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Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses

Interim Recommendations

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

This report describes approaches to calculating and expressing radiation doses to the embryo/fetus from internal radionuclides. Information was obtained for selected, occupationally significant radionuclides in chemical forms that provided a spectrum of metabolic and dosimetric characteristics. Fractional placental transfer and/or ratios of concentration in the embryo/fetus to that in the woman were estimated for these materials, and were combined with data from biokinetic transfer models to predict radioactivity levels in the embryo/fetus as a function of stage of pregnancy and time after entry into the transfer compartment or blood of the pregnant woman.

Medical Internal Radiation Dosimetry (MIRD) methodologies were extended to formalize and describe details for calculating radiation absorbed doses to the embryo/fetus. Calculations were performed for representative situations; introduction of 1 μCi into a woman's blood at successive months of pregnancy was assumed to accommodate the stage dependence of geometric relationships and biological behaviors. Summary tables of results, correlations, and dosimetric relations, and of tentative generalized categorizations, are provided in the report.

These approaches yield radiation absorbed doses, and multiplication by a quality factor converts them to dose equivalent. This is the most common quantity for stating prenatal dose limits and is appropriate for those effects that are unique to prenatal exposure. Our knowledge is currently insufficient to warrant the use of radiation protection limits for prenatal radionuclide exposures that are based on lifetime alterations.

CONTENTS

CONTENTS (contd)

APPENDIXES

FIGURES

FIGURES (contd)

TABLES

TABLES (contd)

TABLES (contd)

TABLES (contd)

TABLES (contd)

TABLES (contd)

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EXECUTIVE SUMMARY

International recognition that the embryo/fetus is especially susceptible to radiation injury has led to ongoing efforts to develop recommendations and draft regulations to limit its exposure. Recommended limits are usually specified in terms of the radiation doses to the embryo/fetus or conceptus, although they are sometimes stated relative to exposure of the pregnant woman, and radiation dose equivalent is the most common and relevant quantity for purposes of this project. These recommendations usually include comments regarding the difficulties in calculating prenatal radiation doses from internally deposited radionuclides, especially those resulting from inadequate quantitative information about prenatal radionuclide concentrations and placental transfer and kinetics. This project was undertaken to identify, locate, and interpret available information to develop recommendations to the U.S. Nuclear Regulatory Commission (NRC) for addressing the questions associated with calculating radiation dose to the embryo/fetus from internal radionuclides.

Our previous activities have included assembling the available literature, analyzing and tabulating data on placental transfer and concentrations in the embryo/fetus relative to the pregnant woman, determining ways to estimate prenatal radioactivity levels from minimal information, and developing dosimetric approaches for calculating radiation absorbed doses to the embryo or fetus from incorporated radionuclides. This report reviews the current status of our approaches to these determinations and discusses the applicability of expressions that have been proposed for stating radiation doses to the conceptus from deposited radionuclides. The appendixes in the current revision give a wide array of calculations and tabulations of dosimetric factors and radiation doses.

Two main types of approach may be used to estimate concentrations or activities of radionuclides in the embryo or fetus for calculating energy deposition and radiation absorbed dose. One approach is particularly relevant when little information is available; it uses measured ratios of embryo/fetal concentrations to those in pregnant animals or women, together with the dilution of activity that results from growth, to estimate relative fetal activity. The other approach estimates fractional transfer from maternal blood to the embryo/fetus, or uses transfer kinetics and patterns to the conceptus as a function of stage of pregnancy, route of intake by the pregnant individual, and time after intake or placental transfer. The implications inherent in the two approaches differ somewhat, but they may be combined to provide complementary analytical and dosimetric results.

To expedite efforts, biological data were first assembled for a selected set of radionuclides that were expected to be of greatest significance for prenatal exposure in the work environment. These materials, which will be referred to as the priority radionuclides, are 1) tritium and carbon in inorganic forms, 2) tritium and carbon in three typical organic forms, i.e., glucose, amino acid, and thymidine, 3) cobalt in inorganic forms and as vitamin B-12, 4) strontium, 5) ruthenium, 6) iodine, 7) cesium, and 8) plutonium. These priority elements are widely available, and substantial amounts of comparative information were available for many of them in human and animal pregnancies. These radionuclides also provided a reasonable spectrum of metabolic

characteristics. For the present report, the metabolic models were expanded, several additional isotopes or chemical forms in selected cases were included, and more complete tables were developed to illustrate biokinetic and dosimetric differences associated with their physical properties. Moreover, tabulations presenting dose rates and monthly doses are provided. It was anticipated that a wider range of elements would be evaluated in subsequent efforts and, because of their importance, biokinetic models and tables of calculated doses for uranium and americium have been added in this report.

The data for the priority materials were used as the primary basis for developing approaches. Radionuclide concentrations in the conceptus are dependent on stage of gestation, which also affects geometry. The Medical Internal Radiation Dosimetry (MIRD) methodologies were used as a basis for efforts that developed procedures to make direct calculations in cases where dosimetric values were available, and to formalize and describe details of approaches for calculating radiation absorbed doses relative to unit maternal burdens.

These approaches were used to provide representative examples of the calculations and to prepare tabulations of results for relevant radioisotopes of the priority materials. These efforts assumed a burden of 1 μCi in the first transfer compartment (blood) of the pregnant woman at initial times corresponding to each month of gestation. Activity in the woman and in the embryo/fetus at each successive month was estimated from the biological considerations and biokinetic behaviors. These were used to select, or calculate when necessary, corresponding values of specific absorbed fractions and S-values for self-dose relative to stage of gestation, as well as the contribution of activity in the woman to the dose, with specific allowances for configuration and size of the embryo/fetus and woman throughout pregnancy.

Our analyses and calculations for these radionuclides provide illustrative examples. Summary tables and graphs of the resulting relationships and of general dosimetric relations are included as appendixes. We also provide some tentative and simplified categorizations for other materials by stage of gestation and dosimetric features. Until additional information on placental transfer and biokinetics for other radionuclides is collated and analyzed, however, the application of the recommended methodologies for calculating dose to the embryo/fetus will be restricted. It is suggested that the most appropriate interim approach to approximation would be to use the sum of the self-dose to the uterus, or uterine contents if available, plus the dose from radioactivity in the pregnant woman; these could be based on publisned geometrical models determined for specific gestational stages.

It has been proposed that overall radiation protection concerns might be best met if prenatal dose limits were stated in terms of effective dose equivalent or committed dose equivalent. Limitations in our knowledge lead to uncertainties in determining these quantities; it seems advisable to defer their use until further information becomes available, when their use may have greater validity. The approaches to calculation suggested in this report result in radiation absorbed doses, and multiplication by the appropriate quality factor readily converts these to dose equivalent. This is the quantity most commonly

used for stating prenatal doses limits from radionuclides, and is considered to be the most appropriate expression relative to controlling for the unique effects associated with prenatal exposure.

FOREWORD

This document was prepared to summarize information of various types that we assembled, concepts that evolved from analyzing this information, and interim recommendations concerning approaches to expressing and calculating radiation doses to the embryo/fetus from internal radionuclides. This version of the report has been prepared in response to reactions to a draft that was widely distributed to members of the radiological protection and health physics communities to solicit their comments. In particular, it now accommodates requests for expansion and clarification of text, inclusion of additional radionuclides, and preparation of a wider array of biokinetic and dosimetric tables. Useful comments and suggestions were received that have facilitated making revisions, which, we hope, have resulted in a document that will be generally acceptable and useful.

The original format selected for the report allowed much of the numerical information to be presented in appendixes. These were considered inherent components of the report and recommendations, although it was anticipated that further values, relationships, and concepts would be developed and made available. This approach has facilitated integration of other biokinetic and dosimetric information and of the enhanced approaches to calculations in this report. In addition, this approach will allow subsequent analyses of information and resulting calculated values to be disseminated as a series of supplemental appendixes or revisions.

Appreciation is again extended to Pacific Northwest Laboratory colleagues, U.S. Nuclear Regulatory Commission staff, and investigators from other institutions who took time to review earlier working drafts of this report. We are also grateful for the helpful suggestions that were made in response to the request for comment; these led to revisions and extensive expansions of content that form the basis for the report in its present form.

I. INTRODUCTION

A. BACKGROUND CONSIDERATIONS

Mammalian embryos and fetuses are more susceptible than adults to being adversely affected by radiation. Prenatal irradiation can result in intrauterine growth retardation, increased prenatal and postnatal mortality, and malformations or congenital deficits of central nervous system function. The likelihoods of producing these various effects are related to the specific stages of prenatal development during the period of exposure. The intent of current regulatory guidance statements of the U.S. Nuclear Regulatory Commission (NRC), as well as recommendations of other national and international organizations, are generally consistent with the recently revised 10 CFR Part 20. In general, all involve limiting total radiation dose to the conceptus through placing more stringent restrictions on exposure of pregnant women than on other members of the occupational population and requiring that the allowable dose does not vary markedly from a uniform monthly rate throughout gestation.

Historically, a more restrictive limit was based on the potential for producing developmental abnormalities, as well as for carcinogenesis; this limit and its rationale appear in sequential versions of NRC Regulatory Guide 8.13. The evolution of the relevant concepts was reviewed in National Council on Radiation Protection (NCRP) Report No. 53 (NCRP 1977b) among other documents, but the limit has long remained at a total of 500 mrem (5 mSv) to the embryo/fetus throughout gestation. Epidemiologic evaluations and some analyses of dose-response relationships for central nervous system dysfunction in the Japanese offspring who had received atomic bomb irradiation during specific stages of gestation suggested that the response was linear and nonthreshold. Although this characterization of the relationship has not been unanimously accepted, it led the NCRP to recommend in Report No. 91 (NCRP 1987) that the monthly fraction of the permissible radiation dose should be no more than one-tenth of the total.

Tumor development following prenatal or neonatal exposure of experimental animals has been studied for external radiations and for a limited number of internally deposited radioisotopes. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1986) calculated that the risk for mental retardation by prenatal irradiation was greater than that for carcinogenesis. The question of carcinogenesis by prenatal radionuclide exposure, however, presents special problems (Sikov 1989). Radionuclides for which perinatal carcinogenesis has been studied include hydrogen, carbon, strontium, iodine, and plutonium; these are among the priority radionuclides to be discussed here. The results illustrate some of the difficulties in deriving direct relationships between maternal exposure to radionuclides, prenatal concentrations, and radiation doses, as well as the role of inhomogeneities of radiation doses to fetal and neonatal tissues and differing effectiveness among particulate radiations.

When considered relative to exposures of short duration from external photon beams, the specific dose-effect relationships for various radionuclides differ among indices of early or prenatal effect, as well as for delayed embryo/fetal toxic effects, such as life-shortening and oncogenesis. These relationships further change throughout progressive developmental stages and interact with the well-known stage-dependent sensitivity differences (critical periods), which are superimposed on dose-rate effectiveness factors (DREF) associated with protraction of the radiation exposure from internal radionuclides, all of which may lead to apparent differences in responsiveness. Thus, the combined contributions of dosimetric factors and developmental considerations help explain the observations of stage-related differences in responses, which range from radionuclide specificity in target organs and tissues and in morphologic lesions to the predominant tumor types and sites at which tumors develop. These factors also bear on the question of appropriate approaches to determine and interpret doses to the embryo/fetus.

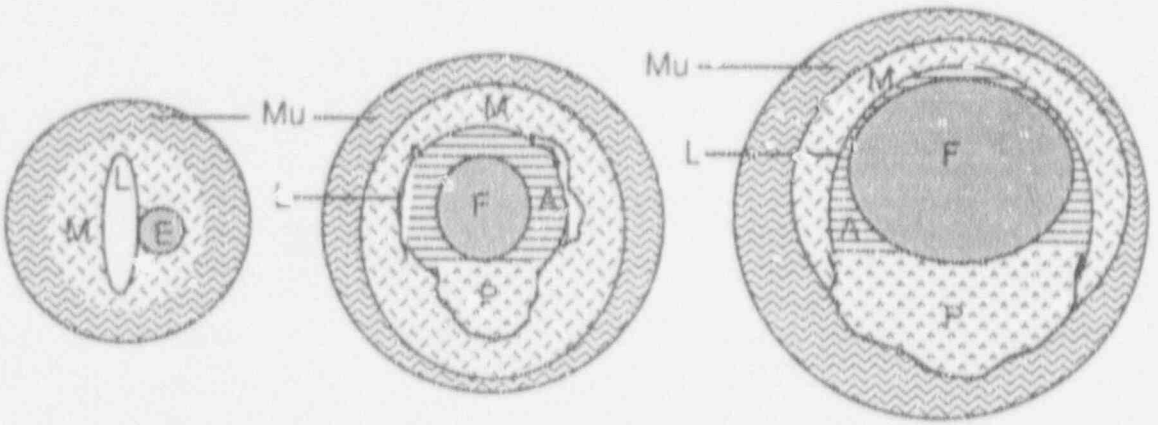
B. RATIONALE FOR EFFORT

The scope of this project does not involve an evaluation of the specific effects associated with prenatal irradiation, nor does it include addressing the basis for determining dose limits or their appropriateness. It is clear that these tasks are the responsibility of other scientific groups. The efforts that were undertaken specifically resulted from the recognition that inadequate availability and utilization of information led to major uncertainties in determining and expressing the radiation doses that the human embryo or fetus would receive as a result of radioactive materials in the pregnant woman. Irrespective of the values that are established as dose limits, the uncertainties in dose determination led to difficulties in defining appropriate operational procedures and in establishing meaningful regulations. The Pacific Northwest Laboratory (PNL) has undertaken this project to provide the NRC with specific types of dosimetric information that are considered to be useful in developing regulations and guidance concerning practices in the occupational use of radionuclides.

This report summarizes our efforts to collate available information concerning the placental transfer of radionuclides, to develop strategies for estimating embryo/fetal concentrations or activity levels, and to evaluate expressions for stating radiation doses to the human embryo or fetus from radionuclides in the pregnant woman. In particular, this effort has included developing interim recommendations concerning general methodologies for calculating prenatal doses from radionuclides and performing representative dose calculations, which are based on placental transfer and on metabolic and dosimetric considerations that were developed as part of this project. These initial evaluations were considered in formulating relevant sections of the Code of Federal Regulations, and the more detailed information in this report will assist the NRC in preparing subsequent statements that will provide licensees with additional detailed regulatory guidance.

C. MORPHOLOGIC CHARACTERISTICS AND STAGE OF GESTATION

The term *embryo/fetus* is often used as an encompassing expression in referring to prenatal stages in statements of exposure limits; this is useful and appropriate terminology for that purpose. It is important to distinguish between the embryo and the fetus, however, when estimating radionuclide concentrations, performing dose calculations, or considering specific effects. The term *embryo* is used in reference to the earliest stages of development, before the time at which external characteristics make it recognizable as a member of the major taxon to which it belongs. This transition occurs during the period between 2 and 3 months in the human conceptus, and it is properly referred to as a fetus from that stage until birth. The following diagram (Figure 1), which is not to scale, shows the embryo, the early fetal stage, and the late fetus in relationship to the uterus, and will be used with the following considerations to help provide orientation.



Embryo	Early Fetus	Later Fetus
Mu - Muscle	E - Embryo	P - Placenta
M - Mucosa	F - Fetus	A - Amniotic Fluid, within embryofetal membranes
L - Uterine Lumen		

Figure 1. Diagrammatic representation of geometric relationships between the conceptus, supporting structures, and the uterus

1. Early Stages

In most mammalian species, the ovum passes from the oviduct into the uterine lumen a few days after fertilization and implants in the mucosa through a complex series of processes, starting at about 1 week. The early embryo, or blastocyst as it is called at this stage, begins its internal development and initiates maternal responses that result in placentation and formation of related transfer and support structures and mechanisms.

There is consensus that radionuclide concentrations in the embryo before implantation and during early post-implantation stages usually may be considered as approximately equal to the average concentration in the uterus. Uterine muscle may have a radionuclide concentration that is different from the mucosa; alpha-emitters (α) and beta-emitters (β) in muscle may not reach the embryo, which could decrease the effective concentration. It would be more accurate to use concentration in the uterine fluids or in the mucosa, rather than average through the uterus, but these values are rarely known.

A lack of information prevents making allowance for the possibilities of concentration inhomogeneities in the early embryo. This may not be a major problem because the β-emitters that are considered to have the greatest likelihood of inhomogeneous distribution are those with the most energetic emissions. Analyses were made, using a modification of a PNL computer code, to quantitatively examine this problem (Traub et al. 1987). At early developmental stages, when the conceptus is approximated by a 0.1-cm-diameter sphere, these calculations show that ^{3}H and ^{14}C will deposit more than 95% of emitted energy in the sphere, but this falls to about 22% with the energetic β particles of ^{32}P.

Thus, a straightforward approach to calculation may apply during early gestation. For β-emitters, it will often be appropriate to regard the small developing embryo, with its extraembryonic trophoplastic structures, as being contained within a large mass of homogeneous concentration, and to apply conventional calculational procedures. The anatomic relationships are such that, for photon emitters, the embryo can be regarded as a point in the center of a sphere, which represents the uterus, and S-factors that are being developed in this project and by other various groups can be used to estimate absorbed dose (Smith and Warner 1976; Elsasser et al. 1986).

2. Subsequent Developmental Stages

The human conceptus is considered as a fetus during the second and third trimesters of gestation, and often during the last month of the first trimester. There are significant differences among species during these stages of pregnancy; however, organogenesis has been completed and progressive histogenesis and growth are the characteristic processes in the human conceptus during this period. The human fetus, as well as those of almost all other mammalian species, is contained in the amniotic fluid and is surrounded by various fetal membranes and modified uterine structures. The fetus is nurtured via the closely located placenta, to which it is attached by the umbilical cord.

Several groups of researchers, including investigators at Oak Ridge National Laboratory and Oak Ridge Associated Universities, are developing geometric models and computer codes for internal dosimetry in the pregnant woman and conceptus. Davis et al. (1987) have published detailed models for 3 months of gestation; these also serve as a fair approximation of morphology at 2 months, the stage at which the embryo has undergone sufficient transition to be considered a fetus, although its linear dimensions and tissue masses are smaller. Other models have been presented for later stages of pregnancy (Watson and Stabin 1987).

Little formal consideration of the geometry of the conceptus in the period between midorganogenesis and the fetal period has been reported. This does not greatly constrain the dosimetric approach, particularly since the models are most relevant to exposure from radioactivity distributed throughout the pregnant woman. Dimensions deliberately have been omitted from the diagrams in Figure 1 to maintain their general nature; later sections provide representative values and references to tabulations and the literature. These include data from the foregoing references, equations, and values obtained from International Committee for Radiological Protection (ICRP) Publication 23 (ICRP 1975), and calculations found in appendixes to this document. These sources provide adequate information to approximate the anatomy, dimensions, and masses of the pregnant woman and her embryo or fetus.

Linear distances in the pregnant uterus usually are relatively large compared to the pathlengths of the β particles. As a broad generalization in this case, we would expect that the contribution to exposure of the embryo/fetus from radionuclides in both nearby and distant maternal organs would be mostly from photons, but a primary contribution to the β-radiation absorbed dose to the embryo/fetus would be from its internal radionuclide content. Thus, if total fetal activity were divided by mass of the embryo/fetus, the resulting values would be the concentrations used in traditional formulas for dose calculation, such as those described by Quimby and Feitelberg (1963). The fetal volume at this time is sufficiently large as to not require correction for unabsorbed β particles, other than perhaps at its surface. Accurate assessment is obviously more complex than these generalities, and the remainder of this document will provide details of approaches to calculations and of the component factors that are required for their implementation.

D. BIOKINETIC CONSIDERATIONS AND LIMITATIONS

1. Extrapolations from Animal Data: Basis and Validity

Most available data regarding placental transfer to the human conceptus and resulting radionuclide concentrations in the conceptus have been obtained from analyses performed following exposures to labeled metabolites or radiopharmaceuticals. Other data concerning radionuclides of occupational and environmental concern were obtained from radioanalyses of abortuses, stillbirths, neonatal decedents, and placentas; interpretations are often clouded by uncertainties regarding corresponding maternal body burden or exposure level. Additional information, primarily applicable to calculation of kinetics, has been obtained through in vitro perfusion studies using human placentas.

The limited breadth and depth of the human database makes it necessary to use data from studies of placental transfer and fetoplacental distribution in animals despite uncertainties associated with extrapolation to humans. These animal data range from values that are derived from toxicity studies, in which terminal measurements of fetoplacental concentrations were performed, to values obtained from sequences of deliberate, dynamic measurements, which provide a basis for calculating kinetic parameters. The latter types of study were directed at measuring concentrations in maternal blood and tissues,

throughout the placental structures, and in tissues of the conceptus as a function of time after exposure. Other studies investigated transport processes and mechanisms, and examined factors that affect or modify placental transfer and fetoplacental distribution. The similarities and dissimilarities between the prenatal development, placental structure and function, and radiation responses of laboratory animals and the human conceptus will not be described here because details and comparisons are available in other documents (Sikov and Mahlum 1969; Shepard 1980; UNSCEAR 1986; NEA 1988).

To expedite efforts leading to preparation of recommendations, initial emphasis was directed at a set of priority radionuclides that were expected to be of greatest significance for prenatal exposure in the work environment: 1) tritium and carbon in inorganic forms, 2) tritium and carbon in three typical organic forms, i.e., glucose, amino acid, and thymidine, 3) cobalt in inorganic forms and as vitamin B-12, 4) strontium, 5) ruthenium, 6) iodine, 7) cesium, and 8) plutonium. In general, based on their properties and general availability, most comparative information was available for these nuclides in human and animal pregnancies, and they provide a spectrum of metabolic and dosimetric characteristics. These analyses, and evaluations of a few additional materials, were used as the primary basis for developing analytical approaches; these will be used to provide illustrations and tabulations of results.

2. Factors Confounding Extrapolations

a. Metabolism

The general aspects of mammalian gestation are remarkably similar among mammalian species, but the developmental stages that are attained at specific elapsed fractions of the gestation period and the degree of maturity at birth differ greatly. Moreover, there are metabolic differences among prenatal, juvenile, and adult stages and among members of different species that may affect transport, the rate of clearance from blood, and tissue deposition. As a consequence, the temporal patterns of the amounts available for placental transfer and components of kinetic calculations may differ.

b. Litter Size

In contrast to human pregnancies, in which a single fetus is the usual situation (monotocous), most of the animal species from which transfer and deposition data have been obtained bear litters consisting of multiple offspring (polytocous). In these species, the total mass of the fetuses or fetoplacental units relative to that of the pregnant animal tends to be much greater than in the human. The quantitative impact of this situation has not been evaluated in detail, but it tentatively appears that total stage-adjusted transfer to the products of conception is greater in polytocous than in monotocous pregnancies, but that the concentration in each individual fetus or placenta is less.

c. Acute Versus Chronic Exposure

Many of the data from animal studies were obtained following a single exposure to readily measurable amounts of activity. Despite applicable caveats, such experiments provide data that are primarily applicable to an accidental exposure of a pregnant woman. Many human exposures, however, may involve repeated intakes of low levels of activity. In some instances, radioanalyses of human autopsy materials have resulted in calculated ratios of fetal-to-adult concentrations that are greater than those that would be expected from animal data obtained after acute exposure. It appears that these differences may result from the contribution and/or interaction of several factors, including mass effects, summation of the contributions of different time periods available for post-exposure excretion, and kinetic and deposition differences relating to the metabolically different stages of gestation during the successive intakes.

3. Sources Contributing to Total Dose

As indicated, information on effects of exposures from sources external to the pregnant woman provided the stimulus for setting special limits for radiation doses to the embryo/fetus. Exposure of the conceptus from external sources can be terminated by discontinuing the generation of radiation, physical separation of the woman and the source, or introduction of shielding. In contrast, radionuclide intake before or during pregnancy also can irradiate the embryo/fetus; this exposure may continue for various periods, and there may be residual radioactivity in the child at the time of its birth, which can result in radiation exposure during postnatal life. This project was originated to develop recommendations concerning prenatal dose, and calculations were restricted to this aspect of the problem. The major uncertainties relate to the dose attributable to radionuclides in the embryo/fetus, or in the immediately surrounding placental and uterine tissues, and so these received special consideration.

In addition, it is necessary to include radiation doses from radionuclides that are incorporated or contained in other major organs or structures of the pregnant woman, such as her liver or bladder, or are distributed throughout her body. Dosimetry for radionuclides external to the uterus are essentially direct, but complex, calculations. Together with the physical factors (presented herein or indicated in references), computation may be made from knowledge of the anatomy and physiology of the woman, dimensions and masses of the embryo, fetus, uterus, and radionuclide disposition or activities with time and stage of gestation.

4. Components of Internal Dose

A major component of the effort involved estimating placental transfer of radionuclides and resulting amounts in the embryo/fetus relative to those in the pregnant woman. Consequently, emphasis was directed toward procedures for estimating exposure of the embryo/fetus from radionuclides that were deposited in the embryo/fetus or remained in the tissues of the woman. These calculations directly provide values relating to energy deposition, which are expressed as radiation absorbed doses (rad or gray [Gy]).

Current recommendations and regulations of the NCRP and NRC for prenatal exposure limits are stated in terms of dose equivalent (rem or Sievert [Sv]), which accommodates differences among biological effectiveness of photons and some particulate radiations. Conversions are readily accomplished by multiplying absorbed dose values by appropriate quality factors (Q), which provides the corresponding values of dose equivalent. The values of Q for specific particles are established, and occasionally revised, by appropriate organizations, and so use of this approach further accommodates any subsequent revisions in the assigned value. The caveat is offered, however, that special dose limits are based on unique responses by the conceptus, and that the validity of these quality factors generally has not been established for these responses.

Making a distinction between two general categories of biological deficits that can result from irradiation during gestation may be especially useful for some considerations of radionuclide exposure. One category of effects, which includes prenatal growth retardation, malformations, and reduced postnatal mental capacities, results specifically from exposure of the embryo/fetus and is the current basis for setting special limits for exposure during gestation. The other category involves the contribution of the prenatal irradiation to lifetime exposure, including such long-term effects as carcinogenesis. As indicated, the derivation, validity, and magnitude of the limits for either prenatal or cumulative exposure do not fall within the scope of this project.

Concepts have been developed relative to protection from deleterious changes of a delayed or cumulative nature and have led to radiation exposure limits that are expressed as more complex dosimetric quantities such as effective and committed dose equivalent. The use of committed and effective dose equivalents for stating prenatal radionuclide dose limits has certain merits, but is considered to be premature because the current lack of information does not permit acceptable determinations of these quantities. The question warrants later consideration, however, when adequate information becomes available 1) to calculate prenatal doses from a wider range of radionuclides and isotopes at relevant stages of gestation and 2) to define dose-response relationships that will allow the assigning of weighting factors. Our suggested approaches and analyses have provided estimates of radionuclide content of the fetus at 9 months of gestation, following administration at the start of each sequential month of pregnancy. These values are available for some selected radionuclides and are presented to provide a basis for calculating postnatal radiation doses (see Table E1).

These factors all suggest that exposure regulations should be expressed in terms of our best estimates of the absorbed dose and dose equivalent to the embryo or fetus, and our recommendations regarding calculations of dose have been directed toward providing these values.

II. INTERNAL DOSE CALCULATIONS AND ESTIMATES

A. BASIC CONSIDERATIONS

1. Underlying Concepts

The most relevant consideration is that absorbed doses and rates could be directly calculated from concentrations in the target tissue and in surrounding tissues, using traditional techniques that combine the energies of the emissions, the number of emissions per unit time, the time over which the emissions are integrated, energy losses in the target tissue, and accepted constants and conversion factors. As is presented here in further detail, these values should be adjusted by appropriate factors such as fractional energy absorption, which is a function of path length and dimensions of the tissue or organ (i.e., conceptus in this instance). In addition to calculations of radiation dose from radioactivity in the embryo/fetus, it is also important to account for radiation dose arising from radioactivity in the maternal organs. Changing biological conditions influence some of the factors, such as anatomical dimensions, but these are relationships that may be defined. As indicated in the following section, these considerations lead to two general approaches to estimating the radiation absorbed dose to the embryo or fetus from radionuclides incorporated in the conceptus or the immediately surrounding tissues. The approaches overlap in some of their details and underlying concepts; both have several potential variations, and insufficient information is the limiting factor. As a consequence, determination or estimation of the concentrations and activities to be used in calculations is the most difficult and uncertain aspect of the process.

2. Estimation of Concentration and Activity

One of the approaches to estimation of concentration is based on ratios of embryo/fetal to maternal concentrations, either in specific tissues or in average or total body, and usually as extrapolated from reports of animal experiments. This approach is assumed by some to serve as the basis for the most conservative (or maximal) estimate of dose to the conceptus.

The other approach is based on estimates of fractional transfer from maternal blood to the conceptus or of transfer kinetics and patterns to the conceptus as a function of stage of pregnancy, route of intake by the pregnant individual, and time after intake or placental transfer. This approach has greater theoretical validity and may be more amenable to biologically valid extrapolation, although it initially requires more information than does the ratio method. However, physiologic information can be introduced into these calculations to extend their potential and accuracy.

3. Current Status and Limitations

The lack of clear precedents necessitated making decisions concerning the desirability and validity of ways to generalize from sometimes limited information and disparate reported values relating to placental transfer and relative fetoplacental concentration. The alternatives include calculating

means and confidence intervals, selecting a mode or median to serve as a representative of the true age-related value, and using approaches that accommodate broad ranges of values. None has proven to be consistently useful, and efforts are required to resolve this problem. In the case of radionuclides for which reports of prenatal concentrations are not available, it is necessary to interpolate from results with chemically related elements or compounds.

Extrapolating concentration values from animals to human pregnancies should be based on anatomic and metabolic correspondence of developmental stages, and other biological factors to some extent. However, the validity of the extrapolated values also depends on the nature, amount, and homogeneity of the calculated values. General schemes have been addressed for using concentrations or activities in the conceptus to calculate radiation doses. These were first generalized to be independent of the metabolism of the radionuclide, but are highly dependent on the fetoplacental morphology that is characteristic of each major sequential stage.

B. DOSIMETRIC AND CONCENTRATION PATTERNS RELATIVE TO STAGE OF GESTATION

1. General Considerations

The availability of reliable estimates of fetal concentrations or of relative concentration values for maternal and fetal tissues is a limiting factor in dose determinations. Continuing efforts are being made to develop procedures for interpolation and extrapolation of the database and of broad metabolic information for eventually establishing time-integrated concentration values and their patterns in the embryo and fetus. Attempts are ongoing to manipulate such data to calculate incremental depositions from transfer coefficients or successive ratios, and to estimate concentration decreases at times subsequent to that represented by a reported ratio. Recent studies examined data from noncontemporaneous experiments and found that placental transfer kinetics from one experiment could be used to correctly predict fetal concentrations as measured in other experiments (Sikov and Kelman 1989).

Although the data are neither complete nor quantitative, we can now generalize about important biological relationships affecting dosimetry, such as changes in transfer kinetics during pregnancy, total fetal activities or concentrations, and the role of developing target organs or tissues. Early attempts at categorization were based on stage-independent approximations of relative availability and net deposition in the conceptus. The major limitations to this nonquantitative approach highlighted the need to develop more objective criteria for evaluation.

2. Relative Dose Estimates from Fetal-to-Maternal Concentration Ratios

The ratio of embryonic/fetal concentration to maternal concentration requires the least amount of information. It is also particularly relevant because when few quantitative data are available, they often consist of one or more ratios of activities or concentrations. The absence of reported data for a radionuclide may suggest that it is not of major concern as a source of

occupational exposure, but its behavior should be extrapolated from chemically related radionuclides. Such reported, calculated, or interpolated ratios of concentrations in the embryo or fetus to those in the woman are used to approximate actual activities in the embryo or fetus for calculation of radiation doses.

When this ratio approach is used with values that were calculated from measurements soon after intravenous exposures of animals, it provides maximal estimates of prenatal radiation dose; subsequent concentrations would be decreased by progressive growth. Greater precision can be achieved when ratios are available at sequential times after exposure or when exposures and determinations are made at several stages of gestation. It would be possible to incorporate the growth equation into such calculations, but this apparently has not been done directly for such analyses.

Other aspects of the ratio approach implicitly require invoking a number of unproven and potentially inaccurate assumptions, some of which also pertain to calculations based on kinetics. For example, extrapolations from animal to human often assume that the ratio is the same, without allowing for the problem of monotocous versus polytocous pregnancies, which was considered earlier. The ratio approach also does not incorporate the possibility of greater transfer or deposition at later stages because of physiologic differences, such as the functional development of target organs in the fetus and their effect on transfer coefficients—concepts that are inherent in the kinetic approach.

3. Doses and Concentrations Calculated from Kinetics

Biokinetics may provide more accurate information in those situations where it can be applied; the results may have greater theoretical validity and be more amenable to biologically valid extrapolations. Proper implementation requires greater amounts of information, so that it would pertain most commonly for radionuclides that have been of greatest interest. Under ideal conditions, the biokinetic approach is based on use of transfer measurements and metabolic data to determine the time course of fractional transfer from maternal blood to the embryo/fetus. From such information, it is possible to calculate deposition or infer kinetics and patterns of transfer to the conceptus as a function of stage of pregnancy, route of intake by the pregnant individual, and time after intake or placental transfer, and to superimpose modifications by retention and growth functions.

In subsequent practice for repeated exposure, calculation might involve estimating each of the fractional amounts that would be transferred and, because each incremental increase in activity is diluted by subsequent growth, obtaining the sum of the resulting integrals of concentration in the conceptus with time. The total contributions from sequential depositions give estimates of time-weighted activities that can be used for calculating radiation doses to the conceptus. These calculations should allow for the continually changing kinetics relating to stage of gestation, fetal growth, and localization within specific tissues of the conceptus.

4. Compartmental Analyses and Impact of Stage-Related Distribution

Even with limited data, simple two- or three-compartment analyses are usually possible from a physiologic or metabolic basis, or relative to implied kinetics from sequential ratios. As mentioned in the foregoing descriptions, activity usually needs to be in the blood of the pregnant woman to be available for transfer to the conceptus. Most transfer is between the maternal and fetal blood circulations, which are not in actual contact, so exchange occurs across the placenta and other fetal membranes. This concept, illustrated in Figure 2, may demonstrate qualitative factors that sometimes can be incorporated into analyses with compartmental models and the enhanced understanding that can be achieved.

Entry into blood varies with the specific radionuclide, its chemical form, and its associated route of exposure and absorption patterns; these have been considered and tabulated in numerous documents and reports. The effect of pregnancy is less well known; the placenta has a potential for affecting kinetics via material-specific facilitated or active transport, but some nuclides are removed and deposited in placental tissues. The rate and degree of deposition in maternal tissue also affect blood concentrations on an absolute and temporal basis; this is of major importance in that decreased concentrations will reduce transfer. On the other hand, as specific sites of deposition begin to develop and function in the fetus, this will increase the rate of removal from the fetal blood and drive the placental transfer kinetics in the direction of the fetus. In the more quantitative sense, the model illustrated in Figure 2 can be expressed in the alternate format of Figure 3, which is more compatible with the nomenclature used by the ICRP and will be utilized in developing the detailed approaches to dosimetric methodology (Section III).

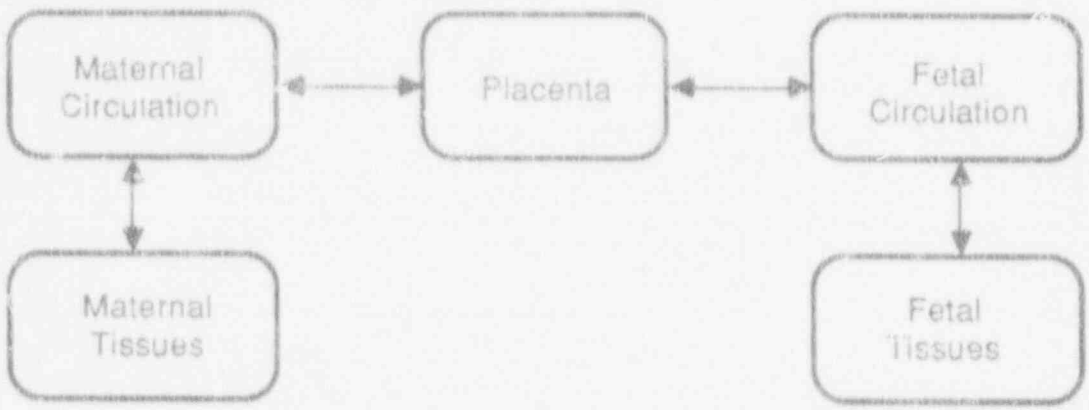


Figure 2. Generalized compartmental model to illustrate concepts of exchange between maternal and fetal circulations, and interactions relating to maturation of fetal target structures

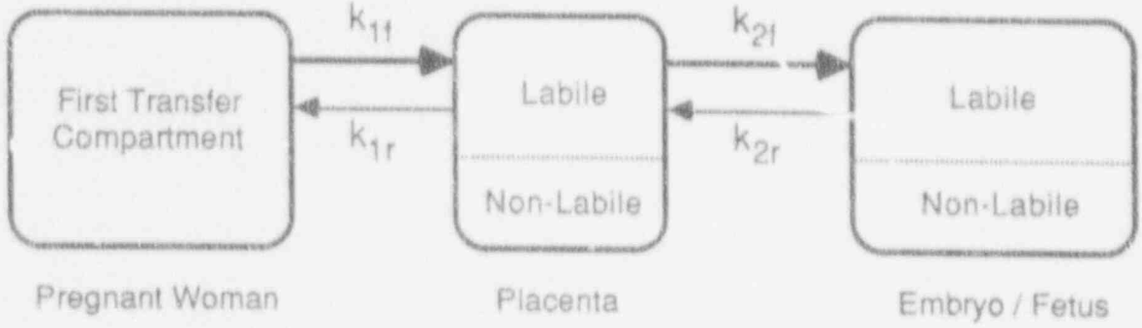


Figure 3. Compartmental model for maternal-fetal exchange as based on ICRP concepts and incorporating kinetic coefficients

As mentioned, stage-dependent differential deposition patterns may also involve inhomogeneous tissue distributions, but these have not been identified as posing a special radiological protection problem. In the present context, therefore, consideration is limited to their general influence on kinetics, total activity, and concentrations in the fetus, as well as the resulting net dosimetric consequence.

5. Comparison of Concentration Estimators and Use for Prediction

If results were available from both types of calculational approach, it obviously would be of interest to compare them and examine their compatibility, but the paucity of quantitative data has restricted this effort to a few elements. Some of the data that were assembled for the priority radionuclides were combined to establish the central values used for descriptions in Section IV; these display reasonably good agreement for comparable stages of gestation.

On a similar basis, and through the use of alternative extrapolation procedures, rough approximations of relative concentration and activity values in the conceptus may be made for other elements. These efforts have not yet progressed far enough to prepare summary tables, but ongoing efforts are expected to lead to reasonable approximations in the near future. As an example, following the ICRP approach will result in the assumption that those alkaline earth elements for which there is no specific information will behave in a manner similar to cerium.

There are several radionuclides for which there is neither information nor a basis to extrapolate. With a few notable exceptions, the absence of reported studies may be taken as suggesting that intake is very unlikely, or that there is no special prenatal affinity for such materials. Therefore, the average embryo/fetal concentration could be assumed to be no more than in the woman. There are occasionally reports of a high ratio in specific tissues, although the overall concentration ratios are not affected. It should cause minimal impact if concentration ratios of uncommon radionuclides were assumed to be 1, even when they are probably less, but it will be important to avoid marked underestimates.

III. RADIATION DOSE CALCULATION METHODOLOGY

At the inception of this effort, it was decided that the method for calculating radiation dose to the embryo/fetus should be compatible with internal dosimetry methodologies currently employed by practicing health physicists. The method should be sufficiently modular for other investigators to extend the calculational system by including additional data. Also, the methodology should be sufficiently robust to allow radiation dose calculations to be performed from a variety of input data. This will accommodate situations in which the dosimetrist may have data that are not always consistent; sometimes the data might be in magnitude of an intake, at other times in body burdens.

For these reasons, the calculational method selected for use in this project is a continuation and extension of the radiodosimetry methodology developed by the Medical Internal Radiation Dosimetry (MIRD) Committee of the Society of Nuclear Medicine. The MIRD schema, or methodology for calculation of radiation dose due to radioactive material in the body, has mostly recently been described in detail by Loevinger et al. (1988), among others. The MIRD methodology provides a system for calculation of the radiation dose to a target region, designated r_k, resulting from radioactive material contained in a source region, designated r_h. In most instances, both r_k and r_h are distinct organs, although they need not be. The system allows the two regions to be separated in space or to be the identical region.

The following briefly summarizes the MIRD calculational methodology; the reader is referred to Loevinger et al. (1988) for a more complete description. The equation for the mean dose rates to a target region, r_k, can be written in the three forms shown below:

$$R\ (r_k \leftarrow r_h) = \frac{A_h \sum_i \Delta_i\ \phi_i\ (r_k \leftarrow r_h)}{m_k} \qquad (1)$$

$$R\ (r_k \leftarrow r_h) = A_h \sum_i \Delta_i\ \phi_i\ (r_k \leftarrow r_h) \qquad (2)$$

$$R\ (r_k \leftarrow r_h) = A_h\ S(r_k \leftarrow r_h) \qquad (3)$$

where $R(r_k \leftarrow r_h)$ = average absorbed dose rate in target region r_k from activity in source region r_h (in rad/hr [Gy/sec])

A_h = activity in source organ h (in μCi [Bq])

Δ_i = mean energy emitted per nuclear transition, the product of the number of particles multiplied by the mean energy per particle (in g-rad/μCi-hr [kg-Gy/Bq-sec]).

$$\Delta_i = Kf_i E_i \tag{4}$$

where K = unit conversion factor
(K = 2.13 when in g-rad/μCi-hr-MeV;
K = 1 when in kg-Gy/Bq-sec-MeV).

f_i = fraction of the disintegrations resulting in radiation, i

E_i = the mean energy of radiation, i (in MeV).

When the units for Δ_i are rad-g/μCi-hr, K = 2.13; however, K = 1 if SI units are used.

$\phi_i(r_k \leftarrow r_h)$ = absorbed fraction, the fraction of the energy of type-i radiation emitted from the source organ that is absorbed in the target organ (unitless)

m_k = mass of the target region (in g [kg])

$\Phi_i(r_k \leftarrow r_h)$ = specific absorbed fraction, the absorbed fraction per unit mass of the target region (in 1/g [1/kg] where $\Phi_i = \phi_i/m_k$).

S = mean absorbed dose to a target organ per unit cumulated activity in the source organ in rad/μCi-hr [Gy/Bq-sec]).

Because there are usually many source regions, r_h, that contribute to the dose received by the target region r_k, the contributions from all source regions must be added together. The addition of the contributions from all source regions is shown in the following equation:

$$R(r_k) = \sum_h R(r_k \leftarrow r_h) \tag{5}$$

where $R(r_k)$ is the average absorbed dose rate in target region r_h (in rad/hr [Gy/sec]).

The ICRP has adopted an internal dosimetry system that is conceptually similar to the MIRD methodology. The ICRP methodology employs terminology that is different than that of MIRD, and the ICRP method also employs a quality factor to account for differences among radiation types in their ability

to cause biological damage. The ICRP methodology is described in ICRP Publication 30, Part 1 (ICRP 1978); supplementary information can be found in Parts 2 and 3 of ICRP Publication 30 (ICRP 1980, 1981) as well as Appendix I of ICRP Publication 23 (ICRP 1975). The MIRD notational system is employed in these interim recommendations because there is a large body of literature that describes its use and several tabulations of dosimetric factors are available.

The preceding equations were derived for the situation in which the values of the parameters that comprise the S-value are constant over the time for which the dose calculations are applicable. In the case of estimating radiation doses to the embryo/fetus, the values of the parameters that compose the S-value are rapidly changing. Consequently, it is not usually sufficient to compute a single S-value and then to estimate an integral activity $\tilde{A}_h$ for the entire remaining course of pregnancy. It is necessary to determine the dose rate to the embryo/fetus at sequential stages of pregnancy, and then to integrate the time-dependent dose rates to determine the total dose:

$$R(t) = A_h(t)\ S(t) \tag{6}$$

where $R(t)$ = time dependent dose rate (in rad/hr [Gy/sec])

$A_h(t)$ = activity in source organ h at time t (in μCi [Bq])

$S(t)$ = S-value at time t (in rad/μCi-hr [Gy/Bq-sec]).

The total average dose to the target region is then given by the integral:

$$D_{total} = \int R(t)\ dt \tag{7}$$

where D total is the total average dose (in rad [Gy]). Using this equation, it remains only to determine the proper values of $A_h(t)$ and $S(t)$ for various values of time, t, during the gestational period.

The advantage of this system is that it allows the dose calculation to be partitioned into two conceptually separate parts. The first part, represented by A_h, is a biokinetic calculation. The biokinetics are determined by the interactions of the physicochemical properties of the radionuclide (e.g., particle size, if inhaled, and solubility) and the physiologic processes of the individual. The second part, represented by the S-value, is the radiation dosimetry portion of the problem. Radiation dosimetry calculations are dependent on the physical properties of the emitted radiation, and the anatomical characteristics (e.g., physical dimensions) as well as the elemental composition and density of the individual.

A. BIOKINETIC CALCULATIONS

The purpose of biokinetic calculations is to provide estimates of the radionuclide content of the maternal organs and of the embryo/fetus, placenta, and uterus to allow the calculation of radiation doses to the embryo/fetus due to intakes of radionuclides by the mother. The embryo/fetus, along with its placenta, may be described as having the three primary compartments shown in Figure 3. The maternal transport compartment shown in the figure is identical to the first transport compartment that is described in ICRP Publication 30 (ICRP 1978). Both the other two compartments, the placenta and the embryo/fetus, may consist of (at least) two subcompartments: labile and nonlabile. The labile subcompartment represents that fraction of the radionuclide which is in a form available for transport to some other compartment. The nonlabile subcompartment represents the fraction of the radioactive material that has been incorporated into anatomical structures, for example, and is thus not available for transport.

The arrows in the figure representing movements in the reverse direction provide for the possibility of cycling. An algorithm to compute the activity in compartments of a recycling system has been described (Birchall and James 1988, 1989). In most instances, data are not sufficient to allow the use of cycling compartmental analysis. In a conceptually simpler system, the reverse arrows of Figure 3 are eliminated from consideration, and recycling of the radioactive material is not modeled. In this case, the compartmental analysis methods, such as those given in Birchall (1986), ICRP Publication 30 (ICRP 1978), or Skrable et al. (1980), may be appropriate.

Summaries of the biological behavior of the priority radionuclides are presented in Section IV. For some radionuclides, the available data are insufficient for the derivation of even simple, nonrecycling coefficients, although concentration ratios are available in many cases. These generally can be converted to ratios of activity in the embryo/fetus relative to activity in the woman or her organs. The sparseness of data concerning maternal concentration varies among radionuclides: for some isotopes, the comparison will be to specific maternal organs; for others, the maternal reference is the woman's whole body.

The calculational approach described in these recommendations requires activity content rather than specific activity (concentrations). It may be necessary to determine the activity in the embryo/fetus using an estimation such as that determined by the following equation:

$$a = A\ C\ m/M \qquad (8)$$

where a = activity in the embryo/fetus

A = activity in the maternal organ relevant to the ratios

C = ratio of nuclide concentrations

m = mass of the embryo/fetus or organ

M = mass of the relevant maternal organ.

The mass of the embryo/fetus may be taken from Table 1, which was obtained from data in ICRP Publication 23 (ICRP 1975). More typical values of embryo/fetal mass and crown-rump length were developed from data in several sources, and are provided graphically in Appendix E to facilitate visualizing the pattern of growth.

Table 1. Assumed physical characteristics of the human embryo/fetus

Stage of Gestation (days)	Length (cm)	Mass (g)	Major Axis (cm)	Minor Axis (cm)
30	0.4	0.0335	0.2	0.2
60	3.34	5.24	1.7	0.85
90	10.6	28.1	5.3	1.1
120	18.9	146	9.5	1.9
150	26.8	421	13	2.7
180	33.7	859	17	3.4
210	39.8	1432	20	4.1
240	45.1	2103	23	4.6
270	49.6	2836	25	5.1

The mass of the maternal organ may be obtained by estimation based on observation of the woman in question or any of several data compilations, e.g., ICRP Publication 23 (ICRP 1975) or Cristy and Eckerman (1987). Masses for the whole body of the woman at various stages of gestation, as employed for this report, are shown in Table 2.

Table 2. Assumed masses of the pregnant woman at various stages of pregnancy

Stage of Gestation (days)	Woman Mass (g)	Uterus Plus Mass of Contents (g)	Mass of Total Soft Tissue (g)	Mass of Maternal Skeleton (g)	Total Mass of Pregnant Woman
0	53721	79	53800	4200	58000
30	53721	330	54051	4200	58251
60	53721	580	54301	4200	58501
90	53721	831	54552	4200	58752
120	53721	1186	54907	4200	59107
130	53721	1693	55414	4200	59614
180	53721	2416	56137	4200	60337
210	53721	3449	57170	4200	61370
240	53721	4923	58644	4200	62844
270	53721	7027	60748	4200	64948

The activity in the relevant maternal organ, A, following an intake could be estimated from the concentrations in air or ingested materials. More appropriately, it would be determined by direct bioassay (whole-body counting or thyroid counting) of the woman in question, or from indirect bioassay (urine or fecal assays) used in conjunction with the results of biokinetic models of radionuclide transport, such as the various commercially available internal dosimetry codes or data compilations, such as Lessard et al. (1987). The major sources of data employed for this report are indicated in discussions of each radionuclide.

B. RADIATION DOSIMETRY CALCULATIONS

The S-value is computed using the following equation (see Eqs. 1-3):

$$S(r_k \leftarrow r_h) = \sum_i \Delta_i \Phi_i (r_k \leftarrow r_h) \qquad (9)$$

The calculation of the components of this equation is described below.

1. Energy Emitted per Nuclear Transition Δ_i

The mean energy emitted per nuclear transition is tabulated in various compendia. MIRD Pamphlet 10 (Dillman and Von der Lage 1975) tabulates delta (Δ) for several radionuclides of importance to the nuclear medicine community. The value may also be determined from Eq. 4, which is repeated below:

$$\Delta_i = K f_i E_i \qquad (4)$$

where, as before,

K = conversion factor (in rad-g/μCi-hr-MeV [Kg-Gy/Bq-sec-MeV])

f_i = fraction of the disintegrations resulting in radiation, i

E_i = the mean energy of radiation, i (in MeV).

When the units for Δ_i are rad-g/μCi-hr, the value for K is 2.13. Values of f_i and E_i are published in ICRP Publication 38 (ICRP 1983), among other sources. These values are physical constants and do not depend on the stage of gestation.

2. Mass of the Target, m_k

The mass of the embryo/fetus was calculated from the equations given in ICRP Publication 23 (ICRP, 1975). These equations seem to be appropriate at times greater than 84 days. The mass of the embryo/fetus for 30 and 60 days was obtained by extrapolation of the curves that were obtained from the equations, and are consistent with values presented in other sources. The mass of the extraembryonic or trophoblastic structures is greater than that of the embryo at early stages. These masses, employed for calculations in this report, are also presented in Table 2.

3. Specific Absorbed Fraction, Φ

The determination of the proper value for the specific absorbed fraction, $\Phi = \phi/m_k$ and, in particular, the calculation of ϕ, may require some explanation. In the MIRD schema, radiations are divided into two major categories, penetrating and nonpenetrating. Nonpenetrating radiation deposits energy in a target tissue only if the source and target are the same; further, if the source and target regions are the same, all the emitted energy is considered to be deposited. Thus, $\phi = 0$ or 1. Penetrating radiation, on the other hand, will deposit a fraction of the emitted energy in all target regions; thus, ϕ ranges from 0 to 1. Alpha particles, beta particles, and electromagnetic radiation having energy less than 10 keV are usually considered nonpenetrating. Electromagnetic radiation having energy greater than 10 keV, and neutrons, are considered penetrating radiations. In the case of the embryo/fetus, the small size at early gestational stages seems to require consideration of the range of beta and electron radiations. These range considerations are discussed for each type of radiation.

a. Alpha Particles

Alpha particles have very short path lengths in tissue and, reasonably, should be considered nonpenetrating radiation. In situations where $r_h = r_k$, then $\phi = 1$; otherwise, $\phi = 0$. Consequently, $\Phi = 1/m_k$, 0, respectively. It should be noted that calculation of dose from alpha particles does not readily fit into the usual MIRD methodology, but the above approach is presented in that mode to maintain consistency. It is clear that mean absorbed dose has little meaning for alpha particles in any specific volume other than perhaps during the earliest stages of gestation, and that microdosimetric considerations may be more relevant. Some laboratories have utilized the concept of average concentrations or specific activities under these circumstances for relating dose to potential effect, which is proper for that purpose. An appropriate modification of this approach would seem to be a logical inclusion in future formulations of prenatal dose regulation and reporting.

b. Beta Particles

Beta particles are usually considered nonpenetrating radiation. However, in the case of the embryo/fetus, especially at early stages of development when the embryo/fetus is very small, ϕ may be much less than 1, particularly for higher energy beta particles such as those emitted by ^{32}P, ^{90}Y, and ^{106}Rh. Conversely, for the same radionuclides, ϕ will be greater than zero when the radionuclide is in tissues external to the embryo/fetus. This latter situation occurs only when the tissue that contains the radioactive material is in direct contact with the embryo/fetus. The following describes the calculational methodology that was developed for purposes of these recommendations, to assist in accounting for the range of beta particle and other electron radiations.

For this report, the embryo/fetus was assumed to be an ellipsoid having the dimensions given in Table 1. The dose to the ellipsoid from activity contained within the ellipsoid was calculated using the Berger (1971) point kernel for beta dose. The Berger kernel can be written as:

$$R_\beta(r) = \frac{Y\ k\ E_{ave}\ F_\beta(r/X_{90})}{4\ \pi\ \rho\ r^2\ X_{90}} \qquad (10)$$

where r = distance from source point to target point (in cm)

$R_\beta(r)$ = beta dose rate (per unit activity) at the target point at a distance (r) from the source point (in rad/s-μCi)

Y = beta yield per disintegration

k = unit conversion constant (= 1.6×10^{-8} g-rad/MeV)

E_{ave} = average beta energy (in MeV)

F_β = scaled absorbed dose distribution (unitless)

X_{90} = radius of a sphere in which 90% of the beta energy is deposited (in cm)

ρ = density of the ellipsoid (in g/cm^3).

The radionuclides were considered to be point sources for the purpose of dose calculation. The beta dose to a target point is the sum of the dose contributions from all the source points within the range of the beta particles, and dose to the target organ is given by:

$$R_\beta(r_k \leftarrow r_h) = \frac{\int\int A_v(x_h, y_h, z_h)\ R_\beta(r)\ dV_h\ dV_k}{\int dV_k} \qquad (11)$$

where $R_\beta(r_k \leftarrow r_h)$ = beta dose rate to the target organ k from source organ h (in rad/s)

A_v = source activity at the source point (x_h, y_h, z_h) per unit volume (in μCi/cm^3)

V_h = source volume (in cm^3)

V_k = target volume (in cm^3).

The distance, r, between the source point and the target point (x_k, y_k, z_k) is given by:

$$r = [(x_h - x_k)^2 + (y_h - y_k)^2 + (z_h - z_k)^{1/2} \qquad (12)$$

For the purpose of dose calculation, the range of beta particles was estimated to be 1.8 times the X_{90} (Berger 1971). The absorbed fractions calculated using this method were compared to the values reported by Akabani et al. (1991) using the electron transport code EGS4 (Nelson et al. 1985). The results generally agreed to within 1%. The S-values computed for these

recommendations are based on the continuous slowing-down approximations for energy deposition by electrons. Calculations of energy depositions by electrons, which account for straggling effects, are being performed at the National Institute for Standards and Technology (personal communication from S. Seltzer, NIST). These more precise calculations may be used when they become available.

c. Photons

Photons are penetrating radiations. In this section we describe approaches to account for the penetrating abilities of photons.

i. Dose to embryo/fetus from radionuclides in maternal organs. At present, no compilations of data exist that present the values of the specific absorbed fraction for the embryo/fetus as the target tissue. In the interim, three compilations of specific absorbed fraction data for photons should be employed: these tabulate specific absorbed fractions for the uterine contents as the target tissue which, for now, represents the embryo/fetus. There are two compilations that may be employed for the nongravid uterus, which will serve as a surrogate for the embryo during the early stages of pregnancy: the MIRD tables and those described by Cristy and Eckerman (1987). For the 3-month-pregnant woman, the data published by Davis et al. (1987) are suggested. The data for the nongravid uterus may be employed for the first two months of pregnancy while the compilations for the 3-month-pregnant woman may be employed for the third through ninth months.

Comparison of the Cristy and Eckerman (1987) data with those of Davis et al. (1987) indicates that, as the pregnancy progresses, values for the cross-organ dose to uterine contents decrease as uterine size and attenuation increase. These limited data suggest that the use of S-values derived from calculations applicable to earlier stages of pregnancy will result in conservative dose estimates. Whether the specific absorbed fractions continue to decrease as pregnancy progresses is not known with certainty. Specific absorbed fractions of photons that are applicable to other stages of gestation should be employed as the data become available.

ii. Dose to embryo/fetus from radionuclides in embryo/fetus. Because appropriate values were not otherwise available, the computer code MCNP, described by Briesmeister (1986) among others, was employed to compute specific absorbed fractions for the situation in which the embryo/fetus was both the source and target tissues. The embryo/fetus was assumed to be an ellipsoid having major and minor axes given in Table 1, with an elemental composition that was assumed to be the composition of the newborn phantom that was described by Cristy and Eckerman (1987). For the times from 30 days to 210 days the composition was that of the newborn soft tissue, while for the 240- and 270-day calculations, the composition was assumed to be a combination of the newborn soft tissue and skeleton. Individual organs were not modeled for any case, so that the present calculations will not represent an adequate treatment when the goal is to calculate dose to the forming bone or thyroid.

The computer code was set to calculate the energy deposition due to Compton, pair production, and photoelectric interactions. Version 3B of MCNP

(Briemeister 1986) was employed, and this version does not transport electrons; the energy transferred to electrons is treated as being deposited at the site of energy transfer. Because electrons are not tracked, kerma, rather than dose, factors were calculated. The activity was assumed to be uniformly distributed throughout the embryo/fetus. The code was set to run for 150,000 histories; the relative errors of the calculations were less than 1%.

Table 3 presents the calculated specific absorbed fraction values for photons having energies ranging from 10 keV to 4 MeV, and for specific monthly gestational times that range from 1 to 9 months or 270 days, which was assumed to be the normal length of gestation. Table 3 also shows the relative error of the Monte Carlo calculation. The reader should be aware that the relative error is an indication of the error associated with the Monte Carlo calculation, and does not indicate how well the phantom description represents reality.

iii. Dose to the embryo/fetus from radionuclids in the extra-embryonic or placental tissue. At present, methods for specific calculations of specific absorbed fractions for radioactive materials in the extraembryonic or placental tissues have not been performed. In the interim, results may be approximated by estimating the self-dose to the uterine contents. This calculation may result in some "double counting" of radiation dose to the embryo/fetus when combined with the dose calculations of item ii (above). However, because few data exist to allow calculation of the activity in the extra-embryonic or placental contents, this difficulty should be considered on a case-by-case basis. Future supplements to this report may provide specific absorbed fraction values for uterine contents as the source tissue.

C. OPERATIONAL METHODOLOGY FOR ESTIMATING DOSE TO EMBRYO/FETUS FROM MATERNAL BURDEN OF RADIONUCLIDES

1. Assumptions

a. The radionuclide(s) will be known or can be identified.

b. The dosimetrist will be able to estimate one of the following:

i. Integral air concentration of radionuclide exposure in DAC-hr

ii. Intake of radionuclide by the woman in μCi (Bq)

iii. Maternal body burden in μCi (Bq)

c. The dosimetrist will be able to relate the dates of exposure or intake or period of burden to the stage of gestation.

d. The dosimetrist will wish to determine either the dose rate at the time of maternal body burden determination or the integral dose to the embryo/fetus following the exposure/intake.

2. Method

a. Determine the date of intake and approximate stage (days) of gestation at intake.

b. Compute the maternal radionuclide burden in the conventional way. That is, use biokinetic analysis for radionuclides not amenable to direct (in vivo) bioassay procedures, and employ whole-body and/or specific organ counting for those situations where direct bioassay is appropriate.

c. Employ the tabulated data and procedures from this report (or other sources) to estimate the activity in the embryo/fetus and the consequent radiation dose rate at monthly intervals. The dose due to activity in the maternal organs should be included in the calculation of dose to the embryo/fetus. For calculations of dose due to activity in the maternal tissues, the interim suggestion is to use the uterine contents as the target tissues. For doses to the embryo/fetus during the first month of pregnancy, consider the dose to the nongravid uterus.

d. Compute the integral dose for the entire pregnancy.

If the dose rates were known at different time points throughout the pregnancy, then the estimate of the total dose, D total, would be given by the equation:

$$D\ \text{total} = \frac{1}{2} \sum_i [R(t_{i+1}) + R(t_i)] (t_{i+1} - t_i) \qquad (13)$$

where t_i and t_{i+1} are consecutive time points for integration, $R(t_{i+1})$ and $R(t_i)$ are dose rates at times t_i and t_{i+1}, respectively. The total dose, dose rates, and the time differences are given in consistent units. This equation is, in effect, application of the trapezoidal rule to the integration shown in Eq. (7).

The appropriate time spacing for dose calculations should be chosen so that the error introduced by use of the trapezoidal rule is minimal. In this report, only the dose rates at the beginning of each monthly postexposure intervals are presented. However, for many radionuclides evaluated in this report, dose rates decrease very rapidly, sometimes by more than an order of magnitude during a monthly period. Thus, using a 30-day time spacing for dose integration would significantly overestimate the dose. Therefore, unless otherwise stated in the text, the time interval used in the tabulations of calculated dose was chosen as 1 day (Appendix D). The dose rates for each day were determined by cubic-spline fitting for the purpose of integration.

Table 3. Specific absorbed fractions for photons for embryo/fetus as source and target tissues (g^{-1})

	Gestational Stage					
	30th Day		60th Day		90th Day	
Photon Energies (MeV)	Specific Absorbed Fractions	Relative Errors(a)	Specific Absorbed Fractions	Relative Errors	Specific Absorbed Fractions	Relative Errors
0.01	1.3E+01	2.1E-03	1.6E-0	2.5E-03	3.2E-02	2.6E-03
0.015	5.0E+00	1.9E-03	1.1E-01	2.3E-03	2.4E-02	2.4E-03
0.03	6.5E-01	1.8E-03	2.3E-02	2.1E-03	6.3E-03	2.4E-03
0.05	1.8E-01	1.8E-03	7.1E-03	2.2E-03	2.1E-03	2.5E-03
0.1	1.1E-01	1.7E-03	4.2E-03	1.9E-03	1.2E-03	2.2E-03
0.2	1.3E-01	1.7E-03	4.6E-03	1.8E-03	1.3E-03	2.1E-03
0.4	1.4E-01	1.7E-03	5.0E-03	1.8E-03	1.4E-03	2.1E-03
0.6	1.4E-01	1.7E-03	5.0E-03	1.8E-03	1.4E-03	2.1E-03
0.8	1.4E-01	1.7E-03	4.8E-03	1.8E-03	1.3E-03	2.1E-03
1.0	1.4E-01	1.7E-03	4.7E-03	1.8E-03	1.3E-03	2.1E-03
1.5	1.2E-01	1.7E-03	4.3E-03	1.8E-03	1.2E-03	2.1E-03
2.0	1.1E-01	1.7E-03	3.9E-03	1.8E-03	1.1E-03	2.1E-03
4.0	9.2E-02	1.7E-03	3.1E-03	1.8E-03	8.7E-04	2.1E-03

	Gestational Stage					
	120th Day		150th Day		180th Day	
Photon Energies (MeV)	Specific Absorbed Fractions	Relative Errors(a)	Specific Absorbed Fractions	Relative Errors	Specific Absorbed Fractions	Relative Errors
0.01	6.4E-03	2.6E-03	2.3E-03	2.6E-03	1.1E-03	2.6E-03
0.015	5.4E-03	2.6E-03	2.0E-03	2.5E-03	1.0E-03	2.6E-03
0.03	2.0E-03	2.4E-03	9.0E-04	2.4E-03	5.2E-04	2.5E-03
0.05	7.6E-04	2.6E-03	3.9E-04	2.6E-03	2.4E-04	2.6E-03
0.1	4.4E-04	2.2E-03	2.3E-04	2.2E-03	1.5E-04	2.2E-03
0.2	4.5E-04	2.0E-03	2.2E-04	2.0E-03	1.4E-04	1.9E-03
0.4	4.6E-04	2.0E-03	2.3E-04	2.0E-03	1.4E-04	1.9E-03
0.6	4.6E-04	2.1E-03	2.2E-04	2.0E-03	1.4E-04	2.0E-03
0.8	4.4E-04	2.1E-03	2.2E-04	2.0E-03	1.3E-04	2.0E-03
1.0	4.3E-04	2.1E-03	2.1E-04	2.0E-03	1.3E-04	2.0E-03
1.5	3.9E-04	2.1E-03	1.9E-04	2.1E-03	1.2E-04	2.1E-03
2.0	3.6E-04	2.1E-03	1.7E-04	2.1E-03	1.1E-04	2.1E-03
4.0	2.9E-04	2.1E-03	1.4E-04	2.1E-03	8.6E-05	2.1E-03

Table 3. (contd)

Photon Energies (MeV)	Gestational Stage: 210th Day Specific Absorbed Fractions	210th Day Relative Errors(a)	240th Day Specific Absorbed Fractions	240th Day Relative Errors	270th Day Specific Absorbed Fractions	270th Day Relative Errors
0.01	6.8E-04	2.6E-03	4.7E-04	2.6E-03	3.5E-04	2.0E-03
0.015	6.3E-04	2.6E-03	4.3E-04	2.6E-03	3.3E-04	2.0E-03
0.03	3.5E-04	2.6E-03	2.8E-04	2.5E-03	2.2E-04	1.9E-03
0.05	1.7E-04	2.6E-03	1.5E-04	2.6E-03	1.2E-04	2.0E-03
0.1	1.1E-04	2.2E-03	8.7E-05	2.3E-03	7.2E-05	1.7E-03
0.2	1.0E-04	1.9E-03	7.9E-05	1.9E-03	6.5E-05	1.5E-03
0.4	1.0E-04	1.9E-03	7.8E-05	1.9E-03	6.3E-05	1.5E-03
0.6	9.7E-05	2.0E-03	7.5E-05	1.9E-03	6.1E-05	1.5E-03
0.8	9.3E-05	2.0E-03	7.2E-05	2.0E-03	5.9E-05	1.5E-03
1.0	9.0E-05	2.0E-03	6.9E-05	2.0E-03	5.6E-05	1.5E-03
1.5	8.2E-05	2.0E-03	6.3E-05	2.0E-03	5.1E-05	1.6E-03
2.0	7.6E-05	2.1E-03	5.8E-05	2.0E-03	4.7E-05	1.6E-03
4.0	6.1E-05	2.1E-03	4.7E-05	2.1E-03	3.8E-05	1.6E-03

(a) Relative errors are the errors associated with the Monte Carlo calculations.

3. Approximation by Uterine Doses

As was discussed in Sections I.D and III.C, radioactivity contained within the embryo/fetus provides the self-dose component of its internal radiation dose while additional dose may be contributed by emissions from radionuclides in tissues of the pregnant woman. For the radionuclides of occupational concern considered in this report, tabulations are presented to provide fractional amounts of radioactivity and radiation doses in the embryo/fetus in months subsequent to an intravenous injection. There will be other nuclides for which the dosimetrist may wish to make determinations before the availability of definitive biokinetic models and dosimetric calculations, and it is suggested that the biological behavior of some elements might be approximated from information in ICRP Publication 30 (ICRP 1980, 1981), or, when necessary, the nonpregnant uterus or uterine contents at selected gestational stages might be used as surrogates for the embryo/fetus. Some compilations of specific absorbed fraction are available and can be used for this purpose (Davis et al. 1987).

The validity of using values of uterine dose from maternally distributed activity as a surrogate for estimating photon dose to the embryo/fetus and the inherent accuracy or error associated with this approach require consideration. Some of the basis for the observed stage-related deviations from complete correlation were discussed in Section III.C; these relate to target sizes and their effect on geometric relationships and specific absorbed fraction. Clearly, the location and dimensions of the nongravid uterus do not

accurately represent the near-term fetus, but models of intermediate stages are increasingly becoming available so that the degree of accuracy will continue to improve. Most current dosimetric models generally assume homogeneous soft tissue composition, but in actuality there are areas of enhanced absorption that assume increasing importance as the fetal skeleton develops and ossifies. This may be a relatively minor source of uncertainty, however, when compared to other assumptions and approximations that are inherent in current development of the model.

The dosimetric calculations of contributions from maternal tissues that were used for developing tabulations in this report did not consider localization in structures such as bone, liver, or bladder. Our calculations have shown, however, that this does not significantly affect the results when the energy of the photons is above 0.01 MeV, irrespective of decay complexity. This would be true also with use of a uterine-content surrogate for the embryo/fetus, although the dose from soft photons emitted by radionuclides in maternal tissues would be less accurate in both cases.

Estimation of dose from localization of beta-emitter deposition in the uterine mucosa assumes equivalence of concentrations in the embryo and uterine mucosa, which should be reasonably accurate during the early stages. We calculated the impact of disparities between uterine and embryonic concentrations and found that this would range from a two- to threefold overestimate or underestimate, numerically corresponding to concentration differences of the same magnitude. Another major inaccuracy during early stages would be the precision to which the activity in the uterus can be estimated, and there is no basis to generalize these estimations to the later fetus. This is particularly pertinent for radioactive elements and/or compounds for which such estimations will be mostly required, those for which minimal information is available. A calculation based on the assumption that average fetal activity is the same as average maternal soft tissue concentration seems to be the most conservative, but all the indicated caveats apply.

To facilitate use of the uterine dose surrogate approach, we employed information on the committed dose equivalent to the uterus per unit intake, as generated during preparation of ICRP 30. This was supplied to the NRC by Dr. Keith F. Eckerman of the Oak Ridge National Laboratory, together with corresponding fractional absorption values (f_1) from the gastrointestinal tract or lung for relevant chemical forms. Committed dose equivalent was divided by the highest f_1 value to convert to the assumed 1 μCi introduced into maternal blood used in other calculations in this report. The resulting estimates of uterine doses (or surrogate embryo/fetus doses) are shown in Appendix F. It must be emphasized that these are based on committed dose equivalent and there may be major differences from the absorbed dose to the embryo/fetus. Sources of these differences include length of time over which the dose is integrated (the 9 months of gestation versus the 50-year commitment) and avidities of the conceptus for the nuclide.

To illustrate the uncertainties, especially as they relate to stage of gestation and associated metabolic factors, Table 4 presents a comparison for nuclides that were used for embryo/fetus dose calculations; minimum and maximum values are shown to account for stage of gestation at exposure. Good

Table 4. Comparison of ICRP 30 uterine doses (converted to an injection of 1 μCi into blood) with embryo/fetus doses calculated in this report

Nuclide	Uterine Dose (rad/μCi)	Embryo/Fetus Dose[a] (rad/μCi) Minimum	Embryo/Fetus Dose[a] (rad/μCi) Maximum	Ratio of Doses[b] (Embryo/Fetus to Uterus)
H-3	6.40E-05	9.03E-06	5.87E-05	0.14 - 0.92
C-14	2.09E-03	1.89E-04	1.29E-03	0.09 - 0.62
Co-57	7.62E-03	1.04E-03	2.20E-03	0.14 - 0.29
Co-58	3.56E-02	6.00E-03	9.17E-03	0.17 - 0.26
Co-60	1.53E-01	1.60E-02	4.18E-02	0.10 - 0.27
Sr-89	2.96E-03	5.23E-03	1.84E-02	1.77 - 6.20
Sr-90	1.86E-02	1.68E-02	5.22E-02	0.90 - 2.80
Ru-106	1.12E-01	2.53E-03	7.23E-03	0.02 - 0.06
I-125	1.09E-04	8.31E-05	1.38E-03	0.76 -12.69
I-131	1.59E-04	6.29E-05	2.07E-03	0.40 -13.04
I-132	9.95E-05	8.43E-05	1.56E-04	0.85 - 1.57
I-133	1.39E-04	2.81E-04	9.04E-04	2.03 - 6.52
I-134	4.59E-05	2.22E-05	4.83E-05	0.48 - 1.05
I-135	1.42E-04	1.95E-04	3.70E-04	1.37 - 2.60
Cs-134	8.25E-02	3.24E-02	1.11E-01	0.39 - 1.34
Cs-137	5.33E-02	1.60E-02	5.94E-02	0.30 - 1.11
U-233	9.69E-03	1.44E-03	2.92E-02	0.15 - 3.02
U-234	9.55E-03	1.43E-03	2.92E-02	0.15 - 3.06
U-235	9.32E-03	1.32E-03	2.67E-02	0.14 - 2.87
U-238	8.51E-03	1.26E-03	2.07E-02	0.15 - 2.43
Pu-238	1.63E-03	2.74E-03	5.56E-02	1.68 -34.11
Pu-239	1.50E-03	2.58E-03	4.23E-02	1.72 -28.19
Am-241	5.55E-03	5.48E-04	1.11E-02	0.10 - 2.00

(a) Minimum and maximum values are shown relating to differences attributable to stage of gestation at exposure.
(b) Fractional relationship of the tabulated minimum and maximum embryo/fetus doses and the doses to the uterus are indicated.

agreement was obtained for materials such as tritiated water, which have uniform distribution and relatively short biological (and thus effective) half-lives. With alkaline earths such as strontium, the overestimate that results from the long retention component in bone is counterbalanced by the increasing amounts that enter the conceptus throughout progressive gestational stages so that there is reasonable agreement of net values. With many actinides, there is a comparable set of retention and increasing activity factors, which implicitly differ with stage of gestation, so that a pronounced diversity in the range of relative values is found (Table 4). The tabulations for the uterine dose surrogate from transuranic elements of interest, as provided in Appendix F, do not reflect these stage-related differences. It is suggested that uterine dose should not be used as a surrogate for other alpha-emitting, long-lived actinide elements. Instead, greater (but still

incomplete) accuracy might be obtained by the use of the ^{241}Am tabulations, with adjustment by proportionation for differences in alpha emission, if desired.

IV. CHARACTERISTICS OF PRIORITY RADIONUCLIDE GROUPS

In this section, we present biological considerations that summarize our evaluations of the literature and which will form the basis for the biokinetic component of the dose calculations. Complementary information from the relative concentration and kinetic approaches was integrated to develop the following descriptions and the dosimetric considerations that are presented in the appendices. Where insufficient quantitative information could be obtained, it was supplemented using available physiologic and metabolic knowledge.

These considerations provide the basis for ongoing efforts that are expected to lead to greater ease and precision by facilitating introduction of physical dosimetric factors into the numerical calculation of doses. Consistent with the MIRD approach, absorbed doses (rad, Gy) will be calculated relative to a specific total body burden or activity, 1.0 μCi, that is considered to instantaneously enter into the blood circulation, or first transfer compartment, of the pregnant woman at the initial moment of consideration, defined as t = 0. To the extent possible, pertinent characteristics will be presented to provide an understanding of the metabolic assumptions that underlay the calculations, which were sometimes performed differently for major gestational periods. There are accepted fractional absorption factors that allow the dosimetrist to relate available estimators of intake levels and these burdens, but the contributions of repeated intakes need to be roughly approximated by summation. Preliminary extrapolations of metabolic patterns that are given in Appendix E will summarize anticipated embryo/fetal doses relative to maternal doses for representative exposure conditions.

A. BASIS FOR SELECTION OF PRIORITY RADIONUCLIDES AND GROUPS

To expedite interim recommendations for determining radiation doses to the embryo/fetus, initial emphasis was placed on detailed analysis of restricted groups of radionuclides. The priority radionuclide groups were selected because they provided a representative spectrum of biological, physical, and dosimetric attributes; some are of potential importance for occupational exposure, and because higher level exposures may involve health concerns. They are, in order of increasing atomic number: 1) tritium and carbon in inorganic forms; 2) tritium and carbon in three typical organic forms - glucose, amino acid, and thymidine; 3) cobalt; 4) strontium; 5) ruthenium; 6) iodine; 7) cesium; and 8) plutonium. Limited biological features of the lead/polonium/radon/radium complex were also presented to provide a basis for comparisons. Based on responses to the document that was disseminated for comments, analyses have been extended to include additional isotopes and chemical forms of these priority nuclides, as well as a few other elements.

B. RELEVANT FEATURES OF PRIORITY GROUPS

The following presents the information and general models that led to the dosimetric approaches and expanded analyses related to typical forms in which these radionuclides may be found in work environments. A few representative examples of relevant relationships and factors that were derived to facilitate biokinetic calculations are provided in Appendix A. Summaries of assumptions and approaches to determination of their biological behaviors are given in Appendix B, and the retained fraction of several isotopes of these materials, which are the basis for dosimetric calculations, are presented in Appendix C. Tabulations of the numerical results for initial monthly dose rates and integral doses are in Appendix D. The bibliography, with keywords, and quantitative databases for these materials became so extensive that there was general agreement that they should be presented in a separate document. Only a few particularly relevant references, or reviews, for each nuclide and form are provided in the literature citations.

1. Inorganic Tritium and Carbon

a. Inorganic Tritium

Trace amounts of tritium in gaseous form or incorporated into water are readily absorbed from the lung or gastrointestinal (GI) tract; thus, it is assumed that both water vapor and hydrogen gas readily cross the lung in both directions equally. In air, however, most hydrogen (stable or tritium) will form water, as will some small amount of that which is absorbed, so that little tritium actually enters the body as gas. The fractions for tritium seem to be approximately the same as for stable hydrogen in air or unlabeled water, respectively. This behavior seems to be less distinctive than that of deuterated water, in which the percentage content of tracer isotope is often higher, so that it is more likely to lead to a detectable "mass" or "isotope effect." Physiologic studies demonstrate that water crosses the placenta, and other membranes, freely in both directions. Accordingly, tritiated water is routinely used as a "marker" in studies of placental transport because a change in rate shows functional deterioration of the biological preparation. The percentage water content of the embryo and fetal tissues generally is measurably greater than that of the corresponding tissues in adults, so that their relative tritium concentrations may be slightly greater. For practical purposes, however, it may be assumed that the initial concentration of tritium in the conceptus will be the same as that of the pregnant woman irrespective of stage of gestation, and that it would readily be excreted in parallel with its loss from her body.

b. Inorganic Carbon

Metabolic models used by ICRP (ICRP 1981) assume the f_1 to be 1 for carbon-labeled organic compounds but it is clear that transfer to the embryo/fetus varies with the molecular species. As will be presented in the following section, patterns presented by Battaglia and Meschia (1986) make it reasonable to assume, for our purposes, that carbon dioxide produced by catabolism of organic compounds in the embryo/fetus is immediately transferred to the woman's circulation.

The special situation associated with inhalation, absorption, and hemoglobin binding of ^{14}C-carbon monoxide is considered to be a remote possibility, and does not require specific evaluation for a pregnant woman. The more likely scenario involves carbon dioxide, and it is assumed that all that enters the respiratory tract is translocated to blood, where it will exist mainly as sodium bicarbonate (ICRP 1981). If we ignore the small fraction that may have a long retention, whole-body retention of bicarbonate in the first 120 minutes is given by

$$R(t) = 0.175\ e^{-0.693t/5} + 0.825e^{-0.693t/60} \qquad (14)$$

The ICRP (1981) makes the assumption that ^{14}C-labeled compounds are instantaneously and uniformly distributed with a biological retention half-life of 40 days. ICRP Publication 30 states that it is recognized that this provides an overestimate of dose from compounds other than metabolites, but this relationship requires that our model be based on introduction into the transfer compartment of ^{14}C as bicarbonate. Detailed models involving its transfer from the maternal to the embryo or the fetal circulation are not available, but the release and transfer of carbon dioxide from fetus to mother would be expected to interact with bicarbonate transfer. Although this probably leads to an overestimate, the lack of full information about transfer and retention requires that conservative estimates should regard the initial activity in the embryo/fetus from maternally injected bicarbonate as corresponding to a concentration associated with the uniform maternal distribution. It will be assumed that one-half of this activity is involved in anabolic processes in the embryo/fetus, incorporated into structural molecules and retained throughout gestation, while the other half is rapidly excreted. This anabolic utilization by the embryo/fetus contrasts with the 40-day half-life for activity in adults assumed in ICRP Publication 30 (ICRP 1981).

2. Organically Bound Tritium and Carbon

The literature on radiological protection gives relatively little consideration to tritium in organic compounds, other than thymidine, but a broad summary of placental transfer is provided in the review by Kistner et al. (1987). It is otherwise considered in passing, almost entirely by comparison to thymidine (see NCRP 1979a, 1979b). NCRP Report No. 63 (NCRP, 1979b) is directed toward the relationship of tritium, and carbon to a minimal extent, when incorporated in genetic material, especially DNA. There are many unknowns, some of which are indicated here, that make it appropriate to consider materials after they have been absorbed and are present in the blood of the pregnant woman in the form under consideration. Thus, materials that first require digestion will be considered in the form that is in the blood after absorption; this will be assumed to represent a nominal 1.0-μCi burden in the pregnant woman at time zero. The following, therefore, is based on generalizations that have been derived from relevant metabolic considerations relating to prenatal development. The approach may be extended to include the ingested form, based on accepted metabolic models, but it is more likely that this will be calculated by the dosimetrist.

a. Glucose

Glucose is actively transported from maternal to fetal blood across the placental layers, uterine blood, and thence to the umbilical circulation and fetus. The concentration difference between glucose in maternal and fetal blood serves as a major driving force for its placental transfer. The most substantial quantitative data are available from studies of pregnant sheep, but the general patterns are consistent with information from other species, including man (Meschia 1982; Battaglia and Meschia 1978; Hay and Meznarich 1989).

Fetal brain, liver, kidney, and skeletal muscle are the major organs that utilize glucose, and the overall glucose utilization rate is higher in the fetus than in the pregnant woman. During late gestation, consumption by the uterus and its contents represents 30% of total maternal glucose utilization. Of this amount, 60% of the net glucose uptake is consumed by the placenta and 40% is utilized by the fetus. Fetal glucose utilization rate is higher during midgestation than in late gestation. Fetal glucose provides energy and building blocks for synthesis and body growth. Umbilical glucose uptake provides 50% of the energy requirement for the fetal lamb, and approximately 60% of uniformly labeled ^{14}C glucose infused to the fetus is oxidized to $^{14}CO_2$. As compared to the fetal lamb, the human fetus is characterized by a higher ratio of brain-to-fetal weight, more efficient placental glucose transfer (a smaller maternal-to-fetal glucose concentration difference), and a higher proportion of fat (16% versus 2% at term).

Glycolysis of tritium-labeled glucose produces tritiated water, which then can exchange and distribute throughout the intracellular and extracellular water pools in both maternal and fetal compartments. A limited fraction of the tritiated water may subsequently become incorporated into lipid via lipogenesis, but this is sufficiently small that it can be ignored for dosimetry purposes. Catabolism of ^{14}C-labeled glucose results in $^{14}CO_2$ production in the fetus. This does not accumulate in the fetus; it is randomly excreted to the mother via the placenta, and then exhaled. Graphic representations of comparisons are presented in Figure A1, Appendix A, to illustrate these patterns.

Fructose and other hexoses are absorbed from the small intestine and are mostly metabolized in the liver, so that blood fructose concentrations are generally negligible in adults of most species. The fetal ungulate has a high fructose concentration in blood, which is produced from glucose in the placenta. The sheep placenta has a lower permeability to fructose than to glucose, but the situation is not clear for the human placenta (Meznarich et al. 1987). Only trace amounts are present in human blood, and it is assumed that negligible amounts of other hexoses are transferred to the fetus.

b. Amino Acids

Amino acids fall into two main categories, based on their physiologic and metabolic characteristics: essential amino acids, which are the most thoroughly studied, and nonessential. The usual studies of amino acids have been directed at defining their metabolic aspects, which dictated experimental

design, and so there is limited information concerning the relative fetal-to-maternal concentrations of radioactivity in tissue for any one amino acid. The essential amino acid, leucine, is the most commonly used marker for studies of amino acid and protein metabolism during fetal development, but confirmatory data are provided by the results of studies with other amino acids. The usual net flux of neutral and basic amino acids is from the maternal blood circulation to the fetal circulation. However, the net flux for some amino acids, such as glutamic acid, is in the direction from the fetus to the woman. Most amino acids are actively transferred across the placenta in both directions. In general, the concentrations of free amino acids in fetal tissues are similar to those in maternal tissues. Concentrations of total amino acids in fetuses and newborns are similar among species at comparable stages of maturation. Illustrative examples and their relationships to hexose metabolism are presented in Figures A2 and A3.

Amino acid nitrogen accounts for about 80% of total nitrogen in fetuses of many species, including the guinea pig and sheep. The major function of amino acids is to serve as metabolic components for synthesis of proteins. When they are not required for protein synthesis, however, amino acids are oxidized to provide energy. Data from oxygen consumption measurements indicate that, on average, amino acids provide approximately 25% of the fetal energy requirement.

Significant amounts of labeled amino acids are incorporated into protein during organogenesis or the growth phases of gestation. It may be anticipated that there will be a high proportional retention of the activity as compared to the dam. Concentration concurrently would be reduced through dilution by further incorporation of amino acids during progressive growth, so that consistently major deviations from maternal concentration would not be expected. Oxidation of ^{3}H-labeled amino acids produces tritiated water, which, as was indicated for glucose, exchanges and distributes throughout the intracellular and extracellular water pools in both maternal and fetal compartments. Although small amounts of ^{14}C-labeled amino acids may enter the carbohydrate pool after oxidation, the predominant fraction will form $^{14}CO_2$; this is rapidly eliminated as described in the previous section, and would not make a substantial contribution to dose.

c. Thymidine

Essentially all information concerning thymidine in intact animals has been obtained from deliberate injections for labeling of cell populations. Thus, biological behavior of radiolabeled thymidine under conditions of accidental or environmental exposure is not clear (Commerford 1984; Ishiwata et al. 1985). The route was usually intravenous in animal experiments, although intraperitoneal injection and subcutaneous infusion were used for studies of long-term toxic effects, which included developmental stages.

There do not appear to be any major differences between the metabolic behaviors of ^{3}H- or ^{14}C-labeled thymidine in intact animals, and both precursors are incorporated into the DNA of proliferating cells. Only a fraction of that which enters the adult, often estimated as about 10%, is incorporated; most of the remainder is catabolized rapidly and excreted. There is long-term

retention of the incorporated thymidine; it remains in the DNA until the cell divides, when it is partitioned between the daughter cells; some may be reutilized when the cell dies.

The processes by which thymidine crosses the placenta and the relative importance of active transport versus diffusion have not been established. Moreover, there are no reliable quantitative measurements of the extent of placental transfer. It may be assumed that any preexisting maternal burdens will be essentially unavailable for transfer. Calculations from the few data suggest that there may be a lower fetal than maternal concentration after either single or multiple exposures, although the possibility that initial concentrations are essentially the same in the conceptus and dam can not be ruled out. Any difference in retention rates between the adult and conceptus, because of differential division, is probably small.

3. Cobalt

Water, as well as many foods, contains low concentrations of inorganic cobalt, and cobalt is an intrinsic component of the vitamin B-12 molecule, which is present in many foods of animal origin. Radioactive isotopes of cobalt are produced by activation in nuclear reactors; this occurs incidentally as well as purposefully, and selected isotopes are also incorporated into radiopharmaceuticals. As a result, there are marked differences in the potential for exposure of women to inorganic and organically bound forms of radiocobalt isotopes.

The basic metabolic patterns are based on ICRP Publication 30 (ICRP 1981), and transfer information is generally consistent among other sources such as Chow et al. (1951), Luhby et al. (1959), and Zylicz et al. (1975). It is commonly assumed $CoCl_2$ is the form that enters the gut; f_1 is considered to be 0.3, and entry is into blood in that form. One-half of the activity in blood is excreted with a half-life of 0.5 day, and essentially all activity is cleared from blood by 24 hours after injection.

Metabolism, including retention, placental transfer, and fetoplacental distribution, is markedly different when cobalt enters the body in inorganic form, rather than as vitamin B-12, the most common organic molecule. After administration as the chloride, it distributes among several organs and tissues, including cartilage, liver, kidney, and pancreas, and is also found in mucous secretions of the respiratory tract. Some investigators report that hepatic concentrations of ^{61}Co reach their maximal level on the day after injection and that concentration in cartilage increases with time, reaching levels that may be four times greater than that in the liver at 4 days after injection. It is usually assumed that of the half that is not excreted, 0.05 goes to liver and 0.45 is uniformly distributed through the rest of the body, so that hepatic concentration is four times that in other tissues of body; this is the most common basis for calculation and has been used in this report.

The rate of placental transfer of inorganic cobalt is dependent on the stage of gestation at administration; transfer appears to continue throughout the first day after administration. In the several studies on metabolism

during gestation, the fetal-to-maternal concentration ratios differ by a 10-fold range for animal experiments; most commonly, the values center about unity. The ratio in most soft tissues of the fetus tends to be slightly less than 1. Concentration in fetal cartilage increases with gestation stage, and in later gestation, the stage at which radiocobalt enters the fetus most rapidly, it may tend to accumulate in fetal bone (Figure A4).

The biological half-life of vitamin B-12 is about 48 to 70 days; it is actively transported across the placenta, and the distribution in soft tissues of the fetus is similar to that in the mother. Some reports indicate that vitamin B-12 levels in maternal plasma may decrease progressively throughout human pregnancy and reach subnormal levels at term, so that plasma levels of the neonate may be two to five times greater than the corresponding maternal level. The ratios for average concentration in fetus to mother show a central value that can reasonably considered to be 1. The range of values, however, in experimental animals as well as in human pregnancies, is even greater than that reported for inorganic cobalt. There is also a wide range of tissue concentration ratios, although the value for prenatal liver and kidney tend to be greater, the spleen and pancreas the same as, and other organs substantially less than that of corresponding maternal tissue.

After single or multiple exposures of the pregnant woman to organic or inorganic cobalt, the average fetal concentration might reasonably be taken as being the same as in the woman, while recognizing that the variations among tissue activities in relation to gestational stage would be substantial. Under the same circumstances, however, the relative concentration in the early embryo would be expected to be substantially less than 1.

4. Strontium

Strontium is an alkaline earth. As described in ICRP Publications 20 and 30 (ICRP 1973; ICRP 1978), Griessl (1987), and Mays and Lloyd (1966), its metabolic behavior is similar to that of calcium in many respects. There are quantitative differences in the net transfer of the two elements between metabolic compartments, however, which is usually expressed in terms of observed ratio (OR) values between biological compartments. These ratios have been the subject of extensive measurement and publication throughout the years. The ICRP considers soluble salts to be absorbed from the GI tract and lung with f_1 values of 0.3, but with 0.01 for insoluble oxides.

Calcium is the most important inorganic component of bone, but it also serves as a membrane component and intracellular messenger. It is not clear to what extent this second function may be assumed by strontium, but it does not seem to represent a major quantitative fraction and is probably independent of time of postnatal or prenatal life or of stage of gestation. In contrast, bone is not present in the embryo during the early gestation period, and it does not begin to assume definitive shape or form until early in the fetal period. The development and calcification of bone matrix become progressively more important through later gestation and postnatal life. Consequently, deposition becomes progressively greater as the fetus approaches term. This is especially pertinent in human development, and is a factor that needs to be considered in extrapolations because the extent of prenatal bone

maturation is substantially greater in the human fetus than in some common laboratory rodent species, such as the mouse and rat, in which substantial calcification takes place in the postnatal period (Figure A5).

This pattern, seen also with some of the other nuclides considered here, illustrates an important factor that was only mentioned in foregoing sections of this report. Almost all the strontium content of the late fetus is in bone and, in one sense, skeletal mass should be used for calculating average concentration from total activity. However, current recommendations are stated in terms of dose to the embryo/fetus, so that its total body would be the appropriate mass to consider at present.

5. Ruthenium

Ruthenium is among the most abundant fission products in waste effluent from reprocessing of nuclear fuels (Nishimura et al. 1988). A primary reason for its selection for consideration here was because of an early whole-body autoradiographic study that had detected a marked deposition in the fetal membranes, as well as in maternal kidney and connective tissue (Nelson et al. 1963). They had found a lesser concentration in the placenta, which seemed to follow blood clearance. It therefore seemed to be one of the few elements, other than actinides and some of the other heavy metals, that localized in the yolk sac. This phenomenon is of interest because of its possible relevance for induction of postnatal effects.

This localization has been confirmed in more recent studies that measured the biokinetics of ^{106}Ru in rats (Nishimura et al. 1988). Biological disposition varied with animal age and the chemical form in which the ruthenium was administered, but the percentage of the injected activity transferred across the placenta after intravenous injection of $^{106}RuCl_3$ in rats consistently increased with gestational age. As an example, approximately 0.4% of the activity was transferred to the totality of the fetuses at 20 days of gestation, which may be calculated as equivalent to an average concentration that is less than 5% of that in the dam. This study quantitatively confirmed that the concentrations in the fetal membranes, and in the placenta to a lesser degree, are higher than those in the fetus.

6. Iodine

Iodine has several radioactive isotopes, with a wide range of half-lives and decay schemes. There are numerous routes and circumstances through which members of the population, including pregnant women, may receive an iodine burden. These range from deliberate administration for medical procedures, occupational intake of materials being prepared or administered as radiopharmaceuticals, and deposition via accidental releases or contamination in the general environment. Other than when administered as organic radiopharmaceuticals, which may release inorganic iodine, direct availability is in the form of iodides. These are readily absorbed into the blood from the gastrointestinal tract, the lung, or from many other sites. The f_1 value for inorganic iodide is considered to be 1, and 30% is assumed to be rapidly taken up from the blood by cells of the thyroid gland, which specifically concentrates iodide. Once inside the thyroid, iodide is incorporated into thyroid

hormones and stored as colloid in the lumen of the thyroid follicles. Under pituitary control, thyroid hormones are released into the blood, and are present in the circulation until transported into tissues.

The literature on the dosimetry and effects of radioiodine is among the most voluminous of that of all elements. There have been several independent assessments of radiation doses to the fetal thyroid from specific isotopes under varied exposure conditions (Book 1978; Johnson 1982, 1987; Roedler 1987). In contrast, little attention has been directed toward other isotopes or the calculational methodologies applicable to radiation doses to the embryo/fetus.

Inorganic iodides, and iodine-containing thyroid hormones to a lesser extent, cross the placenta and are readily accessible to the embryo or fetus. The thyroid gland undergoes substantial morphologic and physiologic development before it has the capacity to trap and metabolize iodide into hormone; these changes are affected by development of pituitary function. In the human, hormone synthesis first occurs at about gestational day (gd) 90, well into the fetal period. The relative concentration in the fetal to maternal thyroid is sometimes thought to be greatest in midgestation, but the peak ratio is most commonly accepted to occur shortly before parturition. Depending on the radioisotope, the decay scheme, the half-life, and whether exposure is chronic or acute, the thyroid concentration in the final months of pregnancy has been estimated to be three- to ninefold greater in the fetus that in its mother.

In addition to the stage of gestation, the time course and magnitude of iodine concentrations in the embryo/fetus, the relative degree of localization, its retention, and the biological consequences depend on the specific isotope half-life. Although there is no specific localization during the embryonic period, a generalized distribution of circulating iodides may be expected, with concentrations approximating those in the maternal blood when adjusted for differences in body weight. Localization in the fetal thyroid will increase as its function progresses.

Iodine may enter the body associated with materials as an iodinated tracer used as a research or nuclear medicine procedure, or become bound to an organic molecule in a biological process. In such cases, the compartments in which it is contained are dependent on the characteristics of the organically bound iodine per se, but thyroid localization can occur once inorganic iodide is released from the molecule. There are many iodinated organic molecules in use as tracers, and they may cross the placenta to varying degrees. However, once released from the organic molecule, iodide will display behavior that is characteristic of the inorganic form at that stage of gestation.

7. Cesium

Cesium is chemically related to potassium, and its behavior is similar in most biological tissues and fluids, where it usually would be in ionic form. Many reports state that pregnancy does not have an appreciable effect on its absorption, distribution, or excretion, although it is commonly

accepted that turnover rates are increased in pregnant women (NCRP 1977a; ICRP 1975, 1978).

As would be expected from its similarities to potassium, cesium has a generalized distribution, with similar concentrations among soft tissues, both in women and in adult animals. Some reports suggest that its transfer is less than that of potassium, but cesium also readily crosses the placenta; the initial concentrations are essentially the same in comparable tissues of the pregnant woman and conceptus. There are reasons to expect that concentration in the embryo/fetus would be greater than in the woman, but this has not been reliably demonstrated by empirical measurement, and the pattern is essentially independent of time of gestation, including early stages. Composites of measurements of activity in the rat fetus indicate that the loss rate is about 0.02% dose/g weight/day, but concentrations decrease more rapidly because of growth. As shown in Figure A6, the rate constants for decreases in concentration (K_d) in the embryo/fetus and in the placenta do not change with gestational age.

Some measurements have found differences among concentrations in various tissues on the day after injection; these remain fairly constant, but their magnitude is not sufficiently great as to require special consideration. For practical purposes, the concentrations throughout the embryo/fetus may be assumed to be uniform and to be the same of those of soft tissues of the pregnant woman.

8. Uranium

The metabolism and toxicity of uranium isotopes have been extensively studied in adult animals of various species, but few data are available concerning its placental transfer or developmental toxicity (Sikov 1987). In studies of distribution and effects in rats after intravenous exposure to citrated solutions of ^{233}U, the highest fetoplacental concentrations were found at 1 day post exposure. The concentrations in the embryo or fetus and the placenta progressively decreased thereafter, but the concentration in the fetal membranes remained relatively constant. After injection during the fetal stages, there was selective deposition in some fetal organs. The placental concentrations tended to be similar at 1 day after injection at any time during the fetal period, and were consistently less than corresponding values for the fetal membranes. Exposures of pregnant rats at 9 or 15 dg produced dose- dependent trends toward increased prenatal mortality, decreased fetal and placental weights, and increased malformation frequency. The evidence suggested that the effects resulted from chemical toxicity to the pregnant animals and their conceptuses.

Significant concentrations of ^{234}U were found in three of seven first-trimester samples in determinations of environmental actinides in human abortuses. The concentrations were similar in the fetal and placental tissue, and the highest concentration was for ^{234}U (Weiner et al. 1985; Wegst, personal communication). Among the 16 second-trimester samples, 12 were positive for ^{234}U. When all uranium isotopes were summed for samples that were positive, ranges of 0.097-0.32, 0.31-0.52, and 3.5-3.8 dpm/kg were found for the fetuses, placentas, and umbilical cords, respectively. The concen-

tration in reference adult tissue was 2.1 dpm/kg, and it was concluded that the fetus did not selectively concentrate uranium.

9. Plutonium

Plutonium is the most thoroughly documented of the actinides. As reviewed in several publications (ICRP 1978, 1980, 1981, 1986; Sikov 1987; NEA 1988), its behavior is generally representative of this group of elements, although there are important differences among them. Animal studies have shown that it crosses the placenta after injection in pregnant animals, albeit poorly, and it can also can be transferred to offspring via lactation. Essentially all animal studies, however, indicate that the extent of placental transfer is less than that of bone-seeking alkaline earth elements such as strontium, and that its clearance from maternal to fetal circulations is lower, as measured in placental perfusion studies.

The biological disposition pattern of plutonium is complex, and involves stage-dependent changes in degree and patterns of deposition within the feto-placental unit, in gross and microscopic localization in the developing skeleton, and in metabolism relative to that of the pregnant animal. Plutonium primarily deposits on bone surfaces, in contrast to calcium, strontium, and radium, which are incorporated into the matrix of the bone. After prenatal or neonatal exposure to plutonium (and other actinides), however, remodeling of bone results in a progressive movement into the matrix. Because the predominant deposition of plutonium is in the skeleton and liver of adults, concentrations in soft tissue are relatively low. Although the activity in the embryo/fetus of animals also is low after single exposures, the average concentration is usually found to be as high or higher than in the dam. As the result of deposition in fetal liver and bone, this concentration is consistently found to be greater as injection is made later in gestation.

The relative fetal concentration values for plutonium, as calculated from data of numerous studies in various animal species, differ from ratios from limited numbers of radioanalyses of prenatal human tissues that were obtained after chronic exposures at environmental levels. Ongoing efforts are developing composite analyses that provide relative concentrations as a function of chronological time and stage of gestation and allow application to either acute or chronic exposures (Sikov 1987; Sikov and Kelman 1989; Morgan et al. 1991). It is anticipated that these may partially reconcile apparent interspecies differences. It appears that many differences among concentration ratios are related to species-specific gestational stages and to the chronicity of exposure, but maternal metabolic differences remain a potentially important factor. These efforts emphasize the need, however, to develop an acceptable basis for extrapolating results from animal experiments to the human and to provide sufficient data for estimating concentrations and calculating ratios among maternal tissues, fetal tissues, and placentas.

10. Americium

Intravenous injection of rats (Sikov and Mahlum 1969; Weiss and Walburg 1980) with high doses of ^{241}Am during the late embryonic and fetal periods demonstrated that average maternal-to-fetal concentrations and americium

content of the fetuses and placentas varied with stage at injection. A smaller fraction of administered americium than of plutonium entered the conceptus or fetoplacental unit, and there was proportionately le selective deposition in the placentas and membranes.

The prenatal effects of americium were similar to those of plutonium, and include prenatal mortality and rib malformations but not intrauterine weight retardation. Effects are quantitatively less when based on dosages administered intravenously to pregnant rats, but there is good correspondence when considered relative to radiation doses to the components of the feto-placental unit, especially the yolk sac. Embryo/fetal radiation doses relative to administered activity were consistently less than with plutonium.

In a series of determinations of transuranic nuclide content after environmental exposure, Weiner et al. (1985) were not able to detect significant amounts of ^{241}Am in first-trimester abortuses. Six of the second-trimester samples were positive, with concentrations ranging from 0.08 to 0.29 dpm/kg in the fetuses. Substantially higher values, 1.0 and 2.1 dpm/kg, were measured in umbilical cords.

11. The Lead/Polonium/Radon/Radium Complex

There have been long-standing health concerns about this complex of naturally occurring elements. Compilations of literature regarding this group of nuclides were included in the expectation that they would provide a basis for comparisons with the priority radionuclides. There is a large body of information concerning lead, which has been used as a benchmark material in other analyses (see Sikov [1987] for overall review). Surprisingly, much less information was found concerning the placental transfer, fetoplacental disposition, and dosimetry of some of these other materials than might be expected from their potential for effects on health. The available information has been summarized here to provide the comparative biological behavior of these natural materials.

a. Lead

Lead has several radioactive isotopes but the most abundant isotope is stable; exposure of pregnant animals to lead results in prenatal mortality and a characteristic complex of malformations. Studies of placental transfer in rats after intravenous injection during later gestations demonstrated an exponential decline of blood and plasma concentrations that was paralleled by a decrease in placental concentration. Fetal concentration increased through the 24 hours after injection, reaching final values that were about 60% of those in placentas. Direct measurement of maternal to fetal transfer in a perfused guinea pig placental preparation found a relatively low clearance value; it appeared that the circulating lead affected maternal blood flow to the placenta, and that the true clearance may have been higher. Other studies have shown that lead metabolism (blood clearance, tissue distribution, fetoplacental concentrations) and toxicity are affected by the presence of carrier, dosage level, and route of administration in pregnant rats exposed by gavage, inhalation, or intravenous injection, and that fetoplacental distribution is dose-dependent. The relationship between dosage and the lead

content during the early postimplantation/organogenesis period was especially complex.

As reviewed by Sikov (1987), mean concentrations of lead are significantly higher in pregnant women from urban than from rural environments, but were not related to stage of gestation, and overall mean concentrations in neonatal cord blood were similar to those in maternal blood. There was a high correlation between lead levels in mothers and corresponding infants A highly significant correlation between lead concentrations in cord and maternal blood has been also found by other research groups, and some also detected a weaker but statistically significant correlation with the concentration in the placenta. These results on placental lead concentrations are the most common findings, although up to fourfold greater placental concentrations have been reported.

Radiation after direct exposure is not usually an important consideration for lead because the radioactive isotopes are rarely used other than as tracers in biological experiments. To the extent that lead serves as surrogate for related radioactive materials, however, one would expect that embryo/fetal radiation absorbed doses would be approximately equal to those received by the pregnant woman, irrespective of the route and multiplicity of exposure. Lead may deposit through radon decay, in the placenta or in hematopoiete, and a role in late effects has been suggested by Richardson et al. (1990).

b. Polonium

It was reported more than 60 years ago that salts of polonium deposited in the chorionic epithelial cells of placental syncytium after injection did not pass into the fetal tissues. More recent reports confirmed the lack of transfer of injected ^{210}Po in rats; some of these studies also found intense labeling of Reichert's membrane and visceral yolk sac, but placental deposition was detected consistently. These results are compatible with the few observations in human materials, where elevated concentrations were measured in placentas from populations who consumed reindeer and caribou meat during the time when fallout was important.

It would appear that there is a minimal average radiation dose to the embryo or fetus from ^{210}Po in the body of the pregnant woman, and that most of the dose would be localized to the bone marrow. The placenta and fetal membranes might receive a radiation dose on an average basis. This could be intense on a local or microscopic basis, as discussed for other radionuclides. Polonium would be formed by decay of radon within the conceptus, and its decay would result in desorption of energy; this would seem to be more a theoretical than measurable event, and dose calculation would be difficult.

c. Radon

Despite recent interest in health effects associated with exposure to radon and its decay products in the home environment, there is essentially no direct information about prenatal radiation associated with exposure of pregnant women, and there are few data from studies of pregnant experimental

animals. Examination of conclusions from data obtained over 60 years ago suggest that they may yield acceptable correlations with extensive information concerning the behavior of other noble gases. Despite some differences in solubility in lipid, it may be inferred that radon would readily cross the placenta in both directions, but that predominant fractions of the radiation exposure from the radon per se would cease following the inhalation period.

From the behavior of lead and radium, it would appear that some of the radon decay products might cross the placenta and could enter or leave the fetus. This is in contrast with polonium and other radionuclides not considered here, which show marked deposition in the placental structures but only minimal accessibility to the fetus from blood. On the contrary, it may be surmised that these other nuclides might not cross the placenta after formation in the fetal compartment.

As a general expectation, with support from a recent experiment in which rats were exposed to radon and progeny, it is not unreasonable to accept that the radiation dose to the embryo/fetus from the radon would be similar to, or less than, that in the pregnant woman. The situation concerning the decay products has not been completely analyzed, but some of the dosimetric considerations relative to the human embryo/fetus have been discussed by Richardson et al. (1989).

d. Radium

Early studies failed to detect radioactivity in placentas or fetuses after intraperitoneal injection of rats with dissolved radium chloride. It is not clear to what extent the nuclide was absorbed into blood under these conditions, and the findings do not correlate with studies of human tissues.

A recently reported analysis of the skeletal remains of a 7-month human fetus and its mother, a former radium dial painter who had died from complications of the pregnancy, estimated that about 0.06% of the radium in the mother had been transferred to the fetus. Based on total ^{226}Ra contents, Ra/g Ca measurements in maternal and fetal bone, and factors from ICRP models, it was calculated that there was a 1.4-fold-greater placental transfer of radium. This is in good general agreement with earlier reports of measurements of ^{226}Ra content of bones and soft tissue of large numbers of human fetuses and placentas. The specific activity of bone ash (10^{-14} Ci/g) was independent of stage of gestation, and thus identical for fetal and adult bone. Concentrations in fetal soft tissues and placentas were similar (10^{-14} Ci/g) and did not change throughout gestation; the total content of the fetuses increased during gestation as a result of increasing fetal mass.

A series of evaluations of children borne to women who had been employed as radium dial painters detected burdens of less than 10^{-8} g of radium. These were considered to be in the normal range, even though the mothers had significantly great radium burdens that subsequently became symptomatic.

Although minimal prenatal dose is probably associated with early stages of gestation, it would seem reasonable to accept that radium concentrations in fetal and maternal bone are similar. This would seem to pertain both for

multiple occupational or continued environmental exposures. Continuing differences in bone composition relative to stage of gestation might be expected, which would influence the associated radiation doses. There would be concurrent changes in the size and shape of anatomic features, and their relationships would interact with composition. Thus, it would require detailed analyses to even consider use of a fetal to maternal radiation dose ratio other than unity.

C. FACTORS INFLUENCING DOSIMETRIC APPROACH

Operational health physicists have encouraged us to provide information in simplified formats that would help them comply with regulations. Some health physicists have hoped that derived levels based on objective criteria might consolidate the extent of placental transfer, fetoplacental concentrations, and potential for radiation exposures from radionuclides and might be expressed in more usual chemical forms and patterns of intake. Such summaries could also help to identify materials for which information was inadequate, and could also lead to quantitative tables, nomograms, or microcomputer programs that would facilitate interpolation and calculation.

In addition to direct calculational approaches, which are described in this report, the information that provided the basis for the synopses and calculations is being used more directly to prepare tentative collations. One such simplified collation is Table E2, "Generalized Estimates of Fetal to Maternal Concentration and Radiation Dose Ratios for Selected Doses for Selected Internal Radionuclides in Humans." However, this collation includes primarily the most commonly encountered radioisotopes and forms of the elements, but will remain incomplete because of limits to our knowledge. This collation is an attempt to *qualitatively* predict radiation doses that would be received by the conceptus relative to the doses received by the pregnant woman; the relationships are presented with respect to exposure pattern and stage of gestation. Clearly, additional data and calculations would be required to define specific *quantitative* relationships. Despite these shortcomings, Table E2 may provide a basis for obtaining the relative impact of the radiation dose to the embryo or fetus from radionuclide deposition in the mother at various stages of gestation.

The results of another approach, summarized in Table E3, "Simplified Categorization by Placental Transfer and Biokinetic Features," presents an overly simplified categorization by intrauterine behaviors. This tabulation typifies one approach toward using similarities of dosimetric features and identifying areas of uncertainty. We also have begun initial efforts toward simplification and use of surrogate measures (see Appendix F).

It is important to emphasize the uncertainties that arise from the lack of quantitative agreement among reports, the incompletely defined effects of deposition and kinetics of various gestational stages, and the potential inexactness of extrapolations. These uncertainties underscore the need for further research to obtain more definitive relationships.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

It is evident from the material presented throughout this report that there are difficulties in accurately determining radionuclide concentrations and activities in the conceptus and surrounding tissues of the pregnant woman. Calculation of radiation absorbed doses to the embryo/fetus from internally deposited radionuclide activity is the sum of two primary components: dose imparted from the mother and dose originating from the embryo/fetus. Estimation of activity in dosimetrically important maternal organs and consequent doses to the embryo/fetus uses straightforward extensions of currently accepted methodologies. This component could be termed the radiation dose equivalent to the embryo or fetus from radionuclides in tissues, organs, and cavities of the declared pregnant woman. Of greater importance to our efforts, however, is the radiation dose equivalent to the embryo/fetus from radionuclides that are contained within the embryo/fetus and adjacent structures. Based on currently available concepts, and until further information is available for reasonable expansion, it seems prudent to calculate or estimate absorbed doses in primary units of rad or Gy, and to multiply by appropriate values of quality factor to obtain dose equivalents (rem or Sv).

To extend and enhance evaluations for additional radionuclides, we suggest tentative approaches of calculations in operational situations in the remainder of this section. Stage-related tabulations of the results for selected radionuclides of current interest are presented in Appendixes C and D.

B. ESTIMATION OF RADIATION DOSE

On an interim basis, we suggest a conservative approach for those radionuclides for which there are little or no data, even though this may sometimes yield an overestimate of dose to the conceptus. Except for situations in which unique metabolic characteristics may be anticipated or some information is available, we should assume that the average embryo/fetal concentration is the same as that of the pregnant woman or of her soft tissue mass. The general biokinetic and dosimetric approaches that we have presented often can be used to estimate the corresponding embryo/fetal activity and the resulting corresponding self-dose under these circumstances. As an alternative approach, this dose could be assumed to be the same as the dose to the uterus or uterine contents shown in Table F2.

Parenthetically, many human radionuclide exposures may relate to the production and use of radiopharmaceuticals. Several of these materials, especially those with ^{14}C- or ^{3}H-labels, pose unique problems, such that we cannot generalize about their ability to cross the placenta. Much of this literature has been reviewed and summarized by Kistner et al. (1987). Further information on radionuclides that are used in nuclear medicine because of their characteristic localization in specific tissues is being collected and

evaluated (Oak Ridge Associated Universities, Oak Ridge, TN 37831; Atomic Energy Control Board of Canada, Ottawa, Ontario).

C. RESEARCH NEEDS

Research needs presented here include some that were mentioned in foregoing sections, and many involve evaluations currently in progress or expected to be undertaken under this or other projects.

1. Absent and Inadequate Data

Additional data would increase confidence in conclusions that are based on limited data from human experience. For most radionuclides, the major source of data is experiments with animals, and the accuracy of estimation is related to data availability and the validity of extrapolations to humans. There are limitations to current approaches, and methodologies for enhancing extrapolations should be developed and validated. Formal strategies are needed to obtain the additional quantitative and biokinetic information that is needed.

2. Evaluation of Dosimetric Factors and Concepts

a. Temporal Distribution of Dose

Temporal distribution of dose has marked qualitative and quantitative effects on responses to prenatal irradiation; fractionation or protraction of exposures usually lessens the incidence and/or severity of developmental effects. This influence is superimposed on the phenomenon that is commonly quantified as the dose rate reduction factor (DREF). This problem is of special concern for internal radionuclide exposures, where a single intake will result in lower dose rates at successive developmental stages. Because many prominent effects of prenatal exposure are related to gestational stages of relatively brief duration, concepts parallel to DREF should be developed to facilitate expression of dose.

b. Dosimetric Concepts for Short- and Long-Term Effects

Currently, dosimetry concepts and the basis for intrauterine dose limits are based on prenatal exposures and radiation doses that produce effects on the embryo/fetus. However, residual radioactivity at birth may produce continuing doses and additional effects, which are of importance to radiation protection. It is, therefore, necessary to develop rational concepts and methodologies to combine postnatal doses from residual radioactivity and their effects with prenatal doses and their effects.

c. Dose to Organs and Tissues

Many radioactive materials have specific organ or tissue affinities or localize in the conceptus and fetoplacental unit. Calculation and assignment of the associated radiation doses are complicated by the interplay of affinities, translocations, and growth. The absence of persistent tissues

that can be identified as the target for either dose or response may pose constraints. Concentrated efforts are necessary to decide how to apportion these organ and tissue doses at subsequent times, and when the exposed tissues have differentiated into other structures and are no longer present in the state in which they were irradiated.

d. Multiple or Chronic Exposures

Essentially all transfer between the fetus and the pregnant woman takes place across the placenta but no single term has been developed and validated for fractional placental transfer. Values comparable to the f_1 values that are used to express fractional absorption of radionuclides from the gastrointestinal tract or lung would be useful. Development of this concept would pose difficulties; although numerical values could change throughout gestation, values should be established that pertain to broad periods of gestation and incorporate the role of relevant target tissues and their metabolic capacities.

Entry of radionuclides into the human conceptus generally results from 1) maternal burdens prior to conception, 2) chronic or multiple low-level exposures associated with intake during pregnancy, or 3) single accidental or purposeful administrations. The biokinetics associated with these different scenarios need to be defined.

3. Development of Biokinetic Concepts

a. Extrapolation

Correlations of animal data with human data, which often do not involve comparable exposure patterns, form the basis for extrapolations that are used in calculating or estimating energy deposition and determining radiation absorbed dose. Current approaches are not completely acceptable because they do not fully incorporate the contribution of mobilization from maternal tissues, repeated intakes, and growth of the embryo/fetus. Interspecies comparisons at the kinetic and quantitative levels should be performed to develop and test rational hypotheses.

b. Nonuniform Fetal Deposition

There are theoretical problems with calculating average radiation doses to the embryo/fetus when the radioactivity is not uniformly distributed throughout the embryo/fetus. Nevertheless, this approach currently is required from a regulatory standpoint. Methodology that will allow calculation of radiation doses to individual organs or tissues of the embryo/fetus should be developed.

c. Extraembryonic Deposition

Some radioactive materials, such as thorium, are deposited in the placenta, which restricts their entry into the fetus, while others, such as actinides, deposit in the chorionic and yolk sac placentas as well as in the embryo/fetus. The progenitor cells of the gametes and hematopoietic lines

appear initially in blood islands of the yolk sac, and therefore receive selective irradiation while they are primitive stem cells. Methodologies should be developed to allow consideration of these exposures in evaluating the dosimetry of these radionuclides and their potential detrimental effects.

4. Operational Simplifications

a. Facilitation of Calculation and Interpolation

The procedures for calculating radiation doses should be such that they can be used in an operational context. The results of our initial attempts were described above, and ongoing efforts are expected to provide more sophisticated data, procedures, and summarizations. Efforts should continue to develop summary tabulations, nomograms, or graphs that will facilitate operational procedures at field offices and by licensees. These efforts would be facilitated by the availability of computer software and databases that would allow the dosimetrist to manipulate the data on microcomputers. These programs might allow calculation of radiation absorbed doses to the embryo or fetus from a variety of concentration data, and full use should be made of both current and emerging dosimetric and modeling techniques.

b. Interpolation and Extrapolation Factors

A broader use is possible for the various placental transfer and kinetic data we are developing as well as the calculational procedures. This information should be used to allow the generalized extension of models for determination of time- and stage-weighted estimates of concentrations, activities, and resulting radiation absorbed doses to the embryo and fetus from counting or bioassay estimates of internal deposition in the pregnant woman. To provide for planning and control, calculations should be extended to relate radiation doses to the embryo/fetus with levels of radioactivity that might be ingested or inhaled by a woman throughout all of her pregnancy or during specific stages.

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APPENDIX A

ILLUSTRATIONS OF METABOLIC RELATIONSHIPS DISCUSSED IN SECTION IV OF TEXT

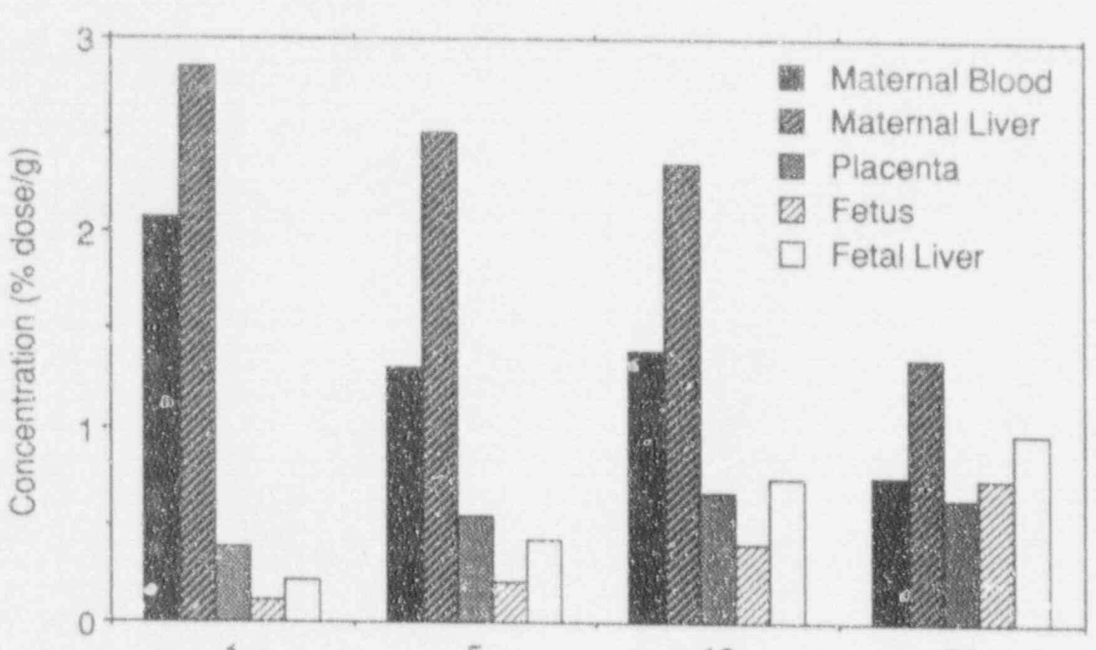


Figure A1. Tissue concentrations of glucose and fructose

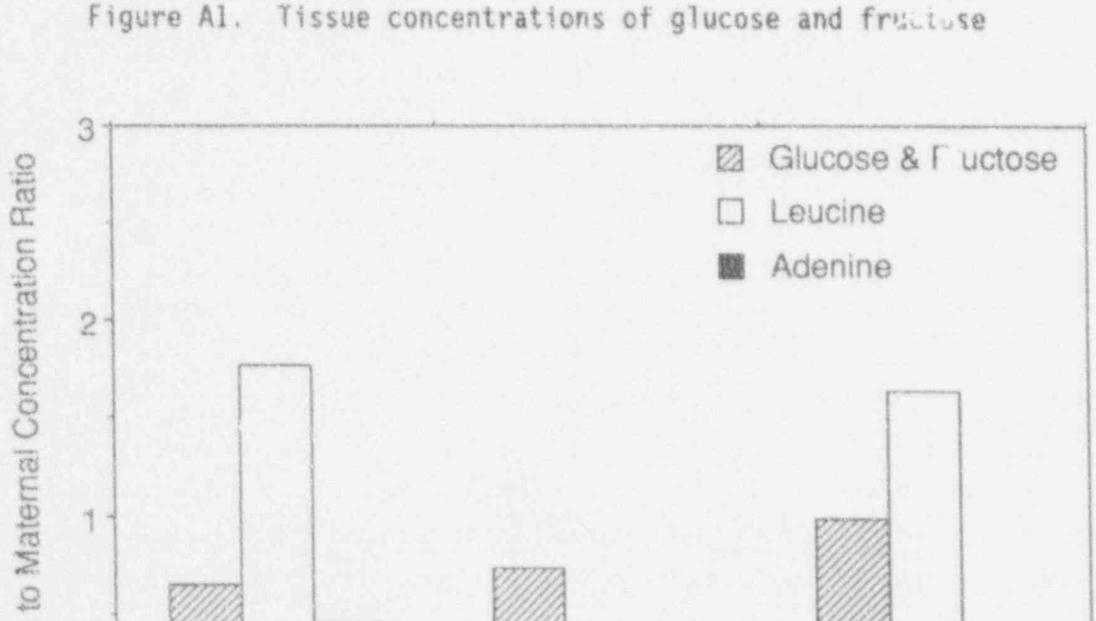


Figure A2. Comparison of fetal to maternal concentrations and distributions of amino acids and hexoses at 30 min after intravenous injection in third-trimester of rats

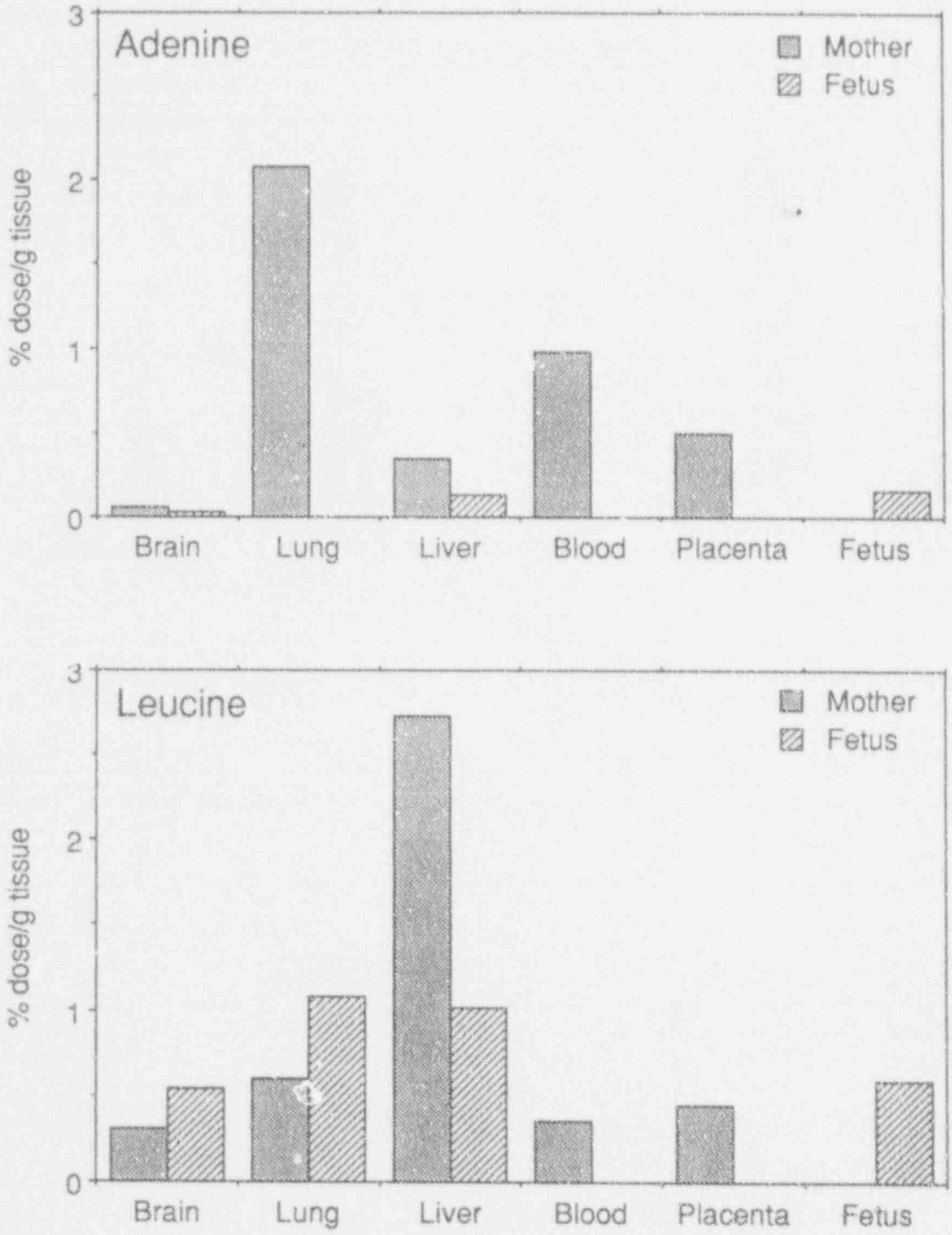


Figure A3. Distribution of adenine and leucine at 30 min after intravenous injection in third-trimester rats

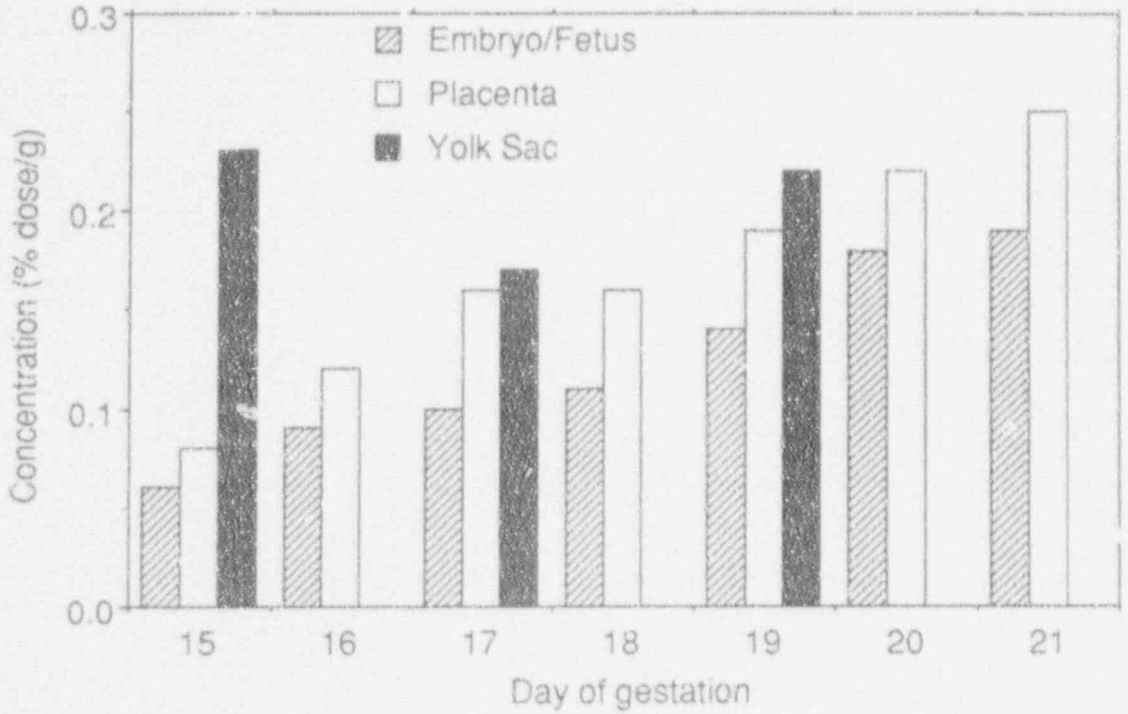


Figure A4. Effect of gestational stage on fetoplacental distribution of cobalt chloride

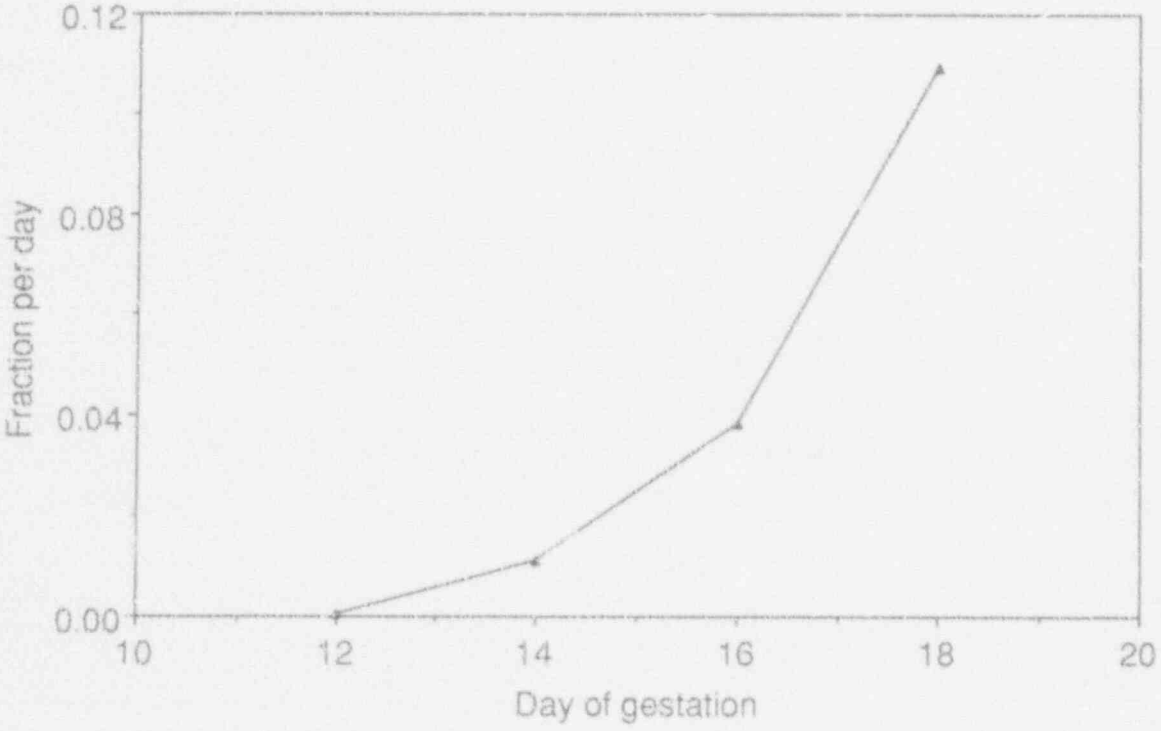


Figure A5. Effect of gestational stage on fractional accumulation rates of strontium in the fetal rat

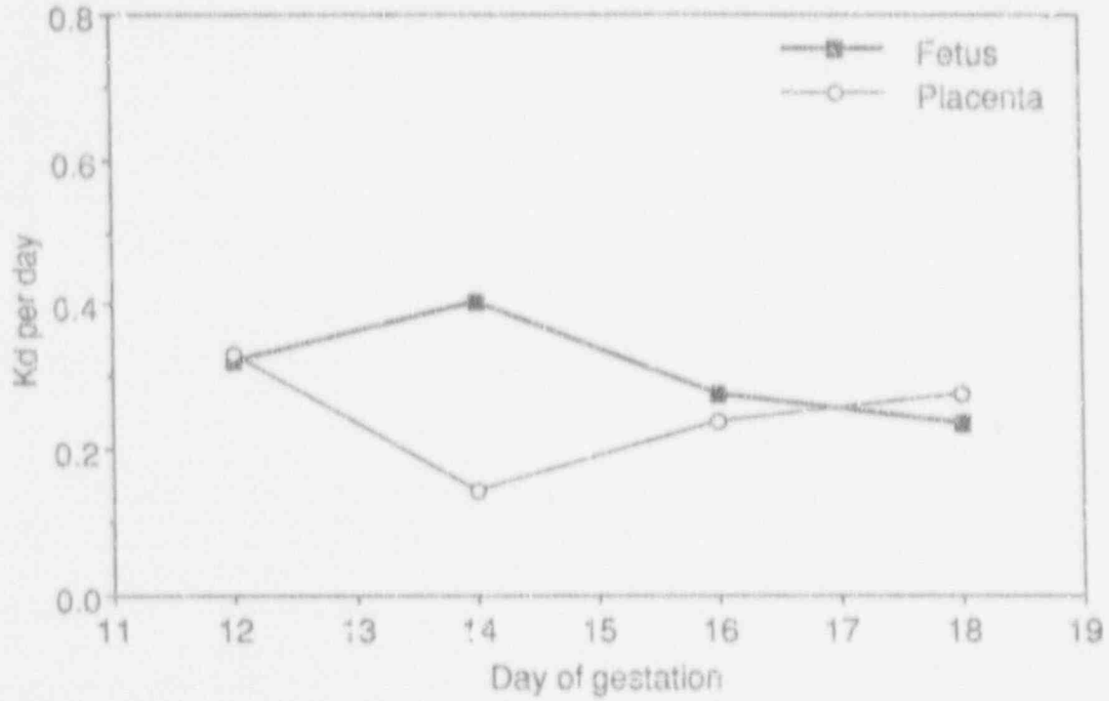


Figure A6. Rate constants (k_d) for decrease in cesium concentration in rat fetoplacental unit as a function of stage of gestation

APPENDIX B

DOSIMETRIC ASSUMPTIONS, FACTORS, AND TABULATIONS

APPENDIX B

DOSIMETRIC ASSUMPTIONS, FACTORS, AND TABULATIONS

This appendix presents the assumptions used to derive dosimetric factors for calculating radiation doses to the embryo/fetus from selected isotopes and chemical forms of the priority radioelements. It has been designed to summarize and extend the dosimetric information presented in Section IV of the report, and follows the same sequence. For consistency, in most cases this information has been divided in three sections: (a) biological aspects, (b) biokinetics, and (c) dosimetry.

Responses to the draft for comment suggested that it would be useful to provide more extensive illustration of the results using the recommended dosimetric approaches, typical dosimetric factors, and the impact of isotopic characteristics. The illustrations include tabulations of the calculated fractions of administered activity in the embryo/fetus (Appendix C) and the resulting dose rates and doses to the conceptus in the months following instantaneous introduction of unit activity (1 μCi) into the first transfer compartment of the pregnant woman, as determined at successive stages of gestation. These tables were prepared directly from the computer outputs, which led to the values generally being expressed to three significant figures. This clearly is greater accuracy than is warranted by the dosimetry model, but the results are presented in this form to facilitate comparisons with calculations by others.

1. Inorganic Tritium and Carbon

Inorganic Tritium

a. Biological Aspects

It is assumed that water vapor and hydrogen gas readily cross into the capillaries of the lung, and do so equally in both directions. In air, however, most free hydrogen (stable or tritium) forms water, as does some of that which is absorbed, but little tritium is actually present in the body as gas. An arbitrary value could be selected for dissolved gas, but the behavior of this small fraction would not be markedly different from that of water and does not require a separate calculation.

As was mentioned, proportional fetal hydration is greater than that of the adult, but the magnitude of the difference is small in comparison to sources of uncertainty. The dosimetric impact would be relatively small, and it is unlikely that a consistent difference could be established. Accordingly, it will be considered that the concentration of tritium in the conceptus is the same as that of the pregnant woman, it would readily be excreted in parallel with its loss from her body, and activities in the conceptus could be calculated on that basis.

Because of the high diffusibility of water, moreover, there will be the same concentration in the implanting blastula as in uterine or extracellular fluids at most stages of gestation. Accordingly, the radiation dose may be calculated assuming a uniform distribution throughout the uterine mucosa; however, entry into the fertilized ovum is not instantaneous, so that there will be negligible activity at t = 0. There will be rapid attainment of equilibrium conditions, so that doses will be received soon after injection. Although these assumptions are not precisely correct and the typical uterine mucosa might tend to have higher than the average body concentration, especially in the pregnant woman, these need to be considered as theoretical differences only, and without practical consequence.

b. Biokinetics

Tritium in the form of tritiated water is assumed to be uniformly distributed throughout the maternal and embryo/fetal soft tissues. For these interim recommendations, it is assumed that tritiated water has a biological half-life of 10 days. The calculated values of retained fraction in the embryo/fetus are shown in Table C1 for administration at successive months of gestation.

c. Dosimetry

Tritium decays by the emission of beta particles whose average energy is 5.683E-3 MeV; all of this energy is assumed to be deposited in the region that contains the tritium. The dose is calculated with the embryo/fetus as the target. The dose rates and integral doses to the embryo/fetus from injection of unit activity of tritiated water (μCi) into the woman's blood are shown in Table D1.

Inorganic Carbon

a. Biological Aspects

Essentially all salient features were discussed in the text. In particular, attention is drawn to the factors that lead to bicarbonate being considered as the chemical form that is present in blood (ICRP 1982).

b. Biokinetics

Consideration will be restricted to introduction of ^{14}C as bicarbonate; appropriate adjustments can be made into the transfer compartment for other materials, if desired. It is assumed that the initial stage-related activity in the embryo/fetus corresponds to 50% of the activity that would result from uniform maternal distribution. One-half of this activity is instantaneously excreted, and the remainder is retained throughout gestation. The initial and retained fractions in the embryo/fetus are shown in Table C2 for administration at successive months of gestation. It is to be noted that these assumptions result in biological behavior that is essentially the same as that pertaining after administration of ^{14}C in organic form.

c. Dosimetry

The dose rates and monthly doses to the embryo/fetus associated with inhalation of CO_2, represented by introduction of 1 μCi of ^{14}C as bicarbonate into the woman's blood circulation are shown in Table D3.

2. Tritium and Carbon in Organic Compounds (General)

a. Biological Aspects

Organic compounds usually require digestion prior to gastrointestinal absorption, but they will be considered only in the form that is in blood after they have been absorbed, and form the woman's initial 1.0 μCi burden. There are essentially no available concentration data for ^{3}H-glucose or ^{14}C-glucose that are directly applicable to radiation dosimetry in the embryo/fetus. However, from the high placental permeability to glucose, its high catabolic rate, and the rapid clearance of its metabolic products, the maximum fetal and maternal concentrations can be assumed to be similar. There is inadequate evidence regarding other labeled hexoses, but it may be inferred that fetal concentrations would be substantially lower than those in pregnant women.

After labeled amino acids have been incorporated into protein during organogenesis or the growth phases of gestation, it is assumed that higher proportional retention of activity, as compared to the mother, is balanced by concurrently reduced concentration as the consequence of dilution by further incorporation of amino acids; major deviations from maternal concentration would not be expected. Oxidation of ^{3}H-labeled amino acids produces tritiated water which exchanges and distributes throughout the intracellular and extracellular water pools in both maternal and fetal compartments. Small amounts of ^{14}C-labeled amino acids may enter the carbohydrate pool after oxidation, but the predominant fraction forms ^{14}C-carbon dioxide, which is rapidly eliminated, as described in a previous section. It is assumed that the fetal concentration of most amino acids, such as leucine, that enter a pregnant woman will be similar to average concentrations in her metabolically active tissues, irrespective of whether they are labeled with ^{3}H or ^{14}C.

b. Biokinetics

The mass of distribution of both ^{3}H or ^{14}C sugars and amino acids are assumed to be the body of the woman, exclusive of the skeleton; in early pregnancy, glucose is uniformly distributed in soft tissues, including uterus and uterine mucosa. At 2 to 3 months and later, glucose readily crosses to the fetus, and the concentration is not considered significantly different from the woman's average. Fetal concentration of some other hexoses may be less, but for generic considerations the same average is assumed, recognizing the possibility of overestimation.

For calculational purposes, it is assumed that one-half of the maternal and embryo/fetal glucose is instantaneously catabolized for energy. The products are tritiated water, which is retained with the 10-day half-life used above, and carbon dioxide, which is considered to cross the placenta

within minutes after formation and to leave via the woman's lung. The other half of the glucose may be assumed to be converted to glycogen or other structural materials, and retained through the remainder of gestation.

There is added uncertainty in pooled considerations of the behavior of amino acids, as suggested by the ranges in the figures of Appendix A. We assume that amino acids behave the same as glucose, with uniform initial distribution at the same concentration as that in the soft tissues of the woman. Thus, when weighted over the fetal period, about 50% may be considered to be synthesized into proteins and retained throughout gestation. The partition of this activity changes during tissue differentiation, so that an assumed uniform fetal distribution is considered appropriate. The comparable value for catabolism of amino acids for energy production may be expected to be higher in the pregnant woman, but there is a lack of human data relating metabolism to stage of gestation. As a time-weighted average, it is assumed that 50% of the amino acids in the embryo/fetus are catabolized to water or CO_2 during the first day. The calculated values of the retained fraction in the embryo/fetus after administration of ^{3}H or ^{14}C as hexose or amino acid are shown in Tables C2 and C3, respectively, for administration at successive months of gestation.

c. Dosimetry

The dose rates and integral doses to the embryo/fetus from introduction of unit activity of ^{3}H as typical organic compounds into the woman's transfer compartment are shown in Table D2. When the organic compound is labeled with ^{14}C the dosimetric values are presented in Table D3.

3. Tritium and Carbon as Thymidine

a. Biological Aspects

The overall metabolism of thymidine is variously defined. ICRP Publication 30 and other sources give gastrointestinal absorption values ranging from one-tenth to one-fifth, while NCRP Report No. 62 suggests that one-eighth of available thymidine is absorbed from the gastrointestinal tract. However, an accurate value is not required because calculations will be based on introduction of 1 μCi of activity, as thymidine, into maternal blood.

b. Biokinetics

Although various standards give conflicting values and ranges for thymidine metabolism in adults, a common scenario assumes the half-time in maternal blood to be 1 hour (or less), and that roughly one-half of the activity in maternal blood is incorporated into proliferating cells. Individual tissues have a wide range of proliferating fractions; this would primarily relate to adult dosimetry, and requires consideration only to obtain the mass of distribution.

Although data are not available to directly estimate placental transfer, it can be approximated by assuming that 10% represents the adult mass of distribution (NCRP Report No. 63, p. 71, Table 5), i.e., 5.8 kg in a 58 kg

nonpregnant woman. The uterine mucosa and embryo begin proliferating at or before the time of implantation, and could be included in this compartment, for 2 to 3 months of gestation without affecting its mass.

Thymidine would be expected to partition with roughly equal participation of the uterine contents (placenta and fetus, primarily), so that fractional activity should progressively increase through gestation. Proliferation is rapid and the proliferating fraction is large, so reutilization is high in the fetus. A definitive value is not available, but an assumption of 80% as the fractional retention through the remainder of gestation should be acceptable. This fraction will change with the stages of gestation. Precision in calculation will be reduced by the pattern of division in which one of two daughter cells leaves the proliferating pool, by programmed cell death, and by other similar developments, particularly during the decreased growth-rate period near term. The contribution of isotope mass effect and the differential reutilization of tritium- and carbon-labeled thymidine are felt to be minor problems.

c. Dosimetry

Thymidine dosimetry involves uncertainties that are independent of placental transfer but which are germane to prenatal dosimetry and effect.

Irrespective of the isotopic label, the thymidine is contained almost entirely in the chromosome. Because of the short path length of the ^{3}H β-particle, the primary dose is to the cell nucleus; with ^{14}C, the exposure to the labeled cell is more uniform. Irrespective of the specific volume in which the energy is absorbed, the circumstances that lead to the dose calculation will influence the dosimetric approach. The energy may be averaged over the nucleus, the whole cell, the tissue, or the organ, and over the entire body mass of the conceptus for calculation of average dose to the embryo/fetus.

In the absence of more specific information, it is necessary to assume that the initial concentration in the conceptus after a single exposure (or after each increment of multiple exposures) would be similar to that in proliferating tissues of the pregnant woman; this assumption provides a basis to calculate activities. Because of the long retention time, and the embryo/fetal growth that takes place during this period, the concentration would decrease more rapidly in the conceptus than in the adult, although the total activity would not be affected. These several unknowns, uncertainties, and variables make it inadvisable to present dosimetric tabulations at this time.

4. Cobalt

a. Biological Aspects

All relevant considerations were presented in the text. Attention is drawn, however, to the fact that cobalt may be accidently or environmentally ingested in inorganic form, and deliberately administered as vitamin B-12 in nuclear medicine procedures.

b. Biokinetics

ICRP Publication 30 (ICRP 1979) gives the fractional uptake and retention equations, that, although similar for inorganic and organic cobalt, have important differences. Of cobalt that enters the transfer compartment, one-half goes directly to excretion; of the remainder, hepatic concentration is four-times that of the rest of the body, for both inorganic cobalt and vitamin B-12. Fetal concentrations are considered equal to the extrahepatic maternal concentrations, which amount to 45% of the activity initially in the transfer compartment. It is assumed that there is the same retention curve for inorganic cobalt in all tissues. The curve involves three components, with fraction sizes and half-lives of 0.6 for 6 days, 0.2 for 60 days, and 0.2 for 800 days. However, a single excretion rate, with a half-life of 60 days, can be used for vitamin B-12 in the fetus and the woman.

c. Dosimetry

The most important radioactive isotopes of cobalt are ^{57}Co, ^{58}Co, and ^{60}Co. Tables C4 to C12 show the retained fractions of the ionic forms of these isotopes, in compartments relevant to calculation of dose to the embryo/fetus. The corresponding dose rates and dose to the embryo/fetus are shown in Tables D4 to D6.

The isotopes used for preparation of vitamin B-12 are ^{57}Co and ^{60}Co. The biokinetic differences described above will affect the retained fractions after intravenous injection of ^{57}Co and ^{60}Co in the form of vitamin B-12. Initial and retained fractions are shown in Tables C13 to C18 and the corresponding dose rates and monthly doses to the embryo/fetus are presented in Tables D7 and D8.

5. Strontium

a. Biological Aspects

Most of the relevant considerations were presented in the text. The ICRP and other organizations employ adult models that consider the skeleton as the major compartment. We also presented the role of the developing skeleton, which becomes increasingly important throughout gestation on placental transfer kinetics and embryo/fetal concentrations and activities. Through 2 months of gestation, therefore, it may be assumed that after tissue redistribution has been completed, a maximum of 10% of the woman's burden will be distributed throughout soft tissues, including the uterus. This distribution pattern does not pertain through the embryo/fetus/placenta compartment at t = 0, as will be discussed below.

b. Biokinetics

A generally accepted gestational stage-related model for entry of strontium into the embryo/fetus is not available. A simplified model was used to illustrate a reasonable calculational approach that might be consistent with the regulatory needs. Accordingly, calculations are based on the assumption that the concentration of strontium in the embryo/fetus becomes the same

as the concentration of strontium in the soft tissue of the mother, immediately upon introduction into the first maternal transfer compartment. The activity is assumed to remain constant in the embryo/fetus, but the strontium concentrations will decrease because of the growth of the conceptus.

c. Dosimetry

The mathematical description of the embryo/fetus that is usually used for dose calculation does not contain distinct organs. This model ignores bone and skeletal tissue, and so the interim dose calculations in this report have been are based on maternal soft tissue contents of strontium. The strontium content of the maternal soft tissues is at a maximum immediately after entry into blood, as shown, for example, in Table 29 of ICRP Publication 20; this maximum soft tissue content has been employed for the tentative calculations.

At early stages of gestation, the amount of strontium that is incorporated into the embryo is very small, almost negligible. The majority of the radiation dose to the embryo will be due to activity in the uterus. Information for calculations of the radiation dose to the embryo from activity in only the uterus is not yet available, and so radiation dose to the entire uterine contents will be used to estimate the radiation dose to the embryo.

Because all soft tissue has the same nominal concentration, a further simplification may be made by employing the radiation dose to all (maternal and uterine contents) soft tissue as an estimate of the radiation dose to the embryo/fetus during the early stages of gestation (i.e., first two months). It is recognized that fetal bone contains significant amounts of strontium after sufficient time has elapsed for deposition. This is implicitly accounted for in this calculational approach, in which average dose is determined from initial burden in the transfer compartment. The retained fractions in the maternal body and in the embryo/fetus are shown in Tables C19 to C22, and the corresponding dose rates and doses to the embryo/fetus are presented in Tables D9 and D10.

6. Ruthenium

a. Biological Aspects

As was described in the text, there are only limited experimental data from animal studies. These data suggest that ruthenium concentrations in the embryo or fetus would be only a small fraction of those in the pregnant woman. Radioactivity levels in the placenta are similar to those in many other maternal tissues, probably reflecting blood content. It should be noted that ^{106}Ru decays to ^{106}Rh, which emits a high-energy β-particle that also contributes to the radiation dose to the embryo/fetus.

The reasons are not known for the observation of marked and persistent location in the yolk sac. The possible significance of the resulting extra-embryonic doses are mentioned elsewhere in this report, but the differences between relative size and location of the yolk sac in rodents and in humans

would be expected to influence the dosimetric implications of dose to the embryo/fetus.

b. Biokinetics

Based on ICRP Publication 30 (Part 2, p. 35) it is assumed that only small amount of ruthenium is absorbed from the gastrointestinal tract and enters blood. Fifteen percent of ruthenium injected into the first transfer compartment is excreted with a half-life of 0.3 days. The other 85% is assumed to be uniformly distributed in all tissues. This presumably would include uterus and mucosa. Thus, initial dose in the early embryo, with a relatively greater contribution from maternal activity, could be different from dose to the fetus. The retained activity (85%) has three components with biological half-lives of 8 days (for 35%), 35 days (for 30%), and 1000 days (for 20%). The placental transfer coefficient has not yet been determined but is considered to be minimal. We tentatively assume that the amount transferred is such that it will give an initial average fetal concentration that is 5% of the average concentration in the pregnant woman, with stage-adjusted activity.

c. Dosimetry

A conservative approach is to tentatively assume that the amount transferred will give an initial average fetal concentration of 5% of the average concentration in the pregnant woman, with stage-adjusted activities calculated from Eq. 8 of this report. A decay product of ^{106}Ru, ^{106}Rh is also radioactive and decays by emission of a high energy β-particle (3.55 MeV). The contribution of ^{106}Ru to the embryo/fetus dose has to be included in any calculations. The retained fractions of ^{106}Ru (in equilibrium with ^{106}Rh) in the pregnant woman and her embryo/fetus are presented in Tables C23 and C24. The corresponding total dose rates and doses are shown in Table D11.

7. Iodine

a. Biological Aspects

Most relevant considerations were discussed in Section IV of the report. Prior to active fetal thyroid function (90 days), the iodide in the maternal blood may be assumed to be available to the embryo by diffusion. Embryo/fetal concentrations and activities are calculated as proportional to maternal blood levels at these times, adjusted for differences in body weight.

b. Biokinetics

The biokinetics of iodide in the fetus have been discussed by Book (1978), Johnson (1982, 1987), Roedler (1987), and Elsasser (1986), among other researchers. The biokinetic models these researchers employed range from simple empirical ratios of fetal to maternal thyroid concentration, to recycling compartmental models with time-dependent transfer coefficients. There is not complete agreement among these authors concerning the various parameters, although calculations of the concentration of iodide in the fetal thyroid using the methods of Book (1978) and Johnson (1982) yield similar results at

3 and 5 months of gestation, even though they differ by nearly a factor of 5 at 8 months. Several reviews and analyses of the available data are in progress; complete consensus has not been reached concerning the most appropriate model and parameters, and in the interim, a biokinetic model based on that developed by Johnson (1982) has been employed.

The availability of several radioisotopes of iodine, moreover, illustrates the effects of physical half-life and decay scheme on biokinetics, which can have a substantially greater effect than other variations in parameters used in the model. Tables in Appendix C present retained fraction in the fetal and maternal thyroid glands, as well as in their total bodies.

c. Dosimetry

Published dosimetry data have been mostly concerned with the radiation doses from radioiodine to the fetal thyroid. Doses to fetal thyroid have been calculated from localized activity in thyroid, a fetal organ that is not considered to exist prior to 3 months of gestation. For a thyroid of a given size, our radiation dose calculations agree well with those of Johnson (1982) and Elsasser (1986). Current regulations require calculations and expression of the radiation dose to the whole fetus. To perform this calculation, we determined the retained fractions of several isotopes of iodine in maternal body and thyroid, as well as in fetal thyroid and the embryo/fetus exclusive of its thyroid; these values are shown in Tables C25 through C54. The short half-lives of the ^{132}I, ^{133}I, ^{134}I, and ^{135}I isotopes lead to extremely low retained fractions in subsequent months. For ^{125}I and ^{131}I, which have longer radioactive half-lives, the initial fractions are presented as values at 1 day after injection. For ^{132}I, ^{133}I, ^{134}I, and ^{135}I, which have shorter half-lives, the initial fractions are shown as values at 1 hour after injection. In addition, for the radioiodines with short half-lives, the tables present peak fractions in the maternal and fetal thyroid and the times at which peak fractions occur. Linear increase was assumed through the peak, followed by a decrease that reflects the physical half-time. The corresponding dose rates and doses to the embryo/fetus and the fetal thyroid after radioiodine introduction into the transfer compartment are presented in Tables D12 through D23.

8. Cesium

a. Biological Aspects

The general aspects of the biological behavior were presented in the text.

b. Biokinetics

The biological half-life of cesium isotopes is 84 days in non-pregnant women (NCRP Report No. 52). Cesium is uniformly distributed throughout the entire body mass (ICRP Publication 30 [ICRP, 1979]). The concentration of cesium in the embryo/fetus and surrounding uterine tissues is assumed to be equal to the concentration in the maternal tissues. Thus, all tissues are considered to be a single metabolic compartment.

To be consistent with previous approaches to calculation, we use 58 kg as the woman's mass at 3 months of gestation (see Table 2), the same or slightly less at conception (0 months), and proportionately consistent weights at subsequent times. It is accepted that the biological half-life decreases to 50 days in pregnant women, but we assume that this change does not occur until after 6 months of gestation. The biological half-lives that are assumed were: 0-5 months - 84 days; 5-6 months - 70 days; 7-9 months - 50 days. For a single acute introduction into the transfer component the initial concentrations are assumed to be the same (equilibrium) in embryo/fetus and woman ($C_f/C_m = 1$). The half-lives are the same, and the embryo in early gestation could reasonably be approximated by the uterus.

c. Dosimetry

The dose to the embryo/fetus was assumed to consist of the sum of the dose due to photons emitted by the radiocesium (and progeny) in the maternal whole body plus the dose due to the betas and photons emitted by the radiocesium (and progeny) in the embryo/fetus. This distinction was made in the dose calculations, because S-values for photons were available for only two gestational stages (nongravid and three-months pregnant). Tables C55 through C58 contain the initial and retained fractions of the ^{134}Cs and ^{137}Cs burden remaining in the pregnant woman and in the embryo/fetus following introduction into the transfer compartment. The corresponding radiation dose rates and doses to the embryo/fetus are presented in Tables D24 and D25.

9. Uranium

a. Biological Aspects

The primary relevant considerations were presented in the text.

b. Biokinetics

The data from experimental animal studies suggest that the distribution pattern of uranium is similar to that of plutonium, especially at the early stage of gestation. The biokinetics of plutonium (see Section 10, following) provide an adequate model for uranium. Accordingly, concentrations of uranium in the embryo/fetus are taken to be the same as those in the "other" maternal tissue (all soft tissues excluding the kidneys) during the first two months, 1.5 times greater at 3 months, 2 times greater at 6 months, and 3 times greater at 8 months. The factors by which these concentration ratios are multiplied, however, need to be adjusted for uranium. In particular, the fraction of activity that is retained in the "other" tissues is 0.12 (compared to 0.1 for plutonium), and the biological half-life is 6 days (ICRP 1979). In addition, the few animal data and human measurements suggest that the tentative estimates of the transfer fractions to the embryo/fetus are only one-half of the stage-related transfer fractions of plutonium. Following transfer into the embryo-fetus, uranium activity is assumed to be distributed uniformly and to remain without excretion. These factors have been introduced into the calculations. The resulting initial and retained fractions of uranium in the embryo/fetus after introduction to the maternal transfer compartment are shown in Table C59.

c. Dosimetry

We assume constant activity in the fetus at all times subsequent to exposure. As a result of the assumed relations to plutonium, dose calculations can be performed using these fetal activity values, which are 0.6 times the multipliers that were used for plutonium. These doses are presented in Tables D26 through D29 for four isotopes of uranium.

10. Plutonium

a. Biological Aspects

The primary relevant considerations were presented in the text.

b. Biokinetics

Irrespective of uncertainties relating to extrapolations and exposure patterns, the radiation doses in the embryonic stages would be relatively homogeneous, they would be a small fraction of the doses received by the pregnant woman when averaged over all tissues, and would constitute an even smaller fraction of the dose to any tissue in which there was specific deposition. High localized concentrations throughout the placental structures, including yolk sac, may result in radiation absorbed doses that are as great or greater than those to any of the maternal tissues. Because of their short path length, alpha particles from extra-embryonic areas would not reach the embryo, but beta emissions could irradiate adjacent extra-embryonic areas. As discussed elsewhere in this report, however, it is during the embryonic stages that deposition in the yolk sac might have the greatest potential significance for producing delayed deleterious effects.

As gestation progresses, there is an increase in the relative concentration in specific fetal tissues. There are uncertainties in the appropriate values to be used for concentration and dose ratios relative to species and chronicity, as was discussed in Section IV of the report. For our tentative approach, however, it will be appropriate to consider the average concentration during the embryonic stages as being roughly the same as that in soft tissues of the woman after a single introduction into the first transfer compartment. For intakes on a continued or undefined basis, the few experimental animal and human data suggest that the average concentration is higher in the fetus during the second or third trimesters than in soft tissues of the pregnant woman, exclusive of the liver. This concentration obviously would be significantly less than that in maternal tissues of primary deposition, the bone and liver.

Following introduction into the transfer compartment, plutonium is assumed to be distributed according to the description given in ICRP 30 (1979). Ten percent of the plutonium in the woman is distributed to the "other" tissues (all soft tissues excluding the gonads and liver). The activity in the embryo/fetus is assumed to be uniformly distributed, at concentrations that relate to the "other" maternal tissue, but with values that allow for increasing relative concentrations as pregnancy progresses. The concentrations are assumed to be the same as that in the "other" tissues of

the woman during the first two months of pregnancy, 1-1/2 times greater at 3 months, twice at 6 months, and thrice at 8 months. Following transfer into the embryo/fetus, the activity is assumed to remain, without excretion.

c. Dosimetry

The alpha particles emitted by ^{239}Pu would be the major contributor to the radiation dose received by the embryo/fetus when the activity is contained within the embryo/fetus. The S-value for photons is about five orders of magnitude less than that for alpha particles.

Table C60 shows initial and retained fractions of the activity in the embryo/fetus after administration at successive stages of pregnancy. The consequent radiation doses for activity contained in the embryo/fetus are presented in Tables D30 and D31 for ^{238}Pu and ^{239}Pu, respectively.

11. Americium

a. Biological Aspects

Many relevant aspects of biological behavior were considered in Section IV of the report. It is to be noted, however, that clearance measured in perfused placentas is similar to that of plutonium, but rapid blood clearance in the woman decreases the amount transferred to the embryo/fetus to about one-fifth to one-tenth that of plutonium (Sikov 1987). The evidence indicates that essentially all activity remains in the embryo/fetus after entry.

b. Biokinetics

Following the deposition pattern suggested by ICRP 30 (ICRP 1979), we will assume that there is no activity in the general soft tissue of the woman, but there is the indicated 0.45 fraction in the liver and in the skeleton. This pattern does not provide a means to estimate activities in the embryo/fetus, but these can be extrapolated from plutonium biokinetics. Therefore, we will assume that the initial fractional activity in the conceptus is one-fifth of the plutonium activity, with the same pattern of stage-related activity only, and that all activity remains thereafter. The resulting values for the initial and retained activities of ^{241}Am in the embryo/fetus are presented in Table C61.

c. Dosimetry

Using calculational procedures similar to the those described for plutonium, the doses from ^{241}Am in the embryo/fetus have been determined. These are shown in Table D32.

APPENDIX C

INITIAL AND RETAINED FRACTIONS OF ACTIVITY IN THE EMBRYO/FETUS AND SELECTED SOURCE ORGANS FOLLOWING INTRODUCTION OF NOMINAL ACTIVITY INTO THE MATERNAL TRANSFER COMPARTMENT

APPENDIX C

INITIAL AND RETAINED FRACTIONS OF ACTIVITY IN THE EMBRYO/FETUS AND SELECTED SOURCE ORGANS FOLLOWING INTRODUCTION OF NOMINAL ACTIVITY INTO THE MATERNAL TRANSFER COMPARTMENT

The tables in this appendix were constructed for selected radionuclides and chemical forms, using the biokinetic models presented in Appendix B, which usually incorporate the metabolic models of ICRP Publication 30. Pregnancy was assumed to begin at the time of fertilization, approximately 2 weeks after menses, and gestation was considered to consist of nine 30-day months. Separate sets of values of initial fractions were calculated for administration at the start of gestation and for each subsequent 30-day time period, including the assumed final day (270) of gestation.

These calculations are based on the assumption of instantaneous introduction of a nominal 1 μCi of activity into the maternal transfer compartment. The resulting fraction of the activity in the embryo/fetus (or in other selected structures, when appropriate) immediately after administration at these times and the fraction at the beginning of each subsequent month of gestation are presented on each line.

It is noted that ICRP Publication 30 employs a metabolic model in which a fraction of activity in the first transfer compartment often is assumed to go immediately to excretion. Because of the minuscule mass of the embryo at that time, for some materials the biokinetic model thus predicts that there will be negligible activity (indicated by N in the table) in the embryo after administration immediately following fertilization. The pattern of partition and clearance usually is such that there will be minimal activity in the maternal blood at later times to provide for subsequent transfer. It occasionally may be desirable to know the fraction that is present in the embryo after intakes during the first month (0-30 days) of pregnancy. This could be estimated using proportionation, by elapsed times, of the fractions given for administration at 30 days. Although it likely would result in a greater overestimate, the residual fraction at subsequent months could be estimated by the same proportion.

Further, this ICRP publication comments that some recognized overestimates for certain chemical forms arise through the use of generalized metabolic models that encompass multiple related forms. Incorporation of these models as part of the basis for predicting the behavior of materials in the pregnant woman together with their placental transfer and subsequent disposition by the embryo/fetus occasionally leads to irregularities. The use of discrete transitions in the geometry of the pregnant woman and in the metabolic behavior of the embryo/fetus may interact with these irregularities to perturb the transitions otherwise anticipated to be regular in fractional content or dose rate.

Table C1. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{3}H, as tritiated water, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.36E-11	1.69E-12	2.10E-13	2.61E-14	3.25E-15	4.04E-16	5.03E-17	6.26E-18	7.78E-19	9.69E-20
30		6.20E-07	7.71E-08	9.60E-09	1.19E-09	1.49E-10	1.85E-11	2.30E-12	2.86E-13	3.56E-14
60			9.65E-05	1.20E-05	1.49E-06	1.86E-07	2.31E-08	2.88E-09	3.58E-10	4.46E-11
90				5.15E-04	6.41E-05	7.97E-06	9.92E-07	1.23E-07	1.54E-08	1.91E-09
120					2.66E-03	3.31E-04	4.12E-05	5.12E-06	6.37E-07	7.93E-08
150						7.60E-03	9.45E-04	1.18E-04	1.46E-05	1.82E-06
180							1.53E-02	1.90E-03	2.37E-04	2.95E-05
210								2.50E-02	3.12E-03	3.88E-04
240									3.59E-02	4.46E-03
270										4.67E-02

Table C2. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{3}H, as a hexose or amino acid, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		6.20E-07	3.47E-07	3.12E-07	3.06E-07	3.04E-07	3.03E-07	3.01E-07	3.00E-07	2.99E-07
60			9.65E-05	5.40E-05	4.86E-05	4.77E-05	4.74E-05	4.72E-05	4.69E-05	4.67E-05
90				5.15E-04	2.88E-04	2.59E-04	2.55E-04	2.53E-04	2.52E-04	2.51E-04
120					2.66E-03	1.49E-03	1.34E-03	1.31E-03	1.31E-03	1.30E-03
150						7.60E-03	4.25E-03	3.82E-03	3.75E-03	3.73E-03
180							1.53E-02	8.57E-03	7.70E-03	7.56E-03
210								2.50E-02	1.40E-02	1.26E-02
240									3.59E-02	2.01E-02
270										4.67E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fractions resulting from administration later during the first month can be approximated as shown on page C-1.

Table C3. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{14}C as bicarbonate or as a hexose or amino acid into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		6.20E-07	3.10E-07	3.10E-07	3.10E-07	3.10E-07	3.10E-07	3.10E-07	3.10E-07	3.10E-07
60			9.65E-05	4.82E-05	4.82E-05	4.82E-05	4.82E-05	4.82E-05	4.82E-05	4.82E-05
90				5.15E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04
120					2.66E-03	1.33E-03	1.33E-03	1.33E-03	1.33E-03	1.33E-03
150						7.60E-03	3.80E-03	3.80E-03	3.80E-03	3.80E-03
180							1.53E-02	7.65E-03	7.65E-03	7.65E-03
210								2.50E-02	1.25E-02	1.25E-02
240									3.59E-02	1.79E-02
270										4.57E-02

Table C4. Fraction of activity in the maternal liver initially and fractions at start of subsequent 30-day periods after introduction of ^{57}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03	7.19E-03	6.19E-03	5.39E-03	4.73E-03	4.19E-03
30		5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03	7.19E-03	6.19E-03	5.39E-03	4.73E-03
60			5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03	7.19E-03	6.19E-03	5.39E-03
90				5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03	7.19E-03	6.19E-03
120					5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03	7.19E-03
150						5.00E-02	1.64E-02	1.25E-02	1.02E-02	8.47E-03
180							5.00E-02	1.64E-02	1.25E-02	1.02E-02
210								5.00E-02	1.64E-02	1.25E-02
240									5.00E-02	1.64E-02
270										5.00E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fractions resulting from administration later during the first month can be approximated as shown on page C-1.

Table C5. Fraction of activity in the maternal body (excluding liver) initially and fractions at start of subsequent 30-day periods after introduction of ^{57}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	9.50E-01	1.48E-01	1.12E-01	9.14E-02	7.60E-02	6.42E-02	5.48E-02	4.73E-02	4.11E-02	3.59E-02
30		9.50E-01	1.48E-01	1.12E-01	9.12E-02	7.56E-02	6.37E-02	5.43E-02	4.67E-02	4.06E-02
60			9.50E-01	1.48E-01	1.12E-01	9.07E-02	7.51E-02	6.31E-02	5.37E-02	4.52E-02
90				9.50E-01	1.48E-01	1.11E-01	9.00E-02	7.43E-02	6.24E-02	5.31E-02
120					9.47E-01	1.47E-01	1.10E-01	8.91E-02	7.35E-02	6.17E-02
150						9.43E-01	1.46E-01	1.09E-01	8.81E-02	7.27E-02
180							9.35E-01	1.44E-01	1.08E-01	8.71E-02
210								9.26E-01	1.43E-01	1.07E-01
140									9.16E-01	1.41E-01
270										9.06E-01

Table C6. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of 1 μCi of ^{57}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	9.17E-08	1.08E-05	4.71E-05	2.03E-04	4.91E-04	8.52E-04	1.21E-03	1.53E-03	1.76E-03
30		5.89E-07	1.43E-05	5.77E-05	2.43E-04	5.79E-04	9.90E-04	1.39E-03	1.74E-03	1.99E-03
60			9.17E-05	7.62E-05	2.98E-04	6.94E-04	1.17E-03	1.62E-03	2.00E-03	2.26E-03
90				4.89E-04	3.93E-04	8.52E-04	1.40E-03	1.91E-03	2.32E-03	2.60E-03
120					2.53E-03	1.12E-03	1.72E-03	2.29E-03	2.73E-03	3.02E-03
150						7.22E-03	2.26E-03	2.81E-03	3.28E-03	3.56E-03
180							1.45E-02	3.71E-03	4.02E-03	4.27E-03
210								2.38E-02	5.31E-03	5.23E-03
240									3.41E-02	6.91E-03
270										4.44E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fractions resulting from administration later during the first month can be approximated as shown on page C-1.

Table C7. Fraction of activity in the maternal liver and fractions at start of subsequent 30-day periods after introduction of ^{58}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E-03	2.43E-03	1.68E-03	1.18E-03	8.35E-04	5.95E-04
30		5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E-03	2.43E-03	1.68E-03	1.18E-03	8.35E-04
60			5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E-03	2.43E-03	1.68E-03	1.18E-03
90				5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E-03	2.43E-03	1.68E-03
120					5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E-03	2.43E-03
150						5.00E-02	1.32E-02	8.07E-03	5.30E-03	3.56E 03
180							5.00E-02	1.32E-02	8.07E-03	5.30E-03
210								5.00E-02	1.32E-02	8.07E-03
240									5.00E-02	1.32E-02
270										5.00E-02

Table C8. Fraction of activity in the maternal body (excluding liver) initially and fractions at start of subsequent 30-day periods after introduction of ^{58}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	9.50E-01	1.19E-01	7.26E-02	4.77E-02	3.19E-02	2.17E-02	1.49E-02	1.04E-02	7.25E-03	5.10E-03
30		9.50E-01	1.19E-01	7.26E-02	4.76E-02	3.18E-02	2.15E-02	1.48E-02	1.02E-02	7.16E-03
60			9.50E-01	1.19E-01	7.25E-02	4.73E-02	3.15E-02	2.13E-02	1.46E-02	1.01E-02
90				9.50E-01	1.19E-01	7.21E-02	4.70E-02	3.12E-02	2.11E-02	1.44E-02
120					9.47E-01	1.18E-01	7.15E-02	4.65E-02	3.09E-02	2.08E-02
150						9.43E-01	1.17E-01	7.08E-02	4.60E-02	3.05E-02
180							9.35E-01	1.16E-01	7.00E-02	4.55E-02
210								9.26E-01	1.15E-01	6.93E-02
240									9.16E-01	1.14E-01
270										9.06E-01

Table C9. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{58}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	7.38E-08	7.01E-06	2.46E-05	8.51E-05	1.66E-04	2.32E-04	2.66E-04	2.70E-04	2.50E-04
30		5.89E-07	1.15E-05	3.74E-05	1.27E-04	2.43E-04	3.35E-04	3.80E-04	3.81E-04	3.51E-04
60			9.17E-05	6.14E-05	1.93E-04	3.62E-04	4.90E-04	5.48E-04	5.44E-04	4.96E-04
90				4.89E-04	3.17E-04	5.52E-04	7.30E-04	8.02E-04	7.84E-04	7.08E-04
120					2.53E-03	9.05E-04	1.11E-03	1.19E-03	1.15E-03	1.02E-03
150						7.22E-03	1.82E-03	1.82E-03	1.71E-03	1.49E-03
180							1.45E-02	2.98E-03	2.61E-03	2.23E-03
210								2.38E-02	4.27E-03	3.39E-03
240									3.41E-02	5.56E-03
270										4.44E-02

Table C10. Fraction of activity in the maternal liver initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02	9.99E-03	9.19E-03	8.55E-03	8.02E-03	7.58E-03
30		5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02	9.99E-03	9.19E-03	8.55E-03	8.02E-03
60			5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02	9.99E-03	9.19E-03	8.55E-03
90				5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02	9.99E-03	9.19E-03
120					5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02	9.99E-03
150						5.00E-02	1.76E-02	1.42E-02	1.24E-02	1.10E-02
180							5.00E-02	1.76E-02	1.42E-02	1.24E-02
210								5.00E-02	1.76E-02	1.42E-02
240									5.00E-02	1.76E-02
270										5.00E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C11. Fraction of activity in the maternal body (excluding liver) initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	9.50E-01	1.58E-01	1.28E-01	1.11E-01	9.90E-02	8.93E-02	8.14E-02	7.50E-02	6.96E-02	6.51E-02
30		9.50E-01	1.58E-01	1.28E-01	1.11E-01	9.85E-02	8.86E-02	8.06E-02	7.42E-02	6.88E-02
60			9.50E-01	1.58E-01	1.28E-01	1.11E-01	9.77E-02	8.77E-02	7.97E-02	7.33E-02
90				9.50E-01	1.58E-01	1.27E-01	1.10E-01	9.67E-02	8.67E-02	7.89E-02
120					9.47E-01	1.57E-01	1.26E-01	1.09E-01	9.57E-02	8.58E-02
150						9.43E-01	1.56E-01	1.25E-01	1.07E-01	9.46E-02
180							9.35E-01	1.54E-01	1.23E-01	1.06E-01
210								9.26E-01	1.52E-01	1.22E-01
240									9.16E-01	1.51E-01
270										9.06E-01

Table C12. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	9.80E-08	1.23E-05	5.74E-05	2.64E-04	6.83E-04	1.27E-03	1.93E-03	2.59E-03	3.19E-03
30		5.89E-07	1.53E-05	6.59E-05	2.96E-04	7.54E-04	1.38E-03	2.07E-03	2.76E-03	3.37E-03
60			9.17E-05	8.14E-05	3.40E-04	8.46E-04	1.52E-03	2.25E-03	2.97E-03	3.59E-03
90				4.89E-04	4.20E-04	9.72E-04	1.70E-03	2.49E-03	3.23E-03	3.86E-03
120					2.53E-03	1.20E-03	1.96E-03	2.79E-03	3.56E-03	4.20E-03
150						7.22E-03	2.42E-03	3.20E-03	4.00E-03	4.63E-03
180							1.45E-02	3.96E-03	4.59E-03	5.20E-03
210								2.38E-02	5.67E-03	5.97E-03
240									3.41E-02	7.38E-03
270										4.44E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C13. Fraction of activity in the maternal liver initially and fractions at start of subsequent 30-day periods after introduction of ^{57}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02	1.20E-02	7.89E-03	5.16E-03	3.38E-03	2.21E-03
30		1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02	1.20E-02	7.89E-03	5.16E-03	3.38E-03
60			1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02	1.20E-02	7.89E-03	5.16E-03
90				1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02	1.20E-02	7.89E-03
120					1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02	1.20E-02
150						1.00E-01	6.55E-02	4.29E-02	2.81E-02	1.84E-02
180							1.00E-01	6.55E-02	4.29E-02	2.81E-02
210								1.00E-01	6.55E-02	4.29E-02
240									1.00E-01	6.55E-02
270										1.00E-01

Table C14. Fraction of activity in the embryo/fetus maternal body (excluding liver) initially and fractions at start of subsequent 30-day periods after introduction of ^{57}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	9.00E-01	5.89E-01	3.86E-01	2.53E-01	1.65E-01	1.08E-01	6.99E-02	4.53E-02	2.93E-02	1.90E-02
30		9.00E-01	5.89E-01	3.86E-01	2.52E-01	1.64E-01	1.07E-01	6.92E-02	4.48E-02	2.90E-02
60			9.00E-01	5.89E-01	3.85E-01	2.51E-01	1.63E-01	1.06E-01	6.84E-02	4.43E-02
90				9.00E-01	5.88E-01	3.83E-01	2.49E-01	1.61E-01	1.05E-01	6.77E-02
120					8.98E-01	5.85E-01	3.80E-01	2.46E-01	1.60E-01	1.03E-01
150						8.93E-01	5.80E-01	3.76E-01	2.44E-01	1.58E-01
180							8.86E-01	5.75E-01	3.72E-01	2.41E-01
210								8.77E-01	5.68E-01	3.68E-01
240									8.68E-01	5.62E-01
270										8.58E-01

Table C15. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{57}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	3.65E-07	3.72E-05	1.30E-04	4.40E-04	8.23E-04	1.09E-03	1.16E-03	1.09E-03	9.31E-04
30		5.58E-07	5.69E-05	1.99E-04	6.72E-04	1.25E-03	1.66E-03	1.78E-03	1.67E-03	1.42E-03
60			8.68E-05	3.04E-04	1.03E-03	1.92E-03	2.53E-03	2.71E-03	2.55E-03	2.17E-03
90				4.64E-04	1.57E-03	2.93E-03	3.87E-03	4.15E-03	3.89E-03	3.31E-03
120					2.39E-03	4.48E-03	5.91E-03	6.33E-03	5.94E-03	5.06E-03
150						6.84E-03	9.02E-03	9.67E-03	9.06E-03	7.73E-03
180							1.38E-02	1.48E-02	1.38E-02	1.18E-02
210								2.25E-02	2.11E-02	1.80E-02
240									3.23E-02	2.75E-02
270										4.20E-02

Table C16. Fraction of activity in the maternal liver initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02	1.67E-02	1.17E-02	8.20E-03	5.73E-03	4.01E-03
30		1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02	1.67E-02	1.17E-02	8.20E-03	5.73E-03
60			1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02	1.67E-02	1.17E-02	8.20E-03
90				1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02	1.67E-02	1.17E-02
120					1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02	1.67E-02
150						1.00E-01	7.00E-02	4.89E-02	3.42E-02	2.39E-02
180							1.00E-01	7.00E-02	4.89E-02	3.42E-02
210								1.00E-01	7.00E-02	4.89E-02
240									1.00E-01	7.00E-02
270										1.00E-01

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C17. Fraction of activity in the maternal whole body (excluding liver) initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	9.00E-01	6.30E-01	4.40E-01	3.08E-01	2.15E-01	1.50E-01	1.04E-01	7.19E-02	4.97E-02	3.44E-02
30		9.00E-01	6.29E-01	4.40E-01	3.07E-01	2.14E-01	1.48E-01	1.03E-01	7.11E-02	4.92E-02
60			9.00E-01	6.29E-01	4.39E-01	3.06E-01	2.12E-01	1.47E-01	1.02E-01	7.03E-02
90				9.00E-01	6.28E-01	4.37E-01	3.03E-01	2.10E-01	1.45E-01	1.01E-01
120					8.98E-01	6.25E-01	4.34E-01	3.00E-01	2.08E-01	1.44E-01
150						8.93E-01	6.20E-01	4.29E-01	2.97E-01	2.05E-01
180							8.86E-01	6.14E-01	4.25E-01	2.94E-01
210								8.77E-01	6.07E-01	4.20E-01
240									8.68E-01	6.00E-01
270										8.58E-01

Table C18. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{60}Co, as vitamin B-12, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	3.90E-07	4.25E-05	1.59E-04	5.73E-04	1.15E-03	1.61E-03	1.85E-03	1.85E-03	1.68E-03
30		5.58E-07	6.08E-05	2.27E-04	8.19E-04	1.64E-03	2.31E-03	2.64E-03	2.64E-03	2.41E-03
60			8.68E-05	3.24E-04	1.17E-03	2.34E-03	3.30E-03	3.78E-03	3.78E-03	3.44E-03
90				4.64E-04	1.67E-03	3.35E-03	4.71E-03	5.40E-03	5.41E-03	4.92E-03
120					2.39E-03	4.78E-03	6.74E-03	7.72E-03	7.73E-03	7.04E-03
150						6.84E-03	9.63E-03	1.10E-02	1.10E-02	1.01E-02
180							1.38E-02	1.58E-02	1.58E-02	1.44E-02
210								2.25E-02	2.26E-02	2.06E-02
240									3.23E-02	2.94E-02
270										4.20E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C19. Fraction of activity in the maternal whole body initially and fractions at start of subsequent 30-day periods after introduction of ^{89}Sr into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	8.18E-01	5.71E-02	2.46E-02	1.22E-02	5.72E-03	2.95E-03	1.70E-03	1.03E-03	6.13E-04	3.57E-04
30		8.18E-01	5.71E-02	2.46E-02	1.22E-02	5.72E-03	2.95E-03	1.70E-03	1.03E-03	6.13E-04
60			8.18E-01	5.71E-02	2.46E-02	1.22E-02	5.72E-03	2.95E-03	1.70E-03	1.03E-03
90				8.17E-01	5.71E-02	2.46E-02	1.22E-02	5.72E-03	2.95E-03	1.70E-03
120					8.16E-01	5.70E-02	2.45E-02	1.22E-02	5.71E-03	2.95E-03
150						8.11E-01	5.67E-02	2.44E-02	1.21E-02	5.68E-03
180							8.05E-01	5.63E-02	2.42E-02	1.20E-02
210								7.97E-01	5.57E-02	2.40E-02
240									7.88E-01	5.51E-02
270										7.80E-01

Table C20. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{89}Sr into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		5.07E-07	3.36E-07	2.22E-07	1.47E-07	9.76E-08	6.47E-08	4.28E-08	2.84E-08	1.88E-08
60			7.89E-05	5.23E-05	3.46E-05	2.29E-05	1.52E-05	1.01E-05	6.67E-06	4.42E-06
90				4.21E-04	2.79E-04	1.85E-04	1.22E-04	8.11E-05	5.37E-05	3.56E-05
120					2.17E-03	1.44E-03	9.54E-04	6.32E-04	4.19E-04	2.77E-04
150						6.21E-03	4.12E-03	2.73E-03	1.81E-03	1.20E-03
180							1.25E-02	8.29E-03	5.49E-03	3.64E-03
210								2.05E-02	1.36E-02	8.99E-03
240									2.93E-02	1.94E-02
270										3.82E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C21. Fraction of activity in the maternal body initially and fractions at start of subsequent 30-day periods after introduction of ^{90}Sr (in equilibrium with ^{90}Y) into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	8.18E-01	8.61E-02	5.58E-02	4.18E-02	2.95E-02	2.29E-02	1.99E-02	1.82E-02	1.63E-02	1.43E-02
30		8.18E-01	8.61E-02	5.58E-02	4.18E-02	2.95E-02	2.29E-02	1.99E-02	1.82E-02	1.63E-02
60			8.18E-01	8.61E-02	5.58E-02	4.18E-02	2.95E-02	2.29E-02	1.99E-02	1.82E-02
90				8.17E-01	8.60E-02	5.58E-02	4.18E-02	2.95E-02	2.29E-02	1.99E-02
120					8.16E-01	8.58E-02	5.56E-02	4.17E-02	2.94E-02	2.29E-02
150						8.11E-01	8.54E-02	5.54E-02	4.15E-02	2.92E-02
180							8.05E-01	8.48E-02	5.49E-02	4.12E-02
210								7.97E-01	8.39E-02	5.44E-02
240									7.88E-01	8.30E-02
270										7.80E-01

Table C22. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{90}Sr (in equilibrium with ^{90}Y) into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		5.07E-07	5.06E-07	5.05E-07	5.04E-07	5.03E-07	5.02E-07	5.01E-07	5.00E-07	4.99E-07
60			7.89E-05	7.88E-05	7.86E-05	7.84E-05	7.83E-05	7.81E-05	7.80E-05	7.78E-05
90				4.21E-04	4.20E-04	4.20E-04	4.19E-04	4.18E-04	4.17E-04	4.16E-04
120					2.17E-03	2.17E-03	2.17E-03	2.16E-03	2.16E-03	2.15E-03
150						6.21E-03	6.20E-03	6.19E-03	6.18E-03	6.16E-03
180							1.25E-02	1.25E-02	1.25E-02	1.24E-02
210								2.05E-02	2.04E-02	2.04E-02
240									2.93E-02	2.93E-02
270										3.82E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C23. Fraction of activity in the maternal body initially and fractions at start of subsequent 30-day periods after introduction of ^{106}Ru, in equilibrium with ^{106}Rh, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01	1.48E-01	1.32E-01	1.20E-01	1.09E-01	1.01E-01
30		1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01	1.48E-01	1.32E-01	1.20E-01	1.09E-01
60			1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01	1.48E-01	1.32E-01	1.20E-01
90				1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01	1.48E-01	1.32E-01
120					1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01	1.48E-01
150						1.00E+00	3.66E-01	2.55E-01	2.01E-01	1.69E-01
180							1.00E+00	3.66E-01	2.55E-01	2.01E-01
210								1.00E+00	3.66E-01	2.55E-01
240									1.00E+00	3.66E-01
270										1.00E+00

Table C24. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{106}Ru, in equilibrium with ^{106}Rh, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	1.13E-08	1.23E-06	5.19E-06	2.25E-05	5.60E-05	1.01E-04	1.50E-04	1.96E-04	2.35E-04
30		3.10E-08	1.77E-06	6.56E-06	2.68E-05	6.42E-05	1.13E-04	1.65E-04	2.14E-04	2.55E-04
60			4.82E-06	9.43E-06	3.39E-05	7.65E-05	1.29E-04	1.85E-04	2.36E-04	2.79E-04
90				2.58E-05	4.87E-05	9.68E-05	1.54E-04	2.12E-04	2.64E-04	3.08E-04
120					1.33E-04	1.39E-04	1.95E-04	2.52E-04	3.03E-04	3.44E-04
150						3.80E-04	2.80E-04	3.19E-04	3.61E-04	3.95E-04
180							7.65E-04	4.59E-04	4.57E-04	4.70E-04
210								1.25E-03	6.57E-04	5.95E-04
240									1.79E-03	8.55E-04
270										2.33E-03

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C25. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of [illegible] into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	3.71E-02	1.33E-02	9.92E-03	6.40E-03	4.03E-03	2.52E-03	1.58E-03	9.89E-04	6.19E-04	3.87E-04
30		3.71E-02	1.33E-02	9.92E-03	6.40E-03	4.03E-03	2.52E-03	1.58E-03	9.89E-04	6.19E-04
60			3.71E-02	1.33E-02	9.92E-03	6.40E-03	4.03E-03	2.52E-03	1.58E-03	9.89E-04
90				3.70E-02	1.33E-02	9.91E-03	6.40E-03	4.03E-03	2.52E-03	1.58E-03
120					3.32E-02	1.31E-02	9.84E-03	6.35E-03	4.00E-03	2.51E-03
150						2.95E-02	1.31E-02	9.77E-03	6.31E-03	3.98E-03
180							2.58E-02	1.30E-02	9.71E-03	6.28E-03
210								2.21E-02	1.29E-02	9.65E-03
240									1.85E-02	1.28E-02
270										1.48E-02

Table C26. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{125}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.50E-01	1.62E-01	1.01E-01	6.31E-02	3.95E-02	2.47E-02	1.55E-02	9.68E-03	6.06E-03	3.79E-03
30		2.50E-01	1.62E-01	1.01E-01	6.31E-02	3.95E-02	2.47E-02	1.55E-02	9.68E-03	6.06E-03
60			2.50E-01	1.62E-01	1.01E-01	6.31E-02	3.95E-02	2.47E-02	1.55E-02	9.68E-03
90				2.50E-01	1.62E-01	1.01E-01	6.31E-02	3.95E-02	2.47E-02	1.55E-02
120					2.49E-01	1.61E-01	1.00E-01	6.26E-02	3.92E-02	2.46E-02
150						2.48E-01	1.59E-01	9.9[illegible]E-02	6.23E-02	3.90E-02
180							2.47E-01	1.58E-01	9.87E-02	6.19E-02
210								2.46E-01	1.57E-01	9.81E-02
240									2.45E-01	1.56E-01
270										2.44E-01

Table C27. Fraction of activity in the embryo/fetus (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{125}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	1.66E-10	1.94E-08	6.78E-08	3.42E-05	1.33E-06	2.86E-06	4.30E-06	5.17E-06	5.34E-06
30		2.24E-08	2.58E-08	1.03E-07	5.41E-07	2.11E-06	4.56E-06	6.86E-06	8.26E-06	8.53E-06
60			3.49E-06	1.38E-07	8.25E-07	3.29E-06	7.18E-06	1.09E-05	1.31E-05	1.36E-05
90				1.86E-05	2.90E-06	7.98E-06	1.43E-05	1.97E-05	2.28E-05	2.29E-05
120					9.06E-05	1.12E-04	1.37E-04	1.30E-04	1.11E-04	8.82E-05
150						2.35E-04	3.34E-04	3.38E-04	2.79E-04	2.11E-04
180							4.20E-04	6.58E-04	5.96E-04	4.46E-04
210								6.00E-04	1.07E-03	8.95E-04
240									7.36E-04	1.56E-03
270										8.02E-04

Table C28. Fraction of activity in the total thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{125}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	7.18E-09	1.33E-05	3.25E-05	4.44E-05	4.71E-05	4.30E-05	3.54E-05
30	-	-	-	1.11E-08	2.11E-05	5.17E-05	7.02E-05	7.51E-05	6.86E-05	5.65E-05
60	-	-	-	1.48E-08	3.16E-05	8.04E-05	1.12E-04	1.19E-04	1.09E-04	9.00E-05
90	-	-	-	1.66E-04	1.57E-04	1.92E-04	2.17E-04	2.13E-04	1.87E-04	1.51E-04
120					4.01E-03	2.85E-03	1.93E-03	1.29E-03	8.38E-04	5.35E-04
150						7.82E-03	5.26E-03	3.34E-03	2.07E-03	1.25E-03
180							1.16E-02	7.41E-03	4.47E-03	2.63E-03
210								1.53E-02	9.31E-03	5.36E-03
240									1.90E-02	1.10E-02
270										2.26E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C29. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{131}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	4.84E-02	1.45E-03	1.14E-04	7.73E-06	5.12E-07	3.37E-08	2.22E-09	1.46E-10	9.60E-12	6.32E-13
30		4.84E-02	1.45E-03	1.14E-04	7.73E-06	5.12E-07	3.37E-08	2.22E-09	1.46E-10	9.60E-12
60			4.84E-02	1.45E-03	1.14E-04	7.73E-06	5.12E-07	3.37E-08	2.22E-09	1.46E-10
90				4.83E-02	1.45E-03	1.19E-04	7.73E-06	5.11E-07	3.37E-08	2.22E-09
120					4.43E-02	1.44E-03	1.13E-04	7.67E-06	5.08E-07	3.35E-08
150						4.04E-02	1.42E-03	1.12E-04	7.62E-06	5.05E-07
180							3.65E-02	1.41E-03	1.11E-04	7.57E-06
210								3.27E-02	1.40E-03	1.11E-04
240									2.88E-02	1.39E-03
270										2.50E-02

Table C30. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{131}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	50	90	120	150	180	210	240	270
0	2.37E-01	1.77E-02	1.16E-03	7.62E-05	5.01E-06	3.30E-07	2.17E-08	1.43E-09	9.40E-11	6.18E-12
30		2.37E-01	1.77E-02	1.16E-03	7.62E-05	5.01E-06	3.30E-07	2.17E-08	1.43E-09	9.40E-11
60			2.37E-01	1.77E-02	1.16E-03	7.62E-05	5.01E-06	3.30E-07	2.17E-08	1.43E-09
90				2.37E-01	1.77E-02	1.16E-03	7.62E-05	5.01E-06	3.30E-07	2.17E-08
120					2.36E-01	1.75E-02	1.15E-03	7.56E-05	4.98E-06	3.28E-07
150						2.35E-01	1.74E-02	1.14E-03	7.51E-05	4.95E-06
180							2.34E-01	1.72E-02	1.13E-03	7.46E-05
210								2.33E-01	1.71E-02	1.12E-03
240									2.32E-01	1.70E-02
270										2.31E-01

Table C31. Fraction of activity in the embryo/fetus (excluding fetal thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{131}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	1.79E-11	2.20E-10	7.90E-11	4.30E-11	1.76E-11	3.99E-12	6.31E-13	7.98E-14	8.67E-15
30		2.94E-08	2.79E-09	1.18E-09	6.48E-10	3.47E-10	6.05E-11	9.58E-12	1.21E-12	1.32E-13
60			4.58E-06	1.49E-08	9.40E-09	3.95E-09	9.06E-10	1.44E-10	1.83E-11	1.99E-12
90				2.44E-05	3.20E-07	9.20E-08	1.72E-08	2.50E-09	3.03E-10	3.21E-11
120					1.20E-04	1.22E-05	1.57E-06	1.58E-07	1.41E-08	1.18E-09
150						3.18E-04	3.65E-05	3.88E-06	3.37E-07	2.67E-08
180							5.84E-04	7.17E-05	6.83E-06	5.38E-07
210								8.63E-04	1.17E-04	1.03E-05
240									1.11E-03	1.70E-04
270										1.27E-03

Table C32. Fraction of activity in the fetal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{131}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	8.87E-12	1.69E-09	4.32E-10	6.21E-11	6.92E-12	6.64E-13	5.75E-14
30	-	-	-	1.31E-10	2.53E-08	6.54E-09	9.41E-10	1.05E-10	1.01E-11	8.73E-13
60	-	-	-	1.65E-09	3.62E-07	9.67E-08	1.41E-08	1.58E-09	1.52E-10	1.32E-11
90	-	-	-	1.58E-04	1.74E-05	2.21E-06	2.62E-07	2.70E-08	2.49E-09	2.11E-10
120					3.81E-03	3.12E-04	2.22E-05	1.55E-06	1.06E-07	7.13E-09
150						7.42E-03	5.74E-04	3.83E-05	2.50E-06	1.59E-07
180							1.10E-02	8.08E-04	5.13E-05	3.17E-06
210								1.45E-02	1.02E-03	6.15E-05
240									1.80E-02	1.20E-03
270										2.15E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C33. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{132}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	6.66E-01	0	0	0	0	0	0	0	0	0
30		6.66E-01	0	0	0	0	0	0	0	0
60			6.66E-01	0	0	0	0	0	0	0
90				6.66E-01	0	0	0	0	0	0
120					6.66E-01	0	0	0	0	0
150						6.65E-01	0	0	0	0
180							6.65E-01	0	0	0
210								6.65E-01	0	0
240									6.65E-01	0
270										6.64E-01

Table C34. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{132}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.89E-02	0	0	0	0	0	0	0	0	0
30		1.89E-02	0	0	0	0	0	0	0	0
60			1.89E-02	0	0	0	0	0	0	0
90				1.89E-02	0	0	0	0	0	0
120					1.89E-02	0	0	0	0	0
150						1.89E-02	0	0	0	0
180							1.89E-02	0	0	0
210								1.89E-02	0	0
240									1.89E-02	0
270										1.89E-02

Table C35. Peak fraction of activity in the maternal thyroid at 3 hours and fractions at start of subsequent 30-day periods after introduction of ^{132}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.78E-02	0	0	0	0	0	0	0	0	0
30		2.78E-02	0	0	0	0	0	0	0	0
60			2.78E-02	0	0	0	0	0	0	0
90				2.78E-02	0	0	0	0	0	0
120					2.78E-02	0	0	0	0	0
150						2.78E-02	0	0	0	0
180							2.78E-02	0	0	0
210								2.78E-02	0	0
240									2.78E-02	0
270										2.78E-02

Table C36. Fraction of activity in the embryo/fetus (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{132}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	0	0	0	0	0	0	0	0	0
30		4.13E-07	0	0	0	0	0	0	0	0
60			6.43E-05	0	0	0	0	0	0	0
90				3.43E-04	0	0	0	0	0	0
120					1.77E-03	0	0	0	0	0
150						5.06E-03	0	0	0	0
180							1.02E-02	0	0	0
210								1.67E-02	0	0
240									2.38E-02	0
270										3.10E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C37. Fraction of activity in the fetal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{132}I into maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	1.98E-07	0	0	0	0	0	0
120					2.91E-04	0	0	0	0	0
150						5.82E-04	0	0	0	0
180							8.73E-04	0	0	0
210								1.16E-03	0	0
240									1.45E-03	0
270										1.75E-03

Table C38. Peak fraction of activity in the fetal thyroid at 3 hours and fractions at start of subsequent 30-day periods after introduction of ^{132}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	8.46E-07	0	0	0	0	0	0
120					4.31E-04	0	0	0	0	0
150						8.60E-04	0	0	0	0
180							1.29E-03	0	0	0
210								1.72E-03	0	0
240									2.15E-03	0
270										2.57E-03

Table C39. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	8.72E-01	0	0	0	0	0	0	0	0	0
30		8.72E-01	0	0	0	0	0	0	0	0
60			8.72E-01	0	0	0	0	0	0	0
90				8.72E-01	0	0	0	0	0	0
120					8.72E-01	0	0	0	0	0
150						8.72E-01	0	0	0	0
180							8.72E-01	0	0	0
210								8.71E-01	0	0
240									8.71E-01	0
270										8.71E-01

Table C40. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.47E-02	0	0	0	0	0	0	0	0	0
30		2.47E-02	0	0	0	0	0	0	0	0
60			2.47E-02	0	0	0	0	0	0	0
90				2.47E-02	0	0	0	0	0	0
120					2.47E-02	0	0	0	0	0
150						2.47E-02	0	0	0	0
180							2.47E-02	0	0	0
210								2.47E-02	0	0
240									2.47E-02	0
270										2.47E-02

Table C4i. Peak fraction of activity in the maternal thyroid at 13 hours and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.22E-01	0	0	0	0	0	0	0	0	0
30		1.22E-01	0	0	0	0	0	0	0	0
60			1.22E-01	0	0	0	0	0	0	0
90				1.22E-01	0	0	0	0	0	0
120					1.22E-01	0	0	0	0	0
150						1.22E-01	0	0	0	0
180							1.22E-01	0	0	0
210								1.22E-01	0	0
240									1.22E-01	0
270										1.22E-01

Table C42. Fraction of activity in the embryo/fetus (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	0	0	0	0	0	0	0	0	0
30		5.41E-07	0	0	0	0	0	0	0	0
60			8.42E-05	0	0	0	0	0	0	0
90				4.49E-04	0	0	0	0	0	0
120					2.32E-03	0	0	0	0	0
150						6.62E-03	0	0	0	0
180							1.33E-02	0	0	0
210								2.18E-02	0	0
240									3.12E-02	0
270										4.06E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fractions resulting from administration later during the first month can be approximated as shown on page C-i.

Table C43. Fraction of activity in the fetal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	2.60E-07	0	0	0	0	0	0
120					3.81E-04	0	0	0	0	0
150						7.62E-04	0	0	0	0
180							1.14E-03	0	0	0
210								1.52E-03	0	0
240									1.90E-03	0
270										2.88E-03

Table C44. Peak fraction of activity in the fetal thyroid at 13 hours and fractions at start of subsequent 30-day periods after introduction of ^{133}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	1.64E-05	0	0	0	0	0	0
120					1.90E-03	0	0	0	0	0
150						3.78E-03	0	0	0	0
180							5.65E-03	0	0	0
210								7.51E-03	0	0
240									9.37E-03	0
270										1.12E-02

Table C45. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{134}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	4.06E-01	0	0	0	0	0	0	0	0	0
30		4.06E-01	0	0	0	0	0	0	0	0
60			4.06E-01	0	0	0	0	0	0	0
90				4.06E-01	0	0	0	0	0	0
120					4.06E-01	0	0	0	0	0
150						4.06E-01	0	0	0	0
180							4.05E-01	0	0	0
210								4.05E-01	0	0
240									4.05E-01	0
270										4.05E-01

Table C46. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{134}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.10E-02	0	0	0	0	0	0	0	0	0
30		1.10E-02	0	0	0	0	0	0	0	0
60			1.10E-02	0	0	0	0	0	0	0
90				1.10E-02	0	0	0	0	0	0
120					1.10E-02	0	0	0	0	0
150						1.10E-02	0	0	0	0
180							1.10E-02	0	0	0
210								1.10E-02	0	0
240									1.10E-02	0
270										1.10E-02

Table C47. Fraction of activity in the embryo/fetus (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{134}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	0	0	0	0	0	0	0	0	0
30		2.52E-07	0	0	0	0	0	0	0	0
60			3.92E-05	0	0	0	0	0	0	0
90				2.09E-04	0	0	0	0	0	0
120					1.08E-03	0	0	0	0	0
150						3.08E-03	0	0	0	0
180							6.20E-03	0	0	0
210								1.02E-02	0	0
240									1.45E-02	0
270										1.89E-02

Table C48. Fraction of activity in the fetal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{134}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	1.15E-07	0	0	0	0	0	0
120					1.70E-04	0	0	0	0	0
150						3.40E-04	0	0	0	0
180							5.10E-04	0	0	0
210								6.80E-03	0	0
240									8.50E-04	0
270										1.02E-03

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Franction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C49. Fraction of activity in the maternal body (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	8.13E-01	0	0	0	0	0	0	0	0	0
30		8.13E-01	0	0	0	0	0	0	0	0
60			8.13E-01	0	0	0	0	0	0	0
90				8.13E-01	0	0	0	0	0	0
120					8.13E-01	0	0	0	0	0
150						8.13E-01	0	0	0	0
180							8.12E-01	0	0	0
210								8.12E-01	0	0
240									8.11E-01	0
270										8.11E-01

Table C50. Fraction of activity in the maternal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.30E-02	0	0	0	0	0	0	0	0	0
30		2.30E-02	0	0	0	0	0	0	0	0
60			2.30E-02	0	0	0	0	0	0	0
90				2.30E-02	0	0	0	0	0	0
120					2.30E-02	0	0	0	0	0
150						2.30E-02	0	0	0	0
180							2.30E-02	0	0	0
210								2.30E-02	0	0
240									2.30E-02	0
270										2.30E-02

Table C51. Peak fraction of activity in the maternal thyroid at 7 hours and fractions at start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	6.40E-02	0	0	0	0	0	0	0	0	0
30		6.40E-02	0	0	0	0	0	0	0	0
60			6.40E-02	0	0	0	0	0	0	0
90				6.40E-02	0	0	0	0	0	0
120					6.40E-02	0	0	0	0	0
150						6.40E-02	0	0	0	0
180							6.39E-02	0	0	0
210								6.39E-02	0	0
240									6.38E-02	0
270										6.37E-02

Table C52. Fraction of activity in the embryo/fetus (excluding thyroid) initially and fractions at start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	0	0	0	0	0	0	0	0	0
30		5.04E-07	0	0	0	0	0	0	0	0
60			7.84E-05	0	0	0	0	0	0	0
90				4.19E-04	0	0	0	0	0	0
120					2.16E-03	0	0	0	0	0
150						6.17E-03	0	0	0	0
180							1.24E-02	0	0	0
210								2.03E-02	0	0
240									2.91E-02	0
270										3.79E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C53. Fraction of activity in the fetal thyroid initially and fractions at start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	2.42E-07	0	0	0	0	0	0
120					3.55E-04	0	0	0	0	0
150						7.10E-04	0	0	0	0
180							1.07E-03	0	0	0
210								1.42E-03	0	0
240									1.77E-03	0
270										2.13E-03

Table C54. Peak fraction of activity in the fetal thyroid at 7 hours and fractions at the start of subsequent 30-day periods after introduction of ^{135}I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	-	-	-	0	0	0	0	0	0	0
30	-	-	-	0	0	0	0	0	0	0
60	-	-	-	0	0	0	0	0	0	0
90	-	-	-	5.30E-06	0	0	0	0	0	0
120					9.92E-04	0	0	0	0	0
150						1.98E-03	0	0	0	0
180							2.96E-03	0	0	0
210								3.95E-03	0	0
240									4.92E-03	0
270										5.90E-03

Table C55. Fraction of activity in the maternal body initially and fractions at the start of subsequent 30-day periods after introduction of ^{134}Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.00E+00	7.59E-01	5.77E-01	4.38E-01	3.32E-01	2.51E-01	1.89E-01	1.35E-01	8.58E-02	5.45E-02
30		1.00E+00	7.59E-01	5.76E-01	4.37E-01	3.30E-01	2.49E-01	1.78E-01	1.13E-01	7.17E-02
60			1.00E+00	7.59E-01	5.75E-01	4.35E-01	3.28E-01	2.34E-01	1.49E-01	9.44E-02
90				9.99E-01	7.57E-01	5.72E-01	4.31E-01	3.09E-01	1.96E-01	1.24E-01
120					9.97E-01	7.54E-01	5.68E-01	4.06E-01	2.58E-01	1.64E-01
150						9.92E-01	7.48E-01	5.35E-01	3.40E-01	2.16E-01
180							9.85E-01	7.05E-01	4.47E-01	2.84E-01
210								9.75E-01	6.19E-01	3.93E-01
240									9.64E-01	6.12E-01
270										9.53E-01

Table C56. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{134}Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	4.71E-07	5.57E-05	2.26E-04	8.85E-04	1.92E-03	2.94E-03	3.47E-03	3.19E-03	2.67E-03
30		6.20E-07	7.33E-05	2.97E-04	1.16E-03	2.53E-03	3.87E-03	4.57E-03	4.20E-03	3.51E-03
60			9.65E-05	3.91E-04	1.53E-03	3.33E-03	5.09E-03	6.02E-03	5.53E-03	4.62E-03
90				5.15E-04	2.02E-03	4.38E-03	6.70E-03	7.93E-03	7.29E-03	6.09E-03
120					2.66E-03	5.77E-03	8.83E-03	1.04E-02	9.59E-03	8.02E-03
150						7.60E-03	1.16E-02	1.37E-02	1.26E-02	1.06E-02
180							1.53E-02	1.81E-02	1.66E-02	1.39E-02
210								2.50E-02	2.30E-02	1.92E-02
240									3.59E-02	3.00E-02
270										4.67E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C57. Fraction of activity in the maternal body initially and fractions at start of subsequent 30-day periods after introduction of ^{137}Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.00E+00	7.79E-01	6.07E-01	4.73E-01	3.68E-01	2.85E-01	2.20E-01	1.62E-01	1.05E-01	6.86E-02
30		1.00E+00	7.79E-01	6.07E-01	4.72E-01	3.66E-01	2.83E-01	2.08E-01	1.35E-01	8.81E-02
60			1.00E+00	7.79E-01	6.06E-01	4.70E-01	3.63E-01	2.67E-01	1.74E-01	1.13E-01
90				9.99E-01	7.77E-01	6.03E-01	4.66E-01	3.42E-01	2.23E-01	1.45E-01
120					9.97E-01	7.73E-01	5.98E-01	4.39E-01	2.86E-01	1.86E-01
150						9.92E-01	7.67E-01	5.63E-01	3.67E-01	2.39E-01
180							9.85E-01	7.23E-01	4.71E-01	3.07E-01
210								9.75E-01	6.35E-01	4.13E-01
240									9.74E-01	6.28E-01
270										9.53E-01

Table C58. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of ^{137}Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	4.83E-07	5.86E-05	2.44E-04	9.80E-04	2.18E-03	3.43E-03	4.16E-03	3.92E-03	3.36E-03
30		6.20E-07	7.52E-05	3.13E-04	1.26E-03	2.80E-03	4.40E-03	5.34E-03	5.03E-03	4.31E-03
60			9.65E-05	4.01E-04	1.61E-03	3.59E-03	5.64E-03	6.85E-03	6.46E-03	5.53E-03
90				5.15E-04	2.07E-03	4.61E-03	7.24E-03	8.79E-03	8.29E-03	7.10E-03
120					2.66E-03	5.92E-03	9.29E-03	1.13E-02	1.06E-02	9.12E-03
150						7.60E-03	1.19E-02	1.45E-02	1.36E-02	1.17E-02
180							1.53E-02	1.86E-02	1.75E-02	1.50E-02
210								2.50E-02	2.36E-02	2.02E-02
240									3.59E-02	3.07E-02
270										4.67E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present initially when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C59. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of uranium into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		4.06E-08	4.06E-08	4.06E-08	4.06E-08	4.06E-08	4.06E-08	4.06E-08	4.06E-08	4.06E-08
60			6.35E-06	6.35E-06	6.35E-06	6.35E-06	6.35E-06	6.35E-06	6.35E-06	6.35E-06
90				5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05	5.11E-05
120					2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04
150						7.65E-04	7.65E-04	7.65E-04	7.65E-04	7.65E-04
180							2.08E-03	2.08E-03	2.08E-03	2.08E-03
210								3.47E-03	3.47E-03	3.47E-03
240									7.65E-03	7.65E-03
270										1.03E-02

Table C60. Fraction of activity in the embryo/fetus initially and fractions at start of subsequent 30-day periods after introduction of plutonium into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		6.77E-08	6.76E-08	6.76E-08	6.75E-08	6.75E-08	6.75E-08	6.74E-08	6.74E-08	6.73E-08
60			1.06E-05	1.06E-05	1.06E-05	1.06E-05	1.06E-05	1.06E-05	1.05E-05	1.05E-05
90				8.52E-05	8.51E-05	8.50E-05	8.50E-05	8.49E-05	8.49E-05	8.48E-05
120					4.42E-04	4.42E-04	4.42E-04	4.42E-04	4.41E-04	4.41E-04
150						1.28E-03	1.27E-03	1.27E-03	1.27E-03	1.27E-03
180							3.47E-03	3.47E-03	3.47E-03	3.46E-03
210								5.79E-03	5.78E-03	5.78E-03
240									1.27E-02	1.27E-02
270										1.72E-02

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

Table C61. Fraction of activity in the embryo/fetus initially and fraction at start of subsequent 30-day periods after introduction of ^{241}Am into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.35E-08	1.35E-08	1.35E-08	1.35E-08	1.35E-08	1.35E-08	1.35E-08	1.35E-08	1.35E-08
60			2.12E-06	2.12E-06	2.12E-06	2.12E-06	2.12E-06	2.12E-06	2.12E-06	2.12E-06
90				1.70E-05	1.70E-05	1.70E-05	1.70E-05	1.70E-05	1.70E-05	1.70E-05
120					8.85E-05	8.85E-05	8.85E-05	8.84E-05	8.84E-05	8.84E-05
150						2.55E-04	2.55E-04	2.55E-04	2.55E-04	2.55E-04
180							6.94E-04	6.94E-04	6.94E-04	6.94E-04
210								1.16E-03	1.16E-03	1.16E-03
240									2.55E-03	2.55E-03
270										3.44E-03

(a) N indicates that the metabolic pattern is such that a negligible fraction is present throughout gestation when activity is administered immediately after fertilization. Fraction resulting from administration later during the first month can be approximated as shown on page C-1.

APPENDIX D

RADIATION ABSORBED DOSE RATES AND DOSE TO THE EMBRYO/FETUS OR INDICATED STRUCTURES FOLLOWING INTRODUCTION OF SPECIFIED RADIONUCLIDES AND CHEMICAL FORMS INTO THE MATERNAL TRANSFER COMPARTMENT

APPENDIX D

RADIATION ABSORBED DOSE RATES AND DOSE TO THE EMBRYO/FETUS OR INDICATED STRUCTURES FOLLOWING INTRODUCTION OF SPECIFIED RADIONUCLIDES AND CHEMICAL FORMS INTO THE MATERNAL TRANSFER COMPARTMENT

The entries in the tables presented in this appendix, for selected radionuclides and chemical forms, were calculated from the corresponding fractional activities given in Appendix C and the dosimetric models presented in Appendix B, and are based on the operational methodology given in Section III.C. It has been assumed that 1 μCi of activity is introduced into the maternal transfer compartment and that this represents the values which would be obtained using the approaches described in Subsection 1, Assumptions. The fractional depositions in the embryo/fetus (Appendix C) were determined using the methodologies presented in Subsection 2, Method. These methodologies were employed for calculating the dose rates and doses presented in Appendix D. Pregnancy was assumed to begin at the time of fertilization, roughly 2 weeks after menses, and gestation was considered to consist of nine 30-day months.

Radiation absorbed dose rates were calculated from the initial fraction that was present after a single administration at the start of each of these months or on the assumed final day (270) of gestation. Monthly doses were determined by integrating under the curve relating the fraction of the activity in the embryo/fetus at the start of each month after administration and the fraction at the beginning of the subsequent month of gestation, and are shown for the inclusive periods, expressed in days. Doses to the embryo/fetus from radionuclides in maternal organs were calculated; when appropriate, these are included to provide total radiation absorbed doses. The tabulated values of cumulated doses were determined as the sum of the monthly doses.

As was noted in Appendix C, ICRP Publication 30 employs a metabolic model in which a fraction of activity in the first transfer compartment often is assumed to go immediately to excretion. Because of the minuscule mass of the conceptus immediately following fertilization, for some materials the biokinetic model thus predicts that there would be negligible initial activity in the embryo after administration at that time, and that there would be minimal activity at later times. As a consequence, the dose rate and doses also would be negligible; this is indicated by N in the table.

It sometimes may be desirable to know the dose rates or doses to the embryo/fetus after intakes during the first month (0-30 days) of pregnancy. These may be estimated by expressing time of intake as a fraction of 30 days (e.g., 15 days/30 days or 1/2) and multiplying this by the corresponding dose rate or monthly dose presented for administration at 30 days.

Table D1. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{3}H, as tritiated water, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	2.25E-07	6.09E-13	4.85E-16	1.12E-17	2.69E-19	1.16E-20	7.09E-22	5.29E-23	4.48E-24	4.13E-25
30		2.24E-07	1.78E-10	4.13E-12	9.90E-14	4.27E-15	2.60E-16	1.94E-17	1.65E-18	1.52E-19
60			2.23E-07	5.17E-09	1.24E-10	5.34E-12	3.26E-13	2.43E-14	2.06E-15	1.90E-16
90				2.22E-07	5.31E-09	2.29E-10	1.40E-11	1.04E-12	8.84E-14	8.16E-15
120					2.20E-07	9.51E-09	5.80E-10	4.33E-11	3.67E-12	3.38E-13
150						2.18E-07	1.33E-08	9.94E-10	8.42E-11	7.77E-12
180							2.16E-07	1.61E-08	1.36E-09	1.26E-10
210								2.12E-07	1.79E-08	1.66E-09
240									2.06E-07	1.90E-08
270										1.99E-07

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	9.03E-06	3.96E-11	7.67E-14	2.00E-15	5.31E-17	2.63E-18	1.72E-19	1.34E-20	1.18E-21	9.03E-06
30		1.77E-05	2.64E-08	7.50E-10	1.94E-11	9.70E-13	6.30E-14	4.94E-15	4.33E-16	1.77E-05
60			3.93E-05	8.96E-07	2.47E-08	1.21E-09	7.91E-11	6.17E-12	5.41E-13	4.02E-05
90				3.82E-05	1.06E-06	5.19E-08	3.39E-09	2.64E-10	2.32E-11	3.93E-05
120					4.50E-05	2.14E-06	1.41E-07	1.10E-08	9.63E-10	4.73E-05
150						4.98E-05	3.22E-06	2.53E-07	2.21E-08	5.33E-05
180							5.28E-05	4.08E-0	3.57E-07	5.72E-05
210								5.40E-05	4.70E-06	5.37E-05
240									5.28E-05	5.28E-05

Table D2. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{3}H, as a hexose or amino acid, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.24E-07	8.02E-10	1.34E-10	2.54E-11	8.75E-12	4.27E-12	2.55E-12	1.73E-12	1.27E-12
60			2.23E-07	2.33E-08	4.03E-09	1.37E-09	6.68E-10	3.99E-10	2.70E-10	1.99E-10
90				2.22E-07	2.39E-08	7.45E-09	3.59E-09	2.14E-09	1.45E-09	1.07E-09
120					2.20E-07	4.28E-08	1.89E-08	1.11E-08	7.51E-09	5.55E-09
150						2.18E-07	5.99E-08	3.23E-08	2.16E-08	1.59E-08
180							2.16E-07	7.24E-08	4.43E-08	3.23E-08
210								2.12E-07	8.07E-08	5.38E-08
240									2.06E-07	8.57E-08
270										1.99E-07

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.21E-05	2.14E-07	4.68E-08	1.04E-08	4.37E-09	2.35E-09	1.50E-09	1.06E-09	2.24E-05
60			6.00E-05	7.27E-06	1.67E-06	6.81E-07	3.68E-07	2.34E-07	1.66E-07	7.04E-05
90				5.82E-05	9.25E-06	3.69E-06	1.97E-06	1.26E-06	8.92E-07	7.53E-05
120					7.24E-05	1.97E-05	1.03E-05	6.50E-06	4.62E-06	1.14E-04
150						8.29E-05	3.05E-05	1.89E-05	1.33E-05	1.46E-04
180							8.96E-05	3.93E-05	2.72E-05	1.56E-04
210								9.31E-05	4.58E-05	1.32E-04
240									1.05E-04	1.05E-04

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D3. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{14}C, as bicarbonate or as a hexose or amino acid, introduced into the maternal transfer compartment (blood)

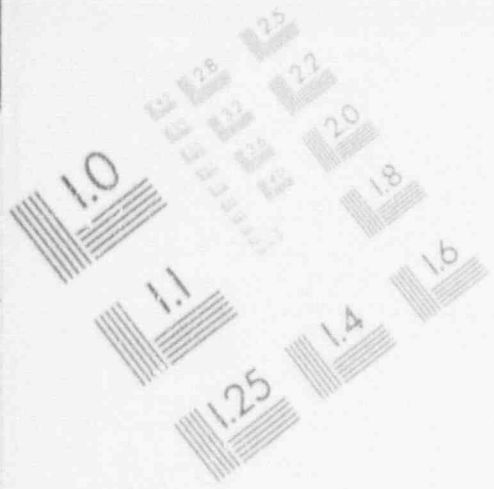
Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.95E-06	6.23E-09	1.16E-09	2.24E-10	7.75E-11	3.80E-11	2.28E-11	1.55E-11	1.15E-11
60			1.94E-06	1.81E-07	3.48E-08	1.21E-08	5.92E-09	3.55E-09	2.42E-09	1.79E-09
90				1.93E-06	1.86E-07	6.44E-08	3.16E-08	1.89E-08	1.29E-08	9.56E-09
120					1.92E-06	3.33E-07	1.63E-07	9.78E-08	6.66E-08	4.94E-08
150						1.90E-06	4.66E-07	2.79E-07	1.90E-07	1.41E-07
180							1.88E-06	5.63E-07	3.83E-07	2.84E-07
210								1.84E-06	6.27E-07	4.65E-07
240									1.80E-06	6.66E-07
270										1.73E-06

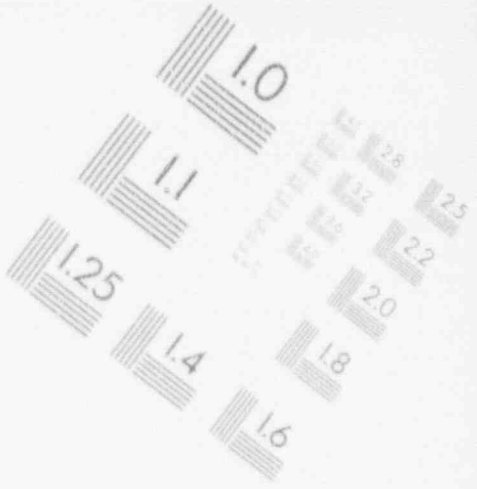
Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.87E-04	1.72E-06	4.12E-07	9.18E-08	3.88E-08	2.09E-08	1.34E-08	9.56E-09	1.89E-04
60			4.96E-04	5.83E-05	1.46E-05	6.02E-06	3.26E-06	2.09E-06	1.49E-06	5.82E-04
90				4.81E-04	7.48E-05	3.24E-05	1.74E-05	1.11E-05	7.95E-06	6.25E-04
120					5.96E-04	1.59E-04	9.09E-05	5.74E-05	4.11E-05	9.44E-04
150						6.80E-04	2.47E-04	1.66E-04	1.17E-04	1.21E-03
180							7.33E-04	3.19E-04	2.39E-04	1.29E-03
210								7.61E-04	3.70E-04	1.13E-03
240									8.88E-04	8.88E-04

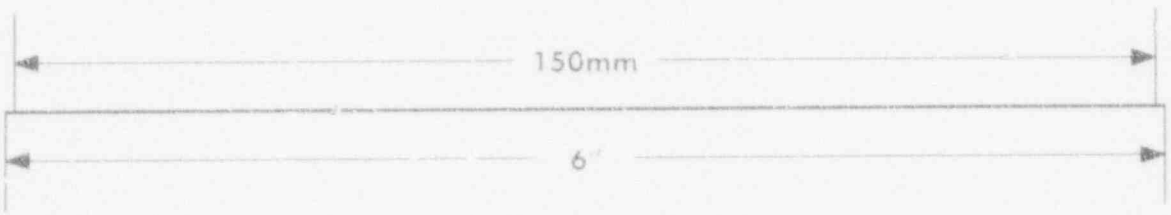
(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

1

IMAGE EVALUATION
TEST TARGET (MT-3)







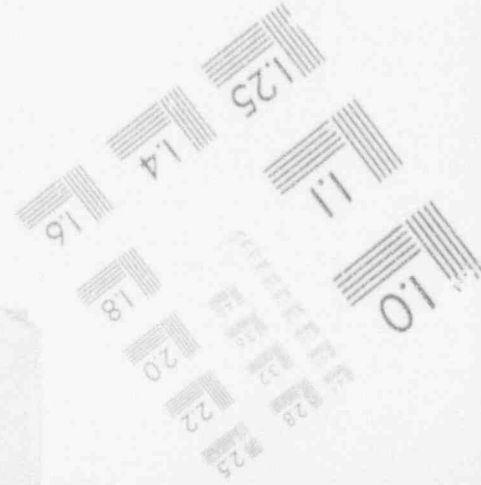


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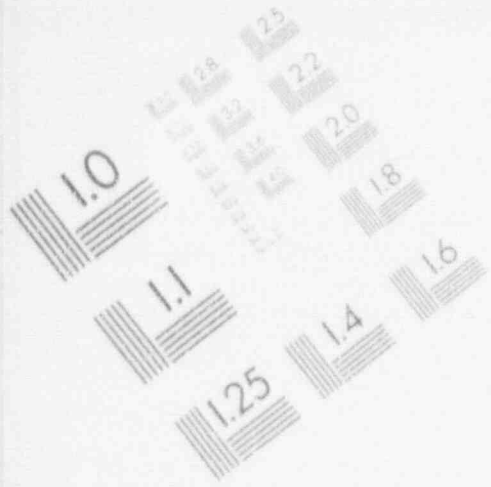
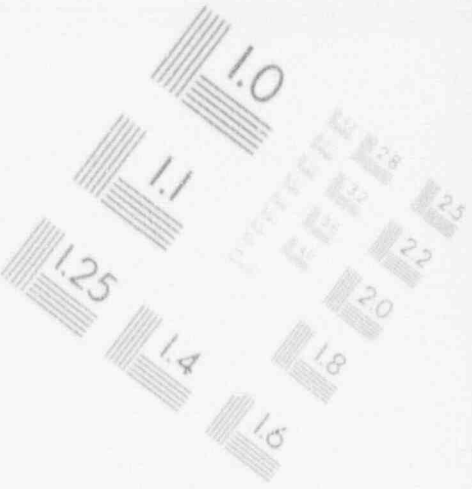
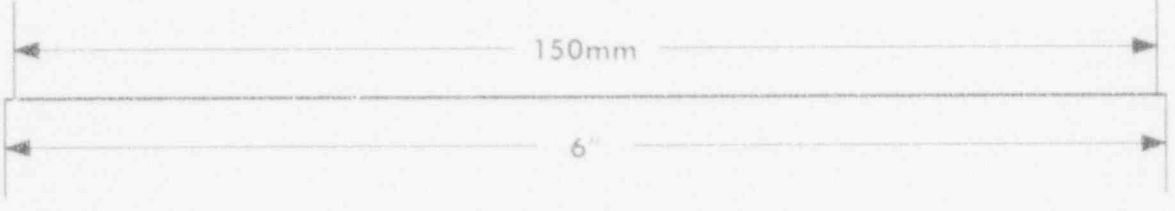
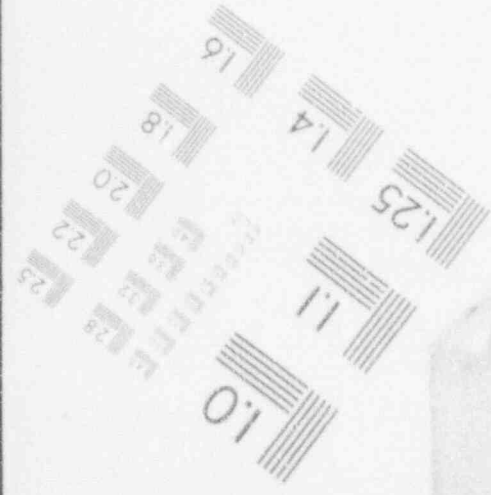
IMAGE EVALUATION
TEST TARGET (MT-3)









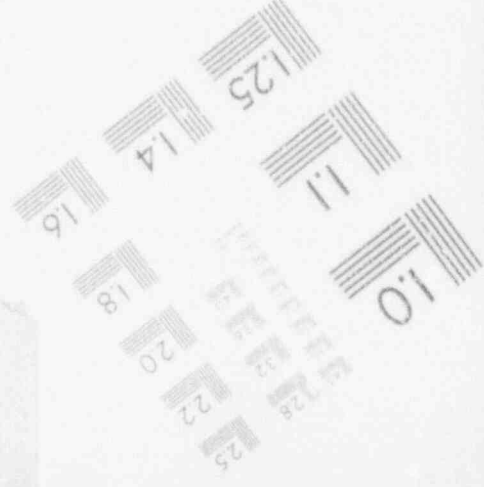


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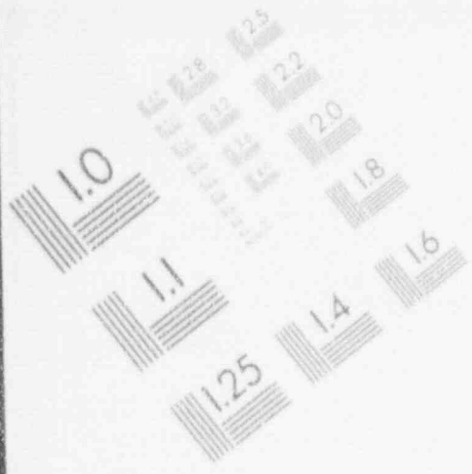
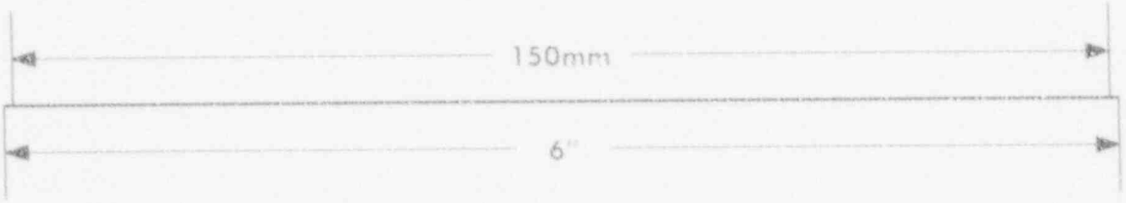
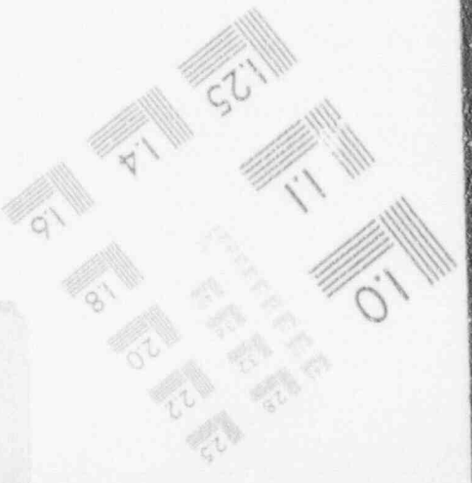
IMAGE EVALUATION
TEST TARGET (MT-3)








1
IMAGE EVALUATION
TEST TARGET (MT-3)
1.0
1.1
1.25
1.4
1.6
2.0
2.2
2.5
1.8
150mm
6"

Table D4. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{57}Co, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	2.21E-06	4.71E-07	3.57E-07	2.96E-07	2.58E-07	2.29E-07	2.05E-07	1.82E-07	1.61E-07	1.44E-07
30		2.99E-06	4.72E-07	3.63E-07	3.10E-07	2.70E-07	2.38E-07	2.09E-07	1.83E-07	1.63E-07
60			3.00E-06	4.79E-07	3.80E-07	3.23E-07	2.80E-07	2.43E-07	2.11E-07	1.85E-07
90				3.04E-06	5.02E-07	3.97E-07	3.36E-07	2.87E-07	2.45E-07	2.13E-07
120					3.18E-06	5.24E-07	4.12E-07	3.44E-07	2.88E-07	2.47E-07
150						3.33E-06	5.44E-07	4.22E-07	3.46E-07	2.92E-07
180							3.45E-06	5.57E-07	4.24E-07	3.50E-07
210								3.54E-06	5.59E-07	4.29E-07
240									3.56E-06	5.66E-07
270										3.60E-06

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	7.30E-04	2.76E-04	2.36E-04	1.97E-04	1.75E-04	1.56E-04	1.39E-04	1.23E-04	1.09E-04	2.14E-03
30		8.66E-04	2.74E-04	2.45E-04	2.07E-04	1.82E-04	1.60E-04	1.41E-04	1.24E-04	2.20E-03
60			8.71E-04	2.82E-04	2.56E-04	2.15E-04	1.88E-04	1.63E-04	1.42E-04	2.12E-03
90				8.96E-04	2.96E-04	2.67E-04	2.22E-04	1.91E-04	1.64E-04	2.04E-03
120					9.37E-04	3.08E-04	2.75E-04	2.25E-04	1.92E-04	1.94E-03
150						9.78E-04	3.18E-04	2.79E-04	2.27E-04	1.80E-03
180							1.01E-03	3.22E-04	2.83E-04	1.61E-03
210								1.03E-03	3.19E-04	1.35E-03
240									1.04E-03	1.04E-03

Table D5. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{58}Co, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	1.74E-05	2.39E-06	1.51E-06	1.01E-06	7.05E-07	4.95E-07	3.52E-07	2.50E-07	1.78E-07	1.28E-07
30		1.88E-05	2.48E-06	1.54E-06	1.05E-06	7.25E-07	5.09E-07	3.56E-07	2.52E-07	1.80E-07
60			1.95E-05	2.53E-06	1.60E-06	1.08E-06	7.44E-07	5.14E-07	3.59E-07	2.54E-07
90				1.98E-05	2.62E-06	1.64E-06	1.11E-06	7.52E-07	5.18E-07	3.62E-07
120					2.06E-05	2.70E-06	1.69E-06	1.12E-06	7.59E-07	5.22E-07
150						2.12E-05	2.77E-06	1.71E-06	1.13E-06	7.65E-07
180							2.18E-05	2.80E-06	1.72E-06	1.14E-06
210								2.20E-05	2.82E-06	1.74E-06
240									2.22E-05	2.84E-06
270										2.24E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	4.81E-03	1.27E-03	9.03E-04	6.03E-04	4.25E-04	3.00E-04	2.13E-04	1.52E-04	1.09E-04	8.79E-03
30		5.12E-03	1.30E-03	9.30E-04	6.24E-04	4.37E-04	3.06E-04	2.15E-04	1.53E-04	9.08E-03
60			5.26E-03	1.34E-03	9.62E-04	6.41E-04	4.45E-04	3.09E-04	2.17E-04	9.17E-03
90				5.39E-03	1.38E-03	9.6 -04	6.54E-04	4.49E-04	3.11E-04	9.17E-03
120					5.59E-03	1.42E-03	1.01E-03	6.59E-04	4.53E-04	9.13E-03
150						5.75E-03	1.45E-03	1.02E-03	6.64E-04	8.88E-03
180							5.87E-03	1.46E-03	1.03E-03	8.36E-03
210								5.95E-03	1.45E-03	7.40E-03
240									6.00E-03	6.00E-03

Table D6. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{60}Co, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	4.16E-05	7.74E-05	6.49E-06	5.52E-06	5.14E-06	4.86E-06	4.60E-06	4.35E-06	4.12E-06	3.89E-06
30		4.57E-05	8.02E-06	6.34E-06	5.77E-06	5.36E-06	5.01E-06	4.67E-06	4.39E-06	4.12E-06
60			4.73E-05	7.83E-06	6.63E-06	6.01E-06	5.52E-06	5.08E-06	4.72E-06	4.39E-06
90				4.64E-05	8.19E-06	6.91E-06	6.20E-06	5.61E-06	5.13E-06	4.72E-06
120					4.85E-05	8.53E-06	7.12E-06	6.30E-06	5.66E-06	5.13E-06
150						5.06E-05	8.80E-06	7.23E-06	6.36E-06	5.66E-06
180							5.21E-05	8.93E-06	7.30E-06	6.36E-06
210								5.30E-05	9.02E-06	7.30E-06
240									5.35E-05	9.02E-06
270										5.35E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.28E-02	4.73E-03	4.37E-03	3.79E-03	3.60E-03	3.40E-03	3.22E-03	3.05E-03	2.88E-03	4.18E-02
30		1.38E-02	4.73E-03	4.40E-03	3.98E-03	3.73E-03	3.48E-03	3.26E-03	3.06E-03	4.04E-02
60			1.39E-02	4.76E-03	4.62E-03	4.12E-03	3.81E-03	3.52E-03	3.27E-03	3.80E-02
90				1.40E-02	4.99E-03	4.79E-03	4.22E-03	3.86E-03	3.54E-03	3.54E-02
120					1.46E-02	5.17E-03	4.90E-03	4.27E-03	3.88E-03	3.28E-02
150						1.52E-02	5.29E-03	4.96E-03	4.29E-03	2.97E-02
180							1.56E-02	5.35E-03	5.01E-03	2.60E-02
210								1.59E-02	5.29E-03	2.12E-02
240									1.60E-02	1.60E-02

Table D7. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{57}Co, as vitamin B-12, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	2.13E-06	1.88E-06	1.23E-06	8.19E-07	5.61E-07	3.83E-07	2.61E-07	1.75E-07	1.15E-07	7.62E-08
30		2.86E-06	1.88E-06	1.25E-06	8.57E-07	5.86E-07	3.98E-07	2.67E-07	1.76E-07	1.16E-07
60			2.87E-06	1.91E-06	1.31E-06	8.94E-07	6.08E-07	4.08E-07	2.68E-07	1.78E-07
90				2.92E-06	2.00E-06	1.37E-06	9.29E-07	6.23E-07	4.10E-07	2.72E-07
120					3.05E-06	2.09E-06	1.42E-06	9.51E-07	6.26E-07	4.15E-07
150						3.18E-06	2.17E-06	1.45E-06	9.56E-07	6.33E-07
180							3.31E-06	2.22E-06	1.46E-06	9.67E-07
210								3.39E-06	2.23E-06	1.48E-06
240									3.40E-06	2.25E-06
270										3.44E-06

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.47E-03	1.11E-03	7.18E-04	4.88E-04	3.34E-04	2.28E-04	1.54E-04	1.02E-04	6.74E-05	4.67E-03
30		1.67E-03	1.10E-03	7.44E-04	5.10E-04	3.48E-04	2.35E-04	1.56E-04	1.03E-04	4.87E-03
60			1.68E-03	1.14E-03	7.80E-04	5.31E-04	3.59E-04	2.38E-04	1.57E-04	4.89E-03
90				1.74E-03	1.19E-03	8.13E-04	5.49E-04	3.64E-04	2.40E-04	4.90E-03
120					1.82E-03	1.24E-03	8.38E-04	5.56E-04	3.67E-04	4.82E-03
150						1.89E-03	1.28E-03	8.48E-04	5.60E-04	4.58E-03
180							1.95E-03	1.30E-03	8.55E-04	4.10E-03
210								1.98E-03	1.31E-03	3.29E-03
240									1.99E-03	1.99E-03

Table D8. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{60}Co, as vitamin B-12, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	4.02E-05	3.08E-05	2.23E-05	1.53E-05	1.12E-05	8.14E-06	5.87E-06	4.17E-06	2.94E-06	2.06E-06
30		4.41E-05	3.19E-05	2.18E-05	1.60E-05	1.16E-05	8.39E-06	5.96E-06	4.21E-06	2.94E-06
60			4.56E-05	3.12E-05	2.28E-05	1.66E-05	1.20E-05	8.52E-06	6.02E-06	4.21E-06
90				4.46E-05	3.26E-05	2.38E-05	1.71E-05	1.22E-05	8.60E-06	6.02E-06
120					4.66E-05	3.40E-05	2.45E-05	1.74E-05	1.23E-05	8.60E-06
150						4.86E-05	3.50E-05	2.49E-05	1.76E-05	1.23E-05
180							5.01E-05	3.56E-05	2.51E-05	1.76E-05
210								5.09E-05	3.59E-05	2.51E-05
240									5.14E-05	3.59E-05
270										5.13E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	2.54E-02	1.90E-02	1.33E-02	9.38E-03	6.88E-03	4.98E-03	3.56E-03	2.52E-03	1.77E-03	8.68E-02
30		2.71E-02	1.90E-02	1.34E-02	9.82E-03	7.10E-03	5.09E-03	3.61E-03	2.53E-03	8.76E-02
60			2.70E-02	1.91E-02	1.40E-02	1.02E-02	7.28E-03	5.16E-03	3.62E-03	8.64E-02
120				2.74E-02	2.00E-02	1.45E-02	1.04E-02	7.38E-03	5.18E-03	8.49E-02
150					2.86E-02	2.08E-02	1.49E-02	1.05E-02	7.41E-03	8.22E-02
180						2.97E-02	2.13E-02	1.51E-02	1.06E-02	7.67E-02
210							3.04E-02	2.15E-02	1.51E-02	6.70E-02
240								3.08E-02	2.16E-02	5.24E-02
270									3.10E-02	3.10E-02

Table D9. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{89}Sr, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	1.88E-05	1.31E-06	5.60E-07	2.77E-07	1.29E-07	6.62E-08	3.77E-08	2.24E-08	1.29E-08	7.29E-09
30		2.77E-05	1.37E-06	5.67E-07	2.77E-07	1.28E-07	6.54E-08	3.70E-08	2.18E-08	1.25E-08
60			3.51E-05	3.43E-06	8.36E-07	3.39E-07	1.48E-07	7.26E-08	3.98E-08	2.29E-08
90				3.58E-05	3.55E-06	1.08E-06	4.43E-07	1.93E-07	9.34E-08	5.01E-08
120					3.61E-05	5.38E-06	1.89E-06	8.00E-07	3.63E-07	1.79E-07
150						3.59E-05	7.06E-06	2.84E-06	1.30E-06	6.30E-07
180							3.54E-05	8.24E-06	3.69E-06	1.81E-06
210								3.46E-05	9.03E-06	4.35E-06
240									3.36E-05	9.48E-06
270										3.23E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	4.09E-03	5.66E-04	2.92E-04	1.37E-04	6.64E-05	3.59E-05	2.10E-05	1.23E-05	7.01E-06	5.23E-03
30		5.35E-03	5.74E-04	2.95E-04	1.36E-04	6.57E-05	3.53E-05	2.05E-05	1.20E-05	6.49E-03
60			9.01E-03	1.20E-03	3.84E-04	1.63E-04	7.45E-05	3.86E-05	2.18E-05	1.09E-02
90				9.09E-03	1.36E-03	5.06E-04	2.12E-04	9.67E-05	4.93E-05	1.13E-02
120					1.07E-02	2.24E-03	8.99E-04	3.90E-04	1.84E-04	1.44E-02
150						1.19E-02	3.15E-03	1.40E-03	6.55E-04	1.71E-02
180							1.26E-02	3.87E-03	1.89E-03	1.84E-02
210								1.29E-02	4.38E-03	1.73E-02
240									1.31E-02	1.31E-02

Table D10. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{90}Sr (in equilibrium with ^{90}Y), introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	3.66E-05	3.83E-06	2.47E-06	1.84E-06	1.29E-06	9.96E-07	8.54E-07	7.65E-07	6.67E-07	5.67E-07
30		5.06E-05	4.01E-06	2.50E-06	1.83E-06	1.28E-06	9.83E-07	8.40E-07	7.46E-07	6.46E-07
60			6.68E-05	9.87E-06	2.76E-06	2.24E-06	1.47E-06	1.09E-06	9.04E-07	7.85E-07
90				6.85E-05	5.49E-06	4.70E-06	2.92E-06	1.92E-06	1.40E-06	1.13E-06
120					4.46E-05	1.55E-05	8.22E-06	5.26E-06	3.60E-06	2.68E-06
150						6.91E-05	2.04E-05	1.24E-05	8.55E-06	6.25E-06
180							6.82E-05	2.38E-05	1.61E-05	1.19E-05
210								6.67E-05	2.61E-05	1.30E-05
240									6.49E-05	2.74E-05
270										6.24E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	9.07E-03	2.01E-03	1.57E-03	1.10E-03	8.07E-04	6.58E-04	5.81E-04	5.15E-04	4.43E-04	1.68E-02
30		1.13E-02	2.04E-03	1.57E-03	1.09E-03	7.99E-04	6.49E-04	5.69E-04	5.00E-04	1.35E-02
60			2.03E-02	3.60E-03	1.72E-03	1.33E-03	8.94E-04	7.10E-04	6.04E-04	2.92E-02
90				1.50E-02	3.31E-03	2.80E-03	1.67E-03	1.17E-03	8.98E-04	2.48E-02
120					1.90E-02	7.93E-03	4.71E-03	3.11E-03	2.22E-03	3.70E-02
150						2.69E-02	1.10E-02	7.41E-03	5.23E-03	5.05E-02
180							2.86E-02	1.36E-02	1.00E-02	5.22E-02
210								2.95E-02	1.54E-02	4.49E-02
240									2.93E-02	2.93E-02

Table D11. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{106}Ru (in equilibrium with ^{106}Rh), introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	3.42E-06	1.48E-06	1.40E-06	1.17E-06	9.89E-07	8.73E-07	7.83E-07	7.08E-07	6.43E-07	5.84E-07
30		4.05E-06	2.01E-06	1.48E-06	1.18E-06	1.00E-06	8.76E-07	7.80E-07	7.02E-07	6.35E-07
60			5.48E-06	2.12E-06	1.49E-06	1.19E-06	1.00E-06	8.73E-07	7.74E-07	6.94E-07
90				5.80E-06	2.14E-06	1.51E-06	1.20E-06	1.00E-06	8.66E-07	7.65E-07
120					5.85E-06	2.17E-06	1.51E-06	1.19E-06	9.93E-07	8.55E-07
150						5.92E-06	2.18E-06	1.51E-06	1.18E-06	9.80E-07
180							5.94E-06	2.17E-06	1.50E-06	1.17E-06
210								5.92E-06	2.15E-06	1.48E-06
240									5.87E-06	2.12E-06
270										5.80E-06

Days of Gestation at Introduction	D ₑe (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.56E-03	1.00E-03	9.36E-04	7.68E-04	6.67E-04	5.94E-04	5.35E-04	4.85E-04	4.41E-04	6.99E-03
30		2.02E-03	1.21E-03	9.48E-04	7.77E-04	6.72E-04	5.94E-04	5.32E-04	4.80E-04	7.23E-03
60			2.42E-03	1.23E-03	9.56E-04	7.80E-04	6.70E-04	5.90E-04	5.27E-04	7.17E-03
90				2.50E-03	1.24E-03	9.68E-04	7.84E-04	6.68E-04	5.85E-04	6.74E-03
120					2.53E-03	1.25E-03	9.63E-04	7.77E-04	6.62E-04	6.18E-03
150						2.55E-03	1.26E-03	9.59E-04	7.69E-04	5.54E-03
180							2.55E-03	1.25E-03	9.55E-04	4.75E-03
210								2.54E-03	1.23E-03	3.77E-03
240									2.53E-03	2.53E-03

Table D12. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{125}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	4.97E-08	1.80E-08	1.35E-08	9.31E-09	2.91E-08	1.07E-08	7.65E-09	5.19E-09	3.42E-09	2.45E-09
30		7.91E-08	1.81E-08	1.44E-08	2.06E-08	1.71E-08	1.22E-08	8.27E-09	5.47E-09	3.92E-09
60			8.57E-08	1.93E-08	3.13E-08	2.67E-08	1.93E-08	1.31E-08	8.70E-09	6.25E-09
90				4.88E-07	1.03E-07	5.62E-08	3.55E-08	2.28E-08	1.47E-08	1.04E-08
120					2.21E-06	6.41E-07	2.50E-07	1.13E-07	5.57E-08	3.26E-08
150						1.74E-06	6.56E-07	2.83E-07	1.33E-07	7.36E-08
180							1.41E-06	6.11E-07	2.81E-07	1.52E-07
210								1.21E-06	5.66E-07	3.05E-07
240									1.08E-06	6.05E-07
270										1.14E-06

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	2.08E-05	1.12E-05	7.34E-06	1.34E-05	1.46E-05	6.07E-06	4.65E-06	3.01E-06	2.07E-06	8.31E-05
30		2.72E-05	1.05E-05	1.27E-05	1.40E-05	1.04E-05	7.27E-06	4.83E-06	3.31E-06	9.02E-05
60			2.74E-05	1.70E-05	2.23E-05	1.63E-05	1.15E-05	7.66E-06	5.28E-06	1.07E-04
90				1.64E-04	5.21E-05	3.23E-05	2.05E-05	1.31E-05	8.84E-06	2.91E-04
120					8.79E-04	2.88E-04	1.22E-04	5.70E-05	3.05E-05	1.38E-03
150						7.81E-04	3.12E-04	1.40E-04	7.08E-05	1.30E-03
180							6.78E-04	2.99E-04	1.48E-04	1.12E-03
210								5.97E-04	2.98E-04	8.95E-04
240									5.33E-04	5.33E-04

Table D13. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{125}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				2.21E-08	8.06E-06	8.00E-06	5.46E-06	3.31E-06	1.87E-06	7.94E-07
30				3.43E-08	1.28E-05	1.27E-05	8.71E-06	5.27E-06	2.99E-06	1.27E-06
60				4.58E-08	1.91E-05	1.98E-05	1.38E-05	8.36E-06	4.74E-06	2.02E-06
90				2.97E-04	9.48E-05	4.72E-05	2.67E-05	1.50E-05	8.14E-06	3.39E-06
120					2.42E-03	7.01E-04	2.37E-04	9.06E-05	3.65E-05	1.20E-05
150						1.92E-03	6.47E-04	2.35E-04	9.01E-05	2.80E-05
180							1.43E-03	5.20E-04	1.94E-04	5.89E-05
210								1.07E-03	4.05E-04	1.20E-04
240									8.27E-04	2.46E-04
270										5.06E-04

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				1.45E-03	7.96E-03	4.51E-03	3.14E-03	1.82E-03	9.10E-04	1.98E-02
30				2.30E-03	1.26E-02	7.18E-03	5.00E-03	2.90E-03	1.46E-03	3.14E-02
60				3.38E-03	1.94E-02	1.13E-02	7.93E-03	4.60E-03	2.31E-03	4.89E-02
90				1.22E-01	4.72E-02	2.57E-02	1.45E-02	8.11E-03	3.92E-03	2.21E-01
120					9.70E-01	2.99E-01	1.07E-01	4.25E-02	1.58E-02	1.43E+00
150						8.25E-01	2.85E-01	1.08E-01	3.81E-02	1.26E+00
180							6.34E-01	2.36E-01	8.12E-02	9.51E-01
210								4.92E-01	1.68E-01	6.60E-01
240									3.86E-01	3.86E-01

Table D14. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{131}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	3.26E-07	1.06E-08	8.20E-10	5.85E-11	1.40E-11	7.92E-13	8.77E-14	6.36E-15	2.74E-16	1.92E-17
30		6.41E-07	1.06E-08	8.65E-10	2.09E-10	1.21E-11	1.33E-12	9.65E-14	4.17E-15	2.92E-16
60			6.90E-07	1.12E-08	3.02E-09	1.79E-10	2.00E-11	1.45E-12	6.29E-14	4.42E-15
90				3.24E-06	1.15E-07	3.66E-09	3.58E-10	2.44E-11	1.01E-12	6.99E-14
120					2.33E-05	4.02E-07	2.64E-08	1.26E-09	3.65E-11	2.07E-12
150						9.63E-06	6.69E-07	3.04E-08	8.30E-10	4.46E-11
180							1.28E-05	6.25E-07	1.67E-08	8.71E-10
210								1.09E-05	3.21E-07	1.66E-08
240									5.44E-06	3.12E-07
270										5.25E-06

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	5.93E-05	2.58E-06	1.88E-07	2.20E-08	3.39E-09	2.10E-10	2.29E-11	1.32E-12	6.35E-14	6.21E-05
30		9.73E-05	2.31E-06	3.38E-07	5.05E-08	3.22E-09	3.47E-10	2.01E-11	9.66E-13	1.00E-04
60			9.44E-05	4.14E-06	7.60E-07	4.75E-08	5.23E-09	3.02E-10	1.46E-11	9.94E-05
90				6.52E-04	2.11E-05	9.30E-07	9.12E-08	5.01E-09	2.33E-10	6.74E-04
120					3.54E-03	8.90E-05	6.03E-06	2.33E-07	7.82E-09	3.64E-03
150						2.35E-03	1.49E-04	5.56E-06	1.75E-07	2.50E-03
180							2.88E-03	1.15E-04	3.48E-06	3.00E-03
210								1.98E-03	6.80E-05	2.05E-03
240									1.00E-03	1.00E-03

Table D15. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{131}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				1.81E-10	8.69E-09	8.82E-10	6.14E-11	4.24E-12	2.47E-13	8.80E-15
30				2.67E-09	1.30E-07	1.33E-08	9.31E-10	6.44E-11	3.76E-12	1.34E-13
60				3.39E-08	1.86E-06	1.97E-07	1.39E-08	9.69E-10	5.66E-11	2.02E-12
90				2.18E-03	8.94E-05	4.51E-06	2.59E-07	1.66E-08	9.27E-10	3.23E-11
120					1.96E-02	6.37E-04	2.20E-05	9.50E-07	3.94E-08	1.09E-09
150						1.51E-02	5.68E-04	2.35E-05	9.30E-07	2.43E-08
180							1.09E-02	4.95E-04	1.91E-05	4.85E-07
210								8.89E-03	3.79E-04	9.41E-06
240									6.70E-03	1.84E-04
270										3.29E-03

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				2.44E-06	3.37E-06	1.99E-07	1.50E-08	9.87E-10	5.02E-11	6.03E-06
30				3.63E-05	5.05E-05	3.00E-06	2.28E-07	1.50E-08	7.64E-10	9.00E-05
60				5.07E-04	7.36E-04	4.46E-05	3.41E-06	2.26E-07	1.15E-08	1.29E-03
90				4.42E-01	1.92E-02	1.01E-03	6.04E-05	3.83E-06	1.87E-07	4.62E-01
120					3.76E+00	1.23E-01	4.51E-03	1.99E-04	7.42E-06	3.89E+00
150						3.01E+00	1.16E-01	4.86E-03	1.73E-04	3.13E+00
180							2.31E+00	1.02E-01	3.52E-03	2.42E+00
210								1.89E+00	6.99E-02	1.96E+00
240									1.42E+00	1.42E+00

Table D16. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{132}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	2.54E-05	0	0	0	0	0	0	0	0	0
30		3.18E-05	0	0	0	0	0	0	0	0
60			3.82E-05	0	0	0	0	0	0	0
90				3.93E-05	0	0	0	0	0	0
120					4.26E-05	0	0	0	0	0
150						4.38E-05	0	0	0	0
180							4.52E-05	0	0	0
210								4.54E-05	0	0
240									4.56E-05	0
270										4.57E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	8.43E-05	0	0	0	0	0	0	0	0	8.43E-05
30		1.06E-04	0	0	0	0	0	0	0	1.06E-04
60			1.27E-04	0	0	0	0	0	0	1.27E-04
90				1.30E-04	0	0	0	0	0	1.30E-04
120					1.51E-04	0	0	0	0	1.51E-04
150						1.53E-04	0	0	0	1.53E-04
180							1.56E-04	0	0	1.56E-04
210								1.56E-04	0	1.56E-04
240									1.56E-04	1.56E-04

Table D17. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{132}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				3.17E-05	0	0	0	0	0	0
120					2.55E-03	0	0	0	0	0
150						2.45E-03	0	0	0	0
180							1.97E-03	0	0	0
210								1.53E-03	0	0
240									1.19E-03	0
270										9.44E-04

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				1.87E-04	0	0	0	0	0	1.87E-04
120					2.19E-02	0	0	0	0	2.19E-02
150						2.10E-02	0	0	0	2.10E-02
180							1.68E-02	0	0	1.68E-02
210								1.30E-02	0	1.30E-02
240									1.02E-02	1.02E-02

Table D18. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{133}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	9.33E-06	0	0	0	0	0	0	0	0	0
30		1.77E-05	0	0	0	0	0	0	0	0
60			2.28E-05	0	0	0	0	0	0	0
90				2.31E-05	0	0	0	0	0	0
120					2.46E-05	0	0	0	0	0
150						2.50E-05	0	0	0	0
180							2.54E-05	0	0	0
210								2.52E-05	0	0
240									2.50E-05	0
270										2.46E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	2.81E-04	0	0	0	0	0	0	0	0	2.81E 04
30		5.32E-04	0	0	0	0	0	0	0	5.32E-04
60			6.85E-04	0	0	0	0	0	0	6.85E-04
90				7.04E-04	0	0	0	0	0	7.04E-04
120					9.04E-04	0	0	0	0	9.04E-04
150						8.59E-04	0	0	0	8.59E-04
180							8.49E-04	0	0	8.49E-04
210								8.27E-04	0	8.27E-04
240									8.11E-04	8.11E-04

Table D19. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{133}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				1.55E-05	0	0	0	0	0	0
120					3.20E-03	0	0	0	0	0
150						3.01E-03	0	0	0	0
180							2.33E-03	0	0	0
210								1.79E-03	0	0
240									1.36E-03	0
270										1.33E-03

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				1.35E-02	0	0	0	0	0	1.35E-02
120					6.01E-01	0	0	0	0	6.01E-01
150						5.64E-01	0	0	0	5.64E-01
180							4.34E-01	0	0	4.34E-01
210								3.33E-01	0	3.33E-01
240									2.53E-01	2.53E-01

Table D20. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{134}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	1.75E-05	0	0	0	0	0	0	0	0	0
30		2.21E-05	0	0	0	0	0	0	0	0
60			2.71E-05	0	0	0	0	0	0	0
90				2.76E-05	0	0	0	0	0	0
120					3.01E-05	0	0	0	0	0
150						3.03E-05	0	0	0	0
180							3.18E-05	0	0	0
210								3.82E-05	0	0
240									3.20E-05	0
270										3.20E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	2.22E-05	0	0	0	0	0	0	0	0	2.22E-05
30		2.79E-05	0	0	0	0	0	0	0	2.79E-05
60			3.44E-05	0	0	0	0	0	0	3.44E-05
90				3.50E-05	0	0	0	0	0	3.50E-05
120					3.81E-05	0	0	0	0	3.81E-05
150						3.91E-05	0	0	0	3.91E-05
180							4.03E-05	0	0	4.03E-05
210								4.83E-05	0	4.83E-05
240									4.06E-05	4.06E-05

Table D21. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{134}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				2.14E-05	0	0	0	0	0	0
120					1.74E-03	0	0	0	0	0
150						1.71E-03	0	0	0	0
180							1.39E-03	0	0	0
210								1.06E-02	0	0
240									8.52E-04	0
270										6.80E-04

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				2.71E-05	0	0	0	0	0	2.71E-05
120					2.20E-03	0	0	0	0	2.20E-03
150						2.16E-03	0	0	0	2.16E-03
180							1.76E-03	0	0	1.76E-03
210								1.35E-02	0	1.35E-02
240									1.08E-03	1.08E-03

Table D22. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{135}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	2.04E-05	0	0	0	0	0	0	0	0	0
30		2.76E-05	0	0	0	0	0	0	0	0
60			3.21E-05	0	0	0	0	0	0	0
90				3.17E-05	0	0	0	0	0	0
120					3.41E-05	0	0	0	0	0
150						3.51E-05	0	0	0	0
180							3.61E-05	0	0	0
210								3.63E-05	0	0
240									3.65E-05	
270										3.62E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.95E-04	0	0	0	0	0	0	0	0	1.95E-04
30		2.63E-04	0	0	0	0	0	0	0	2.63E-04
60			3.07E-04	0	0	0	0	0	0	3.07E-04
90				3.04E-04	0	0	0	0	0	3.04E-04
120					3.65E-04	0	0	0	0	3.65E-04
150						3.66E-04	0	0	0	3.66E-04
180							3.72E-04	0	0	3.72E-04
210								3.69E-04	0	3.69E-04
240									3.70E-04	3.70E-04

Table D23. Radiation dose rates and doses to the fetal thyroid from 1 μCi of ^{135}I, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				2.57E-05	0	0	0	0	0	0
120					2.71E-03	0	0	0	0	0
150						2.50E-03	0	0	0	0
180							1.96E-03	0	0	0
210								1.49E-03	0	0
240									1.14E-03	0
270										8.88E-04

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				1.63E-03	0	0	0	0	0	1.63E-03
120					1.08E-01	0	0	0	0	1.08E-01
150						9.90E-02	0	0	0	9.90E-02
180							7.69E-02	0	0	7.69E-02
210								5.84E-02	0	5.84E-02
240									4.44E-02	4.44E-02

Table D24. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{134}Cs, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	3.77E-05	3.30E-05	2.67E-05	2.07E-05	1.65E-05	1.30E-05	1.02E-05	7.49E-06	4.86E-06	3.15E-06
30		4.35E-05	3.51E-05	2.73E-05	2.17E-05	1.71E-05	1.35E-05	9.86E-06	6.40E-06	4.15E-06
60			4.62E-05	3.59E-05	2.86E-05	2.25E-05	1.77E-05	1.30E-05	8.43E-06	5.47E-06
90				4.73E-05	3.76E-05	2.96E-05	2.33E-05	1.71E-05	1.11E-05	7.20E-06
120					4.95E-05	3.90E-05	3.07E-05	2.25E-05	1.46E-05	9.48E-06
150						5.14E-05	4.04E-05	2.96E-05	1.93E-05	1.25E-05
180							5.32E-05	3.90E-05	2.53E-05	1.64E-05
210								5.40E-05	3.51E-05	2.27E-05
240									5.46E-05	3.54E-05
270										5.52E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	2.55E-02	2.15E-02	1.69E-02	1.33E-02	1.05E-02	8.29E-03	6.35E-03	4.37E-03	2.81E-03	1.10E-01
30		2.82E-02	2.23E-02	1.75E-02	1.38E-02	1.09E-02	8.38E-03	5.75E-03	3.71E-03	1.11E-01
60			2.92E-02	2.30E-02	1.82E-02	1.44E-02	1.10E-02	7.59E-03	4.88E-03	1.08E-01
90				2.03E-02	2.40E-02	1.89E-02	1.45E-02	9.98E-03	6.43E-03	1.04E-01
120					3.13E-02	2.49E-02	1.91E-02	1.31E-02	8.46E-03	9.72E-02
150						3.28E-02	2.51E-02	1.73E-02	1.12E-02	8.64E-02
180							3.30E-02	2.28E-02	1.46E-02	7.04E-02
210								3.14E-02	2.03E-02	5.17E-02
240									3.24E-02	3.24E-02

Table D25. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{137}Cs, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	1.52E-05	1.69E-05	1.42E-05	1.14E-05	9.18E-06	7.36E-06	5.89E-06	4.40E-06	2.92E-06	1.93E-06
30		2.16E-05	1.82E-05	1.46E-05	1.18E-05	9.44E-06	7.55E-06	5.65E-06	3.74E-06	2.48E-06
60			2.33E-05	1.87E-05	1.51E-05	1.21E-05	9.69E-06	7.25E-06	4.80E-06	3.18E-06
90				2.40E-05	1.94E-05	1.56E-05	1.24E-05	9.30E-06	6.16E-06	4.08E-06
120					2.49E-05	2.00E-05	1.60E-05	1.19E-05	7.91E-06	5.24E-06
150						2.56E-05	2.05E-05	1.53E-05	1.02E-05	6.72E-06
180							2.63E-05	1.97E-05	1.30E-05	8.62E-06
210								2.65E-05	1.76E-05	1.16E-05
240									2.67E-05	1.77E-05
270										2.68E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	1.18E-02	1.13E-02	9.13E-03	7.36E-03	5.91E-03	4.74E-03	3.70E-03	2.60E-03	1.71E-03	5.83E-02
30		1.43E-02	1.17E-02	9.43E-03	7.59E-03	6.08E-03	4.74E-03	3.33E-03	2.19E-03	5.94E-02
60			1.50E-02	1.21E-02	9.72E-03	7.80E-03	6.09E-03	4.27E-03	2.81E-03	5.78E-02
90				1.55E-02	1.25E-02	1.00E-02	7.79E-03	5.48E-03	3.60E-03	5.49E-02
120					1.60E-02	1.29E-02	1.00E-02	7.02E-03	4.63E-03	5.05E-02
150						1.65E-02	1.29E-02	9.05E-03	5.96E-03	4.44E-02
180							1.65E-02	1.16E-02	7.60E-03	3.57E-02
210								1.56E-02	1.03E-02	2.59E-02
240									1.60E-02	1.60E-02

Table D26. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{233}U, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.26E-05	8.07E-08	1.51E-08	2.90E-09	1.00E-09	4.92E-10	2.95E-10	2.01E-10	1.49E-10
60			1.26E-05	2.35E-06	4.53E-07	1.57E-07	7.70E-08	4.62E-08	3.15E-08	2.33E-08
90				1.89E-05	3.64E-06	1.26E-06	6.19E-07	3.72E-07	2.53E-07	1.88E-07
120					1.89E-05	6.57E-06	3.22E-06	1.93E-06	1.31E-06	9.75E-07
150						1.89E-05	9.28E-06	5.57E-06	3.79E-06	2.81E-06
180							2.53E-05	1.51E-05	1.03E-05	7.65E-06
210								2.53E-05	1.72E-05	1.27E-05
240									3.79E-05	2.81E-05
270										3.79E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.41E-03	2.31E-05	5.30E-06	1.19E-06	5.01E-07	2.71E-07	1.74E-07	1.24E-07	1.44E-03
60			4.30E-03	7.86E-04	1.89E-04	7.84E-05	4.25E-05	2.72E-05	1.94E-05	5.44E-03
90				6.29E-03	1.52E-03	6.29E-04	3.42E-04	2.19E-04	1.56E-04	9.16E-03
120					8.10E-03	3.25E-03	1.78E-03	1.13E-03	8.09E-04	1.51E-02
150						9.51E-03	5.11E-03	3.28E-03	2.34E-03	2.02E-02
180							1.40E-02	8.88E-03	6.36E-03	2.92E-02
210								1.49E-02	1.06E-02	2.55E-02
240									2.38E-02	2.38E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D27. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{234}U, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.25E-05	8.02E-08	1.50E-08	2.88E-09	9.98E-10	4.89E-10	2.94E-10	2.00E-10	1.48E-10
60			1.25E-05	2.34E-06	4.50E-07	1.56E-07	7.65E-08	4.59E-08	3.13E-08	2.32E-08
90				1.88E-05	3.62E-06	1.26E-06	6.16E-07	3.69E-07	2.51E-07	1.86E-07
120					1.88E-05	6.53E-06	3.20E-06	1.92E-06	1.31E-06	9.69E-07
150						1.88E-05	9.22E-06	5.53E-06	3.77E-06	2.79E-06
180							2.51E-05	1.51E-05	1.03E-05	7.60E-06
210								2.51E-05	1.71E-05	1.27E-05
240									3.76E-05	2.79E-05
270										3.76E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.40E-03	2.30E-05	5.26E-06	1.18E-06	5.00E-07	2.70E-07	1.73E-07	1.23E-07	1.43E-03
60			4.27E-03	7.82E-04	1.87E-04	7.79E-05	4.22E-05	2.70E-05	1.93E-05	5.41E-03
90				6.25E-03	1.51E-03	6.28E-04	3.39E-04	2.17E-04	1.55E-04	9.10E-03
120					8.05E-03	3.23E-03	1.77E-03	1.13E-03	8.07E-04	1.50E-02
150						9.46E-03	5.07E-03	3.26E-03	2.32E-03	2.01E-02
180							1.40E-02	8.88E-03	6.34E-03	2.92E-02
210								1.48E-02	1.05E-02	2.53E-02
240									2.36E-02	2.36E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D28. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{235}U, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.15E-05	7.38E-08	1.38E-08	2.65E-09	9.18E-10	4.50E-10	2.70E-10	1.84E-10	1.36E-10
60			1.15E-05	2.15E-06	4.14E-07	1.44E-07	7.04E-08	4.22E-08	2.88E-08	2.13E-08
90				1.73E-05	3.33E-06	1.16E-06	5.66E-07	3.40E-07	2.31E-07	1.72E-07
120					1.73E-05	6.00E-06	2.94E-06	1.76E-06	1.20E-06	8.91E-07
150						1.73E-05	8.48E-06	5.09E-06	3.47E-06	2.57E-06
180							2.31E-05	1.38E-05	9.43E-06	6.99E-06
210								2.31E-05	1.57E-05	1.17E-05
240									3.46E-05	2.57E-05
270										3.46E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.29E-03	2.11E-05	4.84E-06	1.09E-06	4.60E-07	2.48E-07	1.59E-07	1.13E-07	1.32E-03
60			3.93E-03	7.19E-04	1.73E-04	7.18E-05	3.88E-05	2.49E-05	1.77E-05	4.98E-03
90				5.75E-03	1.39E-03	5.78E-04	3.12E-04	2.00E-04	1.43E-04	8.37E-03
120					7.40E-03	2.97E-03	1.62E-03	1.04E-03	7.41E-04	1.38E-02
150						8.70E-03	4.67E-03	3.00E-03	2.14E-03	1.85E-02
180							1.28E-02	8.12E-03	5.82E-03	2.67E-02
210								1.36E-02	9.69E-03	2.33E-02
240									2.17E-02	2.17E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D29. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{238}U, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.10E-05	7.03E-08	1.31E-08	2.52E-09	8.75E-10	4.29E-10	2.57E-10	1.75E-10	1.30E-10
60			1.10E-05	2.05E-06	3.95E-07	1.37E-07	6.71E-08	4.02E-08	2.74E-08	2.03E-08
90				1.65E-05	3.18E-06	1.10E-06	5.40E-07	3.24E-07	2.20E-07	1.63E-07
120					1.65E-05	5.72E-06	2.80E-06	1.68E-06	1.15E-06	8.49E-07
150						1.65E-05	8.09E-06	4.85E-06	3.30E-06	2.45E-06
180							2.20E-05	1.32E-05	8.99E-06	6.66E-06
210								2.20E-05	1.50E-05	1.11E-05
240									3.30E-05	2.45E-05
270										3.30E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		1.23E-03	2.01E-05	4.59E-06	1.04E-06	4.38E-07	2.36E-07	1.51E-07	1.08E-07	1.26E-03
60			3.75E-03	6.86E-04	1.54E-04	6.83E-05	3.70E-05	2.37E-05	1.69E-05	4.75E-03
90				5.49E-03	1.32E-03	5.49E-04	2.98E-04	1.90E-04	1.36E-04	7.98E-03
120					7.06E-03	2.83E-03	1.55E-03	9.91E-04	7.08E-04	1.31E-02
150						8.30E-03	4.45E-03	2.86E-03	2.04E-03	1.77E-02
180							1.22E-02	7.76E-03	5.54E-03	2.55E-02
210								1.30E-02	9.23E-03	2.22E-02
240									2.07E-02	2.07E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D30. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{238}Pu, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.40E-05	1.53E-07	2.86E-08	5.50E-09	1.91E-09	9.33E-10	5.60E-10	3.81E-10	2.82E-10
60			2.40E-05	4.47E-06	8.61E-07	2.98E-07	1.46E-07	8.76E-08	5.96E-08	4.42E-08
90				3.60E-05	6.93E-06	2.40E-06	1.18E-06	7.05E-07	4.80E-07	3.55E-07
120					3.60E-05	1.25E-05	6.11E-06	3.66E-06	2.49E-06	1.85E-06
150						3.60E-05	1.76E-05	1.06E-05	7.20E-06	5.33E-06
180							4.80E-05	2.88E-05	1.96E-05	1.45E-05
210								4.80E-05	3.27E-05	2.42E-05
240									7.20E-05	5.34E-05
270										7.20E-05

Days of Gestation at Introduction	Dose (rad) the to Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.68E-03	4.38E-05	1.00E-05	2.26E-06	9.55E-07	5.14E-07	3.30E-07	2.35E-07	2.74E-03
60			8.19E-03	1.50E-03	3.58E-04	1.49E-04	8.05E-05	5.16E-05	3.67E-05	1.04E-02
90				1.20E-02	2.89E-03	1.20E-03	6.50E-04	4.15E-04	2.96E-04	1.75E-02
120					1.54E-02	6.18E-03	3.37E-03	2.15E-03	1.54E-03	2.86E-02
150						1.81E-02	9.70E-03	6.24E-03	4.43E-03	3.85E-02
180							2.66E-02	1.69E-02	1.21E-02	5.56E-02
210								2.84E-02	2.01E-02	4.85E-02
240									4.51E-02	4.51E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D31. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{239}Pu, introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.25E-05	1.44E-07	2.68E-08	5.16E-09	1.79E-09	8.78E-10	5.26E-10	3.58E-10	2.66E-10
60			2.25E-05	4.20E-06	8.08E-07	2.80E-07	1.37E-07	8.23E-08	5.61E-08	4.16E-08
90				3.38E-05	6.50E-06	2.25E-06	1.10E-06	6.62E-07	4.51E-07	3.34E-07
120					3.38E-05	1.17E-05	5.74E-06	3.44E-06	2.34E-06	1.74E-06
150						3.38E-05	1.65E-05	9.92E-06	6.76E-06	5.01E-06
180							4.50E-05	2.70E-05	1.84E-05	1.36E-05
210								4.50E-05	3.06E-05	2.27E-05
240									6.75E-05	5.01E-05
270										6.75E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		2.52E-03	4.12E-05	9.40E-06	2.12E-06	8.97E-07	4.83E-07	3.10E-07	2.21E-07	2.57E-03
60			7.68E-03	1.40E-03	3.36E-04	1.40E-04	7.56E-05	4.85E-05	3.46E-05	9.71E-03
90				1.12E-02	2.71E-03	1.12E-03	6.07E-04	3.90E-04	2.78E-04	1.63E-02
120					1.45E-02	5.80E-03	3.17E-03	2.02E-03	1.44E-03	2.69E-02
150						1.70E-02	9.09E-03	5.85E-03	4.17E-03	3.61E-02
180							2.50E-02	1.59E-02	1.13E-02	5.22E-02
210								2.66E-02	1.88E-02	4.54E-02
240									4.23E-02	4.23E-02

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

Table D32. Radiation dose rates and doses to the embryo/fetus from 1 μCi of ^{241}Cm introduced into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose Rate (rad/hr) to the Embryo/Fetus at the Indicated Stage of Gestation (days)									
	0	30	60	90	120	150	180	210	240	270
0	N[a]	N	N	N	N	N	N	N	N	N
30		4.79E-06	3.06E-08	5.71E-09	1.10E-09	3.81E-10	1.87E-10	1.12E-10	7.63E-11	5.66E-11
60			4.79E-06	8.94E-07	1.72E-07	5.96E-08	2.92E-08	1.75E-08	1.19E-08	8.85E-09
90				7.19E-06	1.38E-06	4.80E-07	2.35E-07	1.41E-07	9.60E-08	7.12E-08
120					7.19E-06	2.49E-06	1.22E-06	7.33E-07	4.99E-07	3.70E-07
150						7.19E-06	3.52E-06	2.11E-06	1.44E-06	1.07E-06
180							9.59E-06	5.75E-06	3.91E-06	2.90E-06
210								9.59E-06	6.53E-06	4.84E-06
240									1.44E-05	1.07E-05
270										1.44E-05

Days of Gestation at Introduction	Dose (rad) to the Embryo/Fetus During Indicated Gestation Periods (days)									Cumulated Dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	N[a]	N	N	N	N	N	N	N	N	N
30		5.36E-04	8.76E-06	2.00E-06	4.52E-07	1.91E-07	1.03E-07	6.60E-08	4.71E-08	5.48E-04
60			1.64E-03	2.99E-04	7.16E-05	2.97E-05	1.61E-05	1.03E-05	7.25E-06	2.07E-03
90				2.39E-03	5.76E-04	2.39E-04	1.30E-04	8.30E-05	5.92E-05	3.48E-03
120					3.08E-03	1.23E-03	6.75E-04	4.31E-04	3.08E-04	5.72E-03
150						3.61E-03	1.94E-03	1.24E-03	6.89E-04	7.68E-03
180							5.32E-03	3.38E-03	2.41E-03	1.11E-02
210								5.67E-03	4.02E-03	9.69E-03
240									9.04E-03	9.04E-03

(a) N indicates that the metabolic pattern is such that the dose rates and doses would be negligible throughout gestation when activity is administered immediately after fertilization. Approximations of doses resulting from administration during the first month are described on page D-1.

APPENDIX E

ILLUSTRATIONS OF MISCELLANEOUS RELATIONSHIPS TO SUPPLEMENT DISCUSSIONS IN TEXT

Table E1. Fractions of injected activities that are present in the fetus at the end of the ninth month of gestation (270 days of term) after introduction of 1 μCi of selected radionuclides[a] and forms into the maternal transfer compartment (blood) at the beginning of each month of pregnancy

Months of Gestation at Intake	H-3	H-3[b]	C-14[b]	Co-57	Co-57[c]	Co-58	Co-60	Co-60[c]	Sr-89	Sr-90/ Y-90
0	6.0E-13	-	-	1.8E-03	9.3E-04	2.5E-04	3.2E-03	1.7E-03	-	-
1	5.5E-12	3.0E-07	3.1E-07	2.0E-03	1.4E-03	3.5E-04	3.4E-03	2.4E-03	1.9E-08	5.0E-07
2	4.5E-11	4.7E-05	4.8E-05	2.3E-03	2.2E-03	5.0E-04	3.6E-03	3.4E-03	4.4E-06	7.8E-05
3	1.9E-09	2.5E-04	2.6E-04	2.6E-03	2.3E-03	7.1E-04	3.9E-03	4.9E-03	3.6E-05	4.2E-04
4	7.9E-08	1.3E-03	1.3E-03	3.0E-03	5.1E-03	1.0E-03	4.2E-03	7.0E-03	2.8E-04	2.2E-03
5	1.8E-06	3.7E-03	3.8E-03	3.6E-03	7.7E-03	1.5E-03	4.6E-03	1.0E-02	1.2E-03	6.2E-03
6	3.0E-05	7.6E-03	7.7E-03	4.3E-03	1.2E-02	2.2E-03	5.2E-03	1.4E-02	3.6E-03	1.2E-02
7	3.9E-04	1.3E-02	1.3E-02	5.2E-03	1.8E-02	3.4E-03	6.0E-03	2.1E-02	9.0E-03	2.0E-02
8	4.5E-03	2.0E-02	1.8E-02	6.9E-03	2.8E-02	5.6E-03	7.4E-03	2.9E-02	1.9E-02	2.9E-02
9	4.7E-02	4.7E-02	4.7E-02	4.4E-02	4.2E-02	4.4E-02	4.4E-02	4.2E-02	3.8E-02	3.8E-02

Months of Gestation at Intake	Ru-106/ Rh-106	I-125[d]	I-125[e]	I-131[d]	I-131[e]	Cs-134	Cs-137	Pu-239	U	Am-241
0	2.4E-04	5.3E-06	-	8.7E-15	-	2.7E-03	3.4E-03	-	-	-
1	2.6E-04	8.5E-06	-	1.3E-13	-	3.5E-03	4.3E-03	6.7E-08	4.1E-08	1.4E-08
2	2.8E-04	1.4E-05	-	2.0E-12	-	4.6E-03	5.5E-03	1.1E-05	6.4E-06	2.1E-06
3	3.1E-04	2.3E-05	1.5E-04	3.2E-11	2.1E-10	6.1E-03	7.1E-03	8.5E-05	5.1E-05	1.7E-05
4	3.4E-04	8.8E-05	5.4E-04	1.2E-09	7.1E-09	8.0E-03	9.1E-03	4.4E-04	2.7E-04	8.8E-05
5	4.0E-04	2.1E-04	1.3E-03	2.7E-08	1.6E-07	1.1E-02	1.2E-02	1.3E-03	7.7E-04	2.6E-04
6	4.7E-04	4.5E-04	2.6E-03	5.4E-07	3.2E-06	1.4E-02	1.5E-02	3.5E-03	2.1E-03	6.9E-04
7	6.0E-04	9.0E-04	5.4E-03	1.0E-05	6.2E-05	1.9E-02	2.0E-02	5.8E-03	3.5E-03	1.2E-03
8	8.6E-04	1.6E-03	1.1E-02	1.7E-04	1.2E-03	3.0E-02	3.1E-02	1.3E-02	7.7E-03	2.6E-03
9	2.3E-03	8.0E-04	2.3E-02	1.3E-03	2.2E-02	4.7E-02	4.7E-02	1.7E-02	1.0E-02	3.4E-03

(a) Radionuclides with negligible burden are not included in this table.
(b) Organic forms such as a hexose or an amino acid.
(c) As vitamin B-12.
(d) Exclusive of fetal thyroid.
(e) For fetal thyroid.

COMMENTS REGAPDING TABLE E2

Table E2 illustrates an initial approach toward estimation of relative fetal to maternal radionuclide concentrations and associated radiation doses under conditions that are likely to be experienced under operational conditions. These qualitative estimates were prepared from the information that was used as the basis for the synopses in Section IV of text and for the calculations used for development of the tables in Appendix C and D. These results are presented under the title "Generalized Estimates of Fetal to Maternal Concentration and Radiation Dose Ratios for Selected Internal Radionuclides and Forms" to signify that they are obvious oversimplifications that provide a tentative supplement to the direct calculations. The entries summarize general extrapolations of qualitative biokinetic and dosimetric information relating to the most commonly encountered isotope of each nuclide, and there was not a formal process available for such estimates. Such an approach necessarily remains incomplete until quantitative assessments are undertaken. Revisions will be required when and if specific quantitative relationships become available.

Nevertheless, the entries may provide a basis to anticipate other exposure patterns before pregnancy or at various stages of gestation and allow the approximations of concentrations and radiation doses to the conceptus relative to the pregnant woman for adjustment of dose. However, before Table E2 is used for predicted approximations, the reader is warned that the extrapolation and kinetics in the gestational stage lacks quantitative precision.

Table E2. Generalized estimates of fetal to maternal concentrations and radiation dose ratios for selected internal radionuclides in humans

Z-Nuclide	Form at Exposure or in Blood	Dosing Pattern	Developmental Stages or Times Encompassed: Pre and Early Implantation	Embryo	Embryo-Fetus Transition	Fetus	Overall Gestation	Potential for Selective Deposition: Tissue or Organ	Stage or Time	Placenta or Membranes
1-Hydrogen	Inorganic	Existing	S	S	S	S	S	No	No	No
		Repeated	S	S	S	S	S	No	No	No
		Single	S	S	S	S	S	No	No	No
1-Hydrogen	Glucose	Existing	NA	NA	NA	NA	NA	NA	NA	NA
		Repeated	S	S	S	S	S	No	No	No
		Single	S	S	S	S	S	No	No	No
1-Hydrogen	Amino Acid	Existing	<<	<<	<<	<<	<<	No	No	No
		Repeated	S	S	S	S	S	No?	No?	No
		Single	S	S	S	S	S	No?	No?	No
1-Hydrogen	Thymidine	Existing	<<	<<	<<	<<	<<	NA	NA	NA
		Repeated	<	<	<	<	<	No	Yes?	No
		Single	<	<	<	<	<	Yes?	Yes?	No
6-Carbon	Glucose	Existing	NA	NA	NA	NA	NA	NA	NA	NA
		Repeated	S	S	S	S	S	No	No	No
		Single	S	S	S	S	S	No	No	No
6-Carbon	Amino Acid	Existing	<<	<<	<<	<<	<<	No	No	No
		Repeated	S	S	S	S	S	No?	No?	No
		Single	S	S	S	S	S	No?	No?	No
6-Carbon	Thymidine	Existing	<<	<<	<<	<<	<<	NA	NA	NA
		Repeated	<	<	<	<	<	No	Yes?	No
		Single	<	<	<	<	<	Yes?	Yes?	No

Table E2. (contd)

Z-Nuclide	Form at Exposure or in Blood	Dosing Pattern	Developmental Stages or Times Encompassed: Pre and Early Implantation	Embryo	Embryo-Fetus Transition	Fetus	Overall Gestation	Potential for Selective Retention: Tissue or Organ	Stage or Time	Placenta or Membranes
27-Cobalt	Ionic	Existing	<<	<<	<<	<<	<<	NA	NA	NA
		Repeated	S	S	S	S	S	Yes?	Yes?	No
		Single	S	S	S	S	S	Yes?	Yes?	No
27-Cobalt	Vitamin B-12	Existing	<	<	<	<	<	NA	NA	NA
		Repeated	S	S	S	S	S	No?	No	No
		Single	S	S	S	S	S	No	No	No
38-Strontium	Ionic	Existing	<	<	<	<?	<	Yes?	No	No
		Repeated	<	<	S	S	S	Yes	Yes	No
		Single	<	<	S	S	S	Yes	Yes	No
44-Ruthenium	Ionic	Existing	<<	<<	<<	<<	<<	No?	No?	?
		Repeated	<<	<<	<<	<<	<<	No?	No?	Yes
		Single	<<	<<	<<	<<	<<	No?	No?	Yes
53-Iodine	Ionic	Existing	<	<	<	S?[a]	S?[a]	Yes?	Yes	No
		Repeated	<	<	S	>>	S	Yes	Yes	No
		Single	<	<	S	>>	S	Yes	Yes	No
53-Iodine	Organic	Existing	<<	<<	<<	<<	<<	?	?	No
		Repeated	<	<	S	(>)	S	Yes	Yes	No
		Single	<	<	S	(>)	S	Yes	Yes	No
55-Cesium	Ionic	Existing	S	S	S	S	S	No	No	No
		Repeated	S	S	S	S	S	No	No	No
		Single	S	S	S	S	S	No	No	No

Table E2. (contd)

Z-Nuclide	Form at Exposure or in Blood	Dosing Pattern	Developmental Stages or Times Encompassed: Pre and Early Implantation	Embryo	Embryo-Fetus Transition	Fetus	Overall Gestation	Potential for Selective Deposition: Tissue or Organ	Stage or Time	Placenta or Membranes
82-Lead	Ionic	Existing	B	B	B	B	B	NA	NA	No
		Repeated	S?	S?	S	S	S	Yes	Yes	No?
		Single	S?	S?	S	S	S	Yes	Yes	No?
84-Polonium	??	Existing	<<?	<<?	<<?	<<?	<<?	NA	NA	?
		Repeated	<<	<<	<<	<<	<<	NA	NA	Yes
		Single	<<	<<	<<	<<	<<	NA	NA	Yes
86-Radon	Gas and Daughters	Existing	<<	<<	<	<	<	No?	No?	No
		Repeated	B	B	B	B	B	B	No?	Yes?
		Single	B	B	B	B	B	B	No?	Yes?
88-Radium	Ionic??	Existing	<	<	S	S	S	Yes	Yes	No
		Repeated	<?	<?	S	S	S	Yes	Yes	No
		Single	<?	<?	S	S	S	Yes	Yes	No
94-Plutonium	Organic Complex	Existing	<<	<<	<	<<	NA	NA	NA	NA
		Repeated	NA	<	S?	>	?	?	Yes?	Yes
		Single	<<	<?	<?	<?	Yes?	Yes?	Yes?	Yes

(a) Applicable to longer half-lived isotopes only.
? Indicates there is no basis for decision. Yes? or No? indicate weak empirical results, or inferrential evidence only.

Explanation of Symbols and Ranges

Symbol	Range of Ratios	Symbol	Range of Ratios
S	0.7-1.5	B	((1x0.7 to 1+0.7))
<	0.2-0.7	>	1.5-2.5
<<	0-0.2	>>	2.5-∞

Table E3. Simplified categorization by placental transfer and biokinetic features

1. Free transfer with uniform concentration in the embryo/fetus that is similar to that in the woman. EXAMPLES: tritium (most forms), carbon (most forms), cobalt, and cesium.

2. Free transfer with higher local concentrations in comparable organs of the embryo/fetus than in those of the woman. EXAMPLE: inorganic iodide. This apparently is the only case, although pertechnetate released from radiopharmaceuticals may follow a similar pattern. The fetal thyroid dose from radioiodines may be higher at some gestational stages than the thyroid dose to the woman, but average whole body dose might not be correspondingly greater.

3. Moderate transfer with deposition patterns in the embryo/fetus that are similar to deposition patterns in comparable tissues of the woman. EXAMPLES: strontium, lead, and radium.

4. Limited transfer with most tissue concentrations in the embryo/fetus less than in tissues of the woman. EXAMPLES: plutonium, polonium, and thorium.

5. Selective deposition in extra-embryonic structures, independent of extent of transfer. EXAMPLES: ruthenium, polonium, and plutonium. This category involves dosimetric concepts that are not currently included among regulatory concerns, but they may warrant subsequent consideration.

6. Placental transfer and biokinetics are still undefined; this category includes radionuclides that have not yet been evaluated, and others for which inadequate information is available. Quantitative relationships have been inferred for some materials in this category, based on available information and homologies, but more adequate approaches must be established for these and other groups of radionuclides.

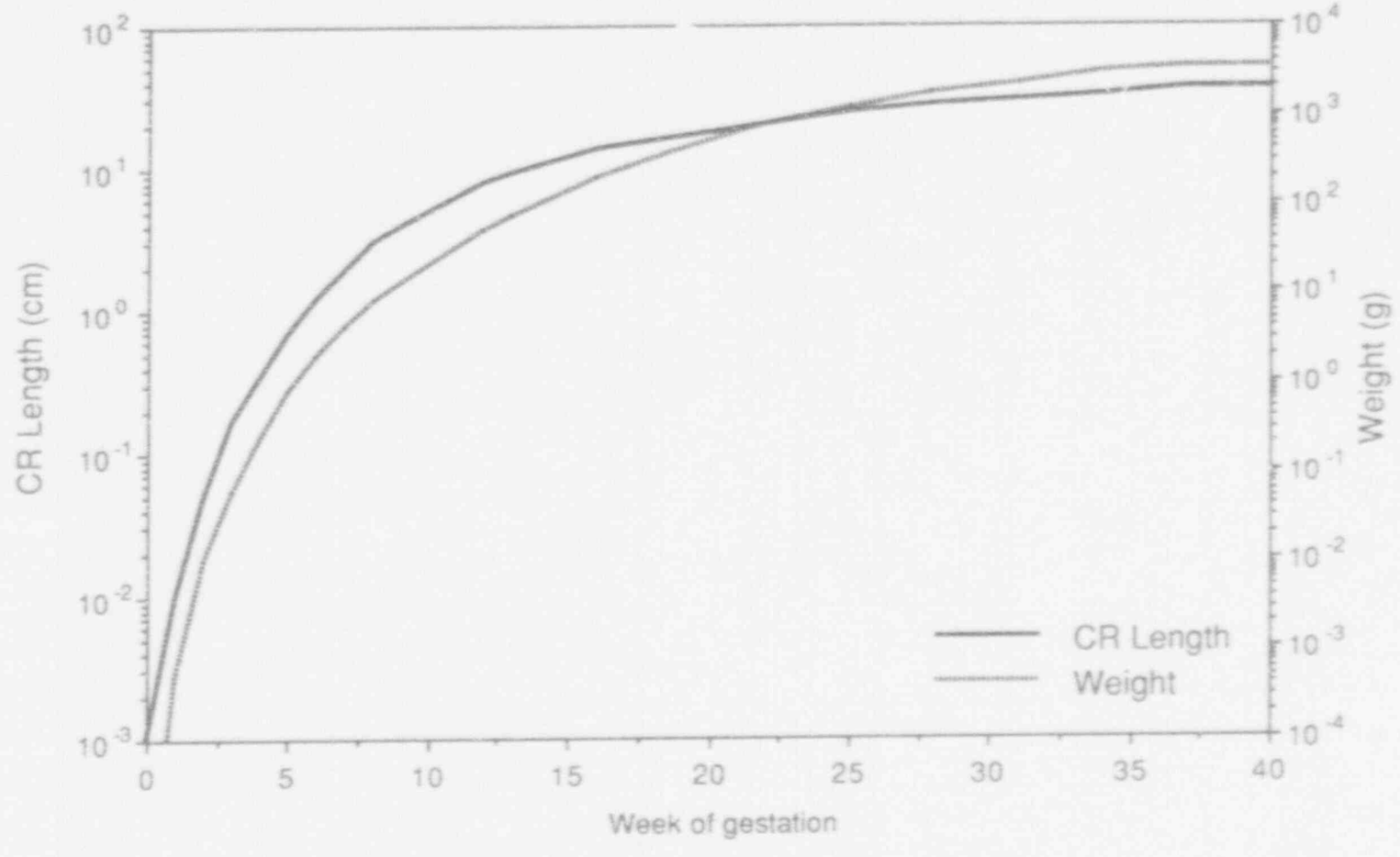


Figure E1. Graphic representation of typical data for increases of mass and length of the human embyro/fetus throughout gestation

APPENDIX F

COMMITTED DOSE EQUIVALENTS TO THE NONPREGNANT UTERUS FROM 1 μCi OF RADIONUCLIDES IN MATERNAL BLOOD FOR ESTIMATING CORRESPONDING CUMULATIVE GESTATIONAL RADIATION ABSORBED DOSE EQUIVALENTS TO THE EMBRYO/FETUS

APPENDIX F

COMMITTED DOSE EQUIVALENTS TO THE NONPREGNANT UTERUS FROM 1 μCi OF RADIONUCLIDES IN MATERNAL BLOOD FOR ESTIMATING CORRESPONDING CUMULATIVE GESTATIONAL RADIATION ABSORBED DOSE EQUIVALENTS TO THE EMBRYO/FETUS

Entries in Table F-1, Appendix F were calculated from tabulated values of committed dose equivalent per unit intake ($H_{T,50}$) and fractional absorption (f_1) from the gastrointestinal tract. These tabulations, which had been determined for inclusion in ICRP Report 30, were supplied to the NRC as files on computer disk by Dr Keith F. Eckerman of Oak Ridge National Laboratory.

The doses presented in the table are expressed relative to activity in blood so that they would correspond to other usage in these recommendations. To obtain these values, each of the committed doses ($H_{T,50}$) in the original computer tabulation were divided by the highest value of f_1 for the radionuclide, which is appropiate for the most soluble form. This approach results in the value that would correspond to the introduction of 1 μCi of radionuclide into maternal blood and give the maximal estimates of doses. These values are provided for use as surrogate estimates of corresponding radiation absorbed dose equivalents received by the embryo/fetus throughout the remainder of gestation.

It is important to emphasize that these derived values are based on committed dose equivalent, as was discussed in the text of the report. This difference thus yields a marked overestimate for nuclides with long effective half-lives, in which the 50-year dose to uterus is assigned to the embryo/fetus with its 9-month duration. Other aspects of the validity and inherent accuracy of using values of uterine dose from maternally distributed activity as a surrogate for estimating photon dose to the embryo/fetus were discussed in Section III.C.3, and include stage-related deviations related to target sizes, effect on geometric relationships, and specific absorbed fraction.

Table F1. Committed dose equivalents to the nonpregnant uterus that result from introduction of 1 μCi of radionuclides into maternal blood[a]

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
H-3	6.40E-05	Cr-51	6.96E-04	Ga-68	5.66E-02
Be-7	1.67E-02	Mn-51	3.65E-04	Ga-70	8.99E-05
Be-10	1.79E-02	Mn-52	4.70E-02	Ga-72	1.53E+00
C-11	1.21E-05	Mn-52M	2.80E-04	Ga-73	9.36E-02
C-14	2.09E-03	Mn-53	5.77E-05	Ge-66	1.42E-04
F-18	1.32E-05	Mn-54	1.36E-02	Ge-67	1.11E-05
Na-22	1.06E-02	Mn-56	2.18E-03	Ge-68	8.81E-04
Na-24	1.21E-03	Fe-52	1.30E-02	Ge-69	3.02E-04
Mg-28	3.83E-03	Fe-55	3.88E-03	Ge-71	6.99E-06
Al-26	5.33E-01	Fe-59	4.63E-02	Ge-75	1.61E-05
Si-31	3.85E-05	Fe-60	1.47E+00	Ge-77	3.40E-04
Si-32	4.33E-02	Co-55	4.01E-03	Ge-78	1.08E-04
P-32	3.03E-03	Co-56	3.43E-02	As-69	2.46E-05
P-33	4.33E-04	Co-57	3.06E-03	As-70	2.90E-04
S-35	3.53E-04	Co-58	9.68E-03	As-71	1.21E-03
Cl-36	2.96E-03	Co-58M	5.17E-05	As-72	2.70E-03
Cl-38	3.17E-05	Co-60	8.79E-02	As-73	3.02E-04
Cl-39	3.89E-05	Co-60M	4.12E-07	As-74	2.90E-03
K-40	1.84E-02	Co-61	4.50E-05	As-76	1.11E-03
K-42	7.73E-04	Co-62M	5.33E-05	As-77	1.88E-04
K-43	7.10E-04	Ni-56	5.39E-02	As-78	1.85E-04
K-44	1.94E-05	Ni-57	3.60E-02	Se-70	1.61E-04
K-45	1.21E-05	Ni-59	2.71E-03	Se-73	3.66E-04
Ca-41	3.21E-05	Ni-63	6.29E-03	Se-73M	3.21E-05
Ca-45	6.61E-04	Ni-65	1.43E-03	Se-75	8.79E-03
Ca-47	5.18E-03	Ni-66	2.81E-03	Se-79	4.19E-03
Sc-43	2.48E+00	Cu-60	9.32E-05	Se-81	1.00E-06
Sc-44	4.59E+00	Cu-61	2.69E-04	Se-81M	1.46E-05
Sc-44M	2.56E+01	Cu-64	2.09E-04	Se-83	3.62E-05
Sc-46	3.15E+01	Cu-67	6.50E-04	Br-74	3.33E-05
Sc-47	1.86E+00	Zn-62	1.38E-03	Br-74M	6.18E-05
Sc-48	3.52E+01	Zn-63	5.92E-05	Br-75	6.07E-05
Sc-49	4.18E-04	Zn-65	3.49E-02	Br-76	1.20E-03
Ti-44	1.36E+00	Zn-69	3.09E-06	Br-77	3.27E-04
Ti-45	1.54E-02	Zn-69M	5.54E-04	Br-80	3.01E-06
V-47	2.29E-03	Zn-71M	5.75E-04	Br-80M	1.46E-04
V-48	4.37E-01	Zn-72	5.28E-03	Br-82	1.87E-03
V-49	8.36E-05	Ga-65	9.18E-03	Br-83	2.72E-05
Cr-48	5.77E-03	Ga-66	9.95E-01	Br-84	2.56E-05
Cr-49	3.51E-04	Ga-67	2.50E-01	Rb-79	1.15E-05

(a) These may be used as surrogate estimates of absorbed dose equivalents to the embryo/fetus throughout gestation. Calculations and interpretations are discussed in Section III.C.3 and page F-1.

Table F1. (contd)

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
Rb-81	8.18E-05	Nb-90	2.39E-01	Rh-105	1.93E-03
Rb-81M	1.08E-05	Nb-93M	9.29E-04	Rh-106M	6.86E-03
Rb-82M	3.49E-04	Nb-94	3.04E-01	Rh-107	8.51E-05
Rb-83	7.07E-03	Nb-95	1.24E-01	Pd-100	3.94E-01
Rb-84	1.05E-02	Nb-95M	1.27E-02	Pd-101	3.33E-02
Rb-86	8.14E-03	Nb-96	2.03E-01	Pd-103	1.39E-03
Rb-87	4.22E-03	Nb-97	4.11E-03	Pd-107	7.33E-05
Rb-88	1.02E-05	Nb-98	9.66E-03	Pd-109	1.27E-03
Rb-89	1.20E-05	Mo-90	7.77E-04	Ag-102	3.76E-04
Sr-80	3.96E-04	Mo-93	4.36E-04	Ag-103	8.58E-04
Sr-81	1.22E-04	Mo-93M	4.76E-04	Ag-104	3.05E-03
Sr-82	1.25E-02	Mo-99	9.39E-04	Ag-104M	1.09E-03
Sr-83	2.31E-03	Mo-101	1.48E-05	Ag-105	1.94E-02
Sr-85	4.03E-03	Tc-93	1.33E-04	Ag-106	2.12E-04
Sr-85M	4.81E-05	Tc-93M	4.67E-05	Ag-106M	8.21E-02
Sr-87M	1.62E-04	Tc-94	4.56E-04	Ag-108M	6.59E-02
Sr-89	2.96E-03	Tc-94M	7.08E-05	Ag-110M	1.04E-01
Sr-90	1.86E-02	Tc-95	3.86E-04	Ag-111	1.41E-03
Sr-91	1.49E-03	Tc-95M	1.23E-03	Ag-112	2.18E-03
Sr-92	7.79E-04	Tc-96	2.62E-03	Ag-115	1.98E-04
Y-86	2.18E+01	Tc-96M	2.29E-05	Cd-104	3.30E-03
Y-86M	1.26E+00	Tc-97	4.67E-05	Cd-107	1.95E-04
Y-87	1.01E+01	Tc-97M	2.42E-04	Cd-109	2.12E-02
Y-88	3.96E+01	Tc-98	2.97E-03	Cd-113	2.77E-01
Y-90	4.66E-04	Tc-99	2.79E-04	Cd-113M	2.55E-01
Y-90M	1.21E+00	Tc-99M	3.32E-05	Cd-115	9.47E-03
Y-91	6.03E-02	Tc-101	2.96E-06	Cd-115M	1.27E-02
Y-91M	2.13E-01	Tc-104	2.07E-05	Cd-117	4.23E-03
Y-92	4.81E-01	Ru-94	2.32E-03	Cd-117M	9.62E-03
Y-93	4.18E-01	Ru-97	6.89E-03	In-109	7.95E-03
Y-94	1.10E-01	Ru-103	1.97E-02	In-110	4.01E-02
Y-95	3.56E-02	Ru-105	4.09E-03	In-110	4.50E-03
Zr-86	8.62E-01	Ru-106	1.12E-01	In-111	3.05E-02
Zr-88	3.87E-01	Rh-99	2.19E-02	In-112	9.47E-05
Zr-89	7.31E-01	Rh-99M	3.51E-03	In-113M	1.24E-03
Zr-93	8.79E-05	Rh-100	3.86E-02	In-114M	3.05E-02
Zr-95	6.16E-01	Rh-101	3.33E-02	In-115	8.99E-01
Zr-97	5.24E-01	Rh-101M	9.40E-03	In-115M	2.16E-03
Nb-88	1.17E-03	Rh-102	1.93E-01	In-116M	4.92E-03
Nb-89	1.83E-02	Rh-102M	3.48E-02	In-117	1.22E-03
Nb-89	1.30E-02	Rh-103M	1.18E-06	In-117M	2.61E-03

Table F1. (contd)

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
In-119M	1.39E-03	Te-127M	1.82E-03	Ba-131M	1.32E-05
Sn-110	2.11E-02	Te-129	2.35E-05	Ba-133	1.27E-02
Sn-111	8.81E-04	Te-129M	3.39E-03	Ba-133M	8.77E-04
Sn-113	2.63E-02	Te-131	2.18E-04	Ba-135M	7.03E-04
Sn-117M	1.57E-02	Te-131M	6.64E-03	Ba-139	4.55E-05
Sn-119M	2.29E-03	Te-132	8.57E-03	Ba-140	1.54E-02
Sn-121	3.70E-05	Te-133	3.26E-05	Ba-141	9.47E-05
Sn-121M	5.70E-03	Te-133M	5.48E-04	Ba-142	2.74E-04
Sn-123	6.35E-03	Te-134	3.98E-04	La-131	3.77E-02
Sn-123M	2.48E-04	I-120	9.36E-05	La-132	5.07E-01
Sn-125	2.37E-02	I-120M	8.73E-05	La-135	3.43E-02
Sn-126	2.35E-01	I-121	1.79E-05	La-137	7.55E-02
Sn-127	1.14E-02	I-123	2.27E-05	La-138	2.84E+00
Sn-128	7.14E-03	I-124	2.16E-04	La-140	2.32E+00
Sb-115	2.00E-04	I-125	1.09E-04	La-141	9.43E-03
Sb-116	1.59E-04	I-126	2.23E-04	La-142	1.91E-01
Sb-116M	1.49E-03	I-128	5.25E-06	La-143	2.85E-03
Sb-117	3.34E-04	I-129	5.11E-04	Ce-134	3.13E+00
Sb-118M	6.59E-03	I-130	2.29E-04	Ce-135	4.44E+00
Sb-119	2.08E-04	I-131	1.59E-04	Ce-137	7.13E-02
Sb-120	3.70E-05	I-132	9.95E-05	Ce-137M	3.31E-01
Sb-120	3.42E-02	I-132M	6.14E-05	Ce-139	1.15E+00
Sb-122	5.85E-03	I-133	1.39E-04	Ce-141	5.56E-01
Sb-124	2.98E-02	I-134	4.59E-05	Ce-143	1.05E+00
Sb-124M	4.88E-05	I-135	1.42E-04	Ce-144	3.79E-01
Sb-125	8.51E-03	Cs-125	1.33E-05	Pr-136	4.12E-02
Sb-126	4.37E-02	Cs-127	5.96E-05	Pr-137	1.26E-01
Sb-126M	1.69E-04	Cs-129	2.13E-04	Pr-138M	9.61E-01
Sb-127	9.66E-03	Cs-130	6.99E-06	Pr-139	1.16E-01
Sb-128	1.33E-04	Cs-131	2.27E-04	Pr-142	1.36E-01
Sb-128	8.73E-03	Cs-132	2.10E-03	Pr-142M	1.73E-03
Sb-129	3.36E-03	Cs-134	8.25E-02	Pr-143	4.53E-08
Sb-130	9.40E-04	Cs-134M	2.66E-05	Pr-144	8.44E-04
Sb-131	3.36E-04	Cs-135	7.07E-03	Pr-145	1.41E-02
Te-116	1.45E-03	Cs-135M	2.42E-05	Pr-147	1.95E-02
Te-121	4.87E-03	Cs-136	1.42E-02	Nd-136	3.59E-01
Te-121M	7.90E-03	Cs-137	5.33E-02	Nd-138	8.26E-01
Te-123	3.09E-05	Cs-138	2.95E-05	Nd-139	4.11E-02
Te-123M	2.94E-03	Ba-126	1.14E-03	Nd-139M	1.74E+00
Te-125M	9.75E-04	Ba-128	1.17E-02	Nd-141	4.33E-02
Te-127	6.31E-05	Ba-131	7.40E-03	Nd-147	8.45E-01

Table F1. (contd)

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
Nd-149	1.37E-01	Gd-149	2.47E+00	Tm-166	2.37E+00
Nd-151	2.53E-02	Gd-151	4.99E-01	Tm-167	1.03E+00
Pm-141	3.63E-02	Gd-152	0.00E-01	Tm-170	5.38E-02
Pm-143	1.79E+00	Gd-153	8.92E-01	Tm-171	8.13E-03
Pm-144	8.68E+00	Gd-159	1.52E-01	Tm-172	1.89E+00
Pm-145	2.58E-01	Tb-147	6.76E-01	Tm-173	5.88E-01
Pm-146	4.34E+00	Tb-149	1.27E+00	Tm-175	2.70E-02
Pm-147	3.49E-05	Tb-150	1.01E+00	Yb-162	8.97E-02
Pm-148	2.60E+00	Tb-151	2.33E+00	Yb-166	6.08E+00
Pm-148M	1.08E+01	Tb-153	1.16E+00	Yb-167	1.23E-02
Pm-149	4.70E-02	Tb-154	5.65E+00	Yb-169	2.47E+00
Pm-150	6.86E-01	Tb-155	9.52E-01	Yb-175	2.10E-01
Pm-151	1.11E+00	Tb-156	8.65E+00	Yb-177	6.98E-02
Sm-141	4.11E-02	Tb-156M	9.32E-01	Yb-178	4.11E-02
Sm-141M	1.42E-01	Tb-156M	2.89E-01	Lu-169	3.60E+00
Sm-142	2.11E-01	Tb-157	2.39E-02	Lu-170	8.42E+00
Sm-145	5.56E-01	Tb-158	4.79E+00	Lu-171	3.72E+00
Sm-146	0.00E-01	Tb-160	6.08E+00	Lu-172	9.20E+00
Sm-147	0.00E-01	Tb-161	2.64E-01	Lu-173	1.10E+00
Sm-151	1.26E-05	Dy-155	1.08E+00	Lu-174	8.93E-01
Sm-153	3.54E-01	Dy-157	5.81E-01	Lu-174M	5.54E-01
Sm-155	5.65E-03	Dy-159	4.19E-01	Lu-176	3.45E+00
Sm-156	3.55E-01	Dy-165	1.38E-02	Lu-176M	1.53E-02
Eu-145	2.00E+00	Dy-166	3.56E-01	Lu-177	2.24E-01
Eu-146	3.38E+00	Ho-155	1.41E-01	Lu-177M	6.80E+00
Eu-147	8.51E-01	Ho-157	2.57E-02	Lu-178	8.18E-03
Eu-148	3.53E+00	Ho-159	3.47E-02	Lu-178M	5.54E-02
Eu-149	1.40E-01	Ho-161	4.70E-02	Lu-179	3.03E-02
Eu-150	2.92E-02	Ho-162	4.66E-03	Hf-170	4.74E-01
Eu-150	3.02E+00	Ho-162M	1.43E-01	Hf-172	4.63E-01
Eu-152	2.20E+00	Ho-164	3.10E-03	Hf-173	2.26E-01
Eu-152M	1.38E-01	Ho-164M	1.32E-02	Hf-175	3.70E-01
Eu-154	2.28E+00	Ho-166	1.04E-01	Hf-177M	5.22E-02
Eu-155	1.60E-01	Ho-166M	1.07E+01	Hf-178M	2.94E+00
Eu-156	1.90E+00	Ho-167	2.38E-01	Hf-179M	8.51E-01
Eu-157	2.01E-01	Er-161	6.29E-01	Hf-180M	1.71E-01
Eu-158	3.56E-02	Er-165	1.12E-01	Hf-181	4.96E-01
Gd-145	1.09E-01	Er-169	1.34E-04	Hf-182	1.16E+00
Gd-146	4.11E+00	Er-171	5.88E-01	Hf-182M	2.61E-02
Gd-147	4.91E+00	Er-172	2.59E+00	Hf-183	2.33E-02
Gd-148	0.00E-01	Tm-162	6.87E-02	Hf-184	1.94E-01

Table F1. (contd)

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
Ta-172	4.07E-02	Os-189M	5.11E-06	Hg-193M	3.23E-04
Ta-173	1.94E-01	Os-191	1.99E-02	Hg-194	1.81E-01
Ta-174	4.25E-02	Os-191M	1.12E-03	Hg-195	7.47E-05
Ta-175	4.96E-01	Os-193	8.55E-03	Hg-195M	5.48E-04
Ta-176	8.25E-01	Os-194	8.69E-02	Hg-197	2.38E-04
Ta-177	1.30E-01	Ir-182	2.23E-03	Hg-197M	2.97E-04
Ta-178	1.47E-01	Ir-184	3.24E-02	Hg-199M	7.55E-06
Ta-179	9.40E-02	Ir-185	3.85E-02	Hg-203	5.33E-03
Ta-180	1.16E+00	Ir-186	1.12E-01	Tl-194	6.44E-06
Ta-180M	3.47E-02	Ir-187	2.08E-02	Tl-194M	2.16E-05
Ta-182	2.15E+00	Ir-188	1.60E-01	Tl-195	3.49E-05
Ta-182M	2.65E-03	Ir-189	1.96E-02	Tl-197	3.85E-05
Ta-183	5.44E-01	Ir-190	2.52E-01	Tl-198	1.94E-04
Ta-184	7.40E-01	Ir-190M	1.01E-03	Tl-198M	8.36E-05
Ta-185	9.25E-03	Ir-192	1.63E-01	Tl-199	5.55E-05
Ta-186	7.03E-03	Ir-192M	8.99E-02	Tl-200	6.55E-04
W-176	6.55E-04	Ir-194	7.55E-03	Tl-201	2.48E-04
W-177	3.66E-04	Ir-194M	4.55E-01	Tl-202	1.38E-03
W-178	6.43E-04	Ir-195	1.24E-03	Tl-204	2.43E-03
W-179	8.12E-06	Ir-195M	1.03E-02	Pb-195M	1.65E-04
W-181	2.80E-04	Pt-186	2.06E-02	Pb-198	3.92E-04
W-185	3.51E-07	Pt-188	1.21E-01	Pb-199	6.51E-04
W-187	1.04E-03	Pt-189	2.08E-02	Pb-200	3.37E-03
W-188	1.68E-04	Pt-191	4.88E-02	Pb-201	1.78E-03
Re-177	1.49E-05	Pt-193	1.07E-04	Pb-202	6.77E-02
Re-178	8.37E-06	Pt-193M	2.71E-03	Pb-202M	1.91E-03
Re-181	4.61E-04	Pt-195M	1.58E-02	Pb-203	2.02E-03
Re-182	4.56E-04	Pt-197	2.64E-03	Pb-205	3.63E-04
Re-182	1.92E-03	Pt-197M	1.12E-03	Pb-209	9.93E-06
Re-184	1.64E-03	Pt-199	5.40E-04	Pb-210	2.31E+00
Re-184M	1.31E-03	Pt-200	2.04E-02	Pb-211	3.63E-04
Re-186	4.53E-04	Au-193	1.63E-03	Pb-212	3.29E-02
Re-186M	9.43E-04	Au-194	1.10E-02	Pb-214	5.64E-04
Re-187	1.82E-06	Au-195	2.35E-03	Bi-200	1.66E-03
Re-188	3.73E-04	Au-198	5.66E-03	Bi-201	4.07E-03
Re-188M	8.19E-06	Au-198M	1.05E-02	Bi-202	4.83E-03
Re-189	2.46E-04	Au-199	1.68E-03	Bi-203	2.54E-02
Os-180	1.78E-03	Au-200	1.01E-04	Bi-205	4.82E-02
Os-181	1.75E-02	Au-200M	1.61E-02	Bi-206	9.03E-02
Os-182	1.07E-01	Au-201	1.15E-05	Bi-207	4.88E-02
Os-185	1.33E-01	Hg-193	4.88E-05	Bi-210	1.46E-03

Table F1. (contd)

Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)	Nuclide	$H_{T,50}$ (rem/μCi)
Bi-210M	8.66E-02	U-233	1.94E-01	Am-245	2.68E-04
Bi-212	1.70E-03	U-234	1.91E-01	Am-246M	1.51E-02
Bi-213	4.36E-04	U-235	1.86E-01	Am-246	2.03E-02
Bi-214	3.52E-04	U-236	1.81E-01	Cm-238	1.31E-01
Po-203	1.07E-03	U-237	5.42E-03	Cm-240	3.50E-02
Po-205	1.64E-03	U-238	1.70E-01	Cm-241	8.69E-01
Po-207	4.03E-03	U-239	5.52E-05	Cm-242	3.30E-02
Po-210	3.05E+00	U-240	4.17E-03	Cm-243	3.74E-01
At-207	8.32E-04	Np-232	8.69E-03	Cm-244	3.19E-02
At-211	3.92E-02	Np-233	2.85E-03	Cm-245	3.11E-01
Fr-222	2.13E-03	Np-234	1.45E+00	Cm-246	1.27E-01
Fr-223	8.58E-03	Np-235	2.99E-03	Cm-247	9.51E-01
Ra-223	7.84E-01	Np-236	4.29E-01	Cm-248	3.49E+01
Ra-224	3.85E-01	Np-236	5.25E-02	Cm-249	1.07E-03
Ra-225	6.23E-01	Np-237	3.59E-01	Cm-250	2.76E+02
Ra-226	1.69E+00	Np-238	6.07E-01	Bk-245	4.11E-01
Ra-227	6.10E-05	Np-239	2.55E-01	Bk-246	1.04E+00
Ra-228	2.90E+00	Np-240	7.07E-02	Bk-247	2.83E-01
Ac-224	9.47E-02	Pu-234	1.24E-01	Bk-249	8.40E-04
Ac-225	3.68E-01	Pu-235	1.72E-03	Bk-250	1.54E-01
Ac-226	1.66E-01	Pu-236	6.81E-02	Cf-244	9.25E-05
Ac-227	2.60E-01	Pu-237	1.07E-01	Cf-246	2.88E-02
Ac-228	3.12E-01	Pu-238	2.98E-02	Cf-248	4.18E-02
Th-226	3.02E-03	Pu-239	2.79E-02	Cf-249	9.80E-01
Th-227	3.52E+00	Pu-240	2.80E-02	Cf-250	3.30E-01
Th-228	4.40E+01	Pu-241	2.96E-04	Cf-251	4.26E-01
Th-229	8.51E+01	Pu-242	2.81E-02	Cf-252	1.15E+01
Th-230	1.26E+01	Pu-243	9.62E-03	Cf-253	8.55E-04
Th-231	8.97E-02	Pu-244	1.07E+00	Cf-254	3.70E+02
Th-232	2.26E+01	Pu-245	2.22E-01	Es-250	4.77E-02
Th-234	2.33E-01	Pu-246	1.34E+00	Es-251	1.24E-01
Pa-227	2.42E-03	Am-237	2.60E-02	Es-253	3.58E-02
Pa-228	9.58E-01	Am-238	7.81E-02	Es-254M	5.22E-01
Pa-230	1.04E+00	Am-239	1.63E-01	Es-254	1.33E+00
Pa-231	2.25E-01	Am-240	1.16E+00	Fm-252	2.61E-02
Pa-232	8.95E-01	Am-241	1.11E-01	Fm-253	1.38E-01
Pa-233	3.81E-01	Am-242M	3.64E-02	Fm-254	6.11E-03
Pa-234	6.77E-01	Am-242	1.32E-02	Fm-255	2.85E-02
U-230	6.13E-01	Am-243	4.74E-01	Fm-257	2.60E-01
U-231	2.63E-03	Am-244M	1.05E-05	Md-257	3.69E-02
U-232	6.02E-01	Am-244	3.92E-01	Md-258	5.96E-02

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11. ABSTRACT (200 words or less)

This report describes approaches for calculating and expressing radiation doses to the embryo/fetus from internal radionuclides. Information was obtained for selected, occupationally significant radionuclides to provide metabolic and dosimetric characteristics. Fractional placental transfer and ratios of concentration in the embryo/fetus to that in the woman were calculated. This information was integrated with data from biokinetic transfer models to estimate the levels of radioactivity in the embryo/fetus as a function of stage of pregnancy and time after entry. The MIRD methodologies were extended to describe details for calculating radiation doses to the embryo/fetus. To accommodate the stage dependence of geometric relationships and biological behaviors, calculations were performed for a representative situation of an introduction of 1 μCi into a woman's transfer compartment (blood) at successive months of pregnancy. Detailed tables of the initial and retained fractions of activity in the embryo/fetus, and the corresponding radiation dose rates and doses are presented. These approaches yield radiation absorbed doses, and multiplication by quality factor (Q) converts them to dose equivalent. This is the most common quantity for stating prenatal dose limits and is appropriate for the unique effects of prenatal exposure. Our knowledge is currently inadequate to warrant the use of effective dose equivalent or committed dose equivalent.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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