample dirt on the hands. The mean weight of hand dirt samples was 11 mg for a 21.5-cm^2 label, or 0.5 mg/cm^2. This weight was assumed to be a lower bound for soil residing on the skin of children because the labels are not 100 percent efficient in transferring contamination. The estimate of dirt on skin derived from the Roels et al. (1980) study is 1.5 mg/cm^2, which is based on the quantity of lead on the hands of 11-year-old children playing on a playground.

The concentration of contamination present on the surface of the skin may be calculated from the quantity of contaminants per unit area on the ground, the mixing depth and mass, and the mass per unit area on the skin. This concentration may be calculated as a fraction of the contamination on the ground, as follows:

$$Ci/m^2 \text{ (skin)} = Ci/m^2 \text{ (ground)} \times \frac{mg/cm^2 \text{ (skin)}}{g/m^2 \text{ (ground)}} \times \frac{g}{1000 \text{ mg}} \times \frac{10000 \text{ cm}^2}{m^2}$$

For a surface contamination mixed in 160 g/m^2 of dust and 1.8 mg/cm^2 on the skin of the maximally exposed individual, the fraction of the concentration of contaminants from the ground that are on the skin would be 1.8/160 x 10, or 0.11 (11 percent of the ground surface concentration). For a 1-mm mixing layer (contaminated layer 1600 g/m^2), the fraction on the skin would be 1.1 percent of the ground concentration. In order to have 100 percent of the contamination from the ground on the skin surface, the dirt loading would have to be 16 mg/cm^2. Table C.1 gives the ratio of skin-to-ground contamination for the assumptions for surface mixing and loading of dirt on the skin. The dirt loading on the skin is assumed not to be a function of age, which means the individual referred to in Table C.1 is the same for an adult or child.

Table C.1 Fraction of Ground Concentration Assumed to be on the Skin Surface.

Surface	Mixing	Fraction of Surface Contamination on Skin: Maximum Individual (loading = 1.8 mg/cm^2)	Average Individual (loading = 1 mg/cm^2)
Pavement	160 g/m^2	0.11	0.063
Ground	1600 g/m^2	0.011	0.0063

The activity residing on skin of the maximally exposed individual is, therefore, estimated to be 1.8 mg/cm^2 divided by 16 mg/cm^2 for a dust layer on pavement, or 11 percent of the total ground concentration. For a soil surface, this is equivalent to 1.1 percent of the contamination mixed in the 160 mg/cm^2 surface soil layer. For the average individual, the contamination is assumed to be 1.0 mg/cm^2, or about 6 percent of the dust layer or about 0.6 percent of the surface soil layer.

C.3 INGESTION OF DIRT/DUST

Ingestion of contaminants can occur when surface contamination is transferred from a surface to hands, foodstuffs, cigarettes, or other items. Ingestion of dirt from contaminated hands has been investigated in the research of lead ingestion by children and more recently in the context of exposure to other hazardous contaminants. Soil ingestion studies have been used to estimate the amount of soil on skin surfaces and age-dependent ingestion quantities.

Ingestion rates assumed for this analysis based on LaGoy (1987) are 100 mg/d for the maximum adult individual, 500 mg/d for the maximum child, 25 mg/d for the average adult, and 100 mg/d for the average child. The quantity of contaminants ingested is dependent on the concentration of the contaminants in the surface dust or dirt layer, or in other words, on the assumed mixing layer. Assumptions concerning the mixing layers, noted above, are 160 g/m^2 for a dust layer on pavement and 1600 g/m^2 (1 mm thick) for other surfaces.

Since the source term is in units of Ci per unit area, the ingestion rate must be converted to an area basis. Ingestion rates based on area then depend on the mass of dust layer calculated as follows:

$$\frac{\text{mg/d ingested}}{\text{g/m}^2\text{ dirt}} \times \frac{\text{g}}{1000\text{ mg}} \times \frac{10{,}000\text{ cm}^2}{\text{m}^2} = \text{cm}^2\text{/d ingested}$$

Ingestion rates based on contamination from a given surface area have been used to assess ingestion of removable radioactive contamination residing on surfaces. Table C.2 presents the area-equivalent contamination ingested for use with the contaminant source term. The ingestion rates used for this analysis are equal to the contamination from about 0.2 to 31 cm^2/d.

These ingestion rates are reasonably comparable to rates calculated by Healy (1971) to estimate ingestion doses. Healy assumed that 1 cm^2 of surface contamination could be taken into the mouth per hour; thus, ingestion rates for workers of 8.0 cm^2/d and for the public of 24 cm^2/d were assumed. The higher ingestion rate for the public was presumed to allow for higher intake by children.

Table C.2 Ingestion Rate of Contaminated Soil for Area Based Source Term

Surface	Mixing	Adult Maximum 100 mg/d	Adult Average 25 mg/d	Child Maximum 500 mg/d	Child Average 100 mg/d
Pavement	160 g/m^2	6.3 cm^2	1.6 cm^2	31 cm^2	6.3 cm^2
Ground	1600 g/m^2	0.63 cm^2	0.16 cm^2	3.1 cm^2	0.63 cm^2

The intake rates given in Table C.2 are used to estimate dose from ingestion of contaminants in the SST2 source term in the text of this paper.

REFERENCES

DUGGAN, M. J. and S. Williams. 1977. "Lead-In-Dust in city Streets." The Science of the Total Environment. pp. 91-97. Elsevier Scientific Publishing Company, Amsterdam.

GALLACHER, J. E. J., P. C. Elwood, K. M. Phillips, B. E. Davies, and D. T. Jones. 1984. "Relation Between Pica and Blood Lead in Areas of Differing Lead Exposure." Archives of Disease in Childhood 59:40-44.

HAWLEY, J. K. 1985. "Assessment of Health Risk from Exposure to Contaminated Soil." Risk Analysis 5(4):289-302.

HEALY, J. W. 1971. Surface Contamination: Decision Levels. LA-4558-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

LAGOY, P. K. 1987. "Estimated Soil Ingestion Rates for Use in Risk Assessment." Risk Analysis 7(3):355-359.

LEPOW, M. L., L. Bruckman, M. Gillette, S. Markowitx, R. Robino, and J. Kapish.1975. "Investigations into Sources of Lead in the Environment of Urban Children." Environmental Research 10:415-426.

ROELS, H. et al. 1980. "Exposure to Lead by the Oral and Pulmonary Routes of Children Living in the Vicinity of a Primary Lead Smelter." Environmental Research 22:81-84.

SCHAUM, J. 1984. Risk Analysis of TCDD Contaminated Soil. Prepared for EPA Office of Solid Waste and Emergency Response by EPA Office of Health and Environmental Assessment, Washington, D.C.

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