Chapter 6

# Methods and Input Data for Calculating Thyroid Doses to People Resulting from the Ingestion of Cows' Milk

*Contents: Estimates of average individual thyroid doses for the population of a county from the ingestion of fresh cows' milk contaminated with $^{131}I$ deposited after a test are derived from: (1) the estimated time-integrated concentrations of $^{131}I$ in fresh cows' milk produced in that county after that test, (2) the estimated origin of the cows' milk consumed, (3) the estimated average cows' milk consumption rate by the population group considered, and (4) the estimated thyroid dose factor for ingestion of $^{131}I$ appropriate for that population group. The data and methodology used to calculate average individual thyroid doses resulting from the ingestion of cows' milk for each age group, as well as average per capita and collective doses in each county, are discussed.*

The thyroid dose, $D_{mc}(te)$, in mrad, received by a given individual as a result of the consumption of milk from cows, mc, that ingested $^{131}I$ from a given test, te, can be estimated by calculating the product:

$$D_{mc}(te) = IMC(te) \times CR \times DCF \qquad (6.1)$$

in which:

IMC(te) = the time-integrated $^{131}I$ concentration in cows' milk, resulting from the test, te, and consumed by the individual considered. In calculating the value of IMC(te), both decay of $^{131}I$ due to the time elapsed between production by the cows and consumption by humans, and, as appropriate, the mixing of milk from various locales are considered. The values of IMC(te) are expressed in units of nanocuries per liter of milk x days (nCi d $L^{-1}$);

CR= the individual's consumption rate (L $d^{-1}$) of cows' milk for a period of 60 days following the test considered;

DCF= the thyroid dose resulting from a unit activity intake of $^{131}I$, also called thyroid dose conversion factor, in mrad $nCi^{-1}$, appropriate for the individual considered.

The purpose of this chapter is to describe the manner in which these variables have been selected and used to calculate the thyroid doses.

Individual doses vary widely from person to person because of variability in such factors as environmental parameters, patterns of milk production and distribution, dietary habits, and biological characteristics. Therefore, realistic estimates of individual doses can be made only if specific information (age, sex, place of residence, source of milk, milk consumption rate, delay time between production and consumption of milk) is available for the individual considered. It will be indicated in **Chapter 9** how an individual can calculate his or her own dose using the personal data mentioned above in conjunction with the information presented in this report.

In the absence of personal data, only average doses over large or homogeneous groups of people can be calculated with reasonable accuracy. For this reason, the doses calculated and presented in this report for each county and for each nuclear test are expressed as geometric means over specified population groups deemed to be representative of a large spectrum of individuals. To accomplish this, the population of each county has been divided into 13 age groups, with adults subdivided by gender. These 14 groups, which include four pre-natal ages in addition to the 10 groups previously defined in **Chapter 5 (Section 5.4.4)** for the consumption of milk, are shown in *Table 6.1.* Doses have been calculated for each post-natal age and sex group for:

(a) the population of persons drinking cows' milk,

(b) a specified "high-exposure" group, with a high consumption rate of milk containing higher-than-average concentrations of $^{131}$I,

(c) a specified "low-exposure" group, with no consumption of fresh cows' milk, and

(d) a group drinking milk from backyard cows.

Collective doses to the population of each county have been obtained by summing, over all post-natal age and sex groups, the products of the arithmetic means of the thyroid doses estimated to have been received by the population of each group by the size of that population group. Per capita doses were computed by dividing the collective doses by the population sizes.

### 6.1. TIME-INTEGRATED CONCENTRATIONS OF $^{131}$I IN COWS' MILK

Time-integrated concentrations of $^{131}$I in cows' milk, IMC, are calculated in each county, i, and for each test that is considered, te, for each of four categories of milk defined in **Chapter 5.** The index for the milk categories is q:

- milk produced and consumed on the farm (q=1),
- milk produced and sold in the county (q=2),
- milk originating from another county of the region (q=3),
- milk originating from another region (q=4).

When calculating the thyroid doses received by the "high-exposure" group in a particular county, it is assumed that the group consumes cows' milk having the highest time-integrated concentration of $^{131}$I found for any of the four categories of milk in the county. In some circumstances, milk that originates in another county or another region may contain more $^{131}$I than milk produced in the county.

In the calculation of the thyroid doses received by the population of cows' milk drinkers in each county for each of the 10 post-natal age and sex groups, the $^{131}$I time-integrated concentrations estimated for the total volume of cows' milk pooled from the four categories, called volume-weighted milk concentrations, are used.

**Table 6.1.** Age and sex groups for which thyroid doses are estimated.

| Age group index, k | Pre-natal age, weeks | Post-natal age | |
|---|---|---|---|
| | | months | years |
| 1 | 0-10 (embryo) | | |
| 2 | 11-20 (fetus) | | |
| 3 | 21-30 (fetus) | | |
| 4 | 31-40 (fetus) | | |
| 5 | | 0-2 (infant) | |
| 6 | | 3-5 (infant) | |
| 7 | | 6-8 (infant) | |
| 8 | | 9-11 (infant) | |
| 9 | | | 1-4 (child) |
| 10 | | | 5-9 (child) |
| 11 | | | 10-14 (child/teenager) |
| 12 | | | 15-19 (teenager) |
| 13 | | | > 19 (adult male) |
| 14 | | | > 19 (adult female) |

Finally, the $^{131}I$ time-integrated concentrations in milk from backyard cows are used in the estimation of the thyroid doses received by the groups drinking milk from backyard cows. Milk from backyard cows is not included in the volume-weighted average that is computed for milk from dairy cows.

### *6.1.1. Calculation of the Time-Integrated Concentrations of $^{131}I$ in Each Milk Category From a Given Test*

In order to estimate the time-integrated concentrations of $^{131}I$ in the milk of the four categories, q, the commercial milk distribution results from **Chapter 5** have been combined with the appropriate delay times between production and consumption, and with the time-integrated concentrations of $^{131}I$ in fresh cows' milk after a test, estimated with the methodology presented in **Chapter 4:**

- the $^{131}I$ activity in the milk in category 1, that which is consumed on the farm, is assumed to have decayed for 1 d between production and consumption, is never mixed with other milk, and is always consumed in the county in which it was produced;
- the activity in the milk in category 2, consumed in the county but not included in category 1, is assumed to have a 2-d delay time;
- if there is a deficit of milk in the county, milk is brought in first from the surplus counties in the region (category 3), with an assumed delay time of 3 days;
- if, after addition of category 3 milk, there is still a deficit of milk in the county, milk is brought in from specified surplus regions (category 4), with an assumed delay time of 4 days.

It is assumed that all the milk in a county in categories 1-4 is available for fluid use by the population living in that county.

Several indices and symbols are repeatedly used in the calculation of the time-integrated concentrations of $^{131}I$ in each milk category:

- i denotes the county for which the $^{131}I$ time-integrated concentrations in milk are calculated;
- ii denotes the counties other than i in the milk region, rr;
- nn denotes the number of counties in the milk region, rr;
- q denotes the milk category;
- rr denotes the milk region that contains the county, i;
- EC(i) is the expected annual milk consumption (kL $y^{-1}$) in county, i, as determined in **Chapter 5;**
- IMC(i,te) is the time-integrated concentration of $^{131}I$ (nCi d $L^{-1}$) in fresh cows' milk resulting from fallout in county, i, following a test, te. The methods for calculating IMC(i,te) and the associated uncertainties are presented in **Chapter 4;**
- $IMC_q$(i,te) is the time-integrated concentration of $^{131}I$ in milk (nCi d $L^{-1}$) of category, q, resulting from fallout in county, i, following a test, te;
- $IMC_{vw}$(i,te) is the volume-weighted time-integrated concentration of $^{131}I$ in milk (nCi d $L^{-1}$) resulting from fallout in county, i, following a test, te;
- $IMC_{bc}$(i,te) is the time-integrated concentration of $^{131}I$ in milk (nCi d $L^{-1}$) from backyard cows, resulting from fallout in county, i, following a test, te;
- $\lambda_r$ is the radioactive decay constant of $^{131}I$, equal to 0.086 $d^{-1}$;
- $TD_q$ is the time delay between production and consumption for milk of category, q, in days;
- TMFU(i) is the production rate (kL $y^{-1}$) of milk available for fluid use in county, i, as determined in **Chapter 5;**
- TN(rr) is the deficit of milk in region, rr, defined in **Section 6.1.1.3;**
- TP(rr) is the surplus of milk in region, rr, defined in **Section 6.1.1.3;**
- $VOL_q$(i) is the rate at which milk of category, q, is made available (kL $y^{-1}$) in county, i;
- VOL(i,ii) is the rate at which milk is imported (kL $y^{-1}$) from county, ii, to county, i;
- VOL(i,rr) is the rate at which milk is imported (kL $y^{-1}$) from milk region, rr, to county, i.

All other indices and symbols appear only once and are defined in the text.

#### *6.1.1.1. Category 1*

Milk of category 1 is fresh cows' milk that is produced in the county of interest and has decayed during a time, $TD_1$, prior to consumption on the farms where it was produced. The time-integrated concentration of $^{131}I$ in milk of category 1, in nCi d $L^{-1}$, resulting from fallout in county, i, following a test, te, is derived from the time-integrated concentration of $^{131}I$ in fresh cows' milk, IMC(i,te), by allowing for decay of $^{131}I$ during time, $TD_1$. It is estimated as:

$$IMC_1(i, te) = IMC(i,te) \times e^{(-\lambda_r \times TD_1)} \quad (6.2)$$

As indicated in **Chapter 4,** the uncertainties attached to IMC(i,te) are usually rather large, as the GSDs of the log-normal distributions of IMC(i,te) are typically about 3 to 4. In comparison, the uncertainties related to the decay term, $\exp(-\lambda_r \times TD_1)$, are small. The physical constant $\lambda_r$ is very well known (±0.2%). Variation of $TD_1$ from 0 to 2 days would result in a variation in the decay term in the narrow range of 0.84 to 1. As a first approximation, the decay term is considered to be exact, so that the distributions of $IMC_1$(i,te) are assumed to be log-normal and to have the same GSDs as those assigned to IMC(i,te).

The notation that is used here for the median and geometric standard deviation of a log-normal distribution was developed in **Section 3.3.** The relationships between those quantities and the arithmetic mean and standard deviation were also described there. The same symbolic designations are used below and in later sections of this chapter.

The median values of $IMC_1$(i,te), denoted as $<IMC_1(i,te)>$, are therefore calculated, using:

$$<IMC_1(i, te)> = <IMC(i,te)> \times e^{(-\lambda_r \times TD_1)} \quad (6.3)$$

The arithmetic means of the $IMC_1$(i,te), denoted as $m(IMC_1(i,te))$, are computed, using:

$$m(IMC_1(i, te)) = <IMC_1(i,te)> \times e^{(0.5 \times \sigma^2 (IMC_1(i,te)))} \quad (6.4)$$

where:

$$\sigma (IMC_1(i, te)) = \ln (GSD (IMC(i,te))) \quad (6.5)$$

The rate of consumption (kL $y^{-1}$) of milk in category 1, $VOL_1(i)$, is calculated, as indicated in **Chapter 5,** from the annual volume of milk consumed on farms in the state, MCF(s), apportioned according to the ratio of the number of farms in the county, FA(i), to the number of farms in the state, FA(s).

$$VOL_1(i) = MCF(s) \times \frac{FA(i)}{FA(s)} \quad (6.6)$$

The reference year for the calculations is 1954.

#### *6.1.1.2. Category 2*

Milk of category 2 is fresh cows' milk that is produced in the county of interest and has decayed during a time $TD_2$ prior to being consumed in the county, but not on farms. There was milk of category 2 in county, i, if the annual volume of milk available for fluid use in the county, TMFU(i), was greater than the annual milk consumption on farms in the county, $VOL_1(i)$. Otherwise, there was no category 2 milk available for consumption away from farms.

The time-integrated concentration of $^{131}I$ in milk of category 2, in nCi d $L^{-1}$, resulting from fallout in county, i, following a test, te, is estimated to be:

$$IMC_2(i, te) = IMC(i,te) \times e^{(-\lambda_r \times TD_2)} \quad (6.7)$$

In the same way as for the milk in category 1, the distributions of $IMC_2$(i,te) are assumed to be log-normal and the uncertainties attached to $IMC_2$(i,te) are taken to be equal to those related to IMC(i,te). The median values of the $IMC_2$(i,te), denoted as $<IMC_2(i,te)>$, are therefore calculated, using:

$$<IMC_2(i, te)> = <IMC(i,te)> \times e^{(-\lambda_r \times TD_2)} \quad (6.8)$$

The arithmetic means of $IMC_2$(i,te), denoted as $m(IMC_2(i,te))$, are computed, using:

$$m(IMC_2(i, te)) = <IMC_2(i,te)> \times e^{(0.5 \times \sigma^2 (IMC_2(i,te)))} \quad (6.9)$$

in which:

$$\sigma (IMC_2(i, te)) = \ln (GSD (IMC(i,te))) \quad (6.10)$$

The rate of consumption (kL $y^{-1}$) of milk in category 2, $VOL_2(i)$, depends whether TMFU(i) was greater or smaller than the expected milk consumption in the county, EC(i). Again, 1954 is the reference year for these calculations:

- if TMFU(i) > EC(i), the remaining demand was filled by milk of category 2 and

$$VOL_2(i) = EC(i) - VOL_1(i) \quad (6.11)$$

- if TMFU(i) < EC(i), part of the demand was filled by milk of category 2 and

$$VOL_2(i) = TMFU(i) - VOL_1(i) \quad (6.12)$$

Under the second condition, milk must be imported from other counties in the same milk region or from other regions, as discussed below.

#### *6.1.1.3. Category 3*

Milk of category 3 is milk that was imported from other counties of the same milk region. It is assumed to have been pooled within the region before shipment to county, i. There was milk in category 3 in county, i, if two conditions were realized: (1) there was an unfilled demand in county, i, and (2) there was milk available within the region. These conditions can be written:

- TMFU(i) < EC(i), and
- TMFU(ii) > EC(ii) in any other county, ii, in the milk region that includes county, i.

Under those conditions, the time-integrated concentration of $^{131}$I in milk of category 3, in nCi d $L^{-1}$, resulting from fallout in county, i, following a test, te, denoted $IMC_3(i,te)$, is the time-integrated concentration in milk pooled from the number, nn, of counties in the same region that have excess milk. Allowing for decay of $^{131}$I during a time, $TD_3$:

$$IMC_3(i,te) = \frac{\sum_{ii}^{nn} (IMC(ii,te) \times VOL(i,ii))}{\sum_{ii}^{nn} VOL(i,ii)} \times e^{(-\lambda_r \times TD_3)} \quad (6.13)$$

where

VOL(i,ii) is the rate of milk transfer (kL y-1) from county ii to county i and the ratio of the sums in *equation 6.13* is the concentration of the pooled milk.

Here again, the distributions of $IMC_3(i,te)$ are assumed to be log-normal and to have the same GSDs as those of IMC(i,te). Ignoring the uncertainties in the milk transfer rates, VOL(i,ii), and in the time delay between production and consumption of milk, $TD_3$, the median values of $IMC_3(i,te)$, denoted as <IMC3(i,te)>, are calculated as follows:

$$<IMC_3(i,te)> = \frac{\sum_{ii}^{nn} (<IMC(ii,te)> \times VOL(i,ii))}{\sum_{ii}^{nn} VOL(i,ii)} \times e^{(-\lambda_r \times TD_3)} \quad (6.14)$$

The arithmetic means of $IMC_3(i,te)$, denoted as $m(IMC_3(i,te))$, are obtained from:

$$m(IMC_3(i, te)) = <IMC_3(i,te)> \times e^{(0.5 \times \sigma^2 (IMC_3(i,te)))} \quad (6.15)$$

with:

$$\sigma (IMC_3(i, te)) = ln (GSD (IMC(i,te))) \quad (6.16)$$

The values of VOL(i,ii) in *equations 6.13 and 6.14* are based on the surplus and deficit amounts of milk in counties in the milk region, rr, in which county, i, is located. For counties in the region with surpluses, the total positive component of the milk balance for the region, TP(rr), in kL $y^{-1}$, is:

$$TP(rr) = \Sigma \, (TMFU(ii) - EC(ii)) \quad (6.17)$$

Similarly, for counties in the region with deficits, the total negative component of the milk balance for the region, TN(rr), in kL $y^{-1}$, is:

$$TN(rr) = \Sigma \, (EC(ii) - TMFU(ii)) \quad (6.18)$$

If TP(rr) was greater than TN(rr), the region had a milk surplus. Counties in the region with a surplus were able to provide enough milk for all the deficit counties. The contributions of the counties with surplus milk are computed using:

$$VOL(i,ii) = (EC(i) - TMFU(i)) \times \frac{TMFU(ii) - EC(ii)}{TP(rr)} \quad (6.19)$$

The contribution of county, ii, which has a surplus, to deficit county, i, is proportional to the size of the deficit in county, i, and to the fraction of the total surplus that is available in county, ii. It is assumed that no milk is transferred out of a county with a deficit of milk.

If TP(rr) is smaller than TN(rr), the region had a milk deficit, but those counties with a surplus could meet part of the needs of deficit counties. The contributions were computed using:

$$VOL(i,ii) = \frac{(EC(i) - TMFU(i))}{TN(rr)} \times (TMFU(ii) - EC(ii)) \quad (6.20)$$

In this case, the contribution to deficit county, i, from surplus county, ii, is proportional to the deficit in county, i, and to the size of the surplus in county, ii. Again, it is assumed that no milk is transferred out of a county that has a milk deficit.

The rate of transfer (kL $y^{-1}$) of milk of category 3 to county, i, ($VOL_3(i)$), is the sum of the volumes of milk imported from other counties in the milk region.

- if TP(rr) > TN(rr), the region has an overall surplus of milk. The deficit in county, i, is completely satisfied using milk produced in the same region, and

$$VOL_3(i) = EC(i) - TMFU(i) \quad (6.21)$$

- if TP(rr) < TN(rr), the region has an overall deficit of milk. The deficit in county, i, is partially filled using surplus milk from other counties in the region. The rate of transfer of milk to county, i, is proportional to the contribution to the deficits within the region and to the total availability of surplus milk in counties within the region:

$$VOL_3(i) = \frac{(EC(i) - TMFU(i))}{TN(rr)} \times TP(rr) \qquad (6.22)$$

### *6.1.1.4. Category 4*

Milk of category 4 is milk that is imported from other milk regions; it is assumed to be pooled before shipment to county, i. There is milk in category 4 in county, i, only if the county has a deficit and the region of which it is part also has a deficit. The conditions are:

- TMFU(i) < EC(i), and
- TP(rr) < TN(rr).

Under those conditions, the time-integrated concentration of $^{131}$I in milk of category 4, in nCi d $L^{-1}$, resulting from fallout in county, i, following a test, te, denoted $IMC_4$(i,te), is the time-integrated concentration in milk pooled from other regions with excess milk. Allowing for the decay of $^{131}$I during time $TD_4$:

$$IMC_4(i,te) = \frac{\sum_{rg} (IMC(rg,te) \times VOL(rr,rg))}{\sum_{rg} VOL(rr,rg)} \times e^{(-\lambda_r \times TD_4)} \qquad (6.23)$$

where:

rg — denotes a region that exports milk to region, rr,

VOL(rr,rg) — is the annual volume of milk that is transferred from region, rg, to region, rr, (given in **Appendix 5**), and

IMC(rg,te) — is the time-integrated concentration of 131I in milk pooled from counties in region, rg, that have surplus milk. The index for these counties is: ig. The volume-weighted concentration of the pooled milk is:

$$IMC(rg,te) = \frac{\sum_{ig} (IMC(ig,te) \times (TMFU(ig) - EC(ig)))}{\sum_{ig} (TMFU(ig) - EC(ig))} \qquad (6.24)$$

The uncertainties attached to the values of $IMC_4$(i,te) are very difficult to determine as they depend on poorly documented volumes and origins of milk that are assumed to have been transferred to region, rr. As a first approximation, it is assumed that the distributions of $IMC_4$(i,te) are log-normal with GSDs equal to those of IMC(i,te). The median values of $IMC_4$(i,te), denoted as $<IMC_4(i,te)>$, are calculated, using:

$$<IMC_4(i,te)> = \frac{\sum_{rg} (<IMC(rg,te)> \times VOL(rr,rg))}{\sum_{rg} VOL(rr,rg)} \times e^{(-\lambda_r \times TD_4)} \qquad (6.25)$$

The arithmetic means of $IMC_1$(i,te), denoted as m($IMC_1$(i,te)), are obtained from:

$$m(IMC_4(i, te)) = <IMC_4(i,te)> \times e^{(0.5 \times \sigma^2 (IMC_4(i,te)))} \qquad (6.26)$$

with:

$$\sigma (IMC_4(i, te)) = \ln (GSD (IMC(i,te))) \qquad (6.27)$$

The rate of transfer (kL $y^{-1}$) of milk in category 4 to county, i, ($VOL_4$(i)) is the sum of the transfer rates of milk imported from other regions to satisfy the milk deficit that remains after importation of category 3 milk from within the region.

$$VOL_4(i,ii) = \frac{EC(i) - TMFU(i)}{TN(rr)} \times (TN(rr) - TP(rr)) \qquad (6.28)$$

### *6.1.1.5. Volume-weighted average*

The volume-weighted average of the time-integrated concentration of $^{131}$I in milk, $IMC_{vw}$(i,te), resulting from fallout in county, i, following a test, te, reflects the contributions of each of the four milk categories to the milk supply in the county. The time-integrated concentrations ($IMC_q$(i,te)) and transfer rates ($VOL_q$(i)) discussed in the four preceding subsections are used to compute $IMC_{vw}$(i,te).

$$IMC_{vw}(i,te) = \frac{\sum_{q=1}^{q=4} (IMC_q(i,te) \times VOL_q(i))}{\sum_{q=1}^{q=4} VOL_q(i)} \qquad (6.29)$$

For the purpose of estimating the uncertainties, the median value of $IMC_{vw}$(i,te), denoted as $<IMC_{vw}(i,te)>$, is expressed as a function of the median value of the time-integrated concentration of $^{131}$I in milk consumed on farms, $<IMC_1(i,te)>$. The factor of proportionality between those two quantities is called the milk distribution factor. Its median value is denoted by $<MF(i,te)>$. The relationship between these quantities is:

$$<IMC_{vw}(i,te)> = <IMC_1(i,te)> \times <MF(i,te)> \qquad (6.30)$$

The milk distribution factor for a particular county reflects the transfers of milk from other counties in the region and from other regions, as appropriate, and the differences in concentration between the milk transferred and that produced locally. It is estimated by taking the ratio of the volume-weighted concentration *(equation 6.29)* to the concentration of milk consumed on farms in the county.

If the county's needs for fresh milk were satisfied by milk consumed on farms, then <MF(i,te)> is 1. If the county was self-sufficient in milk, the median milk distribution factor is between 0.92 and 1. If all the milk in the county was of category 2, the value of <MF(i,te)> would be $\exp(-\lambda_r \times (TD_2 - TD_1)) = 0.92$. If the county imported milk from other counties or regions having different values of the time-integrated concentrations of $^{131}$I in fresh cows' milk, then <MF(i,te)> may be large or small depending upon the $^{131}$I concentrations in and the quantities of imported milk.

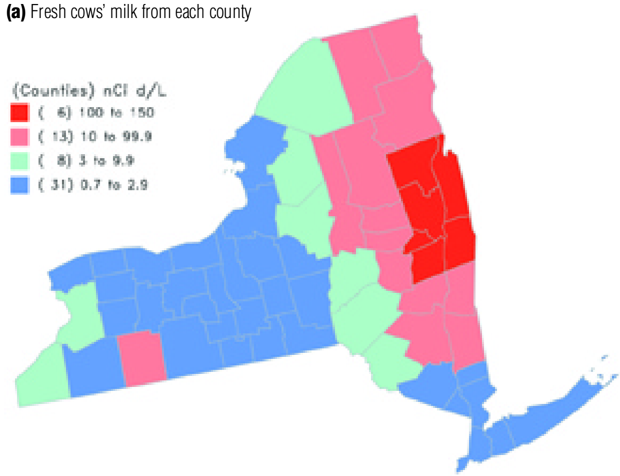
The variability in the values of <$IMC_1$(i,te)>, <$IMC_{vw}$(i,te)>, and <MF(i,te)> is illustrated in *Figure 6.1,* which shows the estimates for those three quantities for the counties of New York state after the shot Simon, detonated 25 April 1953. The figure has three parts:

- The average time-integrated $^{131}$I concentrations in milk consumed on farms, <$IMC_1$(i,te)>, were high in the region of Albany, where relatively high depositions occurred as a result of heavy thunderstorms coincidental with the passage of the radioactive cloud, and low in the remainder of New York state *(Figure 6.1(a))*. There is a factor of about 200 between the maximum and the minimum values of <$IMC_1$(i,te)> in the figure.

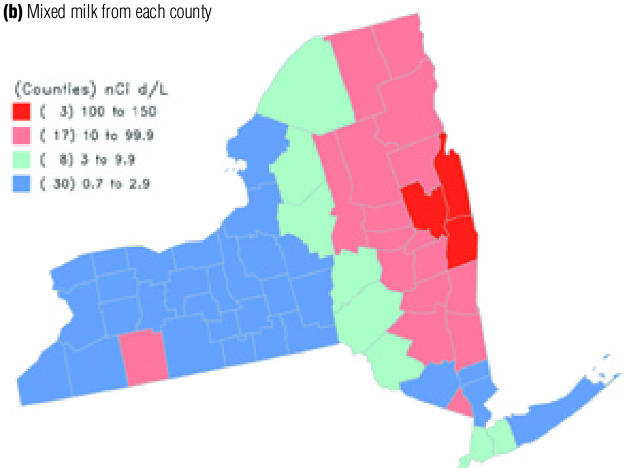
- The average time-integrated $^{131}$I concentrations in volume-weighted milk, <$IMC_{vw}$(i,te)>, were similar to the values of <$IMC_1$(i,te)> for the majority of the counties, because those counties had an excess production of milk in the 1950s *(Figure 6.1(b))*. However, the populated counties of the Greater New York City area needed to import milk from other regions of the state, where the $^{131}$I depositions were higher, and this influx of milk with higher concentrations is the reason why the values of <$IMC_{vw}$(i,te)> are greater than those of <$IMC_1$(i,te)> in the counties of the Greater New York City area. On the other hand, the $^{131}$I concentration in volume-weighted milk is lower than that in milk consumed on farms in two western counties, where some milk was imported from counties with lower $^{131}$I depositions. There is a factor of about 200 between the maximum and the minimum values of <$IMC_{vw}$(i,te)> in the figure.

**Figures 6.1.(a) (b) (c)** Time-integrated concentrations of I-131 in milk in New York State counties resulting from the test Simon detonated 25 April 1953

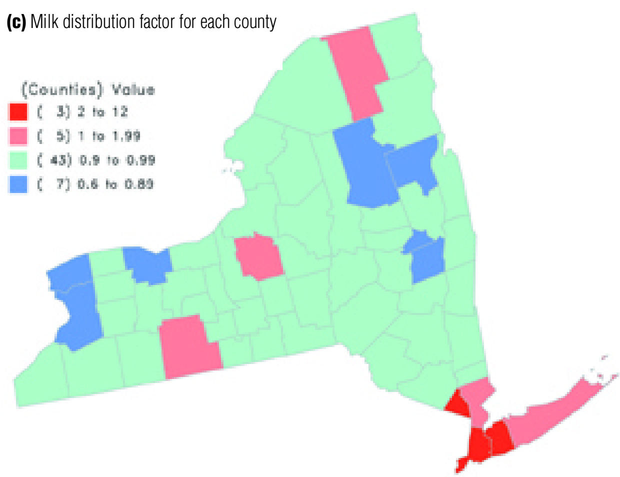
**(a)** Fresh cows' milk from each county




**(b)** Mixed milk from each county




**(c)** Milk distribution factor for each county



- The values of the milk distribution factor, <MF(i,te)>, vary from county to county between 0.65 and 11.5 *(Figure 6.1(c))*. The highest values of <MF(i,te)> are found in counties of the Greater New York City area, which imported milk with higher concentrations. The lowest values are observed in counties around Albany and Buffalo, which imported milk with lower concentrations. Most of the milk distribution factors are close to one because most counties in New York state were self-sufficient in milk.

It is subjectively reasonable to assume that the uncertainty attached to <MF(i,te)> is small when the county is self-sufficient in milk, and becomes larger as the value of <MF(i,te)> deviates from one (that is, when counties import milk from areas with substantially higher or lower milk concentrations than those in the local milk). However, the uncertainties related to MF(i,te) would be extremely difficult to quantify, as they depend on the volumes of milk imported (which are poorly documented), on the origins of the milk imported (which are also poorly documented), and on the $^{131}I$ time-integrated concentrations in the imported milk (which are, to some extent, correlated with the $^{131}I$ time-integrated concentrations in the milk of local origin). For the uncertainty analysis, it is assumed that the distributions of MF(i,te) are log-normal with GSDs that vary in the following way:

- GSD(MF(i,te)) = 2 if <MF(i,te)> is greater than 2,
- GSD(MF(i,te)) = 1.5 if <MF(i,te)> is between 1.1 and 2,
- GSD(MF(i,te)) = 1.1 if <MF(i,te)> is between 0.9 and 1.1,
- GSD(MF(i,te)) = 1.5 if <MF(i,te)> is between 0.5 and 0.9,
- GSD(MF(i,te)) = 2 if <MF(i,te)> is less than 0.5.

According to *equation 6.30,* the median value of $IMC_{vw}(i,te)$ is calculated using:

$$\langle IMC_{vw}(i,te)\rangle = \langle IMC_1(i,te)\rangle \times \langle MF(i,te)\rangle \qquad (6.30)$$

The geometric standard deviation of the distribution is calculated using:

$$GSD(IMC_{vw}(i,te)) = e^{(\sigma(IMC_{vw}(i,te)))} \qquad (6.31)$$

in which:

$$\sigma(IMC_{vw}(i,te)) = \left( (\ln(GSD(IMC_1(i,te))))^2 + (\ln(GSD(MF(i,te))))^2 \right)^{0.5} \qquad (6.32)$$

The arithmetic mean of IMCvw(i,te) is obtained from:

$$m(IMC_{vw}(i,te)) = \langle IMC_{vw}(i,te)\rangle \times e^{(0.5 \times \sigma^2(IMC_{vw}(i,te)))} \qquad (6.33)$$

### *6.1.1.6. Milk consumed by the "high-exposure" groups*

In the calculation of the thyroid doses received by the "high-exposure" groups, the value of the median time-integrated concentration of $^{131}I$ that is used is the highest obtained for any of the four categories.

$$\langle IMC_{high}(i,te)\rangle = Max(\langle IMC_q(i,te)\rangle) \text{ with } q = 1 \text{ to } 4 \qquad (6.34)$$

The geometric standard deviation, $GSD(IMC_{high}(i,te))$, and the arithmetic mean, $m(IMC_{high}(i,te))$, of the distribution of $IMC_{high}(i,te)$ are those corresponding to the category of milk having the highest concentration.

### *6.1.1.7. Milk from backyard cows*

The time-integrated concentrations of $^{131}I$ in milk fresh from backyard cows, IMB(i,te) resulting from fallout in county, i, following a test, te, are calculated using the same methodology as for the dairy, or commercial, cows, which is described in **Chapter 4.** The only difference between dairy and backyard cows is in their diet, as it is assumed that backyard cows eat less than dairy cows and are placed on pasture for a larger portion of their diet. As indicated in **Section 4.1.3.5** of **Chapter 4,** the start and stop dates of the pasture seasons for backyard cows are taken to be one month before and one month after the start and stop dates, respectively, estimated for the dairy cows. The pasture intakes of backyard cows are taken to be the same in all parts of the country: 8 kg $d^{-1}$ (dry mass) during the pasture season and 0.1 kg $d^{-1}$ (dry mass) when cows are not on pasture.

Milk from backyard cows is assumed to be consumed rapidly by the families that own the cows. It is assumed that the average delay between production and consumption, $TD_{bc}$, is equal to 0.5 day. The time-integrated concentration of $^{131}I$ in milk from backyard cows at the time of consumption, $IMC_{bc}(i,te)$ in nCi d $L^{-1}$, resulting from fallout in county, i, following a test, te, therefore is derived from the time-integrated concentration of $^{131}I$ in milk fresh from backyard cows, IMB(i,te), allowing for a decay of $^{131}I$ during time, $TD_{bc}$. It is estimated as:

$$IMC_{bc}(i,te) = IMB(i,te) \times e^{(-\lambda_r \times TD_{bc})} \qquad (6.35)$$

As a first approximation, the decay term is considered to be exact, and the distributions of $IMC_{bc}(i,te)$ are assumed to be log-normal and to have the same GSDs as those assigned to IMB(i,te). The median values of $IMC_{bc}(i,te)$, denoted as $\langle IMC_{bc}(i,te)\rangle$, are therefore calculated, using:

$$\langle IMC_{bc}(i,te)\rangle = \langle IMB(i,te)\rangle \times e^{-\lambda_r \times TD_{bc}} \qquad (6.36)$$

The arithmetic means of $IMC_{bc}(i,te)$, denoted as $m(IMC_{bc}(i,te))$, are obtained from:

$$m(IMC_{bc}(i,te)) = \langle IMC_{bc}(i,te)\rangle \times e^{(0.5 \times \sigma^2(IMC_{bc}(i,te)))} \qquad (6.37)$$

with:

$$\sigma(IMC_{bc}(i,te)) = \ln(GSD(IMB(i,te))) \qquad (6.38)$$

### 6.1.2. *Calculation of the Time-Integrated Concentrations of $^{131}$I in Each Milk Category From a Given Test Series*

The time-integrated concentration of $^{131}$I in cows' milk of category, q, in county, i, resulting from a given test series, ts, is obtained by adding the contributions from each test, te, in the series:

$$IMC_q(i,ts) = \sum_{te+1}^{nte} IMC_q(i,te) \qquad (6.39)$$

where

nte is the number of tests in the series, ts. The median time-integrated concentration, $\langle IMC_q(i,ts)\rangle$, is obtained from the addition of the distributions of $IMC_q(i,te)$. In most cases, the value of $IMC_q(i,ts)$ is dominated by the contributions from one or two tests.

The distribution of $IMC_q(i,ts)$ can be assumed to be log-normal. As in **Section 4.3**, the geometric mean is calculated, using

$$\langle IMC_q(i,ts)\rangle = \frac{\sum_{te=1}^{nte} m(IMC_q(i,te))}{\sqrt{\left(1 + \frac{\sum_{te=1}^{nte} s^2(IMC_q(i,te))}{\sum_{te=1}^{nte} m(IMC_q(i,te))^2}\right)}} \qquad (6.40)$$

where

$m(IMC_q(i,te))$ and $s^2(IMC_q(i,te))$ are the arithmetic mean and the variance of $IMC_q(i,te)$ and are calculated, using:

$$m(IMC_q(i,te)) = \langle IMC_q(i,te)\rangle \times e^{(0.5 \times \sigma^2(IMC_q(i,te)))} \qquad (6.41)$$

and:

$$s^2(IMC_q(i,te)) = \langle IMC_q(i,te)\rangle^2 \times e^{(\sigma^2(IMC_q(i,te)))} \times (e^{(\sigma^2(IMC_q(i,te)))} - 1) \qquad (6.42)$$

Other parameters of the distribution of $IMC_q(i,ts)$ are:

- its geometric standard deviation, $GSD(IMC_q(i,ts))$:

$$GSD(IMC_q(i,ts)) = e^{(\sigma(IMC_q(i,ts)))} \qquad (6.43)$$

computed using $\sigma(IMC_q(i,ts))$ derived from:

$$\sigma^2(IMC_q(i,ts)) = \ln\left(1 + \frac{\sum_{te=1}^{nte} s^2(IMC_q(i,te))}{\sum_{te=1}^{nte} m(IMC_q(i,te))^2}\right) \qquad (6.44)$$

- its arithmetic mean, $m(IMC_q(i,ts))$:

$$m(IMC_q(i,ts)) = \langle IMC_q(i,ts)\rangle \times e^{0.5 \times \sigma^2(IMC_q(i,ts))} \qquad (6.45)$$

- its variance, $s^2(IMC_q(i,ts))$:

$$s^2(IMC_q(i,ts)) = \langle IMC_q(i,ts)\rangle^2 \times e^{(\sigma^2(IMC_q(i,ts)))} \times (e^{(\sigma^2(IMC_q(i,ts)))} - 1) \qquad (6.46)$$

The parameters for the distributions of $IMC_{vw}(i,ts)$, $IMC_{high}(i,ts)$, and $IMC_{bc}(i,ts)$ are obtained using similar equations.

### 6.1.3. *Calculation of the Time-Integrated Concentrations of $^{131}$I in Each Milk Category From All Tests*

The time-integrated concentration of $^{131}$I in cows' milk of category, q, in county, i, resulting from all tests, is obtained by adding the contributions from each of the eight test series, ts (Ranger, Buster-Jangle, Tumbler-Snapper, Upshot-Knothole, Teapot, Plumbbob, Hardtack, and Underground Era):

$$IMC_q(i) = \sum_{ts=1}^{8} IMC_q(i,ts) \qquad (6.47)$$

The parameters of the distribution of $IMC_q(i)$ are obtained using equations similar to those for $IMC_q(i,ts)$, which were described in **Section 6.1.2:**

- geometric mean, $\langle IMC_q(i)\rangle$:

$$\langle IMC_q(i)\rangle = \frac{\sum_{ts=1}^{8} m(IMC_q(i,ts))}{\sqrt{\left(1 + \frac{\sum_{ts=1}^{8} s^2(IMC_q(i,ts))}{\sum_{ts=1}^{8} m(IMC_q(i,ts))^2}\right)}} \qquad (6.48)$$

where $m(IMC_q(i,ts))$ and $s^2(IMC_q(i,ts))$ are the arithmetic mean and the variance of $IMC_q(i,ts)$ and are determined in *equations 6.45 and 6.46,* respectively.

- geometric standard deviation, $GSD(IMC_q(i))$:

$$GSD(IMC_q(i)) = e^{\sigma(IMC_q(i))} \qquad (6.49)$$

computed using $\sigma(IMC_q(i))$ derived from:

$$\sigma^2(IMC_q(i)) = \ln\left(1 + \frac{\sum_{ts=1}^{s} s^2(IMC_q(i,ts))}{\sum_{ts=1}^{s} m(IMC_q(i,ts))^2}\right) \qquad (6.50)$$

- arithmetic mean, $m(IMC_q(i))$:

$$m(IMC_q(i)) = \langle IMC_q(i)\rangle \times e^{0.5 \times \sigma^2(IMC_q(i))} \qquad (6.51)$$

- variance, $s^2(IMC_q(i))$:

$$s^2(IMC_q(i)) = \langle IMC_q(i)\rangle^2 \times e^{\sigma^2(IMC_q(i))} \times (e^{(\sigma^2(IMC_q(i)))} - 1) \qquad (6.52)$$

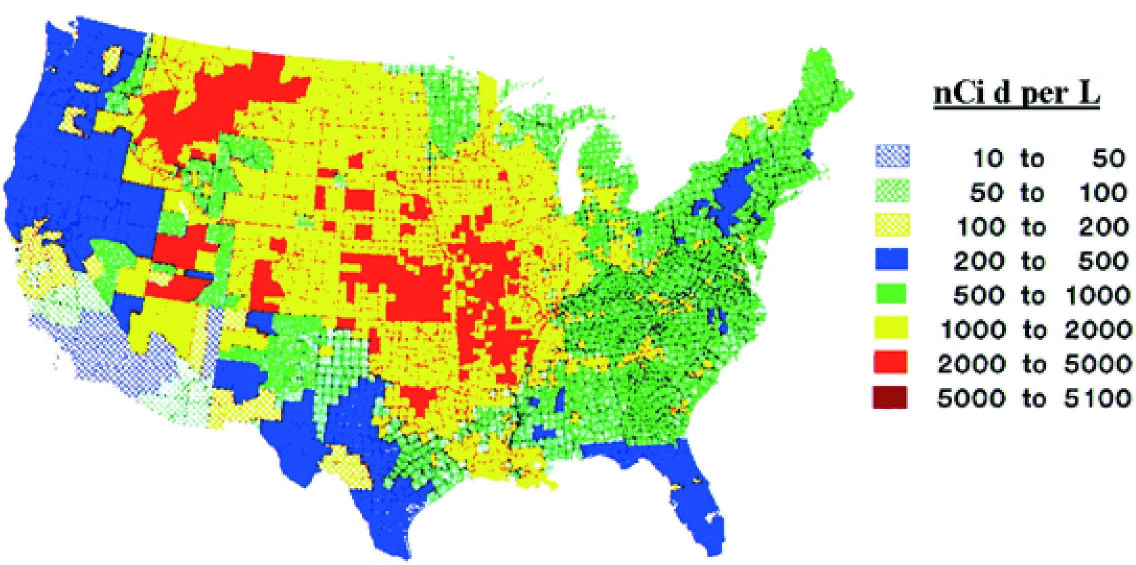
The parameters for the distributions of $IMC_{vw}(i)$, $IMC_{high}(i)$, and $IMC_{bc}(i)$ are obtained using analogous equations.

### *6.1.4. Results*

The estimates of the average time-integrated concentrations of $^{131}I$ for all categories of milk resulting from the deposition of $^{131}I$ in each county of the contiguous United States are tabulated in the Annexes for each test and each test series. For example, **Table UK/7/M** (where UK stands for Upshot-Knothole, 7 represents the seventh test in the series (Simon), and M stands for milk), which is found in Annex UK/7, presents the time-integrated concentrations of $^{131}I$ in fresh cows' milk, milk consumed on farms, milk produced and sold in the county, milk originating from another county of the region, milk originating from another region, milk consumed by the specified "high-exposure" groups, volume-weighted mixed milk, and milk from backyard cows resulting from the shot Simon in all counties of the contiguous United States, along with uncertainty estimates. These uncertainties are characterized by GSDs that are generally in the range from 3 to 5.

*Figure 6.2* presents the estimates of average time-integrated concentrations of $^{131}I$ in volume-weighted mixed milk that are obtained, for each county of the contiguous United States, as a result of all atmospheric tests conducted at the NTS. This figure shows the same general pattern as *Figure 4.25,* related to the time-integrated concentration of $^{131}I$ in fresh cows' milk. Milk was contaminated with $^{131}I$ in all counties of the contiguous U.S. The lowest levels of contamination are estimated to have occurred in southern California, while the highest levels are found not only in locations relatively close to the NTS, like Utah and southern Idaho, but also in places that are farther away, e.g., Kansas, Oklahoma, Missouri, Arkansas, and northern Montana.

**Figure 6.2.** Estimated-integrated concentrations of I-131 in volume weighted milk: All tests.



## 6.2. COWS' MILK CONSUMPTION RATES

The rates of consumption of cows' milk used in this report for the 10 post-natal age and sex groups are derived from the information provided in **Chapter 5.** The age and sex distribution of the population in the US in 1954 *(Table 5.6),* and the distribution and per capita values of the milk consumption rates as a function of age, sex, and area of the country *(Tables 5.4, 5.9, and 5.10)* were used in the analysis.

### *6.2.1. Cows' Milk Consumption Rates of Milk Drinkers*

The median rates of consumption for drinkers of cows' milk in a given age group, k, from a given state, s, (<CR(s,k)>) are obtained using *equation 6.53:*

$$<CR(s,k)> = CR_{pc}(s,k) \times \frac{1}{FMD(k)} \times RM(k) \qquad (6.53)$$

in which:

| | |
|---|---|
| $Cr_{pc}$ (s,k) | is the per capita consumption rate by group, k, in state, s |
| MD(k) | is the fraction of the members of group, k, who drank cows' milk |
| RM(k) | is the ratio of the median to mean consumption rates for age group, k |

Information for infants and older categories is presented in the following subsections.

#### *6.2.1.1. Infants (< 1 y)*

For infants aged 0-2, 3-5, 6-8, and 9-11 months, for which the values of k are 5, 6, 7, and 8, respectively:

- the per capita milk consumption rates are taken from *Table 5.9*; they are assumed to be constant throughout the country;
- the fractions of each of these populations that drank cows' milk are obtained from *Table 5.3*;
- the ratios of the median to mean cows' milk consumption rates are calculated from the data in *Table 5.4*; the distribution for 0 to 1 y infants has been assumed to apply to each of the four groups considered (infants aged 0-2, 3-5, 6-8, and 9-11 months).

The fractions of cows' milk drinkers and the median rates of consumption of cows' milk for these four age groups (k = 5 to 8) are presented in *Table 6.2*. The GSDs associated with the median consumption rates are also listed there.

#### *6.2.1.2. Children (>1 y) and adults*

For children (1-4, 5-9, 10-14 and 15-19 years) (k = 9 to 12), and adults of each sex (k = 13 and 14):

- the per capita milk consumption rates for the entire US are taken from *Table 5.9* and the values for each state are extracted from *Table 5.10*;
- the fractions that drank cows' milk are derived from *Table 5.4*; the aggregated values corresponding to the age and sex groups considered were weighted using the population distribution data presented in *Table 5.6;*
- the ratios of the median to mean cows' milk consumption rates are calculated from the data in *Table 5.4*; here, also, the aggregated values corresponding to the age and sex groups considered were weighted using the population distribution data presented in *Table 5.6*.

The fractions of milk drinkers that drank cows' milk for the groups (k = 9 to 14) and the median consumption rates for the entire U.S. are presented in *Table 6.2*. The values for each state are provided in *Table 6.3*. The geometric standard deviations of the distributions of the consumption rates, also presented in *Table 6.2,* were derived from the distributions shown in *Table 5.4*. These geometric standard deviations also are assumed to apply to the milk consumption rates for each state that is presented in *Table 6.3*.

### *6.2.2. Consumption Rates of Cows' Milk for the "High-Exposure" Groups and for the Groups Drinking Milk From a Backyard Cow*

The milk consumption rates used in this report for the "high-exposure" groups, $CR_{high}$, and for the groups drinking milk from a backyard cow, $CR_{bc}$, correspond to the 95th percentile[1] of the distributions presented in *Table 5.4* of **Chapter 5.** Those values range from 0.8 to 1.4 L $d^{-1}$ and are given for each group in *Table 6.4*. The milk consumption rate for the "high-exposure" groups are assumed to be the same throughout the contiguous U.S.; this assumption is supported by the results of a USDA survey, in which the "high" consumption rates of fresh fluid milk (ninth deciles of per person consumption rates in households) were found to vary over a narrow range (from 0.80 L $d^{-1}$ in the northeast to 0.87 L $d^{-1}$ in the south) (USDA 1960).

### *6.2.3. Consumption Rates of Cows' Milk by Pregnant Women*

Thyroid fetal doses result, in part, from the consumption of $^{131}I$-contaminated milk by the expectant mothers. The milk consumption rate of pregnant women is taken to be 0.8 L $d^{-1}$, corresponding to the 95th percentile of the distribution of milk consumption rates among adult females (shown in *Table 6.4;* derived from data in *Table 5.4*).

[1] This means that 95% of the individuals in the population group considered are expected to have a milk consumption rate lower than $CR_{high}$ and that only 5% of the individuals in that group are expected to have a milk consumption rate greater than $CR_{high}$.

**Table 6.3.** Median milk consumption rates of milk drinkers in each state for the year 1954, according to age and sex, <CR(s,k)>, in L $d^{-1}$. Values for the 0-1 y infants are given in Table 6.2.

| State | Age (years) | | | | Adult male | Adult female |
|---|---|---|---|---|---|---|
| | 1-4 | 5-9 | 10-14 | 15-19 | | |
| Alabama | 0.41 | 0.59 | 0.63 | 0.61 | 0.22 | 0.18 |
| Arizona | 0.48 | 0.69 | 0.74 | 0.71 | 0.26 | 0.21 |
| Arkansas | 0.53 | 0.76 | 0.82 | 0.79 | 0.29 | 0.23 |
| California | 0.61 | 0.88 | 0.94 | 0.91 | 0.34 | 0.27 |
| Colorado | 0.48 | 0.69 | 0.74 | 0.71 | 0.26 | 0.21 |
| Connecticut | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| Delaware | 0.58 | 0.83 | 0.89 | 0.86 | 0.32 | 0.25 |
| District of Columbia | 0.59 | 0.85 | 0.9 | 0.87 | 0.32 | 0.26 |
| Florida | 0.34 | 0.5 | 0.53 | 0.51 | 0.19 | 0.15 |
| Georgia | 0.38 | 0.55 | 0.59 | 0.57 | 0.21 | 0.17 |
| Idaho | 0.69 | 0.99 | 1.06 | 1.02 | 0.38 | 0.3 |
| Illinois | 0.7 | 1.0 | 1.07 | 1.03 | 0.38 | 0.31 |
| Indiana | 0.7 | 1.0 | 1.07 | 1.03 | 0.38 | 0.31 |
| Iowa | 0.7 | 1.0 | 1.07 | 1.03 | 0.38 | 0.31 |
| Kansas | 0.56 | 0.81 | 0.87 | 0.84 | 0.31 | 0.25 |
| Kentucky | 0.57 | 0.82 | 0.88 | 0.85 | 0.32 | 0.25 |
| Louisiana | 0.41 | 0.59 | 0.63 | 0.61 | 0.22 | 0.18 |
| Maine | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| Maryland | 0.58 | 0.83 | 0.89 | 0.86 | 0.32 | 0.25 |
| Massachusetts | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| Michigan | 0.7 | 1.0 | 1.07 | 1.03 | 0.38 | 0.31 |
| Minnesota | 0.73 | 1.05 | 1.12 | 1.08 | 0.4 | 0.32 |
| Mississippi | 0.53 | 0.76 | 0.82 | 0.79 | 0.29 | 0.23 |
| Missouri | 0.53 | 0.76 | 0.82 | 0.79 | 0.29 | 0.23 |

**Table 6.3. cont'd**

| State | Age (years) | | | | Adult male | Adult female |
|---|---|---|---|---|---|---|
| | 1-4 | 5-9 | 10-14 | 15-19 | | |
| Montana | 0.81 | 1.17 | 1.25 | 1.21 | 0.45 | 0.36 |
| Nebraska | 0.65 | 0.93 | 0.99 | 0.96 | 0.36 | 0.28 |
| Nevada | 0.48 | 0.7 | 0.74 | 0.72 | 0.27 | 0.21 |
| New Hampshire | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| New Jersey | 0.58 | 0.83 | 0.89 | 0.86 | 0.32 | 0.25 |
| New Mexico | 0.48 | 0.69 | 0.74 | 0.71 | 0.26 | 0.21 |
| New York | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| North Carolina | 0.44 | 0.63 | 0.67 | 0.65 | 0.24 | 0.19 |
| North Dakota | 0.81 | 1.17 | 1.25 | 1.21 | 0.45 | 0.36 |
| Ohio | 0.66 | 0.95 | 1.02 | 0.98 | 0.36 | 0.29 |
| Oklahoma | 0.53 | 0.76 | 0.82 | 0.79 | 0.29 | 0.23 |
| Oregon | 0.59 | 0.85 | 0.9 | 0.87 | 0.32 | 0.26 |
| Pennsylvania | 0.61 | 0.88 | 0.94 | 0.91 | 0.34 | 0.27 |
| Rhode Island | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| South Carolina | 0.44 | 0.63 | 0.67 | 0.65 | 0.24 | 0.19 |
| South Dakota | 0.81 | 1.17 | 1.25 | 1.21 | 0.45 | 0.36 |
| Tennessee | 0.53 | 0.76 | 0.82 | 0.79 | 0.29 | 0.23 |
| Texas | 0.46 | 0.67 | 0.71 | 0.69 | 0.26 | 0.2 |
| Utah | 0.48 | 0.69 | 0.74 | 0.71 | 0.26 | 0.21 |
| Vermont | 0.72 | 1.04 | 1.11 | 1.07 | 0.4 | 0.32 |
| Virginia | 0.5 | 0.72 | 0.78 | 0.75 | 0.28 | 0.22 |
| Washington | 0.65 | 0.93 | 0.99 | 0.96 | 0.36 | 0.28 |
| West Virginia | 0.44 | 0.63 | 0.67 | 0.65 | 0.24 | 0.19 |
| Wisconsin | 0.7 | 1.0 | 1.07 | 1.03 | 0.38 | 0.31 |
| Wyoming | 0.69 | 0.99 | 1.06 | 1.03 | 0.38 | 0.3 |

**Table 6.2.** Median milk consumption rates of milk drinkers in the population of the contiguous U.S. for the year 1954, according to age and sex, <CR(US,k)>.

| Age group index, k | Age | | Fraction of milk drinkers, FMD(k) | Median consumption rate, <CR(US,k)>, $L\ d^{-1}$ | GSD |
|---|---|---|---|---|---|
| | years | months | | | |
| 5 | | 0-2 | 0.17 | 0.77 | 1.4 |
| 6 | | 3-5 | 0.55 | 0.83 | 1.4 |
| 7 | | 6-8 | 0.90 | 0.78 | 1.4 |
| 8 | | 9-11 | 1.00 | 0.70 | 1.4 |
| 9 | 1-4 | | 0.83 | 0.59 | 1.8 |
| 10 | 5-9 | | 0.78 | 0.84 | 1.8 |
| 11 | 10-14 | | 0.71 | 0.90 | 1.9 |
| 12 | 15-19 | | 0.66 | 0.87 | 2.0 |
| 13 | Adult male | | 0.61 | 0.32 | 2.5 |
| 14 | Adult female | | 0.56 | 0.25 | 2.3 |

**Table 6.4.** Estimates of average daily milk consumption by “high-exposure” groups according to age and sex, derived from the data in Table 5.4.

| Age | | Consumption rate ($L\ d^{-1}$) |
|---|---|---|
| months | years | |
| 0-2 | | 1.3 |
| 3-5 | | 1.4 |
| 6-8 | | 1.3 |
| 9-11 | | 1.2 |
| | 1-4 | 1.2 |
| | 5-9 | 1.2 |
| | 10-14 | 1.4 |
| | 15-19 | 1.3 |
| | > 19 (male) | 1.0 |
| | > 19 (female) | 0.8 |

### *6.2.4. Consumption Rates of Cows' Milk for the "Low-Exposure" Groups*

It is assumed that the "low-exposure" group does not consume any fresh cows' milk, i.e. $CR_{low} = 0$. As shown in **Chapter 5,** this is true for about 30% of the population in any age class on an average day.

## 6.3. DOSE CONVERSION FACTORS

The dose conversion factor, DCF, gives the absorbed dose to the thyroid resulting from a unit activity intake of $^{131}I$ via ingestion. The values of the dose conversion factors for the 10 post-natal age groups are derived from a report prepared by a task group of the Advisory Committee, and is reproduced in **Appendix 6.** The values of the dose conversion factors for the four pre-natal age groups are based on calculations by Zanzonico and Becker (1991). The basis for the dose conversion factors is discussed below.

### *6.3.1. Post-Natal Age Groups*

Iodine-131, when ingested in a water-soluble form, usually iodide, is readily absorbed into the blood from the gastrointestinal tract. Circulating iodide is removed rapidly by both the thyroid and the kidneys. Iodine, an essential trace element, is a component of hormones produced and stored within the thyroid gland. The thyroid hormones, thyroxine (tetraiodothyronine) and triiodothyronine, are required for normal growth, development, and metabolism.

The doses resulting from the intake of $^{131}I$ via ingestion are at least 1000 times greater in the thyroid gland than in any other radiosensitive organ or tissue in the body (ICRP 1989) because: (a) $^{131}I$ concentration in the thyroid is much greater than in any other organ, and (b) a substantial fraction of the energy released during the decay of $^{131}I$ *(Figure 6.3 and Table 6.5)* is absorbed locally. Only thyroid doses are calculated in this report.

The calculation of thyroid doses from $^{131}I$ requires the assignment of numeric values to various biologic parameters that influence the $^{131}I$ concentration within the thyroid. Those parameters include the fractional uptake by the thyroid of iodine from the bloodstream, the mass of the thyroid gland, and the retention of $^{131}I$ by the thyroid. Estimated values of those parameters are provided for various ages in **Appendix 6,** along with the methodology used in this report to calculate the dose conversion factors.

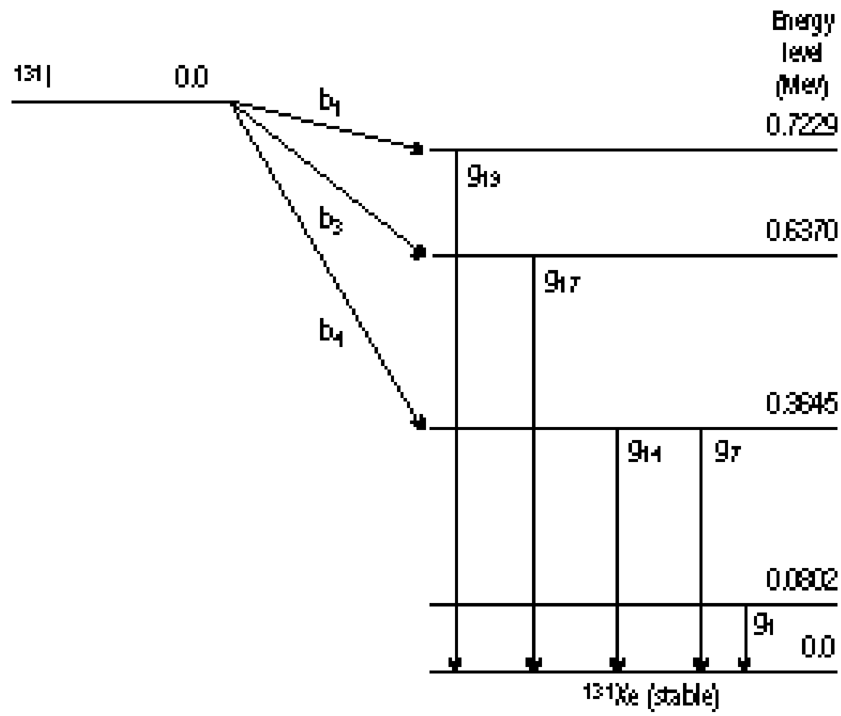
Following a single intake of A (nCi) of $^{131}I$ by ingestion by an individual in age group, k, a fraction, f(k), of the activity is transferred to the thyroid where it is distributed in the mass of the thyroid, $m_{th}(k)$. Assuming that the transfer to the thyroid is

**Table 6.5.** Energies and intensities of the main transitions involved in the decay of $^{131}I$ (ICRP 1983). The corresponding decay scheme of $^{131}I$ is shown in Figure 6.3.

| Radiation | Intensity $(Bq\ s)^{-1}$ | Energy (Mev) |
|---|---|---|
| $\beta^-_1$ | 0.0213 | 0.06935[a] |
| $\beta^-_3$ | 0.0736 | 0.0960[a] |
| $\beta^-_4$ | 0.894 | 0.1915[a] |
| $\gamma_1$ | 0.0262 | 0.0802[a] |
| $\gamma_7$ | 0.0606 | 0.2843 |
| $\gamma_{14}$ | 0.812 | 0.3645 |
| $\gamma_{17}$ | 0.0727 | 0.6370 |
| $\gamma_{19}$ | 0.0180 | 0.7229 |

[a] Average beta particle energy.

**Figure 6.3.** Simplified decay scheme of $^{131}I$ (ICRP 1983). The energy and intensity of each transition are given in Table 6.5.




instantaneous, the maximum concentration of $^{131}I$ in the thyroid, $C_{th}(k)$, in nCi $g^{-1}$, is:

$$C_{th}(k) = A \times \frac{f(k)}{m_{th}(k)} \qquad (6.54)$$

where:

A = activity intake of $^{131}I$ (nCi),

f(k)= fractional uptake of $^{131}I$ by the thyroid from the blood of an individual in age group k, and

$m_{th}$ (k)= mass of the thyroid (g) of an individual in group, k.

As indicated in **Appendix 6**, the standard radiobiological equation for calculating the dose from an internally deposited radionuclide is:

$$D(k) = C_{th}(k) \times T_{eff}(k) \times (73.8 \times E_{\beta} + 0.0346\,\Gamma \times g) \qquad (6.55)$$

where:

D(k)= the total dose from beta and gamma irradiation (mrad)

$C_{th}(k)$= the maximum concentration of $^{131}I$ in the thyroid (nCi $g^{-1}$)

$T_{eff}(k)$= the effective half-life of $^{131}I$ in the thyroid, d, calculated using $(T_b(k) \times T_r)/(T_b(k) + T_r)$, where $T_b(k)$ and $T_r$ are the biological half-life for group k and the physical half-life of $^{131}I$, respectively

$E_{\beta}$= the average energy (0.18 Mev per disintegration) of beta rays resulting from the decay of $^{131}I$,

$\Gamma$ = the specific gamma-ray constant for $^{131}I$ (2.2 R $h^{-1}$ per mCi at 1 cm), and

g= the average geometrical factor for the thyroid, equal to 3r for spheres with radii, r, less than 10 cm.

Substitution of $C_{th}(k)$ from *equation 6.54* and other defined quantities into *equation 6.55* yields:

$$D(k) = A \times \frac{f(k)}{m_{th}(k)} \times \frac{T_b(k) \times T_r}{T_b(k) + T_r} \times (13.3 + 0.717 \times r) \qquad (6.56)$$

The dose conversion factor for an age group, DCF(k), (rad $\mu Ci^{-1}$) is the thyroid dose per unit activity intake and is obtained from *equation 6.56:*

$$DCF(k) = \frac{D(k)}{A} = \frac{f(k)}{m_{th}(k)} \times \frac{T_b(k) \times T_r}{T_b(k) + T_r} \times (13.3 + 0.717 \times r) \qquad (6.57)$$

The parameter values needed to calculate DCF with this equation were interpolated to the mid-point of each age range considered from data contained in **Appendix 6.** All parameter values were linearly interpolated with the exception of the fractional uptake (f) between 0 and 3 months, for which a linear decrease was assumed from age 0 (value: 0.6) to age 2 weeks (value: 0.25), followed by a constant value between 2 weeks and 3 months. The parameter values obtained for each post-natal age group (k = 5 to 14) are presented in *Table 6.6.* The resulting thyroid doses per unit activity intake via ingestion are given in *Table 6.7.* These dose conversion factors are in reasonably good agreement with the dose conversion values for similar age ranges recommended by the ICRP (ICRP 1989).

The thyroid doses per unit activity intake via inhalation are taken to be equal to those via ingestion. This is likely to be a conservative assumption, especially for $^{131}I$ attached to particles (ICRP 1995). However, this assumption has a relatively small impact on the thyroid doses, as the intakes via inhalation are usually much smaller than those resulting from ingestion.

### 6.3.2. Pre-Natal Age Groups

Thyroid doses to the fetus are more difficult to estimate than those to infants and older persons mainly because of: (a) the exchange of iodine between the maternal and fetal circulations, and (b) the rapid changes with gestational age of the fetal thyroid mass and uptake.

The critical event in the fetal thyroid exposure to $^{131}I$ is the onset of its ability to accumulate iodine; before it is capable of such accumulation, the fetal thyroid dose is approximately equivalent to the fetal whole-body dose, which is very small (a few millirad per microcurie) and is neglected in this report (USNRC 1992; Zanzonico and Becker 1991). The onset of iodine accumulation by the fetal thyroid occurs between the 12th and 15th week of gestation (Book and Goldman 1975; Chapman et al. 1948; Evans et al. 1967; Hodges et al. 1955). Expressed as percentage of total $^{131}I$ intake by the mother, fetal thyroid uptake remains very low (from 0.003 to 0.4%) through the 18th to the 22nd week, and appears to increase to a maxi-

**Table 6.6.** Metabolic and anatomic parameters used in calculations of radiation doses to the thyroid gland for post-natal age groups. Uptake and mass data are estimated for pre-1960 values.[a]

| Age and sex | Parameter | | | | |
|---|---|---|---|---|---|
| | Thyroid uptake fraction, f | Thyroid mass, $m_{th}$ (g) | Quotient $f/m_{th}$ ($g^{-1}$) | Thyroid radius, r (cm) | Biological half-life $T_b$(d) |
| Infant 0-2 mo | 0.279 | 1.56 | 0.179 | 0.57 | 24 |
| Infant 3-5 mo | 0.25 | 1.69 | 0.148 | 0.58 | 31 |
| Infant 6-8 mo | 0.25 | 1.81 | 0.138 | 0.60 | 39 |
| Infant 9-11 mo | 0.25 | 1.94 | 0.129 | 0.61 | 46 |
| Child 1-4 [a] | 0.25 | 3.00 | 0.083 | 0.70 | 65 |
| Child 5-9 [a] | 0.25 | 6.25 | 0.040 | 0.89 | 80 |
| Child 10-14 [a] | 0.25 | 9.75 | 0.026 | 1.05 | 85 |
| Child 15-19 [a] | 0.25 | 14.00 | 0.018 | 1.18 | 90 |
| Adult male | 0.23 | 18.00 | 0.013 | 1.29 | 90 |
| Adult female | 0.27 | 16.00 | 0.017 | 1.24 | 90 |

[a] Derived from **Appendix 6.**

**Table 6.7.** Calculated thyroid doses per unit activity intake (DCF, mrad $nCi^{-1}$) for the age and sex groups considered in the assessment.

| Age group index, k | Age and Sex | | Thyroid dose per unit intake (DCF, mrad $nCi^{-1}$) |
|---|---|---|---|
| 1 | Fetus: | 0-10 wk | 0.a |
| 2 | | 11-20 wk | 2.7[a] |
| 3 | | 21-30 wk | 3.8[a] |
| 4 | | 31-40 wk | 1.7[a] |
| 5 | Infant: | 0-2 mo | 15[b] |
| 6 | | 3-5 mo | 13[b] |
| 7 | | 6-8 mo | 13[b] |
| 8 | | 9-11 mo | 12[b] |
| 9 | Child: | 1-4 y | 8.2[b] |
| 10 | | 5-9 y | 4.1[b] |
| 11 | | 10-14 y | 2.6[b] |
| 12 | | 15-19 y | 1.9[b] |
| 13 | Adult male | | 1.3[b] |
| 14 | Adult female | | 1.8[b] |

[a] Based on Zanzonico and Becker (1991); values are referenced to the mother's intake.
[b] Computed using *equation 6.57* and parameters in *Table 6.6*.

mum at term of no more than 2 to 3% (Dyer and Brill 1972; Evans et al. 1967; Morreale de Escobar and Escobar del Rey 1988).

Many measurements of fetal thyroid mass at different gestational ages have been reported (Evans et al. 1967; Mochizuki et al. 1963). The thyroid gland, which weighs only 0.001 to 0.002 g by the 9th week, grows rapidly and weighs approximately 0.005 g at 12 weeks, 0.05 g at 13 weeks, 0.1 to 0.3 g at 20 weeks, 0.2 to 0.6 g at 24 weeks, and 1 to 1.5 g at term.

The fetal thyroid dose is, as a first approximation, directly proportional to the quotient of the fetal uptake and of the fetal thyroid mass. This quotient, expressed as percent of $^{131}I$ intake per gram of fetal thyroid tissue, seems to be about 0.2% per g at 12 to 16 weeks of gestational age, to reach a maximum of about 1% per g at 20 to 28 weeks, and to decrease thereafter to about 0.2% per g at term because the mass of the thyroid gland increases more rapidly than the uptake (Zanzonico and Becker 1991).

The fetal thyroid dose estimates used in this report are based on the calculations of Zanzonico and Becker (1991), who adapted a whole-body compartmental model of iodine in a pregnant woman initially developed by Johnson (1982) (*Figure 6.4*). Zanzonico and Becker (1991) assumed that all of the $^{131}I$ intake is initially in the maternal and fetal inorganic iodine compartment and varied the exchange rates corresponding to input into and output from the maternal thyroid in order to yield a 24-hour maternal thyroid uptake of 25% and a biologic half-time of residence of iodine in the maternal thyroid of 100 days (assumed average values for a euthyroid mother). A slow transplacental exchange between the fetal and maternal organic iodine (protein-bound iodine (PBI)) compartments was introduced and the corresponding exchange rates adjusted to yield a protein-bound $^{131}I$ plasma concentration in the fetus equal to 5% of that in the mother prior to the onset of fetal thyroid function (Morreale de Escobar and Escobar del Rey 1988). Using the formulas of Johnson (1982), the variation in fetal uptake with age was modeled by gestational age-dependent exchange rates corresponding to input into and output from the fetal thyroid. All other exchange rates used by Zanzonico and Becker are from Johnson (1982).

The fetal thyroid doses were calculated by Zanzonico and Becker (1991) for several pre-natal ages on the basis of the $^{131}I$ activities in the fetal thyroid obtained with the model. The variation with gestational age of the fetal thyroid mass and of the fraction of $^{131}I$ energy absorbed by the fetal thyroid were taken into account. In the dose calculations, the compartmental exchange rates and the mass of the fetal thyroid were fixed at their respective values at the time of the $^{131}I$ administration; this means that both gestational age-dependent changes in fetal thyroid function and fetal growth subsequent to the $^{131}$I administration were ignored.

Estimates of fetal thyroid doses as a function of gestational age are plotted in *Figure 6.5*. For the purposes of this report, fetal thyroid doses have been averaged over time periods of 10 weeks; the results are presented in *Table 6.7*.

### *6.3.3. Uncertainties*

The DCF values presented in *Table 6.7* are those used in the dose assessment for all population groups in a given age and sex class. It should be noted that they are representative of the 1950s and that current values would be expected to be lower, mainly because of an increase in the dietary intake of stable iodine during the last 30 years. Geographical variations across the United States were not considered in **Appendix 6,** because goitrogenic regions, which would have led to larger than "normal" thyroid glands, were eliminated from the United States before 1940.

When evaluating uncertainties, care must be taken in utilizing the tabled dosimetric estimates, since they reflect the biological estimates used in their development. There is considerable variation in the anatomic and physiologic characteristics of the human thyroid gland, making an accurate description of any single thyroid difficult, particularly in retrospect. It must be recalled, however, that the three biologic parameters influencing the dose (fractional uptake, effective half-time of $^{131}$I in the thyroid, and thyroid mass) are interrelated. Conditions resulting in an increased iodine uptake for example, may result in an increased thyroid size and a decreased effective half-time. The resulting interplay would offset the impact of each component of the dose equation on the results and would tend to return the estimate toward the central value **(Appendix 6).** Dunning and Schwarz (1981) estimated that the dose conversion factors for ingestion $^{131}$I are log-normally distributed with a GSD of 1.8. It is assumed in this report that the dose conversion factors are log-normally distributed with a GSD of 1.8 for all age groups.

For a given intake of $^{131}$I by ingestion, it is shown in *Table 6.7* that the highest thyroid absorbed doses are received by infants less than 2 months old. The lowest DCF is for group

**Figure 6.4.** Whole-body compartment model of iodine in a pregnant woman (Zanzonico and Becker 1991).

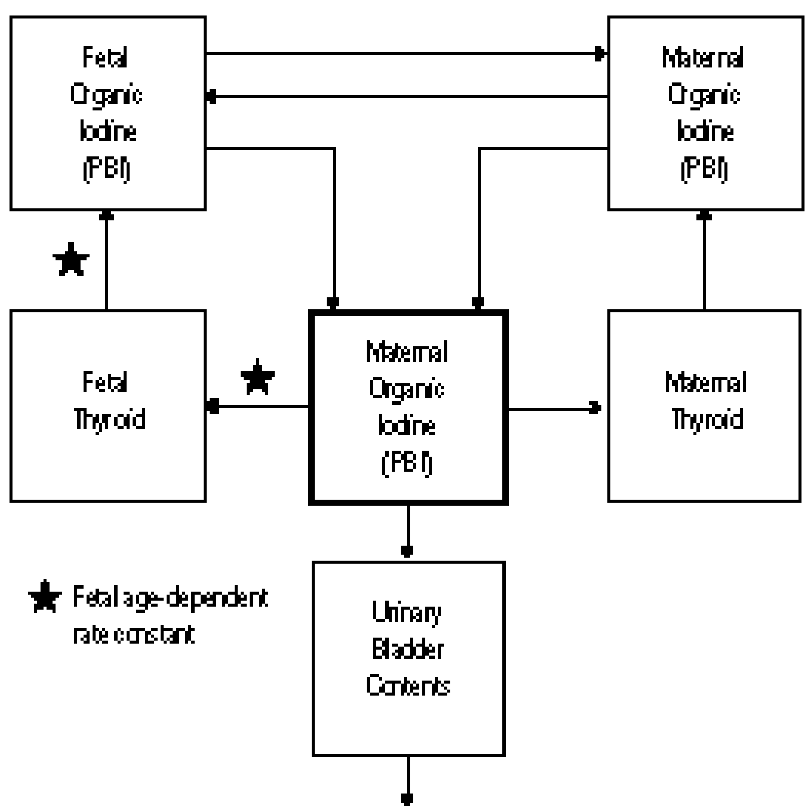
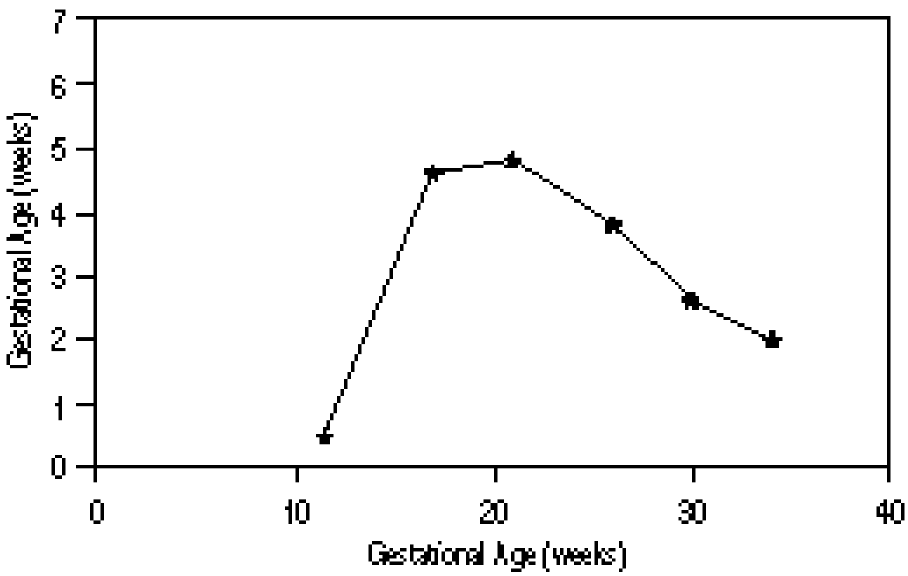


**Figure 6.5.** Fetal thyroid dose conversion factor for gestational ages, from exposure to $^{131}$I ingested by a euthyroid mother (Zanzonico and Becker 1991).




13, the adult male. Doses to the fetus (four age groups) per unit intake by the mother have also been calculated and found to be smaller than those to infants.

## 6.4. ESTIMATED THYROID DOSES FROM INGESTION OF COWS' MILK

The methodology used in the report to estimate thyroid doses to population groups and collective thyroid doses from ingestion of cows' milk is briefly summarized below. It should be noted that the thyroid doses resulting from ingestion of cows' milk are only one component, but usually the most important component, of the total thyroid doses. Other components (discussed in **Chapter** 7) are the inhalation of $^{131}$I-contaminated air and the ingestion of other foodstuffs contaminated with $^{131}$I. Only the total thyroid dose estimates are tabulated for each test and each county in the Annexes and Sub-annexes of this report. However, an exception is made for the collective and per capita thyroid doses from ingestion of cows' milk, averaged over all age groups and both sexes for each county and each test, which are presented in the Sub-annexes. (Note that the units of dose in those tables are rad; 1 rad = 1000 mrad.) For the sake of brevity, none of the other detailed estimates of thyroid doses resulting from the ingestion of $^{131}$I-contaminated cows' milk are provided in the report; however, they can be readily calculated using the equations given below in this section. **Chapter 8** provides a discussion of the methodology and exposure scenarios used to calculate the total thyroid doses, and examples of the results.

### *6.4.1. Thyroid Doses From a Given Test*

#### *6.4.1.1. Doses to milk drinkers of differing age, sex, and location*

The median doses resulting from ingestion of cows' milk, $\langle D_{mc} (i, k, te)\rangle$, due to fallout from a given test, te, received by milk drinkers of a given age and sex group, k, living in a county, i, are estimated as:

$$\langle D_{mc} (i,k,te)\rangle = \langle IMC_{vw} (i,te)\rangle \times CR(i,k)\rangle \times DCF(k)\rangle \qquad (6.58)$$

where:

$\langle IMC_{vw}(i,te)\rangle$ is the geometric mean of the volume-weighted time-integrated $^{131}$I concentration in milk consumed in county, i, after test, te,

$\langle CR(i,k)\rangle$ is the median consumption rate of cows' milk by milk drinkers of a given age and sex group, k, living in county, i, and

$\langle DCF(k)\rangle$ is the median dose conversion factor for the given age and sex group, k.

**Table 6.8.** Variation with age and sex of the median milk consumption rate for milk drinkers, of the fraction of milk drinkers, of the median dose conversion factor, and of the median dose over the population of the contiguous U.S. in 1954 for a unit time-integrated concentration of $^{131}I$ in milk consumed.

| Group index, k | Age and sex | Milk consumption rate of milk drinkers, <CR(US,k)> ($L\ d^{-1}$)[a] | Fraction of milk drinkers FMD (k)[a] | Dose conversion factor, DCF ($mrad\ nCi^{-1}$)[b] | Dose per unit contamination of milk ($mrad$ per $nCi\ d\ L^{-1}$) |
|---|---|---|---|---|---|
| FETUS | | | | | |
| 1 | 0-10 wk | 0.8[c] | 0.56[d] | 0[e] | 0 |
| 2 | 11-20 wk | 0.8[c] | 0.56[d] | 2.7[e] | 1.2 |
| 3 | 21-30 wk | 0.8[c] | 0.56[d] | 3.8[e] | 1.7 |
| 4 | 31-40 wk | 0.8[c] | 0.56[d] | 1.7[e] | 0.8 |
| INFANT | | | | | |
| 5 | 0-2 mo | 0.77 | 0.17 | 15 | 2.0 |
| 6 | 3-5 mo | 0.83 | 0.55 | 13 | 5.9 |
| 7 | 6-8 mo | 0.78 | 0.90 | 13 | 8.4 |
| 8 | 9-11 mo | 0.70 | 1.0 | 12 | 8.4 |
| CHILD | | | | | |
| 9 | 1-4 y | 0.59 | 0.83 | 8.2 | 4.0 |
| 10 | 5-9 y | 0.84 | 0.78 | 4.1 | 2.7 |
| 11 | 10-14 y | 0.90 | 0.71 | 2.6 | 1.7 |
| 12 | 15-19 y | 0.87 | 0.66 | 1.9 | 1.1 |
| ADULT | | | | | |
| 13 | Male | 0.32 | 0.61 | 1.3 | 0.3 |
| 14 | Female | 0.25 | 0.56 | 1.8 | 0.3 |

[a] From *Table 6.2.*
[b] From *Table 6.7.*
[c] Milk consumption rate of the mother.
[d] Fraction of milk drinkers in the group of expectant mothers (average value for adult females; k = 14).
[e] Dose to fetal thyroid per unit activity ingestion by mother.

The values of $<IMC_{vw}(i,te)>$ are derived from the time-integrated concentrations for each category of milk $<IMC_{q}(i,te)>$, as shown in *equation 6.29*. The milk consumption rates <CR(i,k)> are taken from *Tables 6.2 and 6.3*. It should be kept in mind that milk consumption rates vary considerably from one individual to another and that only central values of the intakes of $^{131}$I from ingestion are considered here. The values of the dose conversion factors <DCF(k)> are presented in *Table 6.7*.

*Table 6.8* presents, for each age and sex group, estimates of the product of: (a) the median milk consumption rate, <CR(k)>, for milk drinkers in the U.S. population (*Table 6.2*); (b) the fraction of milk drinkers, FMD(k) (Table 6.2); and (c) the median dose conversion factor, <DCF(k)> (*Table 6.7*). If a constant time-integrated concentration of $^{131}$I in milk consumed by all age and sex groups in a county is assumed, this product is proportional to the average dose received by the age and sex groups. The 6-11 month-old infants are estimated to receive, on average, the highest doses (8.4 mrad per nCi d $L^{-1}$), whereas the lowest estimated doses (0.3 mrad per nCi d $L^{-1}$) are received by adults and are 4% of the highest doses. The per capita thyroid dose per unit time-integrated concentration of $^{131}$I in cows' milk is 3.4 mrad per nCi d $L^{-1}$.

### *6.4.1.2. Doses to the "high-exposure" groups*

The median thyroid doses to the "high-exposure" groups, $<D_{mc,high}(i,k,te)>$, are estimated using the median dose conversion factors defined above and the milk concentrations and consumption rates appropriate for these groups.

$$<D_{mc,high}(i,k,te)> = <IMC_{high}(i,te)> \times CR_{high}(i,k) \times <DCF(k)> \qquad (6.59)$$

where:

- the value of $<IMC_{high}(i,te)>$ is the highest time-integrated concentration of $^{131}$I calculated in the four milk categories, q, in county, i, and test, te. The estimates obtained for each county of the contiguous United States are presented in the Annexes for each test and each test series,

**Table 6.9.** Variation with age and sex of the median dose to the "high-exposure" groups for a unit time-integrated concentration of $^{131}$I in milk consumed by each group.

| Group index, k | Age and sex | Dose per unit contamination of milk (mrad per nCi d $L^{-1}$)[a] |
|---|---|---|
| | FETUS | |
| 1 | 0-10 wk | 0[b] |
| 2 | 11-20 wk | 2.2[b] |
| 3 | 21-30 wk | 3.0[b] |
| 4 | 31-40 wk | 1.4[b] |
| | INFANT | |
| 5 | 0-2 mo | 20 |
| 6 | 3-5 mo | 18 |
| 7 | 6-8 mo | 17 |
| 8 | 9-11 mo | 14 |
| | CHILD | |
| 9 | 1-4 y | 9.8 |
| 10 | 5-9 y | 3.2 |
| 11 | 10-14 y | 3.6 |
| 12 | 15-19 y | 2.5 |
| | ADULT | |
| 13 | Male | 1.3 |
| 14 | Female | 1.4 |

[a] Computed using milk consumption rates in *Table 6.4* and dose conversion factors in *Table 6.8.*
[b] Based upon milk consumption rate of the mother.

- the values of $CR_{high}(i,k)$, which correspond to the 95th percentiles of the distributions presented in *Table 5.4* of **Chapter 5,** range from 0.8 to 1.4 L $d^{-1}$ and are shown in *Table 6.4.*

For a specific time-integrated concentration of $^{131}I$ in milk, $<IMC_{high}(i,te)>$ the products of the milk consumption rates, $<CR_{high}(i.k)>$, (*Table 6.4*) and the dose conversion factors, $<DCF(te)>$, (*Table 6.7*) for all age groups are given in *Table 6.9.* Review of the results shows that the most exposed group consists in this case of 0-2 month old infants. It is emphasized that these results represent approximations to the doses to the most exposed groups. Individual doses may not be the same because of differences in milk consumption rates or dose conversion factors.

### 6.4.1.3. Doses to the "low-exposure" groups

It is assumed that the "low-exposure" groups do not consume any fresh cows' milk, i.e. $CR_{low}(i,k) = 0$. The estimates of the doses due to contamination of cows' milk are therefore equal to zero, irrespective of the time-integrated $^{131}I$ concentrations in fresh cows' milk.

### 6.4.1.4. Doses to the groups drinking milk from backyard cows

Assumptions about the feeding, pasturage, and milk transfer coefficients for backyard cows are given in Chapter 4. Backyard cows are assumed to consume 8 kg (dry matter) of pasture and 3 kg (dry matter) of concentrates during the pasture season. The duration of the pasture season for the backyard cows is assumed to be longer by 2 months than that for dairy cows. The median time-integrated concentrations of $^{131}I$ in milk from backyard cows, $<IMC_{bc}(i,te)>$, estimated for each county, i, are presented in the Annexes for each test, te.

It is assumed that the people drinking milk from backyard cows have "high" consumption rates of milk. These rates are described above and listed in *Table 6.4*. The median doses to the age and sex group, k, located in county, i, following test, te, and drinking milk from backyard cows, $<D_{mc,bc}(i,k,te)>$, are estimated using the median dose conversion factors discussed above and the following equation:

$$<D_{mc,bc}(i,k,te)> = <IMC_{bc}(i,te)> \times CR_{high}(i,k) \times <DCF(k)> \qquad (6.60)$$

### 6.4.1.5. Collective and per capita doses

The collective dose, $CD_{mc}(i,te)$, received by the population of county, i, from $^{131}I$ deposition after a test, te, is the sum of the doses received by all individuals in that population. The collective dose received by the population of a county is estimated by computing the sum of the collective doses received by each of the 10 post-natal age groups (k = 5 to 14), estimated in turn as the products of the arithmetic mean doses received by milk drinkers, $m(D_{mc}(i,k,te))$, the average fraction of milk drinkers in the groups, FMD(k), and the population sizes of the age groups in the county, POP(i,k). The equation is:

$$CD_{mc}(i,te) = \sum_{k=5}^{k=14} m(D_{mc}(i,k,te)) \times FMD(k) \times POP(i,k) \qquad (6.61)$$

The mean doses, $m(D_{mc}(i,k,te))$ are derived from the median thyroid dose for milk drinkers, $<D_{mc}(i,k,te)>$, and from the geometric standard deviation of the thyroid dose distribution using:

$$m(D_{mc}(i,k,te)) = <D_{mc}(i,k,te)> \times e^{0.5 \times \sigma^2(D_{mc}(i,k,te))} \qquad (6.62)$$

The variance, with $\sigma^2(D_{mc}(i,k,te))$, is completed using:

$$\sigma^2(D_{mc}(i,k,te)) = (\sigma^2(IMC_{vw}(i,te)) + \sigma^2(CR(i,k)) + \sigma^2(DCF(k)))^{0.5} \qquad (6.63)$$

The collective dose, $CD_{mc}(US,te)$, received by the population of the entire U.S. from $^{131}I$ deposition in a test, te, can be calculated in turn as the sum of collective doses received by the population of each of the 3,094 counties and subcounties. The summation over the counties is:

$$CD_{mc}(US,te) = \sum_{i} CD_{mc}(i,te) \qquad (6.64)$$

The contribution of each age and sex group to the collective dose can be estimated by computing the product of the population fraction, the fraction of milk drinkers, the dose conversion factor, and the milk consumption rate for each group. The product of the last three terms was already presented in *Table 6.8*. *Table 6.10* includes those results, the population fractions from *Table 5.9,* and the products of all four terms for infants, children, and adults. The last column of *Table 6.10* shows the relative contributions of each age and sex group. The largest contribution to the collective dose (about 30%) is from children aged 1-4 years. The adults, which represent more than 60% of the population, contribute less than 20% to the collective dose.

**Table 6.10.** Relative variation with age and sex of the collective thyroid dose for the population of the contiguous U.S. in 1954 for a unit time-integrated concentration of $^{131}I$ in consumed milk.

| Group index, k | Age and sex | Dose per unit contamination of milk (mrad per nCi d $L^{-1}$)[a] | Population fraction, FPOP(k)[b] | Contribution to collective dose to thyroids[c] | Relative contribution to the collective thyroid dose (%) |
|---|---|---|---|---|---|
| INFANT | | | | | |
| 5 | 0-2 mo | 2.0 | 0.0055 | 0.011 | 1 |
| 6 | 3-5 mo | 5.9 | 0.0055 | 0.033 | 3 |
| 7 | 6-8 mo | 8.4 | 0.0055 | 0.046 | 4 |
| 8 | 9-11 mo | 8.4 | 0.0055 | 0.046 | 4 |
| CHILD | | | | | |
| 9 | 1-4 y | 4.0 | 0.088 | 0.352 | 30 |
| 10 | 5-9 y | 2.7 | 0.095 | 0.257 | 22 |
| 11 | 10-14 y | 1.7 | 0.083 | 0.141 | 12 |
| 12 | 15-19 y | 1.1 | 0.072 | 0.079 | 7 |
| ADULT | | | | | |
| 13 | Male | 0.3 | 0.31 | 0.093 | 8 |
| 14 | Female | 0.3 | 0.33 | 0.099 | 9 |
| | | Totals | 1.0 | 1.157 | 100 |

[a] From *Table 6.8.*
[b] From *Table 5.9* in **Chapter 5.**
[c] Product of columns three and four; units are mrad per nCi d $L^{-1}$.

The per capita dose, $D_{mc,pc}(i,te)$, in county, i, resulting from a test, te, is calculated as the quotient of the collective dose, $CD_{mc}(i,te)$, and of the population of the county:

$$D_{mc,pc}(i,te) = \frac{CD_{mc}(i,te)}{\sum_{k=5}^{k=14} POP(i,k)} \qquad (6.65)$$

The per capita dose to the entire U.S. population for a particular test, te, is the ratio of the collective dose $CD_{mc}$ (US, te), given in *equation 6.63,* to the total population of the country. Estimates of collective and per capita thyroid doses due to the ingestion of $^{131}$I-contaminated cows' milk are presented in the Sub-annexes for each test, for the population of each county, and for the entire population of the contiguous United States. (Note that the units of dose in those tables are rad; 1 rad = 1000 mrad.)

### 6.4.2. Thyroid Doses From A Given Test Series

The median thyroid doses in a population group due to the consumption of cows' milk contaminated by $^{131}$I as a result of a given test series can be estimated by computing the products of: (a) the median time-integrated $^{131}$I concentrations for the test series in the cows' milk consumed by the population group considered, $<IMC_{vw}(i,ts)>$, (b) the median milk consumption rate for the population group, $<CR(i,k)>$, and (c) the median dose conversion factor, $<DCF(k)>$, for the population group considered. For example, the median thyroid dose due to the consumption of cows' milk contaminated as the result of $^{131}$I fallout during the test series, ts, in county, i, among the population of milk drinkers in age group, k, is calculated as:

$$<D_{mc}(i,k,ts)> = <IMC_{vw}(i,ts)> \times <CR(i,k)> \times <DCF(k)> \qquad (6.66)$$

However, this estimate is valid only if it is assumed that:

- the population remained stable during the test series (no births, deaths, or population movement in and out of the county, which is probably unrealistic), and
- the individuals remained in the same age group during the test series (this is not the case for the infants for most of the test series).

For individuals who changed residence or age group between tests of a test series, the thyroid dose from the test series is calculated by combining the thyroid doses from each test in the series and using the appropriate age-dependent parameter values for each test. A detailed presentation of such calculations is provided in **Chapter 9.**

### 6.4.3. Thyroid doses from all tests

The average thyroid doses in a given age group due to the consumption of milk contaminated by $^{131}$I as a result of all tests cannot be obtained by adding the contributions from each of the eight test series (Ranger, Buster-Jangle, Tumbler-Snapper, Upshot-Knothole, Teapot, Plumbbob, Hardtack, and Underground Era). Such an approach presupposes that:

- the population in that age group remained stable during the entire testing era (no population transfer in and out of the county), and
- the individuals remained in the same age group during the entire testing era (this is not the case for most age groups).

In this report, only per capita and collective doses from all tests are calculated for the population of each county.

The calculation of individual thyroid doses from all tests can be carried out by combining the thyroid doses from each test series and using the appropriate parameter values for each test series. A detailed example of such calculations is provided in **Chapter 9.**

## 6.5. SUMMARY

- Median thyroid doses resulting from the ingestion of cows' milk contaminated with $^{131}$I are estimated as the products of the time-integrated concentrations of $^{131}$I in milk, of the milk consumption rates, and of the dose conversion factors for ingestion of $^{131}$I in milk appropriate for the population group considered.
- The population in each county has been divided into 14 age and sex groups (four stages during fetal development, four groups for infants less than one year old, four age groups for children and teenagers, one group for adult males, and one group for adult females). Median thyroid doses have been calculated for each age and sex groups for: (a) the population that drink cows' milk, (b) specified "high-exposure" groups, with a high consumption rates of cows' milk containing a higher-than-average $^{131}$I concentration, (c) specified "low-exposure" groups (non-milk drinkers), and (d) the group that drank milk from backyard cows.
- For a given intake of $^{131}$I, the highest average thyroid dose is delivered to the 0-2 month infant, while the lowest average thyroid dose is received by the adult male.
- The methodology used to estimate collective and per capita doses received by the population of each county and by the population of the entire U.S. as a result of the deposition of $^{131}$I on the ground following each test also has been presented.

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