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APPENDIX B

Risks To Health From Radiation Doses That May Result From Nuclear Incidents

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APPENDIX B

Risks To Health From Radiation Doses That May Result From Nuclear Incidents

B.1 Introduction

This appendix reviews the risks from radiation that form the basis for the choice of Protective Action Guides (PAGs) for the response to a nuclear incident, as well as the choice of limits for occupational exposure during a nuclear incident.

B.1.1 Units of Dose

The objective of protective action is to reduce the risk to health from exposure to radiation. Ideally, one would like to assure the same level of protection for each member of the population. However, protective actions cannot take into account individual variations in radiosensitivity, since these are not known. Therefore, these PAGs are based on assumed average values of risk. We further assume that these risks are proportional to the dose, for any level of dose below the threshold for acute effects (see Section B.2.).

The dose from exposure to radioactive materials may be delivered during the period of environmental exposure only (e.g., external gamma radiation), or over a longer period (e.g., inhaled radionuclides which deposit in body organs). In the latter case, dose is delivered not only at the time of intake from the environment, but continues until all of the radioactive material has decayed or is eliminated from the body. Because of the variable time over which such doses may be delivered, the PAGs are expressed in terms of a quantity called the "committed dose." Conceptually, committed dose is the dose delivered over an individual's remaining lifetime following an intake of radioactive material. However, due to differences in physiology and remaining years of life, the committed dose to a child from internal radioactivity may differ from that to an adult. For simplicity, adult physiology and a remaining lifetime of 50 years are assumed for the purpose of calculating committed doses.

Another important consideration is that different parts of the body are at different risk from the same dose. Since the objective of protective actions is the reduction of health risk, it is appropriate to use a quantity called "effective dose." Effective dose is the sum of the products of the dose to each organ or tissue of the body and a weighting factor representing the relative risk. These weighting factors (IC-77) are chosen as the ratio of mortality (from delayed health effects) from irradiation of particular organs or tissues to the total risk of such

mortality when the whole body is irradiated uniformly at the same dose.

Finally, doses from different types of radiation (e.g. alpha, beta, gamma, and neutron radiation) have different biological effectiveness. These differences are customarily accounted for, for purposes of radiation protection, by multiplicative modifying factors. A dose modified by these factors is designated the "dose equivalent." The PAGs are therefore expressed in terms of committed effective dose equivalent. The PAGs are augmented by limits for a few specific organs (skin and thyroid) which exhibit special sensitivity. These are expressed in terms of committed dose equivalent (rem). In the process of developing PAG values, it is necessary to evaluate the threshold dose levels for acute health effects. These levels are generally expressed in terms of absorbed dose (rad) to the whole body from short term (one month or less) exposure. Other units (Roentgens, rem, and rets) are also used in information cited from various references. They are all approximately numerically equivalent to rads in terms of the risk of acute health effects from beta and gamma radiation.

PAGs are intended to apply to all individuals in a population other than workers performing emergency services. However, there may be identifiable groups that have different average sensitivity to radiation or, because of their living situation, will receive higher or lower doses. In addition, some groups may be at greater risk from taking a given protective action. These factors are separately considered, when it is appropriate, in establishing values for the PAGs.

B.1.2 Principles for Establishing Protective Action Guides

The following four principles provide the basis for establishing values for Protective Action Guides:

1. Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which they are not likely to occur) should be avoided.

2. The risk of delayed effects on health (primarily cancer and genetic effects, for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health, under emergency conditions, and are reasonably achievable.

3. PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health achievable at acceptable cost should be carried out.

4. Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.

With the exception of the second, these principles are similar to those set forth by the International Commission

on Radiological Protection (IC-84b) as the basis for establishing intervention levels for nuclear accidents. We examine, below, the basis for estimating effects on health for use in applying the first two of these principles.

B.2 Acute Effects

This section provides information relevant to the first principle: avoidance of acute effects on health from radiation.

Acute radiation health effects are those clinically observable effects on health which are manifested within two or three months after exposure. Their severity depends on the amount of radiation dose that is received. Acute effects do not occur unless the dose is relatively large, and there is generally a level of dose (i.e., threshold) below which an effect is not expected to occur. Acute effects may be classified as severe or nonsevere clinical pathophysiological effects. Severe pathophysiological effects are those which have clinically observable symptoms and may lead to serious disease and death. Other pathophysiological effects, such as hematologic deficiencies, temporary infertility, and chromosome changes, are not considered to be severe, but may be detrimental in varying degrees. Some pathophysiological effects, such as erythema, nonmalignant skin damage, loss of appetite, nausea, fatigue, and diarrhea, when associated with whole body gamma or neutron exposure, are prodromal (forewarning of more serious pathophysiological effects, including death).

B.2.1 Review of Acute Effects

This section summarizes the results of a literature survey of reports of acute effects from short-term (arbitrarily taken as received in one month or less) radiation exposure in some detail. Many reports of observed effects at lower doses differ, and some are contradictory; however, most have been included for the sake of completeness. The results of the detailed review described in this Section are summarized in Section B.2.2.

The biological response to the rapid delivery of large radiation doses to man has been studied since the end of World War II. Dose-response relationships for prodromal (forewarning) symptoms and for death within 60 days have been developed from data on the Japanese A-bomb survivors, Marshall Island natives exposed to fallout, and patients undergoing radiotherapy. This work has been supplemented by a number of animal studies under controlled conditions.

The animal studies, usually using lethality as the end point, show that many factors can influence the degree of response. The rate at which the dose is delivered can affect the median lethal dose (LD_{50}) in many species, particularly at dose rates less than 5 R/min (PA-68a; BA-68). However, in primates there is less than a 50

percent increase in the LD_{50} as dose rates are decreased from 50 R/min to about 0.01 R/min (PA-68a). There is good evidence of species specificity (PA-68a; BO-69). The LD_{50} ranges from about 100 rad for burros to over 1000 rad for lagomorphs (e.g., rabbits). Response is modulated by: age (CA-68), extent of shielding (partial body irradiation) (BO-65), radiation quality (PA-68a; BO-69), diet, and state of health (CA-68).

While animal studies provide support and supplemental information, they cannot be used to infer the response for man. This lack of comparability of man and animals had already been noted by a review committee for the National Academy of Sciences as early as 1956, in considering the length of time over which acute effects might be expressed (NA-56): "Thus, an LD_{50}, 30-day consideration is inadequate to characterize the acute lethal dose response of man, and an LD_{50}, 60 days would be preferable."[1]

Several estimates of the levels at which acute effects of radiation occur in man have been published. For example, an early estimate of the dose-response curves for prodromal (forewarning) symptoms and for lethality was made in the first edition of "The Effects of Nuclear Weapons" (1957) (GL-57), and a more recent and well documented estimate is given in a NASA publication, "Radiobiological Factors in Manned Space Flight" (LA-67).

B.2.1.1 The Median Dose for Lethality

The radiation dose that would cause 50 percent mortality in 60 days was estimated as 450 Roentgens in early reports (NA-56; GL-57; RD-51). The National Commission on Radiation Protection and Measurements (NCRP) calculated that this would correspond to a midline absorbed dose of 315 rad (NC-74). The ratio of 315 rad to 450 Roentgens is 0.70, which is about the estimated ratio of the active marrow dose, in rads, to the tissue kerma in air, in rads (KE-80). The BEAR Committee noted that the customary reference to LD_{50} in animal studies, as if it were a specific property, independent of age, was not justifiable (NA-56): "...it is evident, now, that the susceptibility of a whole population is not describable by a single LD_{50}. The published values are usually obtained for young adults and are therefore maximal or nearly maximal for the strain. In attempts to estimate LD_{50} in man, this age dependence should be taken into consideration" (NA-56, pp.4-5). They observed that the LD_{50} approximately doubled as rats went from neonates to young adults and then decreased as the animals aged further. Finally, the BEAR

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[1]The committee (known as the BEAR Committee) also noted "The reservation must be made here that the exposed Japanese population was heterogeneous with respect to age, sex, physical condition and degree of added trauma from burns or blast. The extent to which these factors affected the survival time has not been determined. In studies on laboratory animals the converse is true--homogeneous populations are studied" (NA-56, p.I-6).

Committee concluded: "The situation is complex, and it became evident that it is not possible to extrapolate with confidence from one condition of radiation exposure to another, or from animal data to man" (NA-56, p.I-8). Nevertheless, results from animal studies can aid in interpreting the human data that are available.

The NCRP suggested the $LD_{50/60}$ might be 10 to 20 percent lower for the old, very young, or sick, and somewhat greater for healthy adults of intermediate age (RD-51). Other estimates of adult $LD_{50/60}$ have ranged from about 300 rad to 243 $\pm$ 22 rad. These lower estimates are apparently based on a ratio of air to tissue dose similar to those calculated for midline organs in the body; 0.54 to 0.66 (KE-80; OB-76; KO-81).

A NASA panel examined all patient and accident studies, tried to remove confounding factors, and concluded, "On this basis, it may be assumed that the LD_{50} value of 286 rad obtained by a normal fit to the patient data is the preferred value for healthy man" (LA-67).

An $LD_{50/60}$ of 286 $\pm$ 25 rad (standard deviation) midline absorbed dose and an absorbed dose/air dose ratio of 0.66, suggested by the National Academy of Science (LA-67), is probably a reasonable value for healthy males. In the absence of more complete information, we assume that a value of 300 rad $\pm$ 30 rad is a reasonable reflection of current uncertainties for average members of the population.

B.2.1.2 Variation of Response for Lethality

Uncertainty in the dose-response function for acute effects has been expressed in various ways. The slope of the estimated dose-response function has most commonly been estimated on the basis of the percent difference in the LD_{50} and the $LD_{15.9}$ or $LD_{84.1}$ (one standard deviation from the LD_{50}), as was done by NASA (GL-57). These and other parameters derived in a similar manner describe the uncertainty in the central risk estimate for the dose-response function.

Another means is to use an estimate of upper and lower bounds for the central risk estimate, e.g., the 95 percent fiducial limits. At any given response point on the dose-response function, for example, the LD_{10}, the dose causing that response has a 95 percent probability of lying between the lower and upper bounds of the 95 percent fiducial limit for that point. To estimate this value, probit analyses were run for each species using data in published reports (KO-81; TA-71). This provided estimates for each species for comparability analyses. The 95 percent fiducial limits at the LD_{50} response for $LD_{50/30}$ studies averaged $\pm$9 percent (range -9 to +26 percent) and for $LD_{50/60}$ studies $\pm$17 percent (range -20 to +45 percent). At the LD_{15} response, values were $\pm$16 percent (range -12 to +50 percent) for $LD_{15/30}$ data and $\pm$26 percent (range -20 to +65 percent) for $LD_{15/60}$ data. For the LD_{85} response, values were $\pm$17 percent (range -36 to +36 percent) for the $LD_{85/30}$ data and

$\pm$24 percent (range -46 to +31 percent) for $LD_{35/60}$ data.

The differences in the magnitude of the fiducial limits are a function of the differences in age, sex, radiation quality, degree of homogeneity of the experimental animals, husbandry, and other factors. The estimates show that the fiducial limits, expressed as a percent of the dose at any response, get greater the farther from the LD_{50} the estimate is made. For the purpose of estimating fiducial limits for humans, the 95 percent fiducial limits will be considered to be LD_{15} $\pm$15 percent, LD_{50} $\pm$10 percent, and LD_{85} $\pm$15 percent. Beyond these response levels, the fiducial limits are too uncertain and should not be used.

If the median lethal dose, $LD_{50/60}$, is taken as 300 $\pm$30 rad midline absorbed dose, the response to higher and lower doses depends on the degree of biological variation in the exposed population. The NASA panel decided the wide variation in the sensitivity of patients was a reflection of the heterogeneity of the sample; and that the variation in sensitivity, the slope of the central estimate of the response function, would be stated in the form of one standard deviation calculated as 58 percent of the LD_{50}. They further decided the deviation in the patients (58 percent) was too great, and the standard deviation for "normal" man should be closer to that of dogs and monkeys (18 percent) (LA-67). (The rationale for selecting these species was not given.)

Jones attempted to evaluate the hematologic syndrome from mammalian lethality studies using the ratio of dose to LD_{50} dose as an indicator of the steepness of the slope of the dose-response function (JO-81). However, he evaluated LD_{50} studies only of species having a rather steep slope, i.e., dogs, monkeys, mice, and swine. He also looked at several different statistical models for dose-response functions and pointed out the problems caused by different models and assumptions, particularly in evaluating the tails of the dose-response function (less than LD_{10} and greater than LD_{90}). Jones recommended using a log-log model, which he felt provided a better fit at low doses (JO-81).

Scott and Hahn also evaluated acute effects from mammalian lethality, but suggested using a Weibull model (SC-80). One of the advantages of the Weibull model is that in addition to developing the dose-response function, it can also be used to develop hazard functions. These hazard functions, if developed using the same model, can be summed to find the joint hazard of several different types of exposure (SC-83). This would allow estimation of the total hazard from multiple organ exposures to different types of radiation.

As mentioned earlier, the human median lethal dose is commonly reported in terms of the $LD_{50/60}$. Most laboratory animal median lethal doses are reported in terms of the $LD_{50/30}$. In those cases where estimates of both $LD_{50/30}$ and $LD_{50/60}$ are available, i.e.,

the burro (ST-69), the variation (that is, the slope of the dose-response curve) is greater in the $LD_{50/60}$ study than in the $LD_{50/30}$ study. Both the dog and the monkey data are for $LD_{50/30}$, and so are not appropriate for direct comparison to man.

If an estimate of the deviation is made for data from other studies and species, those where most of the fatalities occur within 30 days (like dogs and monkeys) have standard deviations of from around 20 percent [swine (x-ray) (ST-69), dogs (NA-66), hamsters (AI-65), primates (Macaca) (DA-65)] to 30 percent [swine (^{60}Co) (HO-68)]. Those in which most deaths occur in 60 days, like man, have deviations from around 20 percent [sheep (CH-64)] to 40 percent [goats (PA-68b), burros (TA-71)]. Nachtwey, et al. (NA-66) suggested the steepness of the slope of the exposure response curve depends on the inherent variability of the subjects exposed and any variation induced by uncontrolled factors, e.g., temperature, diurnal rhythm, and state of stimulation or arousal. So, while the slope of the response curve for the patients studied by the NASA panel may be unrealistically shallow for normal human populations, there is no reason to think it should be as steep as those for dogs and monkeys.

The average deviation for those species (burros, sheep, and goats) for which the standard deviation of the $LD_{50/60}$ is available has been used as an estimator for man. The mean value is 34 ± 13 percent. This is only slightly greater than the average value for all physically large animals (swine, burros, sheep, and goats), 32 ± 12 percent.

B.2.1.3 Estimated Lethality vs Dose for Man

As noted in Section B.2.1.1, dose-response estimates vary for a number of reasons. Some factors affecting estimates for humans are:

1. Age:
Studies on rats indicate the LD_{50} is minimal for perinatal exposure, rises to maximum around puberty, and then decreases again with increasing age (CA-68). The perinatal LD_{50} is about one-third of that for the healthy young adult rats; that for the geriatric rat is about one-half of that for the young adult rat.

2. Sex:
Females are slightly more sensitive than males in most species (CA-68).

3. Health:
Animals in poor health are usually more sensitive than healthy animals (CA-68), unless elevated hematopoietic activity is occurring in healthy animals (SU-69).

While these and other factors will affect the $LD_{50/60}$ and the response curve for man, there are no numerical data available.

The variation in response at a given dose level increases as the population at risk becomes more heterogeneous and as the length of time over which mortality is expressed

increases. In general, larger species show greater variance and longer periods of expression than do small mammals, e.g., rodents. It is likely that the human population would show at least the same amount of variation as do the larger animals, i.e., a coefficient of variation of about one-third.

The degree of variation exhibited in animal studies follows a Gaussian distribution as well as or better than a log normal distribution over that range of mortality where there are reasonable statistics. We have assumed here that the functional form of human response is Gaussian. Generally, sample sizes for extreme values (the upper and lower tails of the distribution) are too small to give meaningful results. Therefore, we have not projected risks for doses more than two standard deviations from the $LD_{50/60}$. We recognize that estimates of acute effects may not be reliable even beyond one standard deviation for a population containing persons of all ages and states of health. However, in spite of these uncertainties, previous estimates have been made of the acute effects caused by total body exposure to ionizing radiation as a function of the magnitude of the exposure (NC-71; LU-68; FA-73; NA-73).

Given the large uncertainties in the available data, a median lethal dose value of about 300 rad at the midline, with a standard deviation of 100 rad, may be assumed for planning purposes. Such risk estimates should be assumed to apply only in the interval from 5 percent to 95 percent fatality, as shown in Figure B-1. (See also section B.2.1.4.)

Figure B-1 is based on the following values:

Dose (rad)	Percent fatalities
<140	none[2]
140	5
200	15
300	50
400	85
460	95

For moderately severe prodromal (forewarning) effects, we believe the dose at which the same percentage of exposed would show effects would be approximately half of that causing fatality. This yields the following results (see also Figure B-1):

Dose (rad)	Percent affected
50	<2
100	15
150	50
200	85
250	98

Although some incidence of prodromal effects has been observed at doses in the range of 15 to 20 rads in patients (LU-68) and in the 0 to 10 rads range of dose in Japanese A-bomb survivors (SU-80a; GI-84),

[2]The risk of fatality below 140 rad is not necessarily zero; rather, it is indeterminate and likely to remain so. This also applies to prodromal effects below 50 rad.

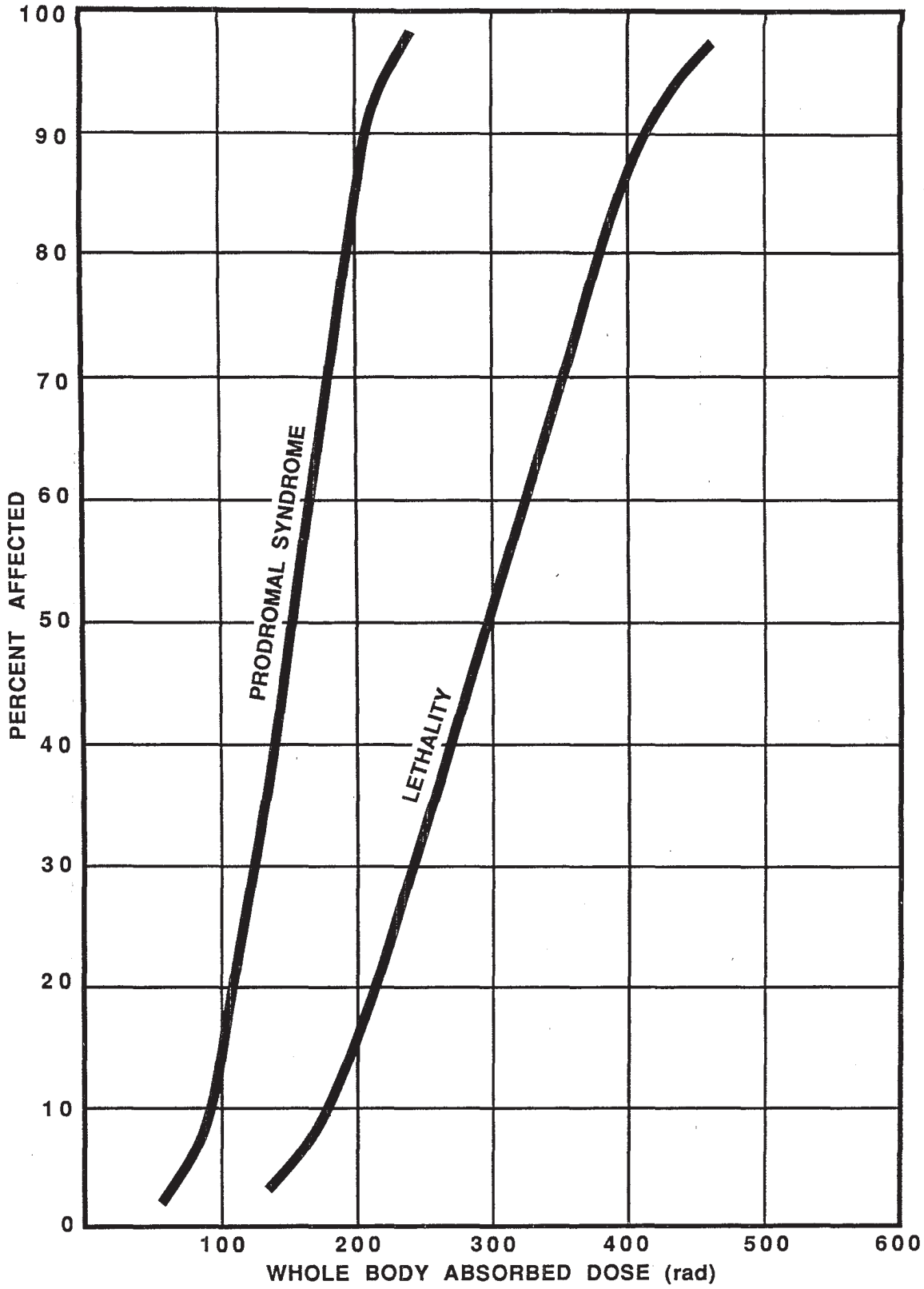

FIGURE B-1. ACUTE HEALTH EFFECTS AS A FUNCTION OF WHOLE BODY DOSE.

there is great uncertainty in interpreting the data. Patients may be abnormally sensitive, so that the dose-response function in patients may represent the lower bound of doses that would show a response in a healthy population (LU-67). The response of Japanese survivors in the low dose ranges is complicated by the blast and thermal exposure that occurred at the same time (SU-80b). For these reasons, care should be taken in applying estimates of prodromal effects. The prodomal dose-response function listed above is more likely to overestimate the proportion of persons affected than to underestimate it.

These estimated ranges and effects are in agreement with estimates made for manned space flights (LA-67; LU-67), which included consideration of the effect of abnormal physiology or sickness in the patients to which the data apply. Uncertainty in estimates of the biological effects of radiation exposure is great. It is probably due in part to variation in the health of individuals in exposed populations. These estimates assume a healthy young adult population and may not be a conservative estimate of risk for other population groups, such as children or the elderly. Lushbaugh, et al. (LU-68) found that prodromal effects probably occur in both healthy and ill persons in about the same dose range. However, Lushbaugh, et al. (LU-68) and NATO (NA-73) suggest that acute mortality in a population which is ill, injured, or in other ways debilitated will occur in 50 percent of that population at doses of 200-250 rad in about 60 days ($LD_{50/60}$), in contrast to an $LD_{50/60}$ from doses of 220-310 rad for a healthy young adult population. Thus, the ill or injured are assumed to have an increased risk of acute mortality at high doses.

The above estimates for $LD_{50/60}$ are also based on the assumption of minimal medical care following exposure. UNSCEAR (UN-88) estimates that the threshold for mortality would be about 50 percent higher in the presence of more intense medical care.

B.2.1.4 Threshold Dose Levels for Acute Effects

This section summarizes information available in the literature regarding thresholds for health effects. It also reviews actions that have been taken as a result of radiation exposure to provide insight on dose levels at which actions to avoid dose may be appropriate.

Some acute effects, such as cellular changes, may occur at low doses with no dose threshold. Most such effects have a minimum threshold of detectability; for example, five rad is about the lower limit of whole body dose which causes a cellular effect detectable by chromosome or other special analyses (NC-71; FA-73). This value is recommended by UNSCEAR as the starting point for biological dosimetry (UN-69). Purrott, et al. have reported a lower limit of detection of chromosome aberrations of 4 rad for x-rays and 10 rad for gamma rays (PU-75).

More recent advanced chromosome banding techniques permit detection of increased incidence of chromosome abnormalities from continuous exposure to systematically deposited radioisotopes or radioisotopes deposited in the lung at very low levels, e.g., body burdens of 100 to 1200 pCi of plutonium-239 (BR-77). While the exact dose associated with such burdens is not known, it is probably on the order of 10 to 100 millirem per year. Lymphocytes exposed to 5 rem in vitro show severe metabolic dysfunction and interphase cell death (ST-64). The extent to which similar effects occur after in vivo exposure is unknown. While chromosome abnormalities in circulating lymphocytes are reported to persist for long periods (UN-69), the significance of such abnormalities is not known (BR-77).

Hug has suggested 5 rem as the lower limit of exposure which might produce acute effects (WH-65). Five rad is also in the low dose, short-term exposure range defined by Cronkite and Haley, and is below the 10 rad which they thought would cause only a slight detectable physiological effect of unknown clinical significance (CR-71).

Although the ICRP has suggested that annual doses of 15 rad would not impair the fertility of normal fertile men (IC-69), an acute dose of 15 rad causes "moderate" oligospermia (approximately 70 percent reduction in sperm count) which lasts for some months (LA-67). Popescu and Lancranjan reported alterations of spermatogenesis and impaired fertility in men exposed to from 500 millirad to 3 rad per year for periods varying from 2 to 22 years (PO-75). The shortest exposure period in which abnormal spermatogenesis was reported was 31 to 41 months (PO-75); at the highest dose rate reported (3 rad/a), this is a cumulative dose of 8 to 10 rem. While more study is required, these results suggest the need to restrict acute doses to below 10 rem to avoid this effect, because a given acute dose is anticipated to be more effective than the same cumulative dose given over a longer period of time (NA-56; UN-58).

Many observations have indicated that doses of 10 rem or more to the pregnant woman are hazardous to the fetus. Mental retardation due to exposure of the fetus is discussed in Section B.3; this discussion is restricted to acute effects. The World Health Organization (WHO) indicates that there is no evidence of teratogenic effects from short term exposure of the fetus to a dose less than 10 rad during the early phase of gestation, the period when the fetus is most sensitive to these effects (WH-84).

A number of authorities have recommended that exposures of 10 roentgens or higher be considered as an indication for carrying out induced abortion (HA-59, DE-70, BR-72, NE-76). Brent and Gorson also suggest that 10 rad is a "practical" threshold for induction of fetal abnormalities (BR-72). The Swedish Government Committee on Urban Siting of Nuclear Power Stations stated the situation as follows: "What we have called unconditional indication of abortion involves the exposure of pregnant

women where radiation dose to the fetus is higher than 10 rad. When such doses are received in connection with medical treatment, it has hitherto been assumed that the probability of damage to the fetus is so high that an abortion is recommended. The probability for such injury is still moderate compared with the normal frequency of similar fetal injuries, and the probability is particularly reduced when the dose is received late in the pregnancy" (NA-74).

B.2.1.5 Acute Effects in the Thyroid

Acute effects are produced in the thyroid by doses from radioiodine on the order of 3,000 to 100,000 rad. Ablation of the thyroid requires doses of 100,000 rad (BE-68). The thyroid can be rendered hypothyroid by doses of about 3,000 to 10,000 rad (IC-71). A thyroid dose from radioiodines of 1000 rad in adults and 400 rad in children implies an associated whole body dose of about 1 rad due to radioiodines circulating in the blood. Following inhalation of ^{131}I, the committed thyroid dose is about one rad/μCi intake of ^{131}I in adults. In the developing fetus, the thyroid dose ranges from one to six rad per μCi of ^{131}I entering the mother's body (IL-74).

Although acute clinical effects are only observed at high doses, subclinical acute thyroid radiation effects may occur at lower doses (DO-72). Impaired thyroid capability may occur above a threshold of about 200 rad (DO-72).

Effects of radiation exposure of the thyroid have been shown in animal experiments. Walinder and Sjoden found that doses in excess of 3,000 rad from ^{131}I caused noticeable depression of fetal and juvenile mouse thyroid development (WA-69). Moore and Calvin, working with the Chinese hamster, showed that an exposure as low as 10 roentgens (x-rays) would give rise to 3 percent aberrant cells when the thyroid was cultured (MO-68). While the direct relationship of these results to human effects is not certain, mammalian thyroid cells can be injured at exposures as low as 10 roentgens.

B.2.1.6 Acute Effects in the Skin

The first stage of skin reaction to radiation exposure is erythema (reddening) with a threshold of from 300 to 800 rad. Acute exudative radiodermatitis results from doses of 1,200 to 2,000 rad (WH-84).

B.2.1.7 Clinical Pathophysiological Effects

A large amount of anecdotal information is available on the injury of organ tissues by high doses of radiation. Acute injury to tissue includes swelling and vacuolation of the cells which make up the blood vessels, increased permeability of vessels to fluids so that exudates form, formation of fibrin clots and thrombi, fibrinoid thickening in the walls of blood vessels, and swelling and vacuolization of parenchymal cells. In summary, there is an initial exudative

reaction followed in time by fibrosis and sclerosis (WH-76, CA-76).

Estimates of radiation doses necessary to cause severe tissue response in various organs are given in Table B-1. These tissue dose estimates are based on response to radiotherapy treatment, which is normally given on a fractionated dose basis, but also may be given as a continuous exposure. Therefore, these estimates must be adjusted to the equivalent single radiation dose for use in the present analysis. The formalism of Kirk, et al. (KI-71) is used to estimate the equivalent dose for a single acute exposure in rad-equivalent therapy units (rets: the dose calculated from the fractionated exposure which is equivalent to a single acute exposure for a specific biological endpoint.) Table B-2 lists acute exposure equivalents in rets for various organs.

With the exception of bone marrow, the exposures required to cause 5 percent injury within 5 years (TD 5/5) in internal organs are in the range of 1,000 to 5,000 rad. Since, with this type of injury, the dose response is nonlinear and has a threshold (i.e., is nonstochastic), there is an exposure below which injury is not expected. If the shape of the injury dose-response curve is the same for all internal organs as it is for the lung, plotting the two acute exposure equivalents (TD 50/5 and 5/5) for each organ on log probability paper allows a crude estimation of the number of clinical pathophysiological effects per 1000 persons exposed as a function of dose level. If one acute effect per 1000 persons within 5 years (TD 0.1/5) is taken as the threshold for the initiation of clinical pathophysiological effects in organs other than thyroid, the equivalent dose level for most organs is 550 rets or more; testes 440 $\pm$ 150 rets, ovary 170 $\pm$ 70 rets, and bone marrow 165 rets.

The radiation exposure to organs in rad units that will cause clinical pathophysiological effects within 5 years to 0.1 percent of the exposed population as a function of the duration of a continuous level of exposure can then be estimated by using Goitein's modification of the Kirk methodology (GO-76). This relationship is shown in Table B-3.

Bone marrow is an organ of particular concern because radionuclides known to concentrate in this organ system occur in nuclear incidents. The acute lethality due to the hematologic syndrome (LA-67) is estimated to occur in the range of 200 to 1,000 rad, so that the difference is small between exposure levels that might cause acute lethality and exposure levels that might cause only "severe clinical pathophysiology," as derived from radiotherapy data.

In summary, organ systems are not expected to show symptoms of severe clinical pathophysiology for projected short-term exposure doses less than a few hundred rad. Projected doses to bone marrow at this high level are relatively more serious and more likely to result in injury than doses to other organ systems.

Table B-1 Radiation Doses Causing Acute Injury to Organs (RU-72, RU-73)

Organ	Volume or area of exposure[a]	Risk of injury in five years		Type of injury
		5 percent (rad)	50 percent (rad)	
Bone marrow	whole	250	450	aplasia and pancytopenia
Liver	segment	3000	4000	acute and chronic hepatitis
	whole	2500	4000	
Stomach	100 cm^2	4500	5500	ulcer, perforation, hemorrhage
Intestine	400 cm^2	4500	5500	ulcer, perforation, hemorrhage
	100 cm^2	5000	6500	
Lung	whole	1500	2500	acute and chronic pneumonitis
	100 cm^2	3000	3500	
Kidney	whole	2000	2500	acute and chronic nephrosclerosis
Brain	whole	6000	7000	infarction, necrosis
Spinal cord	10 cm	4500	5500	infarction, necrosis
Heart	60 percent	4500	5500	pericarditis and pancarditis
Skin	---	5500	7000	ulcers, fibrosis
Fetus	whole	200	400	death
Lens of eye	whole	500	1200	cataracts
Ovary	whole	200-300	625-1200	permanent sterilization
Testes	whole	500-1500	2000	permanent sterilization

[a]Dose delivered in 200-rad fractions, 5 fractions/week.

--- Unspecified.

Table B-2 Acute Radiation Exposure as a Function of Rad Equivalent Therapy Units (rets)

Organ	Volume or area of exposure	Risk of injury in five years	
		5 percent (rets)	50 percent (rets)
Bone marrow	whole	230	340
	segment	1135	1360
Liver	whole	1000	1360
Stomach	100 cm^2	1465	1665
Intestine	400 cm^2	1465	1665
	100 cm^2	1570	1855
Lung	whole	720	1000
	100 cm^2	1135	1245
	75 percent	770[b]	---
Kidney	whole	875	1000
Brain	whole	1770	1950
Spinal cord	10 cm	1465	1665
Heart	60 percent	1465	1665
Skin	---	1665	1950
Fetus	whole	200	315
Lens of eye	whole	355	620
Ovary	whole	200-430[a]	410-875[a]
Testes	whole (sterilization)	340-720[a]	410-875[a]

[a]For a 200-rad/treatment, 5 treatments/week schedule (LU-76).

[b]Reference WA-73.

--- Unspecified.

Table B-3 Radiation Exposure to Organs Estimated to Cause Clinical Pathophysiological Effects within 5 Years to 0.1 Percent of the Exposed Population (GO-76)

Duration of exposure (days)	Ovary (rad)	Bone marrow (rad)	Testes (rad)	Other organs (rad)
(acute)	(170 rets)[a]	(165 rets)	(440 rets)	(550 rets)
1	315	300	810	1020
2	390	380	1010	1260
4	470	450	1210	1510
7	550	540	1430	1790
30	840	820	2190	2740
365[b]	1740	1690	4510	5640

[a]The dose in rets is numerically equal to the dose in rads.

[b]Assuming tissue recovery can continue at the same rate as observed during 30- to 60-day therapeutic exposure courses.

Even if severe clinical pathophysiological effects can be avoided, there is still a possibility of clinical pathophysiological effects of a less severe or transitory nature. The 1982 UNSCEAR report (UN-82) reviewed much of the data on animals and man. In the animal studies, there were reports of: changes in stomach acid secretion and stomach emptying at 50 to 130 rad; stunting in growing animals at the rate of 3 to 5 percent per 100 rad; degeneration of some cells or functions in the brain at 100 rad, particularly in growing animals; temporary changes in weight of hematopoietic tissues at 40 rad; and more damage in ovaries and testes caused by fractionated doses rather than acute doses. Some of the effects are transitory, others are long-lasting, but with only minor reductions in functional capacity.

Human data are limited and are reported primarily in the radiotherapy literature. The data suggest most tissues in man are more radiation resistant than those in animals. However, the human hematopoietic system shows a transient response, reflected by decreased circulating white cells and platelets, at about 50 rad. Temporary sterility has been observed after doses of 150 rad to the ovaries and 10 rad to the testes, when given as fractionated doses.

There is not sufficient data to determine dose-response functions

nor to describe the duration and severity of dysfunction expected.

B.2.2 Summary and Conclusions Regarding Acute Effects

Based on the foregoing review of acute health effects and other biological effects from large doses delivered over short periods of time, the following whole body doses from acute exposure provide useful reference levels for decisionmaking for PAGs:

50 rad - Less than 2 percent of the exposed population would be expected to exhibit prodromal (forewarning) symptoms.

25 rad - Below the dose where prodromal symptoms have been observed.

10 rad - The dose level below which a fetus would not be expected to suffer teratogenesis (but see Section B.3, Mental Retardation.).

5 rad - The approximate minimum level of detectability for acute cellular effects using the most sensitive methods. Although these are not severe pathophysiological effects, they may be detrimental.

Based on the first principle to be satisfied by PAGs (paragraph B.1.6), which calls for avoiding acute health effects, values of 50 rem for adults and 10 rem for fetuses appear to represent upper bounds.

B.3 Mental Retardation

Brain damage to the unborn is a class of injury reported in atomic bomb survivors which does not fall into either an acute or delayed effect category, but exhibits elements of both. What has been observed is a significant, dose-related increase in the incidence and severity of mental retardation, microencephaly (small head size), and microcephaly (small brain size) in Japanese exposed to radiation in utero during the 8th to 15th week after conception (BL-73; MI-76). While the actual injury may be acute, it is not identified until some time after birth.

In an early study Mole (MO-82) suggested that, although radiation may not be the sole cause of these conditions, it is prudent to treat the phenomenon as radiation-related. More recently, Otake and Schull (OT-83) have concluded: (1) there is no risk to live-born due to doses delivered up to 8 weeks after conception, (2) most damage occurs at the time when rapid proliferation of neuronal elements occurs, i.e., 8 to 15 weeks of gestational age, (3) the dose-response function for incidence during this period appears to fit a linear model, (4) the risk of occurrence is about five times greater during the period 8-15 weeks of gestation than in subsequent weeks, and (5) in later stages of gestation, e.g., after the 15th week, a threshold for damage may exist.

In their published reports, Otake and Schull (OT-83) evaluated the incidence of severe mental retardation

using the T-65 dosimetry and the dosimetry estimates developed in the ongoing dose reassessment program for the atomic bomb survivors, and using two tissue dose models. Their estimated ranges of risk were:

8 to 15 weeks after gestation: $3\text{-}4 \times 10^{-3}$ cases/rad;

16 or more weeks after gestation: $5\text{-}7 \times 10^{-4}$ cases/rad.

The higher values are based on the T-65 dosimetry and the Oak Ridge National Laboratory estimate of tissue dose. The lower values are based on Oak Ridge National Laboratory dosimetry and the Japanese National Institute of Radiological Sciences estimates of tissue dose. Later estimates based on the dose reassessment completed in 1986 are consistent with these published results (SC-87).

In view of the foregoing, the risk of mental retardation from exposure of a fetus in the 8th to 15th week of pregnancy is taken to be about 4×10^{-3} per rad. Because of this relatively high risk, special consideration should be given to protection of the fetus during this period. The risk to a fetus exposed after the 15th week is taken as 6×10^{-4} per rad. For the cases studied (OT-84), no increased incidence of mental retardation was observed for exposure during the 1st to the 7th week of pregnancy.

Federal Radiation Protection Guidance, adopted in 1987, recommends that dose to occupationally exposed pregnant women be controlled to keep the fetal dose below 0.5 rem over the entire term of pregnancy, and that no dose be delivered at more than the uniform monthly rate that would satisfy this limit (i.e., approximately 50-60 mrem/month)(EP-87). The NCRP has, for many years, recommended a limit of 0.5 rem (NC-71). ICRP recommends controlling exposure of the fetus to less than 0.5 rem in the first 2 months to provide appropriate protection during the essential period of organogenesis (IC-77).

B.4 Delayed Health Effects

This section addresses information relevant to the second principle (paragraph B.1.5) for establishing PAGs, the risk of delayed health effects in exposed individuals. The following subsections summarize the estimated risks of cancer and genetic effects, the two types of delayed effects caused by exposure to radiation.

B.4.1 Cancer

Because the effects of radiation on human health have been more extensively studied than the effects of many other environmental pollutants, it is possible to make numerical estimates of the risk as a result of a particular dose of radiation. Such estimates, may, however, give an unwarranted aura of certainty to estimated radiation risks. Compared to the baseline incidence of cancer and genetic defects, radiogenic cancer and

genetic defects do not occur very frequently. Even in heavily irradiated populations, the number of cancers and genetic defects resulting from radiation is known with only limited accuracy. In addition, all members of existing exposed populations have not been followed for their full lifetimes, so data on the ultimate numbers of effects is not yet available. Moreover, when considered in light of information gained from experiments with animals and from various theories of carcinogenesis and mutagenesis, the observed data on the effects of human exposure are subject to a number of interpretations. This, in turn, leads to differing estimates of radiation risks by individual scientists and expert groups. In summary, the estimation of radiation risks is not a fully mature science and the evaluation of radiation hazards will continue to change as additional information becomes available.

Most of the observations of radiation-induced carcinogenesis in humans are on groups exposed to low-LET radiations. These groups include the Japanese A-bomb survivors and medical patients treated with x-rays for ankylosing spondylitis in England from 1935 to 1954 (SM-78). The National Academy of Science Committee on the Biological Effects of Ionizing Radiations (BEIR) (NA-80) and UNSCEAR (UN-77) have provided knowledgeable and exhaustive reviews of these and other data on the carcinogenic effects of human exposures. The most recent of the BEIR studies was published in 1980 and is here designated BEIR-3 to distinguish it from previous reports of the BEIR committee.

The most important epidemiological data on radiogenic cancer is that from the A-bomb survivors. The Japanese A-bomb survivors have been studied for more than 40 years, and most of them have been followed in a major, carefully planned and monitored epidemiological survey, the Life Span Study Sample, since 1950 (KA-82, WA-83). They were exposed to a wide range of doses and are the largest group that has been studied. They are virtually the only group providing extensive information on the response pattern at various levels of exposure to low-LET radiation.

The estimated cancer risk from low-LET, whole body, lifetime exposure presented here is based on a life table analysis using a linear response model. We use the arithmetic average of relative and absolute risk projections (the BEIR-3 L-L model) for solid cancers, and an absolute risk projection for leukemia and bone cancer (the BEIR-3 L-L model). For whole body dose, this yields an estimated 280 (with a possible range of 120 to 1200) fatalities per million person-rem for a population cohort representative of the 1970 U.S. population. We assume this estimate also applies to high-LET radiation (e.g. alpha emitters); no reduction has been applied for dose rate. (The rounded value, 3×10^{-4} fatalities[3] per person-rem, has been selected for this analysis.)

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[3]Preliminary reviews of new results from studies of populations exposed at Hiroshima

Whole body dose means a uniform dose to every organ in the body. In practice, such exposure situations seldom occur, particularly for ingested or inhaled radioactivity. Inhaled radioactive particulate materials may be either soluble or insoluble. Soluble particulate materials deposited in the lung will be rapidly absorbed, and the radionuclides associated with them distributed throughout the body by the bloodstream. As these radionuclides are transported in the blood, they irradiate the entire body. Usually, they then redeposit in one or more organs, causing increased irradiation of that organ. Insoluble particulate materials, on the other hand, are only partially absorbed into body fluids. (This fraction is typically assumed to be about 8 percent.) This absorption occurs over a period of years, with a portion entering the bloodstream and another retained in the pulmonary lymph nodes. The balance (92 percent) of inhaled insoluble particulate materials are removed from the lung within a few days by passing up the air passages to the pharynx where they are swallowed. Inhaled insoluble particulate materials thus irradiate both the lung and the gastrointestinal tract, with a small fraction being eventually absorbed into the bloodstream (TG-66). These nonuniform distributions of dose (and therefore risk) are taken into account through use of the weighting factors for calculating effective dose.

There is a latent period associated with the onset of radiation-induced cancers, so the increased risk is not immediately apparent. The increased risk is assumed to commence 2 to 10 years after the time of exposure and continue the remainder of the exposed individual's lifespan (NA-80).

For uniform exposure of the whole body, about 50 percent of radiation-induced cancers in women and about 65 percent in men are fatal (NA-80). Therefore, 1 rem of low-LET radiation would be expected to cause a total of about 500 cancer cases if delivered to a population of one million. (In the case of thyroid and skin, the ratio of nonfatal to fatal cancers are much higher. These are addressed separately below.) This corresponds to an average annual individual probability of developing cancer of about 7×10^{-6} per year. For perspective, the average annual risk of dying of cancer from all causes in the United States, in 1982, was 1.9×10^{-3}.

B.4.1.1 Cancer Risk Due to Radiation Exposure of the Thyroid

Exposure of the thyroid to extremely high levels of radiation may cause it to degenerate. At moderate levels of exposure some loss of thyroid function will occur. At lower levels of exposure, there are delayed health

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(footnote continued)

and Nagasaki indicate that these risk estimates may be revised upwards significantly in the near future, particularly for acute exposure situations. EPA has recently used a slightly higher value, 4×10^{-4} fatalities in standards for air emissions under the Clean Air Act. We will revise these risk estimates to reflect new results following appropriate review.

effects, which take the form of both thyroid nodules and thyroid malignancies (NA-72; NA-80). Doses as low as 14 rad to the thyroid have been associated with thyroid malignancy in the Marshall Islanders (CO-70). The increased risk of radiation-induced cancer is assumed to commence about 10 years after initial exposure and to continue for the remaining lifespan of an exposed individual.

The true nature of thyroid nodules cannot be established until they are surgically removed and examined histologically, and those that are malignant can lead to death if not surgically removed (SA-68; DE-73; PA-74). Although thyroid malignancies are not necessarily fatal, effects requiring surgical removal of the thyroid cannot be considered benign. In this analysis, all thyroid cancers, both fatal and nonfatal, are counted for the purpose of estimating the severity of thyroid exposures.

Based on findings in BEIR-3, we estimate that 1 rem of thyroid exposure carries a risk of producing a thyroid cancer of 3.6×10^{-4}, of which a small fraction (on the order of 1 in 10) will be fatal (NA-80). Since the calculation of effective dose equivalent does not include consideration of nonfatal thyroid cancers and the severity of the medical procedures for their cure, it is appropriate to limit the dose to the thyroid by an additional factor beyond that provided by the PAG expressed in terms of effective dose equivalent. Protective action to limit dose to thyroid is therefore recommended at a thyroid dose 5 times the numerical value of the PAG for effective dose.

B.4.1.2 Cancer Risk Due to Radiation Exposure of the Skin

The risk of fatal skin cancer is estimated to be on the order of one percent of the total risk of fatal cancer for uniform irradiation of the entire body (IC-78). However, since the weighting scheme for calculating effective dose equivalent does not include skin, the PAG expressed in terms of effective dose does not provide protection against radionuclides which primarily expose skin. As in the case of the thyroid, the ratio of nonfatal to fatal cancers from irradiation of the skin is high (on the order of 100 to 1). It would not be appropriate to ignore this high incidence of nonfatal skin cancers by allowing 100 times as much dose to the skin as to the whole body. For this reason, evacuation is recommended at a skin dose 50 times the numerical value of the PAG for effective dose.

B.4.1.3 Cancer Risk Due to Radiation Exposure of the Fetus

The fetus is estimated to be 5 to 10 times as sensitive to radiogenic cancer as an adult (FA-73; WH-65). Stewart reports increased relative incidence of childhood cancers following prenatal x-ray doses as low as 0.20 to 0.25 rem and doubling of childhood cancers between 1-4 rem (ST-73). She concluded that the fetus is about equally sensitive to cancer induction in

each trimester. Her findings are supported by similar results reported by MacMahon and Hutchinson (MA-64), Kaplan (KA-58), Polhemus and Kock (PO-59), MacMahon (MA-63), Ford, et al. (FO-59), Stewart and Kneale (ST-70b), and an AEC report (AE-61). MacMahon reported that although there were both positive and negative findings, the combination of weighted data indicates a 40 percent increase in childhood cancer mortality after in vivo exposure to diagnostic x rays (1.0 to 5.0 rad): about 1 cancer per 2,000 exposed children in the first 10 years after birth (MA-63). He concluded that although the range of dose within which these effects are observed is wide, effects will be fewer at 1 rad than at 5 rad.

Graham, et al., investigating diagnostic x-ray exposure, found a significantly increased relative risk of leukemia in children: by a factor of 1.6 following preconception irradiation of mothers or in utero exposure of the fetus; by a factor of 2 following postnatal irradiation of the children; and by a factor of 2 following preconception irradiation of the mother and in utero exposure of the child (GR-66).

B.4.1.4 Age Dependence of Doses

Almost all dose models are based on ICRP "Reference Man," which adopts the characteristics of male and female adults of working age. ICRP-30 dosimetric models, which use "Reference Man" as a basis, are therefore appropriate for only adult workers and do not take into account differences in dose resulting from the differences in physiological parameters between children and adults, e.g., intake rates, metabolism, and organ size. Although it is difficult to generalize for all radionuclides, in some cases these differences tend to counterbalance each other. For example, the ratio of volume of air breathed per unit time to lung mass is relatively constant with age, so that the ICRP adult model for inhaled materials provides a reasonably good estimate of the dose from a given air concentration of radioactive material throughout life.

The thyroid is an exception because the very young have a relatively high uptake of radioiodine into a gland that is much smaller than the adult thyroid (see Section B.4.2.2.). This results in a larger childhood dose and an increased risk which persists throughout life. We have examined this worst case situation. Age-specific risk coefficients for fatal thyroid cancer (See Table 6-8 of "Risk Assessment Methodology" (EP-89)) are about 1.9 higher per unit dose for persons exposed at ages 0 to 9 years than for the general population. Age-dependent dose factors (see NRPB-R162 (GR-85)) for inhalation of I-131, are a factor of about 1.7 higher for 10 year olds than for adults. Therefore, the net risk of fatal thyroid cancer from a given air concentration of I-131 is estimated to be a factor of about 3 higher for young children than for the remainder of the population. This difference is not considered large enough, given the uncertainties of exposure estimation for implementing

protective actions, to warrant establishing age-dependent PAGs.

B.4.2 Genetic Risk

An average parental dose of 1 rem before conception has been estimated to produce 5 to 75 significant genetically-related disorders per million liveborn offspring (NA-80). For this analysis we use the geometric mean of this range, i.e. 1.9×10^{-5}. This estimate applies to effects in the first generation only, as a result of dose to parents of liveborn offspring. The sum of effects over all generations is estimated to be approximately twelve times greater; that is, 2.3×10^{-4}. In addition, since any radiation dose delivered after a parent's last conception has no genetic effect, and not all members of the population become parents, less than half of the entire dose in an average population is of genetic significance. Taking the above factors into account, we estimate that the risk of genetically-related disorders in all generations is 1×10^{-4} per person-rem to a typical population.

Although the overall severity of the genetic effects included as "significant" in the above estimates is not well known, rough judgements can be made. The 1980 BEIR report referred to "....disorders and traits that cause a serious handicap at some time during lifetime" (NA-80). From the types of defects reported by Stevenson (ST-59), it can be estimated that, of all radiation-induced genetic effects, 50 percent lead to minor to moderate medical problems (i.e., hair or ear anomalies, polydactyl, strabismus, etc.), 25 percent lead to severe medical problems (i.e., congenital cataracts, diabetes insipidus, deaf mutism, etc.), 23 percent would require extended hospitalization (i.e., mongolism, pernicious anemia, manic-depressive psychoses, etc.), and 2 percent would die before age 20 (i.e., anencephalus, hydrocephalus, pancreatic fibrocytic disease, etc.).

B.4.3 Summary of Risks of Delayed Effects

Table B-4 summarizes average lifetime risks of delayed health effects based on results from the above discussion. Because of the nature of the dose-effect relationships assumed for delayed health effects from radiation (linear, nonthreshold), there is no dose value below which no risk can be assumed to exist.

B.4.4 Risks Associated with Other Radiation Standards

A review of radiation standards for protection of members of the general population from radiation shows a range of values spanning several orders of magnitude. This occurs because of the variety of bases (risk, cost, practicability of implementation, and the situations to which they apply) that influenced the choice of these standards. Some source-specific standards are relatively protective, e.g., the EPA standard limiting exposure of the public from nuclear power operations (25 mrem/y) from all path-

Table B-4 Average Risk of Delayed Health Effects in a Population[a]

	Effects per person-rem		
	Whole Body	Thyroid[c]	Skin
Fatal cancers	2.8E-4[b]	3.6E-5	3.0E-6
Nonfatal cancers	2.4E-4[b]	3.2E-4	3.0E-4
Genetic disorders (all generations)	1.0E-4		

[a] We assume a population with the same age distribution as that of the U.S. population in 1970.

[b] Risk to the fetus is estimated to be 5 to 10 times higher.

[c] Risk to young children is estimated to be about two to three times as high.

ways combined corresponds to a risk (for cancer death) of $5x10^{-4}$ for lifetime exposure. Similarly, regulations under the Clean Air Act limit the dose due to emissions of radionuclides to air alone from all DOE and NRC facilities to 0.01 rem per year, which corresponds to a cancer risk of $2x10^{-4}$ for lifetime exposure. Other guides permit much higher risks. For example, the level at which the EPA recommends action to reduce exposure to indoor radon (0.02 working levels) corresponds to a risk of about $2x10^{-2}$ (for fatal lung cancer) for lifetime exposure. All of these standards and guides apply to nonemergency situations and were based on considerations beyond a simple judgement of acceptable risk.

Federal Radiation Protection Guidance for nonemergency situations recommends that the dose from all sources combined (except from exposure to medical and natural background radiation) to individuals in the population not exceed 0.5 rem in a single year (FR-60) and that the dose to the fetus of occupationally-exposed mothers not exceed 0.5 rem during the 9-month gestation period (EP-87). This dose corresponds to an annual incremental risk of fatal cancer to members of the general population of about $1.4x10^{-4}$. If exposure of the fetus is limited to one ninth of 0.5 rem per month over a 9-month gestation period, as recommended, the risk of severe mental retardation in liveborn is limited to about $7x10^{-4}$.

The International Commission on Radiation Protection recommends that the dose to members of the public not exceed 0.5 rem per year due to nonrecurring exposure to all sources of radiation combined, other than natural sources or beneficial medical uses of

radiation (IC-77). They also recommend a limiting dose to members of the public of 0.1 rem per year from all such sources combined for chronic (i.e., planned) exposure (IC-84a). These upper bounds may be taken as representative of acceptable values for the situations to which they apply. That is, these are upper bounds of individual risk that are acceptable for the sum of all sources and exposure pathways under international recommendations, for circumstances that are justified on the basis of public benefit, and when actual doses from individual sources are "as low as reasonably achievable" (ALARA) within these upper bounds.

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APPENDIX C

Protective Action Guides for the Early Phase:

Supporting Information

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APPENDIX C

Protective Action Guides for the Early Phase: Supporting Information

C.1 Introduction

This appendix sets forth supporting information for the choice of Protective Action Guides (PAGs) for the early phase of the response to a nuclear incident involving the release of airborne radioactive material. It then describes application of the basic principles for selection of response levels set forth in Chapter 1 to the guidance on evacuation and sheltering in Chapters 2 and 5.

Response to a radiological emergency will normally be carried out in three phases, as discussed in Chapter 1. Decisions during the first (early) phase will usually be based on predicted or potential radiological conditions in the environment, rather than on actual measurements. The principal protective action is evacuation, with sheltering serving as a suitable alternative under some conditions. This appendix examines the potential magnitudes and consequences of predicted exposures of populations during the early phase, for selected nuclear reactor accident scenarios, in relation to the benefits and detrimental consequences of evacuation and sheltering. Nuclear reactor facilities are chosen for evaluation because, due to their number, size of source, and energy available to drive a release, they are most likely to provide an upper bound on the magnitude of the variety of possible sources of nuclear incidents. Although atmospheric releases from other types of nuclear incidents are likely to involve smaller consequences, the affected populations, and therefore the costs and benefits of protective action are each expected to scale in roughly the same proportion for lesser magnitude incidents. Thus, basic conclusions developed for responses to reactor facilities are assumed to remain valid for other types of nuclear incidents. Supplementary protective actions, such as washing and change of clothing to reduce exposure of the skin and use of stable iodine to reduce uptake of radioiodine to the thyroid, are also considered, but in less detail.

C.1.1 Existing Federal Guidance

In the 1960's, the Federal Radiation Council (FRC) defined PAGs and established limiting guides for ingestion of strontium-89, strontium-90, cesium-137, and iodine-131 (FR-64; FR-65). That guidance applied to restricting the use of food products that had become contaminated as the result of release of radioactivity to the stratosphere from weapons testing. During the period immediately following an incident at any domestic nuclear facility, when the

critical source of exposure is expected to be a nearby airborne plume, the principal protective actions are evacuation or sheltering. The PAGs developed here thus do not supersede previous guidance, but provide additional guidance for prompt exposure pathways specific to a domestic nuclear incident.

C.1.2 Principal Exposure Pathways

The immediate exposure pathway from a sub-stratospheric airborne release of radioactive materials is direct exposure from the cloud of radioactive material carried by prevailing winds. Such a plume can contain radioactive noble gases, iodines, and/or particulate materials, depending on the source involved and conditions of the incident. These materials emit gamma rays, which are not significantly absorbed by air, and will expose the entire bodies of nearby individuals.

Another immediate exposure pathway occurs when people are submerged in the cloud of radioactive materials. In this case radioactive materials are inhaled, and the skin and clothes may be contaminated. Inhaled radioactive materials, depending on their solubility in body fluids, may either remain in the lungs or move via the blood to other organs. Many radionuclides which enter the bloodstream tend to be predominantly concentrated in a single organ. For example, if radioiodines are inhaled, a significant fraction will tend to move rapidly from the lungs through the bloodstream to the thyroid gland where much of the iodine will be deposited and most of the dose[1] will be delivered. Although dose to skin from materials deposited on the skin and clothing could be significant, it will be less important in terms of risk of fatal cancer than dose from inhalation, if early protective actions include washing of exposed skin and changes of clothing.

As the plume passes over an area, radioactive materials may settle onto the ground and other surfaces. People remaining in the area will then continue to be exposed through ingestion and external radiation, and through inhalation of resuspended materials. The total dose from such deposited materials may be more significant than that due to direct exposure to the plume, because the term of exposure can be much longer. However, since the protective actions considered here (evacuation and/or sheltering) may not be appropriate or may not apply for this longer term exposure, doses from these exposures beyond the early phase are not included in the dose considered in the PAGs for the early phase. It is assumed that, within four days after an incident, the population will be

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[1]In this and all subsequent references, the word "dose" means the committed dose equivalent to the specified organ, or, if no organ is specified, the sum of the committed effective dose equivalent from intake of radionuclides and the effective dose equivalent from external sources of radiation. (Section B.1.1 contains a more detailed discussion of units of dose for PAGs.)

protected from these subsequent doses on the basis of the PAGs for relocation and for contaminated food and water. (See Chapters 3 and 4.)

Based on the foregoing considerations, the PAGs for the early phase are expressed in terms of estimated doses from exposure due to external radiation, inhalation, and contamination of the skin only during the early phase following an incident.

C.2 Practicality of Implementation

Whereas Appendix B deals with the risk associated with the projected dose that could be avoided by any protective action, this section addresses the costs and risks associated with evacuation itself. That is, these analyses relate to Principles 3 and 4 for deriving PAGs, set forth in Chapter 1, which address the practicality of protective actions, rather than acceptability of risks under Principles 1 and 2, which is evaluated in Appendix B.

The principal relevant protective actions during the early phase are, as noted earlier, evacuation and sheltering. In some cases, washing and changing of clothing, or thyroid blocking may also be appropriate actions. The costs, risks, and degrees of protection associated with evacuation are generally higher than those for sheltering. Although there may be some costs and risks associated with the other protective actions, they are small and not readily quantifiable. Therefore, only the costs and risks associated with evacuation will be evaluated here. These factors are evaluated to determine whether the costs are low enough to justify lower PAGs than would be required to satisfy upper bounds of acceptable risk under Principles 1 and 2.

C.2.1 Cost of Evacuation

Costs incurred to reduce the radiation risk from nuclear incidents can be considered to fall into several major categories. The first category includes the design, construction, and operation of nuclear facilities in such a manner as to minimize the probability and consequences of radiological incidents. It is recognized that the probability and consequences of such incidents usually cannot be reduced to zero. Therefore, a second category is necessary: the development of emergency response plans to invoke actions which would reduce exposure of potentially exposed populations, and consequently their risks, if a major nuclear incident should occur.

Both of the above categories of cost are properly attributed to the cost of design and operation of a nuclear facility. A third category of costs is the actual expenses incurred by taking protective actions as the result of an incident. In general, the choice of levels for PAGs will affect only this third category of costs. That is, all costs in the first two categories are assumed to be unaffected by decisions on the levels of PAGs. (This will be the case unless the PAGs were to be set so high as to never require protective action, in which case response plans

would be unnecessary.) Therefore, the costs associated with implementing the PAGs are evaluated only in terms of the actual cost of response. In a similar manner, the risk incurred by protective actions is compared only to the risk associated with the radiation dose that would be avoided by the action, and is unaffected by any other measures taken to reduce risks that fall in the first two categories of cost identified above.

C.2.1.1 Cost Assumptions

The analyses in this section are based on evaluation of the costs of evacuation and the doses that would be received in the absence of protective actions for nuclear reactor incidents. These were calculated as a function of offsite location, meteorological condition, and incident type (TA-87). Dose and cost data are based on the following assumptions:

1. Airborne releases are those associated with fuel melt accidents at nuclear reactor facilities followed by containment failure.

2. Meteorological conditions range from stable to unstable, and windspeeds are those typical of the stability class.

3. Plume dispersion follows a Gaussian distribution, with a 0.01 m/s dry deposition velocity for iodine and particulate materials.

4. Doses are those incurred from whole body gamma radiation from the plume, inhalation of radioactive material in the plume, and from four days exposure to deposited radioactive material.

5. Population distributions are the average values observed around 111 nuclear power reactor plants, based on 1970 data.

6. The cost of evacuation is $185 per person for a 4-day evacuation involving a 100-mile round trip, with an average of 3 persons per household. These evacuation costs include wages and salaries of personnel directing the evacuation, transportation costs of evacuees to and from the staging location, food and shelter for the evacuees during the evacuation period, loss of personal and corporate income during the evacuation period, and the costs of any special supplies (TA-87).

The estimated costs and doses avoided are based on the following idealized evacuation area model (see Figure C.1.):

1. All people within a 2-mile radius of the incident are evacuated for all scenarios.

2. People are also evacuated from a downwind area bounded by equivalent rays on either side of the center line of the plume, which define the angular spread (70, 90, or 180 degrees) of the area evacuated by an arc at the distance beyond which the evacuation dose would not be exceeded on the plume centerline.

Figure C-1 shows the relationship between the area in which the evacuation dose would be exceeded and the larger area that might be evacuated. The figure shows the plume centered in an idealized evacuation area.

C.2.1.2 Analysis

Evaluation of costs for evacuation and doses to populations as a function of the area evacuated depends on a variety of assumptions. Three fuel-melt accident categories, six meteorological stability classes, and the three evacuation area models discussed above were examined. Detailed assumptions and data are reported elsewhere (EP-87a). Selected data, including the cost per unit of collective dose to the population Figure C.1 (person-rem) avoided, are presented in Tables C-1, C-2, and C-3, for three stability classes, for the median nuclear accident category examined (SST-2). (SST accident categories are described in Section E.1.2).

The data are presented for both the total area and the incremental area evacuated for each change in dose level examined. When evaluating the cost per person-rem avoided for a specific set of circumstances, it is appropriate to assess the ratio of the total cost to the total dose avoided to calculate the average cost per person-rem avoided. However, when one is comparing the cost versus dose avoided to make a judgment between a variety of different limiting dose values, it is appropriate to compare the dose savings and costs at the margin, since the cost of evacuating the additional area is incurred to avoid the incremental collective dose. Therefore, the appropriate quantities are the cost and risk for the additional area evacuated. Results of analyses on both a total and incremental basis are presented in Tables C-1, C-2, and C-3 for accident category SST-2. This is the smallest category of fuel melt accident yielding effective dose equivalents during the first 4 days of exposure that are greater than 0.5 rem outside the assumed 2-mile evacuation circle for all stability classes. Data on costs versus dose saved for all three accident categories are summarized in Table C-4 in the next section.

Changes in population density would not affect the above results, since both cost and collective dose are proportional to the size of the population affected. Factors that could affect these results are different assumptions for cost of evacuation, accident scenarios, and evacuation area models. The results will be directly proportional to different assumptions for the cost of evacuation. Some data on the variation with accident scenario are presented in the next section. In situations where different widths of evacuation area are assumed, the change in cost per unit dose avoided will be approximately proportional to the change in width in degrees. This approximation is more accurate for the higher stability classes (E and F). Evacuation within a 2 mile radius circle and a 90 degree sector in the downwind direction is generally considered to be adequate for release

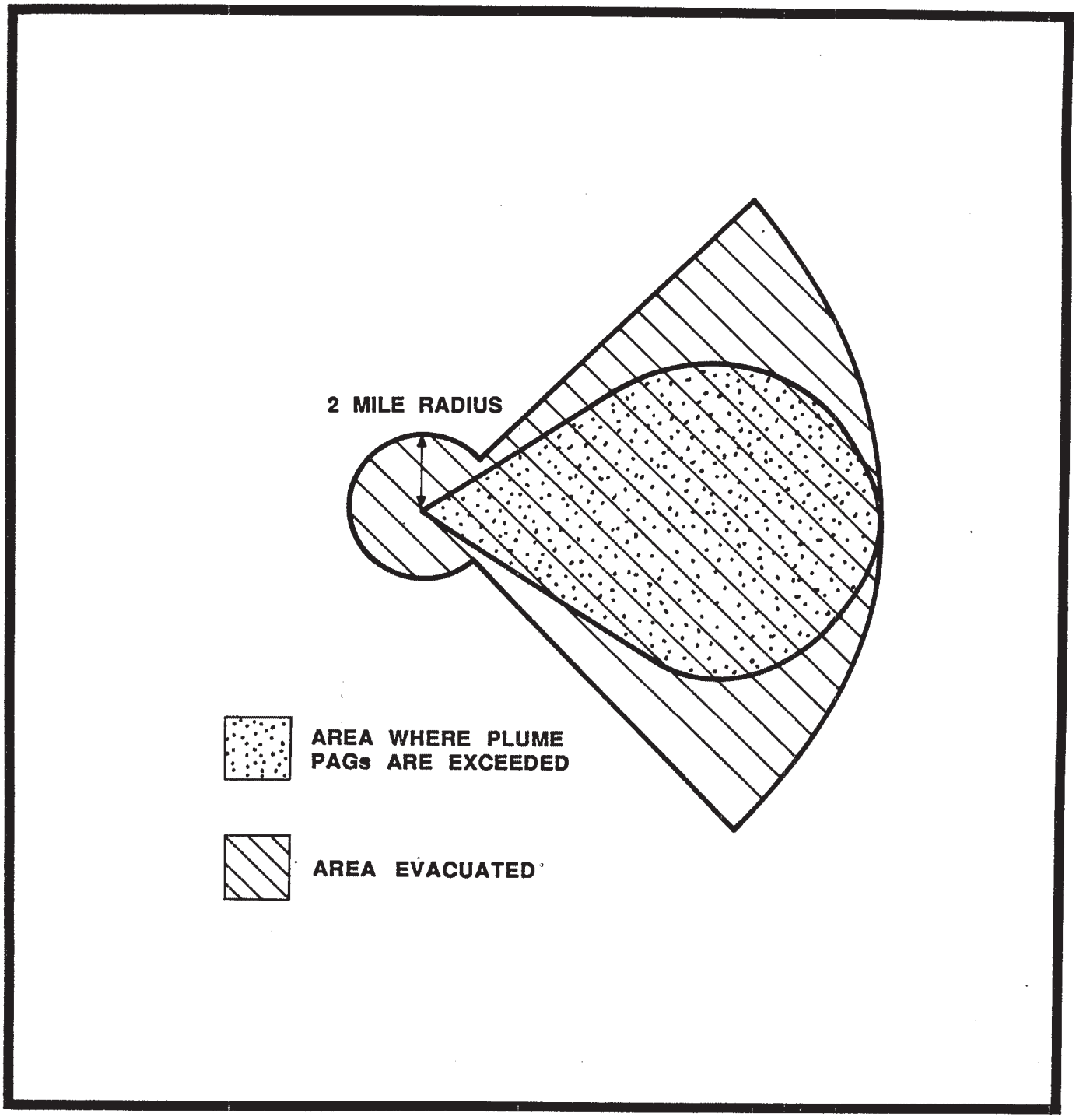

FIGURE C-1. EVACUATION MODEL.

Table C-1 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class A)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	Δ Cost (dollars)	Δ Dose avoided (person-rem)	Δ Dollars/ Δperson-rem avoided
70	0.5	2.83E+7	8.97E+4	315			
	1	6.68E+6	4.06E+4	164	2.16E+7	4.91E+4	440
	2	1.49E+6	1.73E+4	88	5.19E+6	2.33E+4	223
	5	2.99E+5	5.22E+3	57	1.19E+6	1.21E+4	98
	10	(a)	(a)	(a)	9.70E+4	2.44E+3	40
90	0.5	3.63E+7	9.29E+4	391			
	1	8.54E+6	4.24E+4	201	2.78E+7	5.05E+4	550
	2	1.86E+6	1.82E+4	102	6.68E+6	2.42E+4	276
	5	3.26E+5	5.41E+3	60	1.54E+6	1.28E+4	120
	10	(a)	(a)	(a)	1.25E+5	2.63E+3	47
180	0.5	7.16E+7	9.33E+4	767			
	1	1.67E+7	4.27E+4	391	5.49E+7	5.06E+4	1080
	2	3.48E+6	1.84E+4	190	1.32E+7	2.43E+4	543
	5	4.48E+5	5.46E+3	82	3.04E+6	1.29E+4	235
	10	(a)	(a)	(a)	2.47E+5	2.68E+3	92

[a] The 4-day dose does not exceed the PAG outside the 2-mile radius of the accident site. The total cost of evacuation within this radius is 2.02E+5 dollars; the total dose avoided is 2.78E+3 person-rem; and the total cost per person-rem avoided is $73.

Table C-2 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class C)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	Δ Cost (dollars)	Δ Dose avoided (person-rem)	Δ Dollars/ Δperson-rem avoided
70	0.5	4.95E+7	1.13E+5	439			
	1	1.23E+7	6.31E+4	195	3.71E+7	4.95E+4	750
	2	2.46E+6	3.73E+4	66	9.87E+6	2.58E+4	382
	5	7.82E+5	2.71E+4	29	1.68E+6	1.02E+4	165
	10	3.93E+5	2.10E+4	19	3.89E+5	6.15E+3	63
	20	2.60E+5	1.62E+4	16	1.32E+5	4.75E+3	28
	50	(a)	(a)	(a)	3.40E+4	2.50E+3	10
90	0.5	6.35E+7	1.13E+5	564			
	1	1.58E+7	6.32E+4	250	4.77E+7	4.95E+4	964
	2	3.11E+6	3.74E+4	83	1.27E+7	2.58E+4	491
	5	9.48E+5	2.72E+4	35	2.16E+6	1.02E+4	212
	10	4.47E+5	2.10E+4	21	5.00E+5	6.16E+3	81
	20	2.77E+5	1.63E+4	17	1.70E+5	4.76E+3	36
	50	(a)	(a)	(a)	3.40E+4	2.50E+3	14
180	0.5	1.25E+8	1.13E+5	1110			
	1	3.10E+7	6.32E+4	491	9.44E+7	4.95E+4	1910
	2	5.95E+6	3.74E+4	159	2.51E+7	2.58E+4	971
	5	1.68E+6	2.72E+4	62	4.28E+6	1.02E+4	419
	10	6.87E+5	2.10E+4	33	9.90E+5	6.16E+3	161
	20	3.51E+5	1.63E+4	22	3.36E+5	4.77E+3	70
	50	(a)	(a)	(a)	6.70E+4	2.50E+3	27

[a] The 4-day dose does not exceed the PAG outside the 2-mile radius of the accident site. The total cost of evacuation within this radius is 2.02E+5 dollars; the total dose avoided is 2.78E+3 person-rem; and the total cost per person-rem avoided is $73.

Table C-3 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class F)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	Δ Cost (dollars)	Δ Dose avoided (person-rem)	Δ Dollars/ Δ person-rem avoided
70	0.5	8.95E+7	4.61E+5	194			
	1	4.95E+7	4.41E+5	112	4.01E+7	1.98E+4	2020
	2	2.83E+7	4.19E+5	67	2.12E+7	2.17E+4	977
	5	1.23E+7	3.83E+5	32	1.59E+7	3.66E+4	436
	10	6.68E+6	3.53E+5	19	5.65E+6	2.93E+4	193
	20	3.65E+6	3.22E+5	11	3.03E+6	3.18E+4	95
	50	1.49E+6	2.68E+5	5.6	9.70E+5	3.10E+4	32
90	0.5	1.15E+8	4.61E+5	250			
	1	6.35E+7	4.41E+5	144	5.15E+7	1.98E+4	2600
	2	3.63E+7	4.19E+5	87	2.72E+7	2.17E+4	1260
	5	1.58E+7	3.83E+5	41	2.05E+7	3.66E+4	560
	10	8.54E+6	3.53E+5	24	7.26E+6	2.93E+4	248
	20	4.64E+6	3.22E+5	14	3.90E+6	3.18E+4	123
	50	1.86E+6	2.68E+5	6.9	1.30E+6	3.10E+4	41
180	0.5	2.27E+8	4.61E+5	493			
	1	1.25E+8	4.41E+5	285	1.02E+8	1.99E+4	5120
	2	7.16E+7	4.19E+5	171	5.39E+7	2.17E+4	2480
	5	3.10E+7	3.83E+5	81	4.05E+7	3.66E+4	1110
	10	1.67E+7	3.53E+5	47	1.44E+7	2.92E+4	492
	20	8.98E+6	3.22E+5	28	7.71E+6	3.18E+4	242
	50	3.51E+6	2.68E+5	13	2.40E+6	3.10E+4	80

durations not exceeding a few hours and where reliable wind direction forecasts are available.

C.2.1.3 Conclusions

As shown in Tables C-1, C-2, and C-3 for an SST-2 accident, the cost per unit dose avoided is greatest for wide angle evacuation and for the most stable conditions, class (F). Although a few emergency plans call for evacuation over wider angles (up to 360 degrees), the model shown in Figure C-1 with a 90 degree angle is most common.

To estimate an upper bound on dose for evacuation based on cost, we first consider common values placed on avoiding risk. As one input into its risk management decisions, EPA has used a range of $400,000 to $7,000,000 as an acceptable range of costs for avoiding a statistical death from pollutants other than radiation. For a risk of $3x10^{-4}$ cancer deaths per person-rem (see Appendix B), these dollar values are equivalent to a range of from about $120 to $2,000 per person-rem avoided. These values can be compared to the marginal cost-effectiveness (dollars per person-rem) of evacuation over an angle of 90 degrees. The resulting ranges of upper bounds on dose are shown in Table C-4 for SST-1, SST-2, and SST-3 accident scenarios. The maximum upper bounds (based on minimum costs for avoiding risk) range from 1 to 10 rem, with most values being approximately 5 rem. The minimum upper bounds (based on maximum costs for avoiding risk) range from 0.15 to 0.8 rem, with 0.5 rem being representative of most situations. From these data we conclude that, based on the cost of evacuation, a PAG larger than the range of values 0.5 to 5 rem would be incompatible with Principle 3.

C.2.2 Risk of Evacuation

Principle 4 requires that the risk of the protective action not exceed the risk associated with the dose that will be avoided. Risk from evacuation can come from several sources, including (1) transportation incidents for both pedestrians and vehicle passengers, (2) exposure to severe weather conditions or a competing disaster, and (3), in the case of immobile persons, anxiety, unusual activity, and separation from medical care or services. The first source, transportation incidents, is the only category for which the risk has been quantified. An EPA report (HA-75) evaluated the risk of transportation fatalities associated with emergency evacuations that have actually occurred and concluded that the risk of death per mile traveled is about the same as that for routine automobile travel. Using this as a basis, the risk of death from travel is about $9x10^{-8}$ deaths per person-mile, or $9x10^{-6}$ deaths per person for the 100-mile round trip assumed for evacuation. Assuming a risk of fatal cancer from radiation of approximately $3x10^{-4}$ per person-rem, such an evacuation risk is equivalent to a dose of about 0.03 rem.

Table C-4 Upper Bounds on Dose for Evacuation, Based on the Cost of Avoiding Fatalities[a]

Accident Category	Atmospheric Stability Class	Dose Upper Bounds[b,c] Maximum (rem)	Minimum (rem)
SST-1	A	5	0.4
	C	5	0.4
	F	10	0.8
SST-2	A	1	0.15
	C	3.5	0.25
	F	10	0.7
SST-3	A	(d)	(d)
	C	(d)	(d)
	F	5	0.45

[a] Based on data from EP-87a.

[b] Windspeeds typical of each stability class were chosen.

[c] Based on an assumed range of $400,000 to $7,000,000 per life saved.

[d] For stability classes A and C, the dose from an SST-3 accident is not predicted to exceed 0.5 rem outside a 2-mile radius. It is assumed that evacuation inside this radius would be carried out based on the emergency condition on the site. No differential evacuation costs were calculated within this area.

In comparing this risk (or, more exactly, its equivalent in dose) to the risk avoided by evacuation, it is important to note that protective action must be implemented over a larger population than will actually be exposed at the level of the PAG. Because of uncertainty or unpredictable changes in wind direction, the exact location of the plume will not be precisely known. Dose projections are made for the maximum exposed individuals - those at the assumed location of the plume centerline. To assure that these individuals will be protected, it is necessary that others on either side take protective action at exposures that are less than at the plume centerline, and, in some cases, are zero. Thus, the entire evacuated population could incur, on the average, a risk from the protective action which exceeds the risk of the radiation dose avoided. Although it is not possible to assure that no individuals incur risks from evacuation greater than their radiation risks, we can assure that this does not

occur, on the average, at the outer margin of the evacuation area. For this reason, we also examined the average dose avoided for the incrementally evacuated population for various choices of evacuation levels. Table C-5 presents the results, which are derived from the data in Tables C-1, C-2, and C-3. For the levels analyzed, the average dose avoided is always significantly greater than 0.03 rem. We conclude, therefore, that the choice of PAGs will not be influenced by Principle 4, for persons in the general population whose risk from evacuation is primarily the normal risk of transportation, if the centerline dose avoided is at or above 0.5 rem.

As previously discussed, hazardous environmental conditions (e.g., severe weather or a competing disaster) could create transportation risks from evacuation that would be higher than normal. It is therefore appropriate to make an exception to allow higher projected doses for evacuation decisions under these circumstances. In the absence of any definitive information on such higher risks from evacuation, we have arbitrarily assumed that it would be appropriate to increase the

Table C-5 Average Dose Avoided per Evacuated Individual for Incremental Dose Levels for Evacuation

Centerline dose (rem)	Average dose avoided (rem per individual) by stability class		
	A	C	F
0.5 to 1	0.34	0.19	0.07
1 to 2	0.67	0.38	0.15
2 to 5		0.87	0.33
5 to 10			0.75

recommended projected dose for evacuation of the general population under hazardous environmental conditions up to a factor of 5 higher than that used under normal environmental conditions.

It is also recognized that those persons who are not readily mobile are at higher risk from evacuation than are average members of the population. It would be appropriate to adopt higher PAGs for evacuation of individuals who would be at greater risk from evacuation itself than for the typically healthy members of the population, who are at low risk from evacuation. In the absence of definitive information

on the higher risk associated with the evacuation of this group, we have arbitrarily assumed that it is appropriate to adopt PAGs a factor of five higher for evacuation of high risk groups under normal environmental conditions. If both conditions exist, (high risk groups and hazardous environmental conditions) projected doses up to 10 times higher than the PAGs for evacuation of the general population under normal conditions may be justified. These doses are expected to satisfy Principle 4 without violating Principles 1 and 3. Although they violate Principle 2, Principle 4 becomes, for such cases, the overriding consideration.

C.2.3 Thyroid Blocking

The ingestion of stable potassium iodide (KI) to block the uptake of radioiodine by the thyroid has been identified as an effective protective action. The Food and Drug Administration (FDA) analyzed available information on the risk of radioiodine-induced thyroid cancers and the incidence and severity of side effects from potassium iodide (FD-82). They concluded "...risks from the short-term use of relatively low doses of potassium iodide for thyroid blocking in a radiation emergency are outweighed by the risks of radioiodine-induced thyroid nodules or cancer at a projected dose to the thyroid gland of 25 rem. FDA recommends that potassium iodide in doses of 130 milligrams (mg) per day for adults and children above 1 year and 65 mg per day for children below 1 year of age be considered for thyroid blocking in radiation emergencies in those persons who are likely to receive a projected radiation dose of 25 rem or greater to the thyroid gland from radioiodines released into the environment. To have the greatest effect in decreasing the accumulation of radioiodine in the thyroid gland, these doses of potassium iodide should be administered immediately before or after exposure. If a person is exposed to radioiodine when circumstances do not permit the immediate administration of potassium iodide, the initial administration will still have substantial benefit even if it is taken 3 or 4 hours after acute exposure". Evacuation and sheltering are, however, preferred alternatives for most situations because they provide protection for the whole body and avoid the risk of misapplication of potassium iodide.

The Federal Emergency Management Agency has published a Federal policy developed by the Federal Radiological Preparedness Coordinating Committee regarding the use of KI as a protective action (FE-85). In summary, the policy recommends the stock-piling of KI and distribution during emergencies to emergency workers and institutionalized persons, but does not recommend requiring stockpiling or distribution to the general public. The policy recognizes, however, that options on the distribution and use of KI rests with the States and, hence, the policy statement permits State and local governments, within the limits of their authority, to take measures beyond

those recommended or required nationally.

C.2.4 Sheltering

Sheltering means staying inside a structure with doors and windows closed and, generally, with exterior ventilation systems shut off. Sheltering in place (i.e. at or near the location of an individual when the incident occurs) is a low-cost, low-risk protective action that can provide protection with an efficiency ranging from almost 100 percent to zero, depending on the circumstances. It can also be particularly useful to assure that a population is positioned so that, if the need arises, communication with the population can be carried out expeditiously. The degree of protection provided by a structure is governed by attenuation of radiation by structural components (the mass of walls, ceilings, etc.) and by its outside/inside air-exchange rate. These two protective characteristics are considered separately.

The protection factor may be characterized by a dose reduction factor (DRF), defined as:

$$DRF = \frac{\text{dose with protective action}}{\text{dose without protective action}}$$

The shielding characteristics of most structures for gamma radiation can be categorized based on whether they are "small" or "large." Small structures are primarily single-family dwellings, and large structures include office, industrial, and commercial buildings. The typical attenuation factors given in Table C-6 show the importance of the type of structure for protection from external gamma radiation (EP-78a). If the structure is a wood frame house without a basement, then sheltering from gamma radiation would provide a DRF of 0.9; i.e., only 10 percent of the dose would be avoided. The DRFs shown in Table C-6 are initial values prior to infiltration of contaminated air, and therefore apply only to short duration plumes. The values will increase with increasing time of exposure to a plume because of the increasing importance of inside-outside air exchange. However, this reduction

Table C-6 Representative Dose Reduction Factors for External Radiation

Structure	DRF	Effectiveness (percent)
Wood frame house (first floor)	0.9	10
Wood frame house (basement)	0.6	40
Masonry house	0.6	40
Large office or industrial building	0.2 or less	80 or better

in efficiency is not dramatic for source terms involving primarily gamma radiation, because most of the dose arises from outside, not from the small volume of contaminated air inside a shelter. Therefore, most shelters will retain their efficiency as shields against gamma radiation, even if the concentration inside equals the concentration outside.

The second factor is the inside/outside air exchange rate. This factor primarily affects protection against exposure by inhalation of airborne radionuclides with half lives long compared to the air exchange rate. The factor is expressed as the number of air exchanges per hour, L (h^{-1}), or the volume of fresh air flowing into and out of the structure per hour divided by the volume of the structure. Virtually any structure that can be used for sheltering has some degree of outside/inside air exchange due to natural ventilation, forced ventilation, or uncontrollable outside forces, primarily wind.

Assuming constant atmospheric and source conditions and no effects from filtration, deposition, or radioactive decay, the following model can be used to estimate the buildup of indoor concentration of radioactivity, for a given outdoor concentration, as a function of time after appearance of the plume and of ventilation rate:

$$C_i = C_o(1 - e^{-Lt}),$$

where C_i = concentration inside,

C_o = concentration outside,

L = ventilation rate (h^{-1}), and

t = elapsed time (h).

Typical values for ventilation rates range from one-fifth to several air exchanges per hour. In the absence of measurements, an air exchange rate of 1.0/h may be assumed for structures with no special preparation except for closing the doors and windows. An air exchange rate of 0.3/h is appropriate for relatively air-tight structures, such as well-sealed residences, interior rooms with doors chinked and no windows, or large structures with ventilation shut off. Using the above model to calculate indoor concentration relative to outdoor concentration after one, two, and four complete air exchanges, the indoor concentration would be about 64 percent, 87 percent, and 98 percent of the outside concentration, respectively. It is apparent that staying in a shelter for more time than that required for one or two complete air exchanges is not very effective for reducing inhalation exposure.

The inhalation DRF is equal to the ratio of the average inside to outside air concentration over the period of sheltering. Studies have been conducted of typical ventilation rates for dwellings (EP-78a) and for large commercial structures (GR-86). In each case the rate varies according to the air tightness of the structure, windspeed, and the indoor-to-outdoor temperature difference. For the purpose of deriving PAGs, average ventilation rates were chosen for the two types of structures that are of

greatest interest. Table C-7 shows calculated dose reduction factors for inhalation exposure as a function of plume duration, for beta-gamma source terms, assuming average ventilation rates for these structures.

A potential problem with sheltering is that persons may not leave the shelter as soon as the plume passes and, as a result, will receive exposure from radioactive gases trapped inside. The values for DRFs tabulated in Table C-7 ignore this potential additional contribution. This effect is generally minor for gamma dose (generally less than a 10 percent increase in the dose received during plume passage, (EP-78b)), but can be greater for inhalation dose.

Doses from inhalation during sheltering can be reduced in several ways, including reducing air exchange rates by sealing cracks and openings with cloth or weather stripping, tape, etc., and filtering the inhaled air with commonly available items like wet towels and handkerchiefs. Analyses for some hypothesized accidents, such as short-term transuranic releases, show that sheltering in residences and other

Table C-7 Dose Reduction Factors for Sheltering from Inhalation of Beta-Gamma Emitters

Ventilation rate (air changes/h)	Duration of plume exposure(h)	DRF
0.3[a]	0.5	0.07
	1	0.14
	2	0.25
	4	0.41
	6	0.54
1.0[b]	0.5	0.21
	1	0.36
	2	0.56
	4	0.75
	6	0.83

[a]Applicable to relatively "airtight" structures such as well- sealed residences, interior rooms with chinked doors and no windows, or large structures with outside ventilation shut off.

[b]Applicable to structures with no special preparation except for closing of doors and windows.

buildings can be more effective than for beta-gamma emitters, may provide adequate protection, and may be more effective than evacuation when evacuation cannot be completed before plume arrival (DO-90). However, sheltering effectiveness for the inhalation exposure pathway can be reduced drastically by open windows and doors or by forced air ventilation. Therefore, reliance on protection assumed to be afforded based on large dose reduction factors for sheltering should be accompanied by cautious examination of possible failure mechanisms, and, except in very unusual circumstances, should not be relied upon at projected doses greater than 10 rem. Such analysis should be based on realistic or "best estimate" dose models and include consideration of unavoidable dose if evacuation were carried out.

C.3 Recommended PAGs for Exposure to a Plume during the Early Phase

The four principles which form the basis for the selection of PAG values are presented in Chapter 1. The risks of health effects from radiation that are relevant to satisfying Principles 1 and 2 are presented in Appendix B and analyses of the costs and risks associated with evacuation relative to Principles 3 and 4 have been presented in this appendix. These results, for application to the early phase, are summarized in Table C-8.

The following describes how these results lead to the selection of the PAGs. Conformance to Principle 1 (avoidance of acute health effects) is assured by the low risk required to satisfy Principle 2, and thus requires no additional consideration. Principle 2 (acceptable risk of delayed health effects) leads to the choice of 0.5 rem as an upper bound on the avoided dose below which evacuation of the general population is justified under normal conditions. This represents a risk of about 2E-4 of fatal cancer. Maximum lifetime risk levels considered acceptable by EPA from routine operations of individual sources range from 1E-6 to 1E-4. Risk levels that are higher than this must be justified on the basis of the emergency nature of a situation. In this case, we judge that up to an order of magnitude higher combined risk from all phases of an incident may be justifiable. The choice of 0.5 rem avoided dose as an appropriate criterion for an acceptable level of risk during the early phase is a subjective judgment that includes consideration of possible contributions from exposure during other phases of the incident, as well as the possibility that risk estimates may increase moderately in the near future as a result of current reevaluations of radiation risk.

Principle 4 (risk from the protective action must be less than that from the radiation risk avoided) supplies a lower bound of 0.03 rem on the dose at which evacuation of most members of the public is justified. Finally, under Principle 3 (cost/risk considerations) evacuation is justified only at values equal to or greater than 0.5 rem. This will be limiting unless lower values are required for purely health-based

Table C-8 Summary of Considerations for Selecting the Evacuation PAGs.

Dose (rem)	Consideration	Principle	Section
50	Assumed threshold for acute health effects in adults.	1	B.2.1.4
10	Assumed threshold for acute health effects in the fetus.	1	B.2.1.4
5	Maximum acceptable dose for normal occupational exposure of adults.	2	C.5
5	Maximum dose justified to average members of the population, based on the cost of evacuation.	3	C.2.1.3
0.5	Maximum acceptable dose to the general population from all sources from nonrecurring, non-accidental exposure.	2	B.4.4
0.5	Minimum dose justified to average members of the population, based on the cost of evacuation.	3	C.2.1.3
0.5	Maximum acceptable dose[a] to the fetus from occupational exposure of the mother.	2	C.5
0.1	Maximum acceptable dose to the general population from all sources from routine (chronic), nonaccidental exposure.	2	B.4.4
0.03	Dose that carries a risk assumed to be equal to or less than that from evacuation.	4	C.2.2

[a]This is also the dose to the 8- to 15-week-old fetus at which the risk of mental retardation is assumed to be equal to the risk of fatal cancer to adults from a dose of 5 rem.

reasons (Principle 2). But this is not the case. The single lower purely health-based value, 0.1 rem, is only valid as a health-based criterion for chronic exposure.

In summary, we have selected the value 0.5 rem as the avoided dose which justifies evacuation, because 1) it limits the risk of delayed effects on health to levels adequately protective of public health under emergency conditions, 2) the cost of implementation of a lower value is not justified, and 3) it satisfies the two bounding requirements to avoid acute radiation effects and to avoid increasing risk through the protective action itself. We note that this choice also satisfies the criterion for acceptable risk to the fetus of occupationally exposed mothers (as well as falling well below dose values at which abortion is recommended).

As noted in Section C.2.4, we assume that the dose normally avoidable by evacuation (the dose that is not avoided by the assumed alternative of sheltering) is one half of the projected dose. The value of the PAG for evacuation of the general public under normal circumstances is therefore chosen as one rem projected sum of the committed effective dose equivalent from inhalation of radionuclides and effective dose equivalent from exposure to external radiation.

The above considerations apply to evacuation of typical members of the population under normal circumstances, and apply to effective doses (i.e. the weighted sum of doses to all organs). As discussed in previous sections, it may be appropriate to further limit dose to the thyroid and skin, to adjust the value for special groups of the population at unusually high risk from evacuation, and to provide for situations in which the general population may be at higher than normal risk from evacuation. These are addressed, in turn, below.

In the case of exposure of the thyroid to radioiodine, action based solely on effective dose would not occur until a thyroid dose about 33 times higher than the corresponding effective dose to the entire body. As noted in Section B.4.1.1, because the weighting factor for thyroid used to calculate effective dose does not reflect the high ratio of curable to fatal thyroid cancers, protective action to limit dose to the thyroid is recommended at a thyroid dose 5 times the numerical value of the PAG.

Similarly, since effective dose does not include dose to the skin, and for other reasons discussed in Section B.4.1.2, protective action to limit dose to skin is recommended at a skin dose 50 times the numerical value of the PAG. As in the case of the thyroid, this includes consideration of the risk of both curable and noncurable cancers.

Special risk groups include fetuses, and persons who are not readily mobile. As noted in Sections B.4.1.3 and B3, we assume that the risk of radiation-induced cancer is about 5 to 10 times higher for fetuses than for adults and that the risk of mental

retardation in fetuses exposed during the 8th to 15th weeks of gestation is about 10 times higher than the risk of fatal cancer in equivalently exposed adults. However, due to the difficulty of rapidly evacuating only pregnant women in a population, and the assumed higher-than-average risk associated with their evacuation, it is not considered appropriate to establish separate PAGs for pregnant women. We note that the PAG is chosen sufficiently low to satisfy Federal guidance for limiting exposure of the fetus in pregnant workers.

Higher PAGs for situations involving higher risks from evacuation were discussed in Section C.2.2. Under normal, low-risk, environmental conditions, PAGs for evacuation of groups who present higher than average risks from evacuation (e.g., persons who are not readily mobile) are recommended at projected doses up to 5 rem. Evacuation of the general population under high-risk environmental conditions is also recommended at projected doses up to 5 rem. If evacuation of high risk groups under hazardous environmental conditions is being considered, projected doses up to 10 rem may, therefore, be justified.

Short-term sheltering is recognized as a low-cost, low-risk, protective action primarily suited for protection from exposure to an airborne plume. Sheltering will usually be clearly justified to avoid projected doses above 0.5 rem, on the basis of avoidance of health risks. However, data are not available to establish a lower level at which sheltering is no longer justified because of its cost or the risk associated with its implementation. Sheltering will usually have other benefits related to emergency communication with members of the public. It is expected that protective action planners and decision authorities will take into account the added benefits of sheltering (e.g., communication and established planning areas) for decisions on sheltering at levels below 0.5 rem.

Bathing and changing of clothing are effective for reducing beta dose to the skin of persons exposed to an airborne plume of radioactive materials. Since these are also low-cost, low-risk actions, no PAG is recommended for initiating their implementation. It is expected that any persons exposed in areas where evacuation is justified based on projected dose from inhalation will be routinely advised by emergency response officials to take these actions within 12 hours after exposure.

The use of stable iodine to protect against uptake of inhaled radioiodine by the thyroid is recognized as an effective alternative to evacuation for situations involving radioiodine releases where evacuation cannot be implemented. If procedures are included in the applicable emergency response plan, use of stable iodine should be considered for any such situation in which evacuation or sheltering will not be effective in preventing thyroid doses of 25 rem (see also C.2.3).

C.4 Comparison to Previous PAGs

This section compares the level of protection provided by the previously published PAGs for evacuation (one rem external gamma dose from the plume and 5 rem committed dose to the thyroid from inhalation, under normal evacuation circumstances) with this PAG. The effective dose addressed by this PAG, as well as skin, thyroid, and external gamma doses from the plume during the early phase from the three major exposure pathways for an airborne release were calculated for radionuclide mixes postulated for three nuclear power plant accident sequences. The doses were then normalized for each accident so that they represent a location in the environment where the controlling dose would be equal to the current PAG. These results are shown in Table C-9.

Based on the results shown in Table C-9, the following conclusions are

Table C-9. Comparison of Projected Doses for Various Reactor Accident Scenarios[a]

Accident category[b]	Effective dose equivalent[c] (rem)	Skin dose[d] (rem)	Thyroid dose[e] (rem)	External dose[f] (rem)
SST-1	0.7	6	5	0.02
SST-2	1	5	5	0.4
SST-3	0.4	6	5	0.1

[a]Doses are normalized to the limiting PAG.

[b]See Table E-1 for a description of these accident scenarios.

[c]The dose is the sum of doses from 4-day exposure to external gamma radiation from deposited materials, external exposure to the plume, and the committed effective dose equivalent from inhalation of the plume.

[d]The dose equivalent from external beta radiation from the plume and from 12 hours exposure to materials deposited on skin and clothing.

[e]Committed dose equivalent to the thyroid from inhalation.

[f]External gamma dose equivalent from the plume.

apparent, for the accident sequences analyzed:

1. The PAG for the thyroid is controlling for all three accident categories. For the SST-2 category, effective dose is also controlling. Thus,application of the previous PAG (5 rem) for thyroid would provide the same protection as the revised PAG for all three accident categories.

2. Skin doses will not be controlling for any of the accident sequences (if bathing and change of clothing is completed within 12 hours of plume passage, as assumed).

3. Gamma dose from direct exposure to the plume is small compared to the effective dose from the three major exposure pathways combined.

In summary, for the accident sequences analyzed, the old PAGs provide the same level of protection as the new PAGs. For releases that contain a smaller fraction radioiodines than these accident scenarios the new PAGs are slightly more protective.

C.5 Dose Limits for Workers Performing Emergency Services

Dose limits for workers during emergencies are based on avoiding acute health effects and limiting the risk of delayed health effects, in the context of the need to assure protection of the population and of valuable properties. It is assumed that most such workers are accustomed to accepting an element of risk as a condition of their employment. Examples of occupations that may be affected include law enforcement, firefighting, radiation protection, civil defense, traffic control, health services, environmental monitoring, animal care, and transportation services. In addition, selected workers at utility, industrial, and at farms and other agribusinesses may be required to protect others, or to protect valuable property during an emergency. The above are examples -- not designations -- of workers that may be exposed to radiation during emergencies.

Radiation exposure of workers during an emergency should normally be governed by the Federal Radiation Protection Guidance for Occupational Exposure (EP-87). This guidance specifies an upper bound of five rem committed effective dose equivalent per year for most workers. (Pregnant women, who, under this guidance should not normally engage in work situations that involve more than approximately 50 mrem/month, would normally be evacuated as part of the general population.) The guidance also specifies that doses to workers should be maintained as low as reasonably achievable; that doses should be monitored; and that workers should be informed of the risks involved and of basic principles for radiation protection.

There are some emergency situations, however, for which higher doses may be justified. These include lifesaving operations and the protection of valuable property. International guidance (IC-77) recognizes two

additional dose levels for workers under specially justified circumstances: two times the annual limit for any single event, and five times the annual limit in a lifetime. The dose limits recommended here adopt the former value (10 rem) for operations limited to the protection of valuable property. The latter value (25 rem) may be permitted for situations involving lifesaving operations or activities that are essential to preventing substantial risks to populations. In this context "substantial risks" means collective doses that are significantly larger than those incurred through the protective activities engaged in by the workers. Workers should not operate under dose limits higher than five rem unless the following conditions are satisfied:

1. Lower doses through the rotation of workers or other commonly-used dose reduction methods are not possible, and

2. Instrumentation is available to measure their exposure.

In addition to the limitation on effective dose equivalent, the dose equivalent received in any year by workers under normal occupational conditions is limited to 15 rem to the lens of the eye and 50 rem to any other organ, tissue (including skin), or extremity of the body. (Extremity is defined as the forearms and hands or the lower legs and feet (EP-87).) By analogy to these dose limits for organs and extremities, the limits for workers performing the various categories of emergency services are established at numerical values that are 5 times the limits for effective dose to the lens of the eye and 10 times the limits for effective dose to any other organ, tissue (including skin), or extremity of the body.

Situations may occur in which a dose in excess of 25 rem would be required for lifesaving operations. It is not possible to prejudge the risk that one person should be allowed to take to save the life of another. However, persons undertaking an emergency mission in which the dose would exceed 25 rem to the whole body should do so only on a voluntary basis and with full awareness of the risks involved, including the numerical levels of dose at which acute effects of radiation will be incurred and numerical estimates of the risk of delayed effects.

The risk of acute health effects is discussed in B.2. Table C-10 presents estimated cancer mortality rates for a dose of 25 rem, as a function of age at the time of exposure. The risk of cancer from moderately higher doses will increase proportionately. These values were calculated using risk estimates from BEIR-3 (NA-80) as discussed in Section B.4, and life table analyses that assume the period of cancer risk lasts for the worker's lifetime (BU-81). The risk was calculated for the midpoint of each age range. Roughly equivalent risks of nonfatal cancer and serious genetic effects (if gonadal tissue is exposed) will also be incurred.

The dose limits of 75 rem to the whole body previously recommended by EPA and 100 rem that has been

recommended by NCRP (GL-57) for lifesaving action represents a very high level of risk of acute and delayed health effects. A dose of 100 rem is expected to result in an approximately 15 percent risk of temporary incapacity from nonlethal acute effects and an indeterminate, but less than 5 percent, chance of death within 60 days. This is in addition to a risk of about 1 in 30 of incurring fatal cancer. Such high risk levels can only be accepted by a recipient who has been made aware of the risks involved. Therefore, no absolute dose limit for lifesaving activities is offered.

Table C-10 Cancer Risk to Emergency Workers Receiving 25 Rem Whole Body Dose

Age of the emergency worker at time of exposure (years)	Approximate risk of premature death (deaths per 1,000 persons exposed)	Average years of life lost if premature death occurs (years)
20 to 30	9.1	24
30 to 40	7.2	19
40 to 50	5.3	15
50 to 60	3.5	11

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APPENDIX D

Background for Protective Action Recommendations: Accidental Radioactive Contamination of Food and Animal Feeds*

*This background document concerning food and animal feeds was published by the Food and Drug Administration in 1982.

APPENDIX E

Protective Action Guides for the Intermediate Phase

(Relocation)

Background Information

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Appendix E

Protective Action Guides for the Intermediate Phase (Relocation) Background Information

E.1 Introduction

This Appendix provides background information for the choice of Protective Action Guides (PAGs) for relocation and other protective actions to reduce exposure to deposited radioactive materials during the intermediate phase of the response to a nuclear incident. The resulting PAGs and associated implementing guidance are provided in Chapters 4 and 7, respectively.

This analysis is based on the assumption that an airborne plume of radioactive material has already passed over an area and left a deposit of radioactive material behind, or that such material exists from some other source, and that the public has already been either sheltered or evacuated, as necessary, on the basis of PAGs for the early phase of a nuclear incident, as discussed in Chapters 2 and 5. PAGs for subsequent relocation of the public and other protective actions, as well as dose limits for persons reentering the area from which the public is relocated, are addressed in this Appendix.

We first set forth the assumptions used to derive information pertinent to choosing the dose level at which relocation of the public is appropriate. This is followed by an examination of information relevant to this decision, and selection of the PAG for relocation. The Appendix concludes with a brief discussion of the basis for dose limits for persons temporarily reentering areas from which the public has been relocated.

E.1.1 Response Duration

In order to decide whether to initiate relocation of the public from specific areas it is necessary to predict the dose that would be avoided. One factor in this prediction is the duration of the exposure to be avoided. Relocation can begin as soon as patterns of exposure from deposited radioactivity permit restricted areas to be identified. For the purpose of this analysis, relocation of persons who have not already been evacuated from the restricted zone is assumed to take place on the fourth day after the incident. Return of evacuated persons to their residences outside the restricted zone and transition to relocation status of persons already evacuated is assumed to occur over a period of a week or more.

The period of exposure avoided by relocation ends when the relocated person either returns to his property or is permanently resettled in a new

location. At the time of relocation decisions, it will usually not be possible to predict when either of these actions will occur. Therefore, for convenience of dose projection, it is assumed that the period of exposure avoided is one year and that any extension beyond this period will be determined on the basis of recovery criteria. This assumption corresponds to emergency response planning guidance by ICRP (IC-84) and IAEA (IA-85).

E.1.2 Source Term

The "source term" for this analysis is comprised of the quantities and types of particulate radioactive material found in the environment following a nuclear incident. Nuclear incidents can be postulated with a wide range of release characteristics. The characteristics of the source terms assumed for the development of these PAGs are those postulated for releases from various types of fuel-melt accidents at nuclear power plants (SN-82). Table E-1 provides brief descriptions of these accident types. Radionuclide releases have been estimated for the three most severe accident types (SST-1, SST-2, SST-3) based on postulated core inventories and release fractions (Table E-2). The other types (SST-4 and SST-5) would generally not produce offsite doses from exposure to deposited material sufficient to warrant consideration of relocation.

Table E-1 Brief Descriptions Characterizing Various Nuclear Power Plant Accident Types (SN-82)

Type	Description
SST-1	Severe core damage. Essentially involves loss of all installed safety features. Severe direct breach of containment.
SST-2	Severe core damage. Containment fails to isolate. Fission product release mitigating systems (e.g., sprays, suppression pool, fan coolers) operate to reduce release.
SST-3	Severe core damage. Containment fails by base-mat melt-through. All other release mitigation systems function as designed.
SST-4	Modest core damage. Containment systems operate in a degraded mode.
SST-5	Limited core damage. No failures of engineered safety features beyond those postulated by the various design basis accidents. Containment is assumed to function for even the most severe accidents in this group.

Table E-2 Release Quantities for Postulated Nuclear Reactor Accidents

Principal radionuclides contributing to dose from deposited materials	Half-life (days)	Estimated quantity released[a] (Curies)		
		SST-1	SST-2	SST-3
Zr-95	6.52E+1	1.4E+6	4.5E+4	1.5E+2
Nb-95	3.50E+1	1.3E+6	4.2E+4	1.4E+2
Ru-103	3.95E+1	6.0E+6	2.4E+5	2.4E+2
Ru-106	3.66E+2	1.5E+6	5.8E+4	5.8E+1
Te-132	3.25	8.3E+7	3.9E+6	2.6E+3
I-131	8.05	3.9E+7	2.6E+5	1.7E+4
CS-134	7.50E+2	8.7E+6	1.2E+5	1.3E+2
CS-137	1.10E+4	4.4E+6	5.9E+4	6.5E+1
Ba-140	1.28E+1	1.2E+7	1.7E+5	1.7E+2
La-140	1.67	1.5E+6	5.1E+4	1.7E+2

[a]Based on the product of reactor inventories of radionuclides and estimated fractions released for three accident categories (SN-82).

For other types of source terms, additional analysis may be necessary to assure adequate protection. For example, if the release includes a large proportion of long-lived radionuclides, doses will continue to be delivered over a long period of time, and, if no remedial actions are taken, the dose delivered in the first year may represent only a small portion of the total dose delivered over a lifetime. On the other hand, if the release consists primarily of short-lived radionuclides, almost the entire dose may be delivered within the first year.

From the data in Table E-2, it is apparent that, for the groups of accidents listed, both long and short lived radionuclides would be released. Consequently, doses due to deposited materials from such accidents would be relatively high during the first year followed by long term exposures at lower rates.

E.1.3 Exposure Pathways

The principal exposure pathway to members of the public occupying land contaminated by deposits of radioactive materials from reactor incidents is expected to be exposure of the whole body to external gamma radiation. Although it is normally expected to be of only minor importance, the inhalation pathway would contribute

additional doses to internal organs. The health risks from other pathways, such as beta dose to the skin and direct ingestion of dirt, are also expected to be minor in comparison to the risks due to external gamma radiation (AR-89). Skin and inhalation dose would, however, be important exposure pathways for source terms with significant fractions of pure beta emitters, and inhalation dose would be important for source terms with significant fractions of alpha emitters.

Since relocation, in most cases, would not be an appropriate action to prevent radiation exposure from ingestion of food and water, these exposure pathways have not been included in this analysis. They are addressed in Chapters 3 and 6. In some instances, however, where withdrawal of food and/or water from use would, in itself, create a health risk, relocation may be an appropriate alternative protective action. In this case, the committed effective dose equivalent from ingestion should be added to the projected dose from deposited radionuclides via other pathways, for decisions on relocation.

E.1.4 Response Scenario

This section defines the response zones, population groups, and the activities assumed for implementation of protective actions during the intermediate phase.

After passage of the radioactive plume, the results of environmental monitoring will become available for use in making decisions to protect the public. Sheltering, evacuation, and other actions taken to protect the public from the plume will have already been implemented. The tasks immediately ahead will be to (1) define the extent and characteristics of deposited radioactive material and identify a restricted zone in accordance with the PAG for relocation, (2) relocate persons from and control access to the restricted zone, (3) allow persons to return to areas outside the restricted zone, (4) control the spread of and exposure to surface contamination, and (5) apply simple decontamination and other low-cost, low-risk techniques to reduce the dose to persons who are not relocated.

Because of the various source term characteristics and the different protective actions involved (evacuation, sheltering, relocation, decontamination, and other actions to reduce doses to "as low as reasonably achievable" levels), the response areas for different protective actions may be complex and may vary in size with respect to each other. Figure E-1 shows a generic example of some of the principal areas involved. The area covered by the plume is assumed to be represented by area 1. In reality, variations in meteorological conditions would almost certainly produce a more complicated shape.

Based on plant conditions or other considerations prior to or after the release, members of the public are assumed to have already been evacuated from area 2 and sheltered in area 3. Persons who were evacuated or

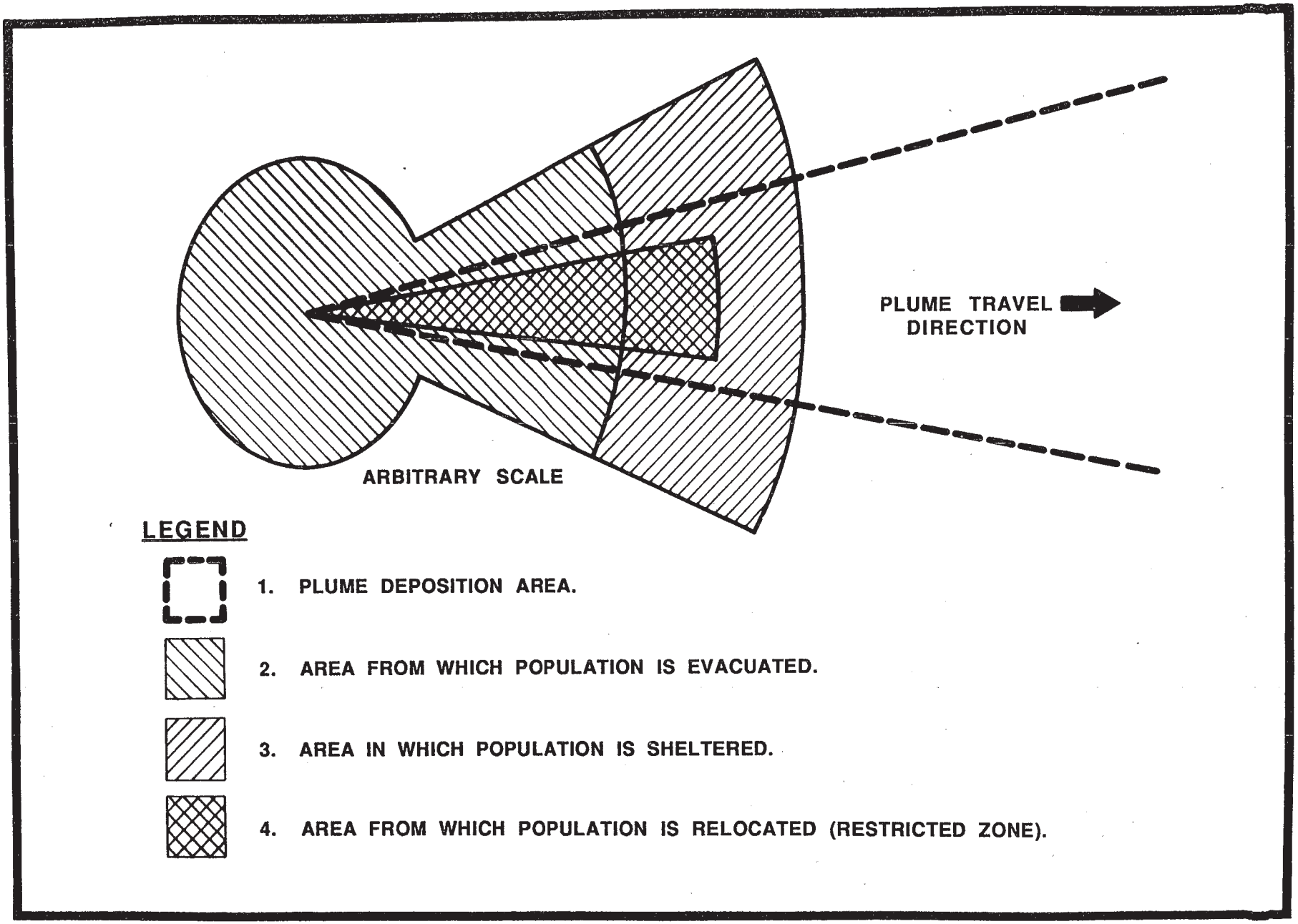

FIGURE E-1. RESPONSE AREAS.

sheltered as a precautionary action for protection from the plume but whose homes are outside the plume deposition area (area 1) are assumed to return to their homes or discontinue sheltering when environmental monitoring verifies the outer boundary of area 1.

Area 4 is the restricted zone and is defined as the area where projected doses are equal to or greater than the relocation PAG. The portion of area 1 outside of area 4 is designated as a study zone and is assumed to be occupied by the public. However, contamination levels may exist here that would be of concern for continued monitoring and decontamination to maintain radiation doses "as low as reasonably achievable" (ALARA).

The relative positions of the boundaries shown in Figure E-1 are dependent on areas evacuated and sheltered. For example, area 4 could fall entirely inside area 2 (the area evacuated) so that relocation of persons from additional areas would not be required. In this case, the relocation PAG would be used only to determine areas to which evacuees could return.

Figure E-2 provides, for perspective, a schematic representation of the response activities expected to be in progress in association with implementation of the PAGs during the intermediate phase of the response to a nuclear incident.

E.2 Considerations for Establishing PAGs for the Intermediate Phase

The major considerations in selecting values for these PAGs for relocation and other actions during the intermediate phase are the four principles that form the basis for selecting all PAGs. Those are discussed in Section E.2.1. Other considerations (Federal radiation protection guidance and risks commonly confronting the public) are discussed in Sections E.2.2 and E.5.

In addition, a planning group consisting of State, Federal, and industry officials provided recommendations in 1982 which EPA considered in the development of the format, nature, and applicability of PAGs for relocation. Abbreviated versions of these recommendations are as follows:

a. The PAGs should apply to commercial, light-water power reactors.

b. The PAGs should be based primarily on health effects.

c. Consideration should be given to establishing a range of PAG values.

d. The PAGs should be established as high as justifiable because at the time of the response, it would be possible to lower them, if justified, but it probably would not be possible to increase them.

e. Only two zones (restricted and unrestricted) should be established to simplify implementation of the PAGs.

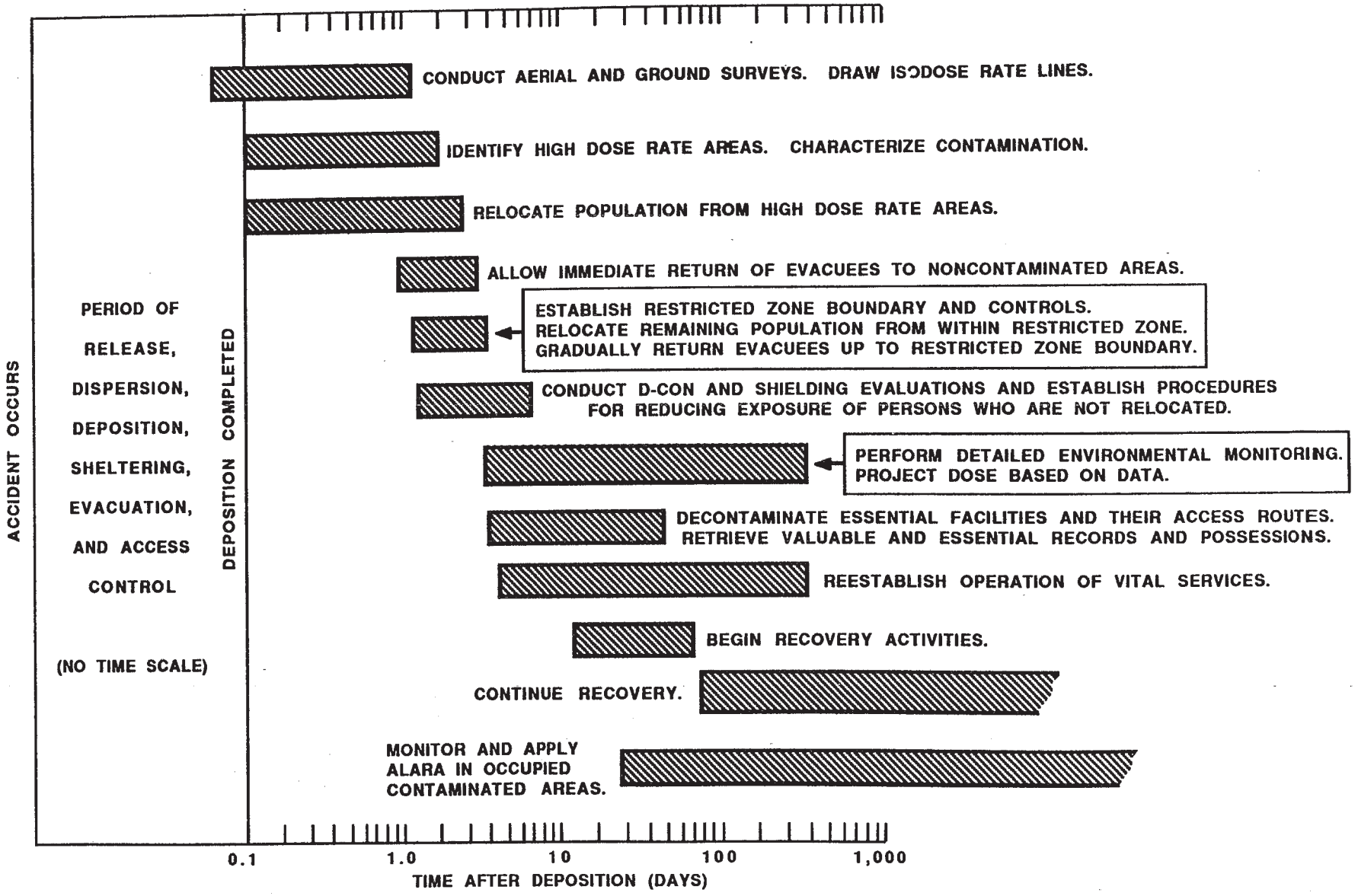

FIGURE E-2 POTENTIAL TIME FRAME OF RESPONSE TO A NUCLEAR INCIDENT.

f. The PAGs should not include past exposures.

g. Separate PAGs should be used for ingestion pathways.

h. PAGs should apply only to exposure during the first year after an incident.

Although these PAGs apply to any nuclear incident, primary consideration was given to the case of commercial U.S. reactors. In general, we have found it possible to accommodate most of the above recommendations.

E.2.1 Principles

In selecting values for these PAGs, EPA has been guided by the principles that were set forth in Chapter 1. They are repeated here for convenience:

1. Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which they are not likely to occur) should be avoided.

2. The risk of delayed effects on health (primarily cancer and genetic effects, for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health, under emergency conditions, and are reasonably achievable.

3. PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health achievable at acceptable cost should be carried out.

4. Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.

Appendix B analyzed the risks of health effects as a function of dose (Principles 1 and 2). Considerations for selection of PAGs for the intermediate phase of a nuclear incident differ from those for selection of PAGs for the early phase primarily with regard to implementation factors (i.e., Principles 3 and 4). Specifically, they differ with regard to cost of avoiding dose, the practicability of leaving infirm persons and prisoners in the restricted zone, and avoiding dose to fetuses. Although sheltering is not generally a suitable alternative to relocation, other alternatives (e.g., decontamination and shielding) are suitable. These considerations are reviewed in the sections that follow.

E.2.1.1 Cost/Risk Considerations

The Environmental Protection Agency has issued guidelines for internal use in performing regulatory impact analyses (EP-83). These include consideration of the appropriate range of costs for avoiding a statistical death. The values are inferred from the additional compensation associated with employment carrying a higher than normal risk of mortality and are expressed as a range of $0.4 to $7

million per statistical death avoided. The following discussion compares these values to the cost of avoiding radiation-induced fatal cancers through relocation.

The basis for estimating the societal costs of relocation are analyzed in a report by Bunger (BU-89). Estimated incremental societal costs per day per person relocated are shown below. (Moving and loss of inventory costs are averaged over one year.)

Moving	$1.70
Loss of use of residence	2.96
Maintain and secure vacated property	0.74
Extra living costs	1.28
Lost business and inventories	14.10
Extra travel costs	4.48
Idle government facilities	1.29
Total	$26.55

The quantity of interest is the dose at which the value of the risk avoided is equal to the cost of relocation. Since the above costs are expressed in dollars/person-day, it is convenient to calculate the dose that must be avoided per-person day. The equation for this is:

$$H_E = \frac{C}{VR}$$

where:

H_E = dose
C = cost of relocation
V = value of avoiding a statistical death
R = statistical risk of death from radiation dose

Using the values cited above, and a value for R of 3×10^{-4} deaths/rem (See Appendix B), one obtains a range of doses of about 0.01 to 0.2 rem/day. Thus, over a period of one year the total dose that should be avoided to justify the cost of relocation would be about 5 to 80 rem.

These doses are based on exposure accumulated over a period of one year. However, exposure rates decrease with time due to radioactive decay and weathering. Thus, for any given cumulative dose in the first year, the daily exposure rate continually decreases, so that a relocated person will avoid dose more rapidly in the first part of the year than later. Figure E-3 shows the effect of changing exposure rate on the relationship between the cost of avoiding a statistical death and the time after an SST-2 accident (See Table E-1) for several assumed cumulative annual doses. The curves represent the cost per day divided by the risk of fatality avoided by relocation per day, at time t, for the annual dose under consideration, where t is the number of days after the accident. The right ordinate shows the gamma exposure rate (mR/h) as a function of time for the postulated radionuclide mix at one meter height.

The convex downward curvature results from the rapid decay of short-lived radionuclides during the first few weeks following the accident. Since the cost per day for relocation is assumed to be constant and the dose avoided per day decreases, the cost effectiveness of relocation decreases with time. For this reason it is cost

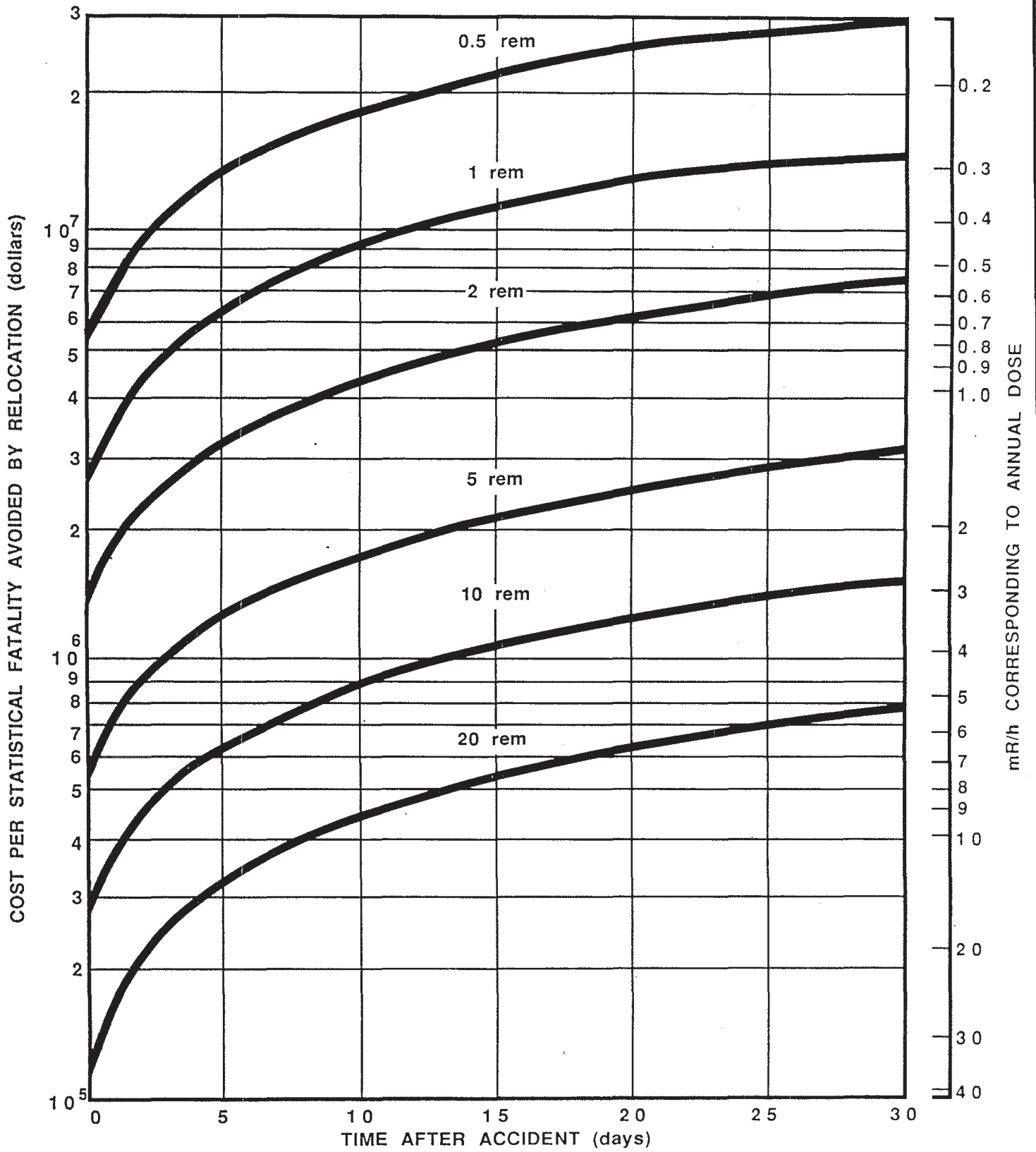

FIGURE E-3. COST OF AVOIDING STATISTICAL FATALITIES AND EXPOSURE RATES CORRESPONDING TO VARIOUS TOTAL FIRST YEAR DOSES (ASSUMES AN SST-2 ACCIDENT AND A $27 PER PERSON-DAY COST OF RELOCATION).

effective to quickly recover areas where the population has been relocated at projected doses only marginally greater than the PAG.

Only trends and general relationships can be inferred from Figure E-3 because it applies to a specific mix of radionuclides. However, for this radionuclide mix, cost analysis supports relocation at doses as low as one rem for the first week and two rem for up to 25 days after an accident.

E.2.1.2 Protection of Special Groups

Contrary to the situation for evacuation during the early phase of an incident, it is generally not practical to leave a few persons behind when most members of the general population have been relocated from a specified area for extended periods of time. Further, no data are available on differing risks of relocation for different population groups. In the absence of such data, we have assumed that these risks will be similar to those from evacuation. Those risks were taken as equivalent to the health risk from doses of 30 mrem for members of the general population and of 150 mrem for persons at high risk from evacuation (see Appendix C). Therefore, to satisfy Principle 4 for population groups at high risk, the PAG for relocation should not be lower than 150 millirem. Given the arbitrary nature of this derivation, it is fortunate that this value is much lower than the PAG selected, and is therefore not an important factor in its choice.

Fetuses are a special group at greater risk of health effects from radiation dose than is the general population, but not at significantly greater risk from relocation itself. The risk of mental retardation from fetal exposure (see Appendix B) is significant. It is affected by the stage of pregnancy relative to the assumed one-year exposure, because the 8th to 15th week critical period during which the risk is greatest, must be considered in relation to the rapidly changing dose rate. Taking these factors into account, it can be postulated that the risk of mental retardation due to exposure of the fetus during the intermediate phase will range from one to five times the cancer risk of an average member of the public, depending upon when conception occurs relative to the time of the incident. The elevated risk of radiation-induced cancer from exposure of fetuses is less significant, as discussed in Appendix B.

It will usually be practicable to reduce these risks by establishing a high priority for efforts other than relocation to reduce the dose in cases where pregnant women reside near the boundary of the restricted zone. However, women who are less than seven months pregnant may wish to relocate for the balance of their pregnancy if the projected dose during pregnancy cannot be reduced below 0.5 rem.

E.2.2 Federal Radiation Protection Guides

The choice of a PAG at which relocation should be implemented does not mean that persons outside the boundary of the restricted zone should not be the subject of other protective actions to reduce dose. Such actions are justified on the basis of existing Federal radiation protection guidance (FR-65) for protecting the public, including implementation of the principle of maintaining doses "as low as reasonably achievable" (ALARA).

The intended actions to protect the public from radiation doses on the basis of Radiation Protection Guides (RPGs) are those related to source control. Although it is reasonable for members of the public to receive higher exposure rates prior to the source term being brought under control, the establishment of acceptable values for relocation PAGs must include consideration of the total dose over the average remaining lifetime of exposed individuals (usually taken as 50 years).

The nationally and internationally recommended upper bound for dose in a single year from man-made sources, excluding medical radiation, is 500 mrem per year to the whole body of individuals in the general population (IC-77, FR-65). These recommendations were not developed for nuclear incidents. They are also not appropriate for chronic exposure. The ICRP recommends an upper bound of 100 mrem per year, from all sources combined, for chronic exposure (IC-77). The corresponding 50-year dose at 100 mrem/yr is 5 rem. We have chosen to limit: a) the projected first year dose to individuals from an incident to the Relocation PAG, b) the projected second year dose to 500 mrem, and c) the dose projected over a fifty-year period to 5 rem. Due to the extended duration of exposures and the short half-life of important radioiodines, no special limits for thyroid dose are needed.

E.3. Dose from Reactor Incidents

Doses from an environmental source will be reduced through the natural processes of weathering and radioactive decay, and from the shielding associated with part time occupancy in homes and other structures. Results of dose calculations based on the radiological characteristics of releases from three categories of postulated, fuel-melt, reactor accidents (SST-1, SST-2, and SST-3) (SN-82) and a weathering model from WASH-1400 (NR-75) are shown in Table E-3. This table shows the relationship between annual doses for the case where the sum, over fifty years, of the effective dose equivalent from gamma radiation and the committed effective dose equivalent from inhalation of resuspended materials is 5 rem. Radioactive decay and weathering reduces the second year dose from reactor incidents to 20 to 40 percent of the first year dose, depending on the radionuclide mix in the release.

Based on studies reported in WASH-1400 (NR-75), the most conservative dose reduction factor for

Table E-3 Annual Doses Corresponding to 5 Rem in 50 Years[a]

Year	Dose According to Accident Category[b] (rem)		
	SST-1	SST-2	SST-3
1	1.25	1.60	1.91
2	0.52	0.44	0.38
3	0.33	0.28	0.24
4	0.24	0.20	0.17
5	0.18	0.16	0.13
6	0.14	0.12	0.11
7	0.12	0.11	0.090
8	0.10	0.085	0.070
9	0.085	0.075	0.065
10	0.080	0.070	0.060
11	0.070	0.060	0.050
12	0.060	0.055	0.050
15	0.055	0.045	0.040
20	0.045	0.040	0.030
25	0.040	0.035	0.025
30	0.030	0.030	0.025
40	0.025	0.020	0.020
50	0.020	0.015	0.010

[a]Whole body dose equivalent from gamma radiation plus committed effective dose equivalent from inhalation assuming a resuspension factor of 10^{-6} m^{-1}. Weathering according to the WASH-1400 model (NR-75) and radioactive decay are assumed.

[b]Radionuclide abundance ratios are based on reactor inventories from WASH-1400 (NR-75). Release quantities for accident categories SST-1, SST-2 and SST-3 are shown in Table E-2. Initial concentrations are assumed to have decayed for 4 days after reactor shutdown.

structures (frame structures) is about 0.4 (dose inside divided by dose outside) and the average fraction of time spent in a home is about 0.7. Combining these factors yields a net dose reduction factor of about 0.6. In most cases, therefore, structural shielding would be expected to reduce the dose to persons who are not relocated to 60 percent (or less) of the values shown in Table E-3 before the application of decontamination.

E.4. Alternatives to Relocation

Persons who are not relocated, in addition to dose reduction provided by

partial occupancy in homes and other structures, can reduce their dose by the application of various techniques. Dose reduction efforts can range from the simple processes of scrubbing and/or flushing surfaces, soaking or plowing of soil, removal and disposal of small spots of soil found to be highly contaminated (e.g., from settlement of water), and spending more time than usual in lower exposure rate areas (e.g., indoors), to the difficult and time consuming processes of removal, disposal, and replacement of contaminated surfaces. It is anticipated that simple processes would be most appropriate to reduce exposure rates for persons living in contaminated areas outside the restricted zone. Many of these can be carried out by the residents with support from officials for monitoring, guidance on appropriate actions, and disposal. The more difficult processes will usually be appropriate for recovery of areas from which the population is relocated.

Decontamination experiments involving radioactive fallout from nuclear weapons tests have shown reduction factors for simple decontamination methods in the vicinity of 0.1 (i.e., exposure rate reduced to 10 percent of original values). However, recent experiments at the Riso National Laboratory in Denmark (WA-82, WA-84), using firehoses to flush asphalt and concrete surfaces contaminated with radioactive material of the type that might be deposited from reactor accidents, show decontamination factors for radionuclides chemically similar to cesium that are in the range of 0.5 to 0.95, depending on the delay time after deposition before flushing is applied. The factor for ruthenium on asphalt was about 0.7 and was independent of the delay of flushing. The results of these experiments indicate that decontamination of the important reactor fission products from asphalt or concrete surfaces may be much more difficult than decontamination of nuclear weapons fallout. Other simple dose reduction methods listed above would be effective to varying degrees. The average dose reduction factor for gamma radiation from combinations of simple decontamination methods is estimated to be at least 0.7. Combining this with the 40 percent reduction estimated above for structural shielding indicates that the doses listed in Table E-3 may be more than twice as high as those which would actually be received by persons who are not relocated.

E.5 Risk Comparisons

Many hazardous conditions and their associated risks are routinely faced by the public. A lingering radiation dose will add to those risks, as opposed to substituting one risk for another, and, therefore, radiation protection criteria cannot be justified on the basis of the existence of other risks. It is, however, useful to review those risks to provide perspective. This section compares the risks associated with radiation doses to those associated with several other risks to which the public is commonly exposed.

Figure E-4 compares recent statistics for the average lifetime risk of accidental death in various occupations to the estimated lifetime risk of fatal cancer for members of the general population exposed to radiation doses ranging up to 25 rem. Non-radiation risk values are derived from information in reference (EP-81) and radiation risk values are from Appendix B. These comparisons show, for example, that the lifetime cancer risk associated with a dose of 5 rem is comparable to the lifetime risk of accidental death in some of the safest occupations, and is well below the average lifetime risk of accidental death for all industry.

Risks of health effects associated with radiation dose can also be compared to other risks facing individuals in the general population. The risks listed in Table E-4 are expressed as the number of premature deaths and the average reduction of life-span due to these deaths within a group of 100,000 persons. For purposes of comparison, a dose of 5 rem to each member of a population group of 100,000 persons representative of the average U.S. population carries an estimated lifetime risk of about 150 fatal cancers (see Appendix B). The number of deaths resulting from the various causes listed in Table E-4 is based on data from mortality records.

In summary, the risk of premature death normally confronting the public from specific types of accidents ranges from about 2 to 1000 per 100,000 population. The estimated radiation doses required to produce a similar risk of death from radiation-induced cancer range from about 0.07 to 33 rem.

E.6 Relocation PAG Recommendations

Previous sections have reviewed data, standards, and other information relevant to establishing PAGs for relocation. The results are summarized in Table E-5, in relation to the principles set forth in Section E.2.1.

Based on the avoidance of acute effects alone (Principle 1) 50 rem and 10 rem are upper bounds on the dose at which relocation of the general population and fetuses, respectively, is justified. However, on the basis of control of chronic risks (Principle 2) a lower upper bound is appropriate. Five rem is taken as an upper bound on acceptable risk for controllable lifetime exposure to radiation, including avoidable exposure to accidentally deposited radioactive materials. This corresponds to an average of 100 mrem per year for fifty years, a value commonly accepted as an upper bound for chronic annual exposure of members of the public from all sources of exposure combined, other than natural background and medical radiation (IC-77). In the case of projected doses from nuclear reactor accidents, a five rem lifetime dose corresponds to about 1.25 to 2 rem from exposure during the first year and 0.4 to 0.5 rem from exposure during the second year.

Analyses based on Principle 3 (cost/risk) indicate that considering cost

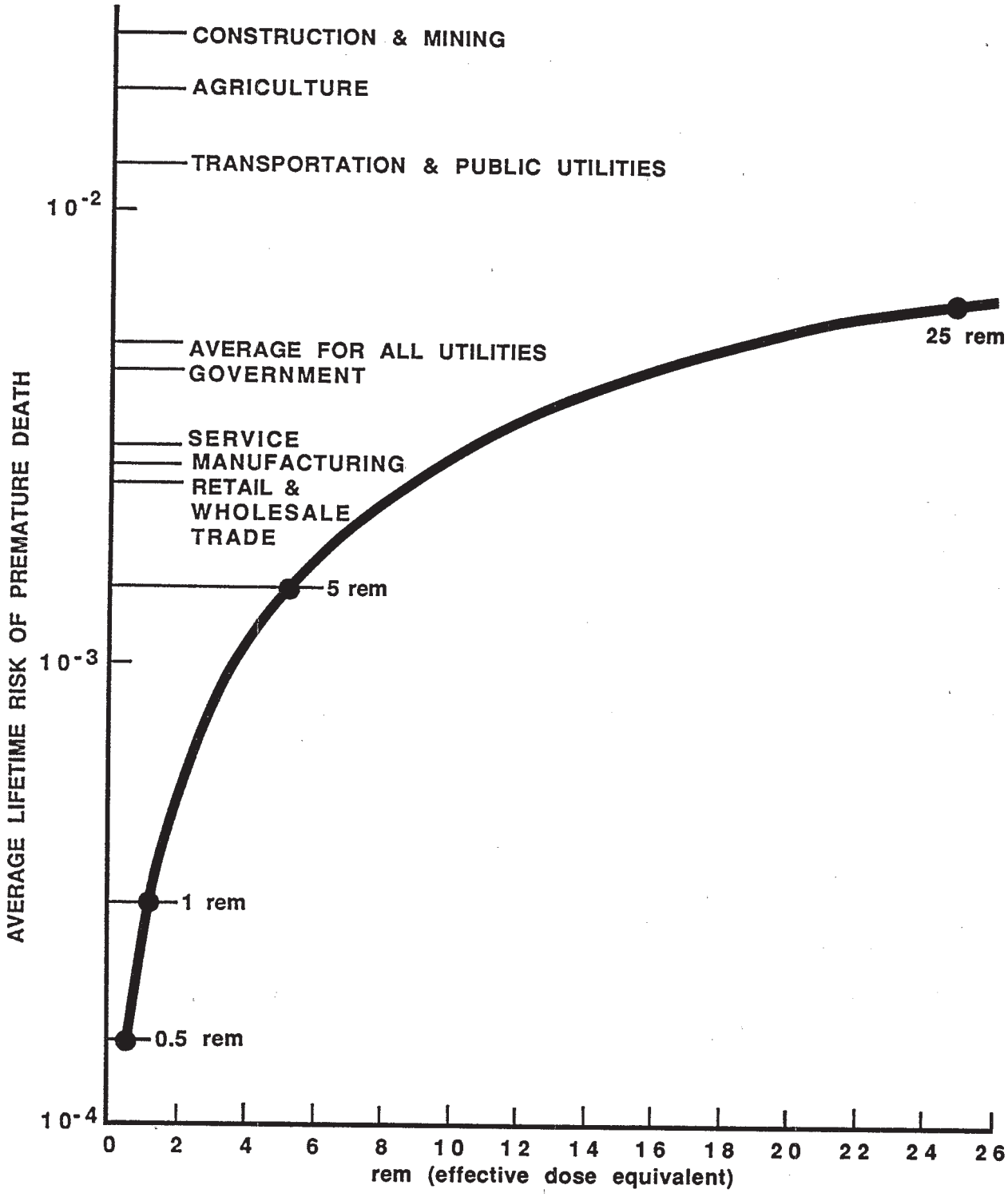

FIGURE E-4. AVERAGE LIFETIME RISK OF DEATH FROM WHOLE BODY RADIATION DOSE COMPARED TO THE AVERAGE RISK OF ACCIDENTAL DEATH FROM LIFETIME (47 YEARS) OCCUPATION IN VARIOUS INDUSTRIES.

Table E-4 Measure of Lifetime Risk of Mortality from a Variety of Causes[a] (Cohort Size = 100,000)

Nature of accident	Premature deaths	Aggregate years of life lost to cohort	Reduction of life expectancy at birth (years)	Average years of life lost to premature deaths
Falls	1,000	12,000	0.12	11
Fires	300	7,600	0.076	26
Drowning	190	8,700	0.087	45
Poisoning by drugs and medicaments	69	2,500	0.025	37
Cataclysm[b]	17	490	0.005	30
Bites and stings[c]	8	220	0.002	27
Electric current in homes[d]	8	290	0.003	37

[a]All mortality effects shown are calculated as changes from the U.S. Life Tables for 1970 to life tables with the cause of death under investigation removed. These effects also can be interpreted as changes in the opposite direction, from life tables with the cause of death removed to the 1970 Life Table. Therefore, the premature deaths and years of life lost are those that would be experienced in changing from an environment where the indicated cause of death is not present to one where it is present. All values are rounded to no more than two significant figures.

[b]Cataclysm is defined to include cloudburst, cyclone, earthquake, flood, hurricane, tidal waves, tornado, torrential rain, and volcanic eruption.

[c]Accidents by bite and sting of venomous animals and insects include bites by centipedes, venomous sea animals, snakes, and spiders; stings of bees, insects, scorpions, and wasps; and other venomous bites and stings. Other accidents caused by animals include bites by any animal and nonvenomous insect; fallen on by horse or other animal; gored; kicked or stepped on by animal; ant bites; and run over by horse or other animal. It excludes transport accidents involving ridden animals; and tripping, falling over an animal. Rabies is also excluded.

[d]Accidents caused by electric current from home wiring and appliances include burn by electric current, electric shock or electrocution from exposed wires, faulty appliances, high voltage cable, live rail, and open socket. It excludes burn by heat from electrical appliances and lighting.

Table E-5 Summary of Considerations for Selecting PAGs for Relocation

Dose (rem)	Consideration	Principle
50	Assumed threshold for acute health effects in adults.	1
10	Assumed threshold for acute health effects in the fetus.	1
6	Maximum projected dose in first year to meet 0.5 rem in the second year[a].	2
5	Maximum acceptable annual dose for normal occupational exposure of adults.	2
5	Minimum dose that must be avoided by one year relocation based on cost.	3
3	Minimum projected first-year dose corresponding to 5 rem in 50 years[a].	2
3	Minimum projected first-year dose corresponding to 0.5 rem in the second year[a].	2
2	Maximum dose in first year corresponding to 5 rem in 50 years from a reactor incident, based on radioactive decay and weathering only.	2
1.25	Minimum dose in first year corresponding to 5 rem in 50 years from a reactor incident based on radioactive decay and weathering only.	2
0.5	Maximum acceptable single-year dose to the general population from all sources from non-recurring, non-incident exposure.	2
0.5	Maximum acceptable dose to the fetus from occupational exposure of the mother.	2
0.1	Maximum acceptable annual dose to the general population from all sources due to routine (chronic), non-incident, exposure.	2
0.03	Dose that carries a risk assumed to be equal to or less than that from relocation.	4

[a]Assumes the source term is from a reactor incident and that simple dose reduction methods are applied during the first month after the incident to reduce the dose to persons not relocated from contaminated areas.

alone would not drive the PAG to values less than 5 rem. Analyses in support of Principle 4 (risk of the protective action itself) provide a lower bound for relocation PAGs of 0.15 rem.

Based on the above, 2 rem projected committed effective dose equivalent from exposure in the first year is selected as the PAG for relocation. Implementation of relocation at this value will provide reasonable assurance that, for a reactor accident, a person relocated from the outer margin of the relocation zone will, by such action, avoid an exposure rate which, if continued over a period of one year, would result in a dose of about 1.2 rem. This assumes that 0.8 rem would be avoided without relocation through normal partial occupancy of homes and other structures. This PAG will provide reasonable assurance that persons outside the relocation zone, following a reactor accident, will not exceed 1.2 rem in the first year, 0.5 rem in the second year, and 5 rem in 50 years. The implementation of simple dose reduction techniques, as discussed in section E-4, will further reduce dose to persons who are not relocated from contaminated areas. Table E-6 summarizes the estimated maximum dose that would be received by these persons for various reactor accident categories with and without the application of simple dose reduction techniques. In the case of non-reactor accidents these doses will, in general, differ, and it may be necessary to apply more restrictive PAGs to the first year in order to assure conformance to the second year and lifetime objectives noted above.

Since effective dose does not include dose to the skin (and for other reasons discussed in Appendix B) protective action to limit dose to skin is recommended at a skin dose 50 times the numerical value of the PAG for effective dose. This includes consideration of the risk of both curable and fatal cancers.

E.7 Criteria for Reentry into the Restricted Zone

Persons may need to reenter the restricted zone for a variety of reasons, including radiation monitoring, recovery work, animal care, property maintenance, and factory or utility operation. Some persons outside the restricted zone, by nature of their employment or habits, may also receive higher than average radiation doses. Tasks that could cause such exposures include: 1) changing of filters on air handling equipment (including vehicles), 2) handling and disposal of contaminated vegetation (e.g., grass and leaves) and, 3) operation of control points for the restricted zone.

Individuals who reenter the restricted zone or who perform tasks involving exposure rates that would cause their radiation dose to exceed that permitted by the PAGs should do so in accordance with existing Federal radiation protection guidance for occupationally exposed workers (EP-87). The basis for that guidance has been provided elsewhere (EP-87).

Table E-6 Estimated Maximum Doses to Nonrelocated Persons From Areas Where the Projected Dose is 2 REM[a]

Accident Category	Dose (rem)					
	No additional dose reduction			Early simple dose reduction[b]		
	Year 1	Year 2	50 years	Year 1	Year 2	50 years
SST-1	1.2	0.5	5.0	0.9	0.35	3.5
SST-2	1.2	0.34	3.9	0.9	0.24	2.7
SST-3	1.2	0.20	3.3	0.9	0.14	2.3

[a]Based on relocation at a projected dose of 2 rem in the first year and 40 percent dose reduction to nonrelocated persons from normal, partial occupancy in structures. No dose reduction is assumed from decontamination, shielding, or special limitations on time spent in high exposure rate areas.

[b]The projected dose is assumed to be reduced 30 percent by the application of simple dose reduction techniques during the first month. If these techniques are completed later in the first year, the first year dose will be greater.

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APPENDIX F

Radiation Protection Criteria for the Late Phase

Background Information

(Reserved)

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