ANNUAL DOSE AT THE EXCLUSION AREA BOUNDARY OF A MULTI-UNIT CANDU® SITE

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1. INTRODUCTION

The annual dose to members of the public from CANDU nuclear power stations is dominated by the contribution from airborne effluents. The principal radionuclides contributing to the annual dose are tritium, carbon-14 and noble gases. The tritium is released as tritiated heavy-water vapour; the carbon-14 is released principally as carbon dioxide.

Currently, the Canadian limit on dose to the most exposed member of the public is 5000 μSv/a, but this is about to change as Canada adopts the 1991 recommendation of the International Commission on Radiological Protection (ICRP 60) [1], which reduces the value to 1000 μSv/a. In Canada, the licensee has undertaken to release activity that would deliver no more than 50 μSv/a in each radionuclide pathway and this undertaking becomes part of the license.

This undertaking can be interpreted in two ways: either the dose from the emissions in the 7 airborne and waterborne pathways will total less than 50 μSv/a, or each type of emission will contribute no more than 50 μSv/a, for a total of 350 μSv/a. In practice, the emissions experienced at CANDU nuclear power plant sites correspond to public doses that are well below either the old Canadian or the more recent international public dose limit. However, in its off-shore marketing and licensing work, AECL needs to demonstrate compliance with a public dose limit of 250 μSv/a. For such a dose limit, one of the interpretations given above would be unacceptable. Thus in marketing CANDU products offshore, AECL must demonstrate that the most exposed member of the public receives no more than 250 μSv/a. For a multi-unit site, the demonstration must include the contribution from each unit. In addition, there is, offshore, more ready acceptance of the prescriptive approach imposed by the Nuclear Regulatory Commission in the United States.

To demonstrate compliance with the public dose limit, AECL has calculated the annual dose from airborne emissions from 10 CANDU units at an extended Wolsong site. The analysis has used the treatment of atmospheric dispersion described in the US Regulatory Guide 1.111 [2] and programmed in the code XOQDOQ [3]. The analysis has then modelled the transport of these airborne emissions through the environment as they expose the critical group using the US Regulatory Guide 1.109 [4]. The study takes account of the different annual emissions from each unit to reflect the different design features of the units. This study also includes a treatment of topography and makes allowance for building wake effects.

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2. ANALYSIS

It would be possible, in principle, to site up to 6 CANDU 9 units to the north of the 4 CANDU 6 units built at Wolsong. For the CANDU 6 units, the exclusion area boundary (EAB) was set at 914 m, but for the CANDU 9 units, the EAB was set at 500 m. This smaller exclusion boundary is partially a result of design improvements to the containment system. When these exclusion area boundaries are superimposed, they create a long north-south site with a deeper (inland) dimension to the south than to the north (Figure 1).

For receptor points at the exclusion area fence around this site, the direction (angle) from each unit is different. That is, one wind direction cannot bring effluent from all 10 units to the same receptor point (a receptor that would be located in the NNW sector in relation to Wolsong 1 might be in the NW sector with respect to Wolsong 2). For that reason, each unit was modelled individually, using XOQDOQ, and an atmospheric dispersion factor was calculated at ten receptor points on the EAB. The ground-level concentration of contaminants from each of the 10 units at each receptor point was added up and, finally, a dose was calculated.

2.1 XOQDOQ Analysis

The atmospheric dispersion factor calculated by XOQDOQ, χ/Q, is a measure of the volume of air into which the airborne contaminants are dispersed. It may be thought of as the reciprocal of that volume of air passing a receptor per unit time. The concentration of a contaminant is then the product of the atmospheric dispersion factor and the rate of activity released. The atmospheric dispersion factor calculated by XOQDOQ at any receptor location is the value averaged over the period of collected weather data.

2.1.1 Sources

The height of the stack on the CANDU 6 was taken to be 50 m, and the exit velocity was taken as 12 m/s. The cross section of the nearby building was taken as 1400 m^2. The height of release on the CANDU 9 was taken to be 75 m, and the exit velocity 15 m/s. The cross section of the nearby building was taken as 2827 m^2.

2.1.2 Receptors

As mentioned previously, the location of the EAB and the extended EAB are shown on Figure 1. The administration building, which is located to the north of the 4 CANDU 6 units, is midway between the Wolsong site and the site proposed for the 6 CANDU 9 units. This point was selected as a reference point. Sixteen receptor points were identified marking the intersection of the site perimeter with the cardinal points of the compass from the reference point and 200 m beyond that first point. The 16 points were identified as A-P.

The receptors in the seaward sectors (NE, ENE, E, ESE, SE, SSE) were discarded, because the annual dose is based on 24-h occupancy every day of the year, leaving the 10 receptor points A-J (Figure 2). It is acknowledged that members of the public may, intermittently, be located at these seaward locations. However, the treatment of public dose has always concentrated on a small homogeneous group rather than on individuals who, as the result of extreme behaviour, increase their annual exposure. It is argued that 24-h occupancy in the seaward sectors would be very atypical.

Also note that receptor A, representing the south sector, has been moved slightly to the west so that it is on land.

2.1.3 Topography

The Wolsong site, located on the south-east coast of the Republic of Korea, is surrounded by mountains to the north and west, a beach to the east, and a village to the south. Clearly, the topography around each unit is unique to that particular unit. One cannot assume that the atmospheric dilution from one stack to the receptor will be that of another stack.

One XOQDOQ run was executed for 4 Wolsong CANDU 6 units and 6 proposed CANDU 9 units. For each reactor unit, the 22.5° sectors about each of the cardinal points of the compass were used to establish in which direction the receptor stands with respect to each unit (Figure 3). For example, for Wolsong 4, receptor D is in the WNW sector. The sectors are numbered from 1 to 16, in a clockwise direction, sector 1 being the southern sector. The topography, starting from each unit and extending in each of the 16 directions, was also input.

2.1.4 Weather Data

In Regulatory Guide 1.111, the atmospheric dispersion factor for a release above the height of the nearby building is modelled as a mixture of ground-level release and elevated release. The decision to treat the release as ground-level or elevated depends on the ratio of the exit velocity from the stack to the wind speed. When the release is treated as a ground-level release the wind speed at an elevation of 10 m is used, and, when the release is treated as an elevated release, the wind speed input is adjusted by XOQDOQ. The adjustment is a function of the release height and the height at which the weather data were collected. For the Wolsong site, weather data at elevations of 10 and 58 m were available. However, this study used the 10-m weather data set, collected over a 7-year period, with the frequency of occurrence as a function of both wind speed and stability category. For elevated releases, the wind speed was adjusted for a height of release of 50 m (stack height) by XOQDOQ.

2.1.5 Results

The calculated long-term atmospheric dispersion coefficients, χ/Q (s/m^3), for each receptor and source, are given in Table 1. The calculated concentration of deposited activity per unit area, D/Q (s/m^2) for each receptor and source are given in Table 2.

The atmospheric dispersion factors show substantial differences between the different units. For example, for receptor A, the value of χ/Q is largest for the nearest unit (Wolsong 4) and more than a factor of 10 smaller for the most distant extended Wolsong site unit 6. Even between the four CANDU 6 units, there is a factor of 2 difference between the χ/Q for Wolsong 4 and Wolsong 1.

It is clear from this last example that it would be too conservative to treat emissions from all 4 CANDU 6 units as releases from Wolsong 4; the atmospheric dilution factor would be $4.6\ 1x\ 10^{-6}$ s/m^3 using the individual units, but 6.80×10^{-6} s/m^3 using the value for Wolsong 4 multiplied by 4. It was for that reason the study chose to consider the releases from each unit. The treatment of individual units also considered the activity released from each unit and the related topography.

2.2 Estimated Emissions

Differences between the design of the original CANDU 6 model (Wolsong 1), and the later CANDU 6 models (Wolsong Units 2, 3, and 4) will reduce the emissions of tritium in the airborne and waterborne pathways. The tritium emissions will drop even more in the evolutionary design of the CANDU 9 reactor. There are also design differences between the CANDU 6 and CANDU 9 reactors that will reduce the releases of noble gases from CANDU 9 units, per megaWatt of electricity produced.

Based on the performances of the operating CANDU 6 reactors and the design differences between CANDU 6 and CANDU 9 reactors, one can project the emissions from CANDU 6 and CANDU 9 designs, as shown in Table 3.

2.2.1 Average Concentration of Contaminants

The product of the atmospheric dispersion factor, χ/Q, (Table 1), and the annual release of a radionuclide, Q, (Table 3) provides an estimate of the ground-level concentration, χ, of that radionuclide from one unit. The ground-level concentrations of any radionuclide from all units were summed to provide the average ground-level concentration of that radionuclide (Table 4).

3. PATHWAYS

As mentioned above, the ground-level concentration of any radionuclide is the product of the activity released annually and the atmospheric dispersion factor. Normally that concentration is specified for one release point with the assumption that all the releases occur from that point; in the pathways analyses discussed in Regulatory Guide 1.109, the equations assume the analyst is dealing with one release point.

This study assumed ten release points. However, rather than undertake separate pathways analyses for ten release points, the study chose to simulate one release point. The point chosen was the unit closest to the receptor having the highest ground-level concentrations. The analysis was based on the activity released from that unit. To reconcile this approach with the ground-level concentrations of Table 4, the study calculated an effective value of atmospheric dilution factor. When multiplied by the activity of the selected unit, this effective value of atmospheric dilution factor would generate the ground-level concentrations of Table 4.

The effective value of atmospheric dilution factor varied among the different radionuclides. Consequently, a normalisation factor was introduced to reconcile the differences between the effective atmospheric dilution factor for tritium and that for other radionuclides. This normalisation factor modifies the equations of Regulatory Guide 1.109 used to calculate the public exposures via the airborne pathway from inhalation, immersion, groundshine (or external exposure from deposited activity) and ingestion as shown below.

3.1 Inhalation

The inhalation pathway exposes the individual by an exchange of radioactivity between the radioactivity inhaled in air and the tissue of the respiratory system. For example, some exchange of tritiated water vapour will occur between the air in the lungs and fluids lining lung tissue. The consequences of this type of exchange are modelled in studies of the metabolic behaviour of radioactivity in the body. The doses received by the body or individual organs in the body have been summarized in so-called dose conversion factors. These dose conversion factors provide an estimate of dose committed per unit of activity inhaled. Dose conversion factors are available for whole-body dose or specific organ dose and for different age groups.

The calculation of dose by inhalation becomes a calculation of activity inhaled over one year which can then be converted to dose using the factors. The activity inhaled is simply the product of the ground-level concentration of contaminant and the inhalation rate as shown in the following equation for nuclide i at location (r,θ):

$$\chi_i(r,\theta) = 3.17E{+}04\, Q_i \;\; XF_i^* \, [\chi/Q]^D(r,\theta) \qquad (1)$$

where

$\chi_i(r,\theta)$ = the annual average ground-level concentration of nuclide i in air in sector θ, at distance r, in pCi/m^3 (1 Ci = 37 GBq)

Q_i = the annual release rate of nuclide i to the atmosphere, in Ci/a

XF_i^* = χ/Q normalization factor

$[\chi/Q]^D$ = the annual depleted atmospheric dispersion factor, in s/m^3

3.17E+04 = conversion factor from Ci/a to pCi/s

Although the atmospheric dispersion factor, $[\chi/Q]^D$, includes a correction for radioactive decay between the source and receptor as indicated by the superscript, the study took no credit for decay. Then the annual dose to organ j associated with inhalation of all radionuclides by an individual in an age group a is :

$$D_{ja}(r,\theta) = R_a \; \Sigma \; \chi_i(r,\theta) \; DFA_{ija} \qquad (2)$$

where

$D_{ja}(r,\theta)$ = is the annual dose to organ j of an individual in age group a at location (r,θ), resulting from inhalation, in mrem/a (1 rem = 10 mSv)

R_a = the annual air intake for an individual in the age group a, in m^3 / a

DFA_{ija} = the inhalation dose factor for radionuclide i, organ j, and age group a, in mrem/pCi

3.2 External

The external pathway exposes the individual to gamma radiation from the activity deposited on the ground (Section 3.2) and from activity in the airborne cloud surrounding the individual (Section 3.3). For most radionuclides, the activity deposited on the ground will reach an equilibrium dictated by the rate of activity deposited and the half-life of the radionuclide. However, in the model used in Regulatory Guide 1.109, the activity is considered to accumulate for 15 years (typically half of station life) and the dose to the individual is a simple calculation of dose rate above a plane source of contamination. For the radionuclides of interest to this study, the concentrations will have reached equilibrium.

The amount of surface contamination can be found from the average relative deposition per unit area which is calculated by XOQDOQ as D/Q. Since the deposition per unit area is analogous to χ/Q, a normalisation factor was introduced for D/Q to simplify the pathways treatment.

The ground-plane concentration of radionuclide i at location (r,θ) is

$$\mathbf{C_{ig}}(r,\theta) = \frac{\left[1.0E+12\right]\left[\delta_i(r,\theta)\ DF_i^*\ Q_i\right]}{\lambda_i}\left[1-\exp(-\lambda_i\ t_b\ )\right] \qquad (3)$$

where

$C_{ig}(r,\theta)$	= ground-plane concentration of radionuclide i in the sector angle θ at distance r from the release point, in pCi /m^2
$\delta_i(r,\theta)$	= annual average relative deposition of effluent species i at location (r,θ), considering depletion of the plume during transport, in m^{-2}
DF_i^*	= D/Q normalization factor
λ_i	= radiological decay constant for nuclide i, in a^{-1}
t_b	= period of time soil is exposed to the contamination in the plume, in years
1.0E+12	= number of pCi per Ci

The annual dose from external irradiation from radionuclides deposited onto the ground surface in mrem / a is

$$\mathbf{D_{jg}(r,\theta) = 8760\ S_F\ \Sigma\ C_{ig}(r,\theta)\ DFG_{ij}} \qquad (4)$$

where

$D_{jg}(r,\theta)$	= annual dose to organ j at location (r,θ), in mrem-a
S_F	= shielding factor that accounts for the dose reduction due to shielding provided by residential structures (default = 0.7)
DFG_{ij}	= open-field ground-plane dose conversion factor for organ j radionuclide i, in mrem*m^2 / pCi*h
8760	= number of hours in a year

All other parameters were defined above.

3.3 Immersion

The releases of airborne activity will create a cloud of extremely low concentrations of contaminated air at ground level. An individual living in this cloud would receive a small exposure from the gamma radiation emitted by the contaminants. In Regulatory Guide 1.109, the noble gases are the only contaminants considered to contribute to this external dose. Thus, in this study no contribution is included from other radionuclides. In addition the study only considers releases below 80 metres height and although the Regulatory Guide 1.109 includes equations for calculating air dose, this paper only reports the total body dose.

The calculation is made for a semi-infinite cloud of activity with a uniform concentration of contaminants. In addition a beta dose is calculated for the skin.

3.3.1 The Annual Gamma And Beta Air Dose From Noble Gases Released From Free-Standing Stacks Less Than 80 m High :

$$D_\gamma(r,\theta) = 3.17E{+}04 \;\; \Sigma \; Q_i \; XF_i^* \; [\, \chi/Q \,]^D \; (r,\theta) \;\; DF_i(\gamma) \qquad (5a)$$

$$D_\beta(r,\theta) = 3.17E{+}04 \;\; \Sigma \; Q_i \; XF_i^* \; [\, \chi/Q \,]^D \; (r,\theta) \;\; DF_i(\beta) \qquad (5b)$$

where

$D_\gamma(r,\theta)$	= annual gamma air dose at the distance r in the sector at angle θ from the discharge point, in mrad/a
$D_\beta(r,\theta)$	= annual beta air dose at the distance r in the sector at angle θ from the discharge point, in mrad/a
XF_i^*	= χ/Q normalization factor
$DF_i(\gamma)$	= gamma air dose factor for a uniform semi-infinite cloud of radionuclide i, in mrad*m^3 / pCi*a
$DF_i(\beta)$	= beta air dose factor for a uniform semi-infinite cloud of radionuclide i, in mrad*m^3 / pCi*a^{-1}
3.17E+04	= conversion factor from Ci/a to pCi/s

3.3.2 The Annual Total Body Dose From Noble Gases Released From Free-Standing Stacks Less Than 80 m High :

$$D_T(r,\theta) = S_F \;\; \Sigma \; \chi_i(r,\theta) \;\; DFB_i \qquad (6)$$

where

$D_T(r,\theta)$	= annual total body dose resulting from immersion in a semi-infinite cloud at distance r in sector θ, in mrem-a
DFB_i	= total body dose factor for a semi-infinite cloud of the radionuclide i, which includes the attenuation of 5 g/cm^2 of tissue, in mrem-m^3 / pCi-a.

3.3.3 The Annual Skin Dose From Noble Gases Released From Free-Standing Stacks Less Than 80 m High

$$D_S(r,\theta) = 1.11 \; S_F \;\; \Sigma \; \chi_i(r,\theta) \;\; DF_i(\gamma) \; + \; \Sigma \; \chi_i(r,\theta) \; DFS_i \qquad (7)$$

where

$D_S(r,\theta)$	= annual skin dose due to immersion in a semi-infinite cloud at distance r in sector θ, in mrem-a.
DFS_i	= beta skin dose factor for a semi-infinite cloud of the radionuclide i, which includes the attenuation by the outer 'dead' layer of the skin, in mrem*m^3 / pCi*a^{-1}.
1.11	= average ratio of tissue to air energy absorption coefficients.

All other parameters were defined previously.

3.4 Ingestion

The exposure of the public is usually dominated by the activity ingested by eating contaminated food. The whole-body dose and organ dose can be calculated from sets of dose conversion factors that relate the amount of activity ingested to the committed dose. Throughout the calculation of public dose from this source, the dose conversion factors of Regulatory Guide 1.109 were used. Thus the calculation is reduced to calculating how much activity is

in the food consumed. For that calculation the make-up of the diet and the concentrations of radionuclides in the different food are needed.
Details of the diet are given in Table 5. Details of the calculation of radionuclide concentrations in food are given in the following sections.

3.4.1 Calculation of Radionuclide Concentration in Forage, Produce and Leafy Vegetables

The calculations of radionuclide concentrations in vegetable matter vary with different radionuclides. Tritium is present in the air as tritiated water vapour and will exchange with the hydrogen (protium) present in the plant taken up from roots or transpiration. Carbon-14 will be fixed in the plant by photosynthesis since it is released principally as carbon dioxide. The other radionuclides are principally deposited on the leaves of vegetation.

3.4.1.1 For Nuclides Other Than Tritium And Carbon-14

The amount of activity deposited on the leaves of vegetation will be a function of the rate of deposition of activity per unit area. That activity will be distributed over the leafy surface of the vegetation grown per unit area. The amount of activity accumulated will be a function of the time spent in growing and the amount retained on the leafy surfaces. In addition to the activity directly deposited on the leaves of all vegetation there will also be an uptake from activity deposited on the soil. These two components were evaluated using default values of the different parameters in the expressions:

$$\mathbf{C_i(r,\theta) = d_i(r,\theta)\left\{\frac{r\,[1-\exp(-\lambda_{Ei}t_e)]}{Y_v\,\lambda_{Ei}} + \frac{B_{iv}\,[1-\exp(-\lambda_i t_b)]}{P\lambda_i}\right\}\exp(-\lambda_i t_h)} \quad (8)$$

$$\mathbf{d_i(r,\theta) = 1.14E{+}08\ DF_i^*\ \delta_i(r,\theta)\ Q_i} \quad (9)$$

where

DF_i^*	= D/Q normalization factor
$C_i(r,\theta)$	= concentration of nuclide i in and on vegetation at the location (r,θ), in pCi/kg
$d_i(r,\theta)$	= deposition rate of radionuclide i onto ground at location (r,θ) in pCi/m^2*h.
1.14E+08	= the number of pCi per Ci divided by the number of hours per year
r	= fraction of deposited activity retained on crops, leafy vegetables, or pasture grass
λ_{Ei}	= effective removal rate constant for radionuclide i from crops, in h^{-1}, where $\lambda_{Ei} = \lambda_i + \lambda_w$, λ_i is the radioactive decay constant, and λ_w is the removal rate constant for physical loss by weathering
t_e	= period of crop, leafy vegetable, or pasture grass exposure during growing season, in hours
Y_v	= agricultural productivity by unit area.
B_{iv}	= concentration factor for uptake of radionuclide i from soil by edible parts of crops in pCi / kg (wet weight) per pCi / kg dry soil
P	= effective surface density of soil
t_h	= time delay between harvest of vegetation or crops and ingestion, in years.

Note that the yields for agricultural productivity were based on Korean data.

3.4.1.2 Radioiodines

The model assumes half of the radioiodines are in an elemental form and only half in non-elemental form which will deposit on vegetation.

$$d_i(r,\theta) = 5.7E+07\ DF_i^*\ \delta_i\ (r,\theta)\ Q_i \qquad (10)$$

3.4.1.3 Carbon-14 (Assumed To Be Released In Oxide Form (CO Or CO_2))

For carbon-14, the activity is bound in the plant via photosynthesis and the calculation assumes that the normal ratio of carbon-14 to natural carbon in the atmosphere is preserved in the plant:

$$C_{14}(r,\theta) = 3.17E+07\ p\ Q_{14}\ XF_i^*\ [\chi(r,\theta)/Q\ ]\ 0.11\ /\ 0.16 \qquad (11)$$

where

$C_{14}(r,\theta)$	= concentration of carbon-14 in vegetation, pCi/kg
Q_{14}	= annual release rate of carbon-14, in Ci/a
XF_i^*	= χ/Q normalization factor
p	= fractional equilibrium ratio (1.0).
0.11	= fraction of total plant mass that is natural carbon
0.16	= concentration of natural carbon in the atmosphere, in g/m^3
3.17E+07	= (1.0E+12 pCi/Ci) (1.0E+03 g/kg) / (3.15E+07 s/a)

3.4.1.4 Tritium

For tritium the calculation of tritium concentrations in vegetation assumes the tritium concentration in the plant water is one-half that in the atmosphere surrounding the plant:

$$C_T\ (r,\theta) = 3.17E+07\ \ Q_T\ XF_i^*\ [\ \chi(r,\theta)/Q\ ]\ (0.75)\ (0.5/H) \qquad (12)$$

where

XF_i^*	= χ/Q normalization factor
$C_T\ (r,\theta)$	= the concentration of tritium in vegetation grown at location (r,θ), pCi/kg
0.75	= the fraction of total plant mass that is water
0.5	= the ratio of tritium concentration in plant water to tritium concentration in atmospheric water
H	= the absolute humidity of the atmosphere at location (r,θ), in g/m^3

3.4.2 Calculation of Radionuclide Concentration In Milk

To calculate the concentrations of radionuclides in milk, the equation takes account of the radionuclide concentrations in the animal feed which may be either pasture or stored feed. The calculation also takes account of the transfer parameter from the animal intake to milk and uses default values for these transfer parameters.

$$C_{im}\ (r,\theta) = F_m\ \ C_{iv}\ (r,\theta)\ q_F\ \ exp\ (\ -\lambda_i\ t_f) \qquad (13)$$

$$C_{iv}\ (r,\theta) = f_p\ f_s\ C_{ip}(r,\theta) + (1-f_p)\ C_{is}(r,\theta) + f_p\ (1-f_s)\ C_{is}(r,\theta\ ) \qquad (14)$$

where

$C_{im}(r,\theta)$ = concentration in milk of nuclide i, in pCi/litre
$C_{iv}(r,\theta)$ = concentration of radionuclide i in the animal's feed, in pCi/kg
$C_{ip}(r,\theta)$ = concentration of radionuclide i on pasture grass (calculated using equation (8) with $t_h = 0$), in pCi/kg
$C_{is}(r,\theta)$ = concentration of radionuclide i in stored feed (calculated using equation (8) with $t_h = 90$ days), in pCi/kg
F_m = average fraction of the animal's daily intake of radionuclide which appears in each litre of milk, in days/litre.
q_F = amount of feed consumed by the animal per day, in kg/day
t_f = the average transport time of the activity from the feed into the milk and to the receptor
f_p = fraction of the year that animals graze on pasture
f_s = fraction of daily feed that is pasture grass when the animal grazes on pasture

3.4.3 Calculation of Radionuclide Concentration In Meat

The calculation of radionuclide concentration in meat uses the same expression for the intake as the calculation for milk. However, the calculation takes account of the time from slaughter to consumption and uses transfer parameters for transfer from animal intake to meat product:

$$\mathbf{C_{if}(r,\theta) = F_f \; C_{iv}(r,\theta) \, Q_F \;\; exp\,(-\lambda_i t_s)} \qquad (15)$$

where

$C_{if}(r,\theta)$ = concentration of nuclide i in animal flesh, in pCi/kg
F_f = fraction of the animal's daily intake of nuclide i which appears in each kilogram of flesh, in days/kg
t_s = the average time from slaughter to consumption

3.4.4 The annual dose from all airborne activity ingested by the public from food products is

This formula, which calculates the total dose from ingestion, sums up the contributions from ingestion of leafy vegetables, produce, forage, milk and meat

$$\mathbf{D_{ja}(r,\theta) = \Sigma \, DFI_{ija} \;\; [\, U_{av} f_g C_{iv}(r,\theta) + U_{am} C_{im}(r,\theta) + U_{af} C_{if}(r,\theta) + U_{al} f_l C_{il}(r,\theta) \,]} \qquad (16)$$

where

$D_{ja}(r,\theta)$ = annual dose to organ j of an individual in age group a from dietary intake of atmospherically released radionuclides, in mrem/a
DFI_{ija} = dose conversion factor for the ingestion of nuclide i, organ j, and age group a, in mrem/pCi
$U_{av}, U_{am}, U_{af}, U_{al}$ = ingestion rates of produce, milk, meat, and leafy vegetables, respectively, for individuals in age group a
f_g, f_l = the respective fractions of the ingestion rates of produce and leafy vegetables that are produced in the garden of interest

3.5 RESULTS

The annual doses calculated using the methodology of RG 1.109 are summarized in Table 6, totalled for all pathways. They show that the annual dose to the whole body is dominated by the airborne emissions of tritium. The emissions of carbon-14 and noble gases also make a significant contribution to the whole-body dose. However, the contributions to annual whole-body dose from the particulates and radioiodines are small.

Regulatory guide 1.109 also describes a methodology for calculating annual doses to individual organs. In this Table 6 the final column refers to the dose to the large lower intestine of the gastro-intestinal tract. These organ doses generally show the same behaviour as the whole-body dose, the dose from tritium is normally the major contribution to the total dose. However, the dose to bone is dominated by the contribution from carbon-14. Indeed, for the teen and child, the total dose to bone is higher than the total whole-body dose, and the annual dose to bone would appear to be limiting.

The high dose to bone tissue is a direct consequence of the dose conversion factor prescribed in RG 1.109 [4]. These dose conversion factors (between intake and organ dose) were based on ICRP 2 [5] and include a relative damage factor of 5 for carbon-14 in bone. In later ICRP publications the modifying factor is unity. Consequently, the contribution from carbon-14 to the annual bone dose is overestimated.

4. CONCLUSION

The annual whole-body dose to the most exposed members of the public from 4 CANDU 6 units and 6 CANDU 9 units located at an extended Wolsong site would be 52 μSv for a child and 32 μSv for an adult. Because the dose limit for members of the public is 250 μSv/a, the study shows that 10 CANDU units could be accommodated at the Wolsong site and still meet the limit imposed by Korean regulations.

The organ dose would be 75 μSv/a to the bone of a child but only 25 μSv/a to the bone of an adult. These doses would meet Korean regulatory limits for organ dose (250 μSv/a) even though, as outlined above, the major contribution is from carbon-14 and the dose conversion factor for carbon-14 is overestimated. Thus the bone doses presented here are overestimated.

Because the study used a 914-m exclusion area boundary for the 4 CANDU 6 units and a 500-m exclusion area boundary for the 6 CANDU 9 units, the study shows that the 500-m exclusion area boundary for CANDU 9 would be acceptable from a perspective of public dose during normal operation.

5. ACKNOWLEDGMENTS

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5. ICRP (International Commission on Radiological Protection), "Limits for Intakes of Radionuclides by Workers", Annals of the ICRP 2(3/4) (ICRP Publication 30), 1979.

Figure 1: External Area Boundary And Extended External Area Boundary

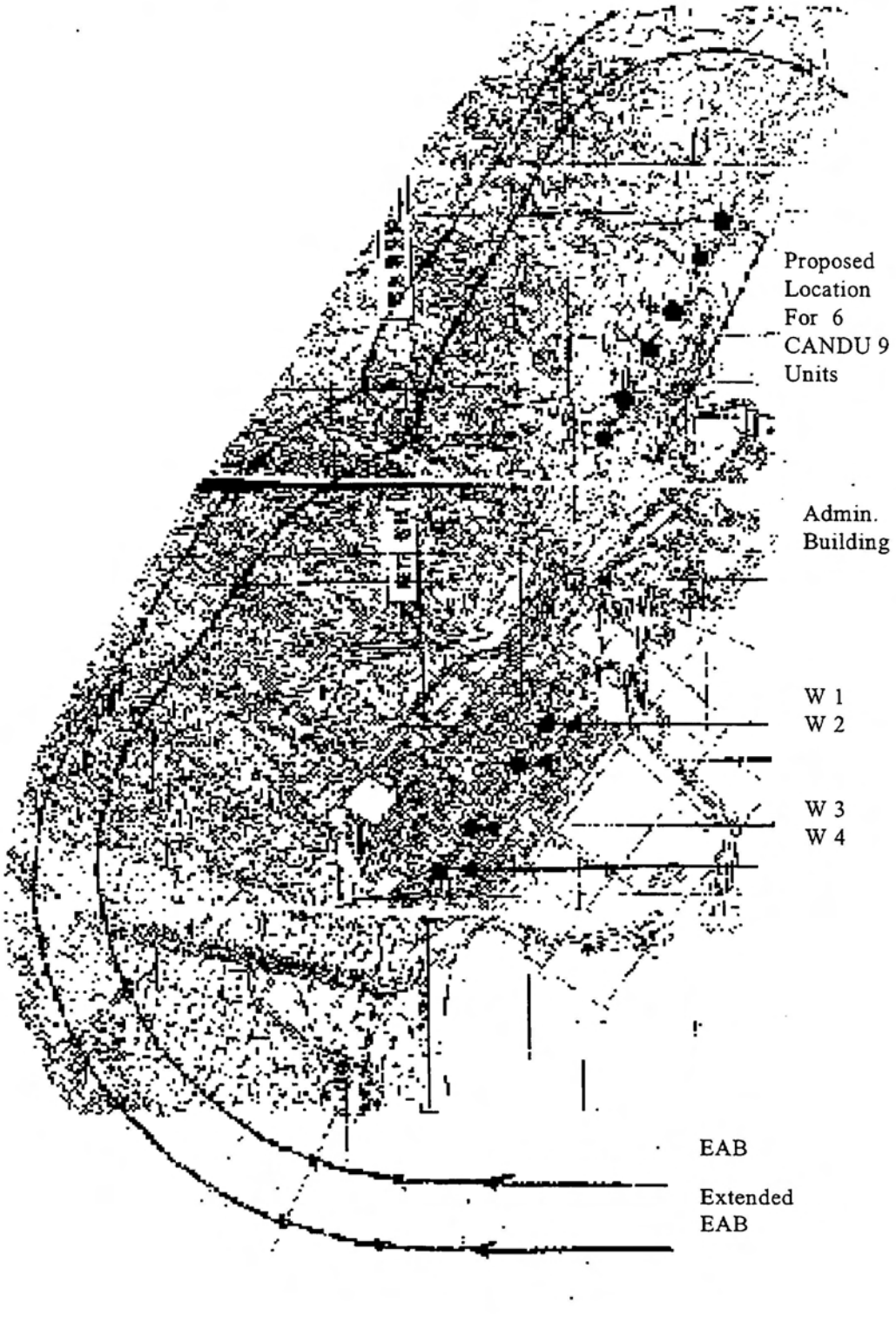

Figure 2: Receptor Points On External Area Boundary

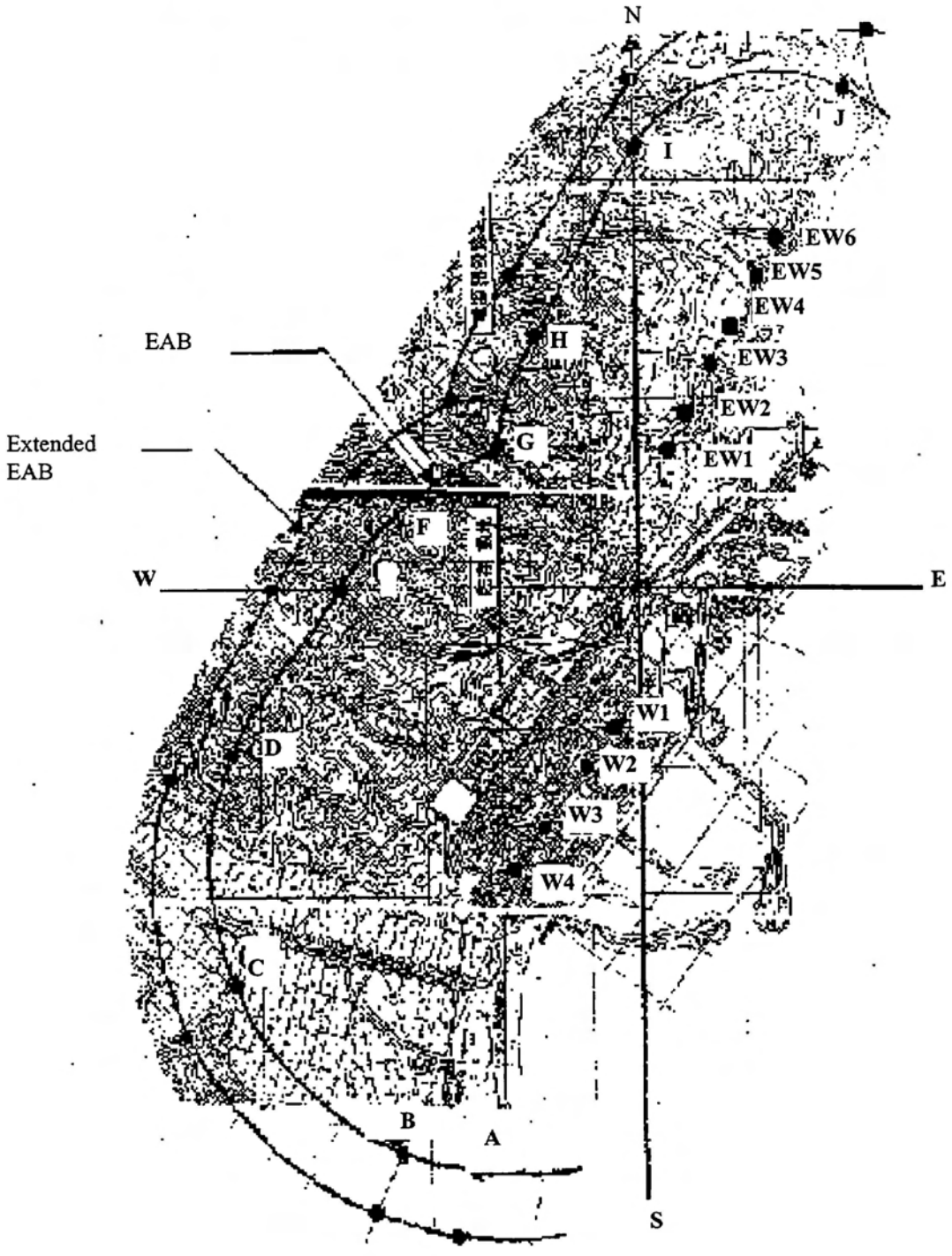

Figure 3: Receptor Point Location (Sector) In Relation To Wolsong 4

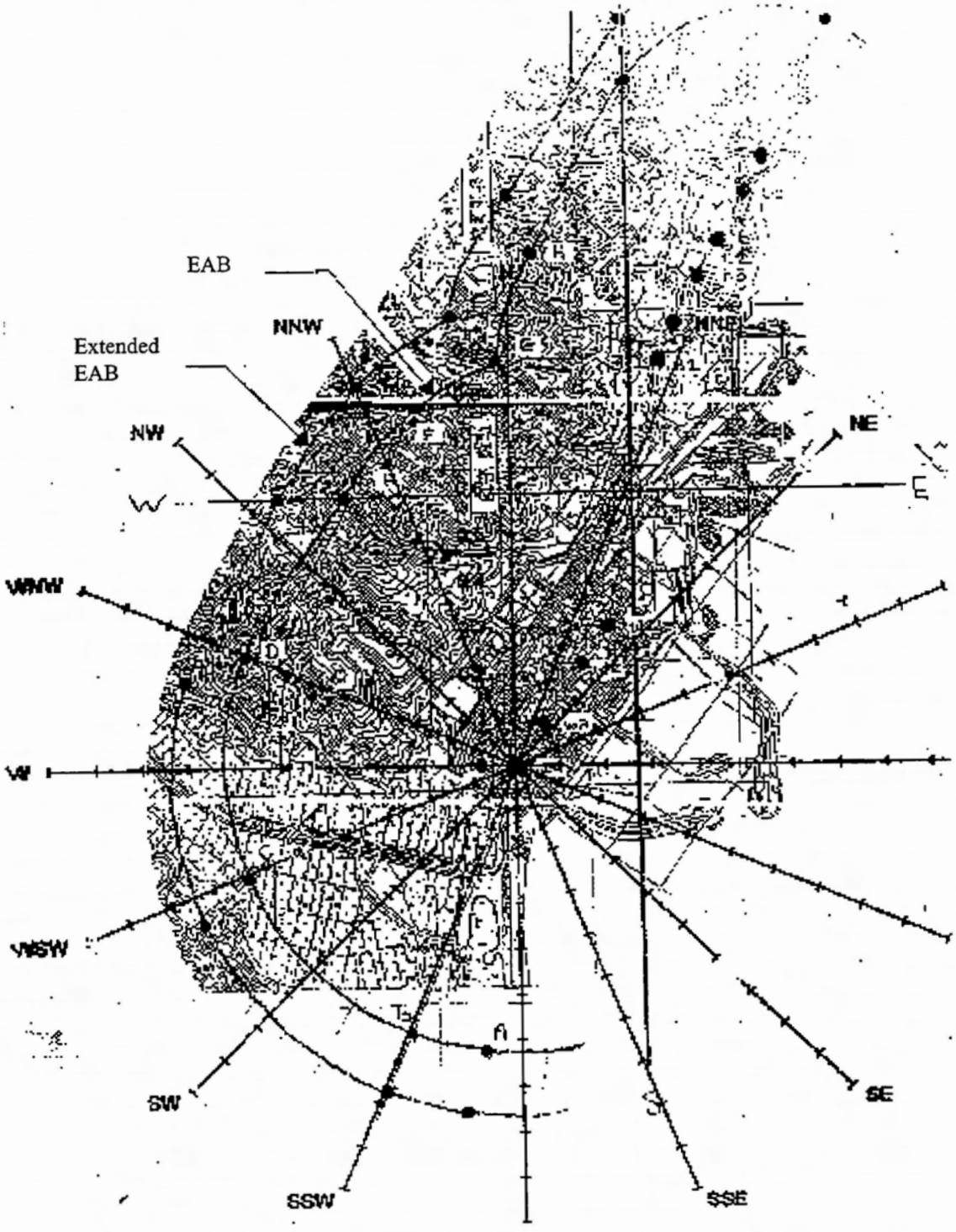

TABLE 1

χ/Q From XOQDOQ At EAB And Extended EAB (s/m^3)

χ/Q CALCULATED AT EAB										
REC.	W 1	W 2	W 3	W 4	EW 1	EW 2	EW 3	EW 4	EW 5	EW 6
A	7.90E-07	9.20E-07	1.20E-06	1.70E-06	2.10E-07	1.90E-07	1.70E-07	1.60E-07	1.50E-07	1.30E-07
B	5.00E-07	8.80E-07	1.20E-06	1.40E-06	2.00E-07	1.80E-07	1.70E-07	1.60E-07	1.50E-07	1.30E-07
C	3.20E-07	3.30E-07	3.10E-07	3.60E-07	1.40E-07	1.30E-07	1.30E-07	1.20E-07	1.70E-07	1.60E-07
D	6.80E-07	3.40E-07	8.60E-07	4.00E-07	2.70E-07	2.20E-07	2.00E-07	1.80E-07	2.80E-07	2.60E-07
E	9.30E-07	1.40E-06	1.30E-06	1.10E-06	3.90E-07	5.20E-07	4.80E-07	2.00E-07	4.10E-07	4.60E-07
F	1.50E-06	6.30E-07	1.30E-06	1.10E-06	2.20E-07	9.30E-07	9.60E-07	3.10E-07	4.70E-07	6.80E-07
G	1.50E-06	5.50E-07	9.50E-07	1.00E-06	5.00E-07	1.20E-06	5.30E-07	1.00E-06	8.70E-07	8.80E-07
H	7.60E-07	7.10E-07	6.50E-07	6.40E-07	9.00E-07	1.90E-06	1.70E-06	7.20E-07	1.40E-06	8.20E-07
I	3.90E-07	3.30E-07	3.50E-07	3.10E-07	6.70E-07	8.00E-07	5.00E-07	6.80E-07	6.10E-07	5.40E-07
J	3.60E-07	3.10E-07	2.90E-07	2.60E-07	8.50E-07	5.50E-07	1.20E-06	1.40E-06	1.80E-06	2.60E-06
χ/Q CALCULATED AT EXTENDED EAB										
REC.	WOLS 1	W 2	W 3	W 4	EW 1	EW 2	EW 3	EW 4	EW 5	EW 6
A	6.00E-07	6.80E-07	9.60E-07	1.30E-06	1.80E-07	1.60E-07	1.50E-07	1.40E-07	1.30E-07	1.10E-07
B	5.80E-07	6.60E-07	9.40E-07	1.10E-06	1.70E-07	1.60E-07	1.50E-07	1.40E-07	1.30E-07	1.10E-07
C	4.40E-07	3.50E-07	2.90E-07	3.10E-07	1.10E-07	1.10E-07	1.20E-07	1.10E-07	1.60E-07	1.40E-07
D	5.00E-07	3.50E-07	1.60E-07	4.80E-07	9.30E-08	1.70E-07	1.60E-07	1.50E-07	2.40E-07	2.20E-07
E	6.80E-07	6.90E-07	1.00E-06	8.80E-07	2.60E-07	2.80E-07	2.50E-07	1.60E-07	1.70E-07	3.90E-07
F	1.10E-06	9.70E-07	1.00E-06	8.60E-07	1.90E-07	6.30E-07	7.60E-07	2.70E-07	3.50E-07	4.10E-07
G	1.20E-06	6.80E-07	7.90E-07	8.30E-07	1.40E-06	5.30E-07	1.20E-06	6.30E-07	7.40E-07	8.00E-07
H	7.40E-07	5.20E-07	5.30E-07	5.00E-07	8.50E-07	1.20E-06	1.00E-06	9.20E-07	1.30E-06	7.80E-07
I	3.20E-07	2.60E-07	2.80E-07	2.50E-07	5.40E-07	6.10E-07	3.90E-07	5.30E-07	7.20E-07	4.40E-07
J	3.00E-07	2.60E-07	2.50E-07	2.30E-07	6.20E-07	7.50E-07	9.50E-07	1.10E-06	1.30E-06	1.60E-06

TABLE 2

D/Q From XOQDOQ At EAB And Extended EAB (s/m^3)

D/Q CALCULATED AT EAB										
REC.	W 1	W 2	W 3	W 4	EW 1	EW 2	EW 3	EW 4	EW 5	EW 6
A	1.20E-08	1.50E-08	2.10E-08	3.10E-08	3.40E-09	3.00E-09	2.50E-09	2.20E-09	2.00E-09	1.80E-09
B	6.90E-09	1.50E-08	2.10E-08	2.60E-08	3.40E-09	3.00E-09	2.50E-09	2.20E-09	1.90E-09	1.70E-09
C	3.50E-09	4.50E-09	5.40E-09	6.50E-09	2.20E-09	2.00E-09	1.80E-09	1.60E-09	2.20E-09	1.70E-09
D	4.20E-09	3.30E-09	6.10E-09	4.50E-09	4.70E-09	3.80E-09	3.20E-09	2.80E-09	3.10E-09	2.80E-09
E	6.40E-09	9.50E-09	9.00E-09	8.10E-09	5.90E-09	6.50E-09	5.10E-09	2.90E-09	5.30E-09	5.70E-09
F	9.60E-09	7.80E-09	9.90E-09	8.60E-09	4.10E-09	1.10E-08	9.40E-09	5.10E-09	5.60E-09	8.80E-09
G	1.20E-08	7.40E-09	1.20E-08	1.20E-08	9.00E-09	1.20E-08	9.50E-09	1.30E-08	9.70E-09	1.40E-08
H	1.00E-08	8.60E-09	7.30E-09	6.60E-09	1.40E-08	1.60E-08	1.40E-08	9.30E-09	1.60E-08	1.20E-08
I	4.00E-09	3.40E-09	3.50E-09	3.10E-09	1.40E-08	1.70E-08	9.80E-09	1.20E-08	1.10E-08	9.30E-09
J	4.30E-09	3.80E-09	3.00E-09	2.70E-09	1.50E-08	1.10E-08	2.20E-08	2.70E-08	3.40E-08	4.00E-08
D/Q Calculated At Extended EAB										
REC.	W 1	W 2	W 3	W 4	EW 1	EW 2	EW 3	EW 4	EW 5	EW 6
A	8.80E-09	1.10E-08	1.60E-08	2.40E-08	2.80E-09	2.50E-09	2.10E-09	1.90E-09	1.70E-09	1.60E-09
B	8.40E-09	1.10E-08	1.50E-08	2.00E-08	2.80E-09	2.50E-09	2.10E-09	1.90E-09	1.70E-09	1.60E-09
C	5.40E-09	3.70E-09	4.20E-09	5.00E-09	1.80E-09	1.60E-09	1.50E-09	1.40E-09	1.60E-09	1.40E-09
D	3.10E-09	2.90E-09	2.50E-09	4.50E-09	1.50E-09	2.80E-09	2.50E-09	2.20E-09	2.50E-09	2.30E-09
E	4.80E-09	5.00E-09	7.20E-09	6.70E-09	4.00E-09	3.70E-09	2.90E-09	2.20E-09	1.90E-09	4.50E-09
F	7.10E-09	6.70E-09	8.00E-09	6.80E-09	3.30E-09	5.10E-09	7.50E-09	4.30E-09	4.00E-09	4.10E-09
G	9.40E-09	6.70E-09	9.70E-09	9.00E-09	1.10E-08	6.70E-09	8.00E-09	8.80E-09	8.60E-09	7.90E-09
II	5.50E-09	6.00E-09	5.70E-09	5.20E-09	1.00E-08	1.40E-08	9.90E-09	9.50E-09	8.60E-09	7.20E-09
I	3.10E-09	2.60E-09	2.80E-09	2.50E-09	1.10E-08	1.20E-08	7.30E-09	8.80E-09	1.20E-08	7.40E-09
J	3.40E-09	3.00E-09	2.50E-09	2.20E-09	1.00E-08	1.30E-08	1.70E-08	2.00E-08	2.40E-08	2.70E-08

TABLE 3

Projected Airborne Emissions From Four CANDU 6 And Six CANDU 9 Units (Ci/a)

NUCLIDE	W 1	W 2	W 3	W 4	EW 1	EW 2	EW 3	EW 4	EW 5	EW 6	TOTAL
TRITIUM	3.784E+03	3.784E+03	3.784E+03	3.784E+03	3.874E+03	3.874E+03	3.874E+03	3.874E+03	3.874E+03	3.874E+03	3.838E+04
CARBON 14	5.676E+00	5.676E+00	5.676E+00	5.676E+00	7.568E+00	7.568E+00	7.568E+00	7.568E+00	7.568E+00	7.568E+00	6.811E+01
NOBLE GASES	3.243E+02	3.243E+02	3.243E+02	3.243E+02	4.054E+02	4.054E+02	4.054E+02	4.054E+02	4.054E+02	4.054E+02	3.730E+03
RADIO-IODINES	2.622E-04	2.622E-04	2.622E-04	2.622E-04	3.243E-04	3.243E-04	3.243E-04	3.243E-04	3.243E-04	3.243E-04	2.995E-03
PARTICULATE	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-04	8.108E-03

TABLE 4

Ground Level Concentration For Each Type Of Release From All Reactor Units (Ci/m^3)

	POINT A	POINT B	POINT C	POINT D	POINT E	POINT F	POINT G	POINT H	POINT I	POINT J
Tritium	6.87E-10	6.04E-10	2.65E-10	4.53E-10	8.77E-10	9.97E-10	1.10E-09	1.23E-09	6.27E-10	1.16E-09
Carbon-14	1.07E-12	9.53E-13	4.40E-13	7.47E-13	1.44E-12	1.67E-12	1.91E-12	2.28E-12	1.16E-12	2.23E-12
Noble Gases	6.01E-11	5.35E-11	2.45E-11	4.15E-11	8.01E-11	9.24E-11	1.05E-10	1.24E-10	6.30E-11	1.20E-10
Radioiodines	4.87E-17	4.30E-17	1.97E-17	3.35E-17	6.46E-17	7.44E-17	8.42E-17	9.94E-17	5.03E-17	9.62E-17
Particulate	1.44E-16	1.28E-16	5.57E-17	9.46E-17	1.84E-16	2.08E-16	2.30E-16	2.62E-16	1.33E-16	2.47E-16
TOTAL	7.48E-10	6.59E-10	2.90E-10	4.95E-10	9.58E-10	1.09E-09	1.21E-09	1.36E-09	6.91E-10	1.28E-09

TABLE 5

The Korean Diet

	Fresh Vegetables (kg/a)	Grains (kg/a)	Milk (l/a)	Meat (kg/a)	Leafy Vegetables (kg/a)	Fruit (kg/a)	Dry Milk (l/a)
Adult	66.3	188.5	63.4	55.1	126.7	66.3	0
Teen	102.2	196.9	66.7	57.5	132.3	69.1	0
Child	65.3	125.7	41.9	36.6	84.5	44.2	0
Infant	0	0	367.7	0	0	0	3.42

TABLE 6

Annual Dose From Airborne Emissions (μSv/a)

ISOTOPES	WHOLE BODY	SKIN	BONE	LIVER	THYROID	KIDNEY	LUNG	GI-LLI
Adult								
Tritium	2.06E+01	0.00E+00	0.00E+00	2.06E+01	2.06E+01	2.06E+01	2.06E+01	2.06E+01
Carbon-14	4.95E+00	0.00E+00	2.48E+01	4.95E+00	4.95E+00	4.95E+00	4.95E+00	4.95E+00
Particulates	7.21E-03	8.39E-03	1.51E-04	5.94E-05	0.00E+00	7.84E-05	2.19E-03	4.86E-03
Iodines	6.83E-04	3.44E-04	4.91E-04	7.04E-04	1.67E-02	1.21E-03	0.00E+00	1.91E-04
Noble Gases	6.04E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	3.16E+01	1.45E+01	2.48E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01	2.55E+01
Teen								
Tritium	2.20E+01	0.00E+00	0.00E+00	2.20E+01	2.20E+01	2.20E+01	2.20E+01	2.20E+01
Carbon-14	7.81E+00	0.00E+00	3.91E+01	7.81E+00	7.81E+00	7.81E+00	7.81E+00	7.81E+00
Particulates	7.23E-03	8.39E-03	2.17E-04	8.41E-05	0.00E+00	1.06E-04	3.53E-03	1.01E-01
Iodines	8.48E-04	3.44E-04	7.55E-04	1.06E-03	1.71E-02	1.82E-03	0.00E+00	2.16E-04
Noble Gases	6.04E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	3.59E+01	1.45E+01	3.91E+01	2.98E+01	2.98E+01	2.98E+01	2.98E+01	2.99E+01
Child								
Tritium	3.05E+01	0.00E+00	0.00E+00	3.05E+01	3.05E+01	3.05E+01	3.05E+01	3.06E+01
Carbon-14	1.49E+01	0.00E+00	7.47E+01	1.49E+01	1.49E+01	1.49E+01	1.49E+01	1.49E+01
Particulates	7.28E-03	8.39E-03	4.77E-04	1.27E-04	0.00E+00	1.57E-04	5.34E-03	5.41E-02
Iodines	1.10E-03	3.44E-04	1.44E-03	1.45E-03	4.77E-01	2.38E-03	0.00E+00	1.34E-04
Noble Gases	6.04E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	5.15E+01	1.45E+01	7.47E+01	4.54E+01	4.59E+01	4.54E+01	4.54E+01	4.55E+01
Infant								
Tritium	4.68E+00	0.00E+00	0.00E+00	4.68E+00	4.68E+00	4.68E+00	4.68E+00	4.68E+00
Carbon-14	3.02E-01	0.00E+00	1.45E+00	3.02E-01	3.02E-01	3.02E-01	3.02E-01	3.02E-01
Particulates	7.20E-03	8.39E-03	1.24E-04	3.47E-05	0.00E+00	3.43E-05	2.31E-03	6.99E-05
Iodines	3.08E-04	3.44E-04	4.81E-05	5.63E-05	1.88E-02	6.58E-05	0.00E+00	1.49E-06
Noble Gases	6.04E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	1.10E+01	1.45E+01	1.45E+00	4.98E+00	5.00E+00	4.98E+00	4.98E+00	4.98E+00