Preliminary Results of Modelling Radionuclide Depositions in Agricultural and Forest Environments Using the CHERPAC Code

Draft 153-112320-CONF-001

S.L. Chouhan
Environmental Technologies Branch
Atomic Energy of Canada Limited (AECL)
Chalk River, Ontario, K0J 1J0, Canada
Email: ChouhanS@aecl.ca

2010 June 30

1. Introduction

This document discusses the methodology and results of the calculations performed for the Environmental Sensitivities Working Group of the IAEA EMRAS-II (Environmental Modelling for Radiation Safety) project. As requested by the Working Group Leader, these are only preliminary results and the final quality assured results will be submitted later.

Please note: CHERPAC results for the uncertainty and sensitivity analysis of doses from accidental releases have not as yet been published in the international literature. As I am thinking of writing a journal paper on this topic, please, for now, do not post the results presented here on the internet, and do not circulate them.

2. CHERPAC Code

2.1 CHERPAC

- CHERPAC (Chalk River Environmental Research Pathways Analysis Code) is an AECL developed time-dependent food-chain model.
- Calculates stochastic ingestion, inhalation, immersion and groundshine doses for twenty-five radionuclides released to the atmosphere in accidental situations (Figure 1)
- Developed for participating in international model intercomparison scenarios after Chernobyl fallout data
- Some models and parameter values were originally taken from the routine-release dose calculation model CSA N288.1 (1987) and adapted into this accidental release model

2.2. Model description

- CHERPAC uses Latin Hypercube Sampling (LHS) of distributions of parameter values to generate input for the multiple runs
- Predicts best estimates, means, and 2.5% and 97.5% confidence limits of the output distributions

- For terrestrial pathways, starts with the daily values of either (1) ground-level air concentrations and rainfall, or (2) measured depositions

- Outputs human body burden and concentrations in soil, forage, leafy and non-leafy vegetables, potatoes, other root crops, fruit, winter and spring grains, wild berries and mushrooms, milk, cheese, beef, pork, eggs, poultry, small game and big game

- CHERPAC takes concentrations of ^{137}Cs in freshwater and saltwater fish as input and predicts human dose and body burden

- Handles accident occurring at any time of the year, and delays between harvest or production and ingestion of beef, pork, eggs, chicken, cheese, root crops, potatoes and grain.

- Calculates losses due to food processing for all foods

- Parameter values (e.g., diet, growing season, yield, animal diets and concentration ratios) in CHERPAC are Canadian, Ontario, specific

- Radionuclides: ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{65}Zn, ^{89}Sr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{99}Mo, ^{103}Ru, ^{106}Ru, ^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{140}Ba, ^{141}Ce and ^{144}Ce

2.3. Mathematical description

These selected equations are given below just to give a flavor of CHERPAC's model but in reality there are many more equations in it. The parameters' symbol descriptions are also omitted to keep this document brief but may be added in the future.

Deposition:
$D = C_a\ (v_g * 86400 + w * I * R_w/1000) = D_d + D_w$

Leafy vegetable plant concentration:
$C_v = D \exp(-\lambda_{w,r} * d\,t) / Y + C_s * (B_v + adhr) / S_w$

Fruit, potato or root vegetables concentration:
$C_{trans} = (D_r * T) + (C_s * (B_v + adhr) / S_w)$

Grain concentration:

$$C_g = \{D_{pg}(t_i)\ 9.8E\text{-}2 \exp[-0.0013 * (t_i - 34)^2]\}_{\text{previous calendar month avg}} + \{D_{pg}(t_i)\ 9.8E\text{-}2 \exp[-0.0013 * (t_i - 34)^2]\}_{\text{current calendar month avg}} + (C_s * B_v / S_w)$$

Dairy and beef cows body burden:

$$A_{b\ \text{Current step}} = A_{b\ \text{Previous step}} * \exp(-\lambda_r * dt) + U_g * C_g + U_{pg} * C_{pg} + U_{s\ \text{dairy cow only}} * C_{sw\ \text{dairy cow only}}) * f_{food} * dt + U_a * C_a * f_{breath} * dt$$

Milk and beef concentrations:

- $C = F_{\text{milk from activity in cow}} * A_b$

Similarly CHERPAC calculates the concentrations in other meat products.

Then CHERPAC calculates the ingestion doses from all food products.

CHERPAC also calculates inhalation, immersion and groundshine doses in a manner similar to other models.

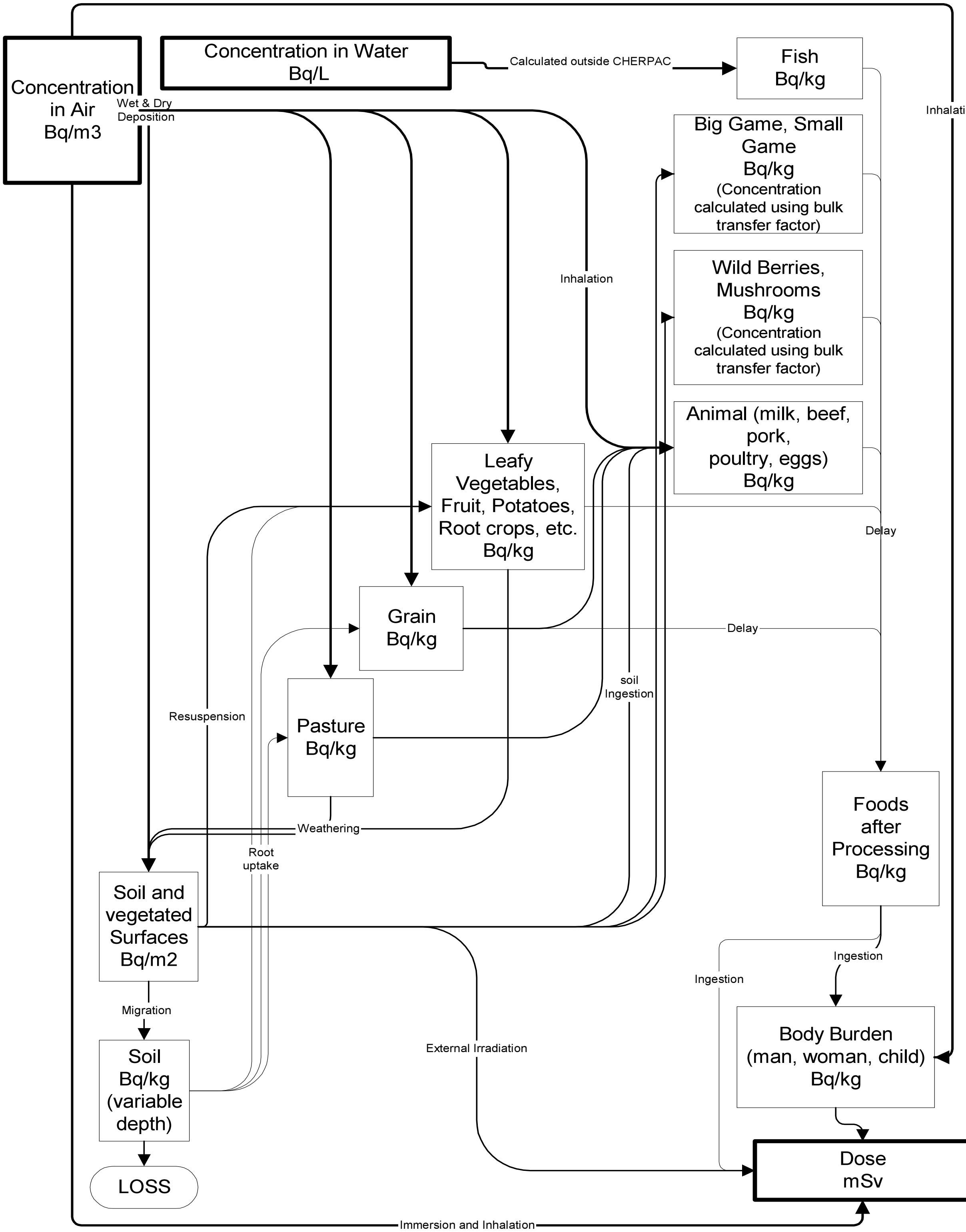

Figure 1. Simplified structure of CHERPAC

2.4. Parameter values

- To do the uncertainty analysis, CHERPAC is coupled with the LHS code (Iman and Shortencarier, NUREG/CR-3624, 1984)

- There are several types of distributions (i.e. normal, lognormal, uniform, triangular and user) used for parameters in CHERPAC
- Correlation coefficients between parameters are also used

- Distributions are defined for the parameters related to agricultural pathways, plants, animals (some parameters are nuclide specific)

2.5. Preparing input files (distribution type, best estimate value, and limits)

- Suppose, there were 70 values (A1, A2, A3,…,A70) found for a parameter

- These values were used to plot a histogram

- Histogram indicated Log Normal distribution

- Natural Logarithm a1 = ln(A1), a2 = ln(A2), a3 = ln(A3), …, a70 = ln(A70) were calculated.

- Mean(a1,a2,a3,…,a70) and Standard Deviation(a1,a2,a3,…,a70) were calculated

- Geometric Mean = Exp (Mean) was calculated and used as a best estimate in most cases.

- 0.01 Percentile = Exp (Mean - 3.09 * Standard Deviation) was calculated and used as lower limit

- 99.9 Percentile = Exp (Mean + 3.09 * Standard Deviation) was calculated and used as upper limit.

2.6. Sensitivity analysis

- CHERPAC is also coupled with the PCCSRC code (Iman et al 1985) which ranks the importance of the input parameters to variation in the output

- Sensitivity analyses results are always scenario-specific and time-dependent

- Based on past work with CHERPAC, there is a high probability that the model output will be sensitive to parameters such as dry deposition velocity and washout ratio

- If required, the sensitivity analysis for the Agricultural and Forest Environments will be performed using some parameter values and distributions already present in CHERPAC and by adding some new parameter values.

2.7. Validation and usage of CHERPAC

- CB scenario
- VAMP S scenario
- User-specific modelling uncertainties scenario.

3. Scenario description

A hypothetical source term is given to be an instantaneous deposition of 1000 Bq m^{-2} each of Cs-137, Sr-90 and I-131. Deposition is to be considered under both dry (will be referred as a dry deposition case in the CHERPAC results) and heavy rainfall (20 mm/hour) conditions (will be referred as a wet deposition case in the CHERPAC results). Seasonal effects are to be considered by assuming that the depositions occur in each of winter (February 15), spring (May 15), summer (August 15), and autumn (November 15). The concentrations in common food products and doses to an adult, a 10 year old child, and a one year old infant are to be predicted for two years duration after the deposition event.

4. Adapting the model to the scenario and the assumptions made

- Best estimate predictions were made, and stochastic predictions and parametric sensitivities may be added later.

- CHERPAC's Canadian specific default parameter values including the growing and harvest months for various crops were used.

- All three radionuclides were assumed to be deposited in the particulate form.

- CHERPAC was started with the air concentrations, which were calibrated to achieve the given depositions on grass and soil surface. The depositions to other surfaces were tried to be set closer to 1000 Bq/m2. The direct contribution of air concentration into plant and animal product was disabled.

- Originally CHERPAC had a lake and fish model for Cs-137 only. This model was adapted to Sr-90 and I-131 also by combining it with the CSA N288.1 (2008)'s pond model. Time dependent I-131 concentrations in water were dominated by its 8 day half life. The Clay soil type was used in this model.

- CHERPAC originally contained the intake rates by humans from the agricultural and the forest pathways combined. The intake rates from forest products were much lower than those from agricultural products. For the two pathways separated, the forest products intake rates were increased assuming that people living closer to the forest consume more forest food.

- Originally CHERPAC only contained the bulk transfer factors for the forest food products for Cs-137. These parameter values for Sr-90 were derived by comparing Cs-137 and Sr-90 concentrations in fruits, forest plants, beef, and forest animal products. These values for I-131 were derived from its radioactive decay with 8-day halflife.

- CHERPAC has relatively old values of dietary intakes in the form of PDFs (probability density function). CSA N288.1 (2008) has newer deterministic values. Original CHERPAC values were used in this deterministic analysis in view of their convenience for the future uncertainty and sensitivity analysis.

- Only monthly CHERPAC predictions were made, although it can make daily predictions also.

- An infant 1 year age class was added to CHERPAC. Only the whole body effective doses from ingestion and groundshine were predicted.

5. Results

The discussion of the reasons behind fluctuations in the concentrations of various food products is beyond the scope of this document. It is difficult for a model to make realistic predictions for every single time step; therefore, more attention should be paid to the aggregate predictions.

The results from one selected case (i.e. Cs-137, dry deposition, and the release assumed to occur in the summer) are discussed below, but many of these observations are expected to apply for other cases also.

5.1 Soil (CHERPAC uses the same soil model for agricultural and forest environments) (Figure 2)

- Some of the wet deposition is retained by plant leafs and some is washed off.

- Results for the dry and wet deposition cases were similar because CHERPAC adds both depositions together to carry out the rest of the simulation.

- Soil deposition is lower in the first few months because material is retained by the plant leaves, but it slowly washes off and transfers to soil.

- Soil predictions are sensitive to the season in which the release occurs. If the release occurs closer to the harvest season, then some of the deposition gets removed with plants, so the soil inventory is reduced.

- Radioncuclides are lost from the system as a function of to their half lives.

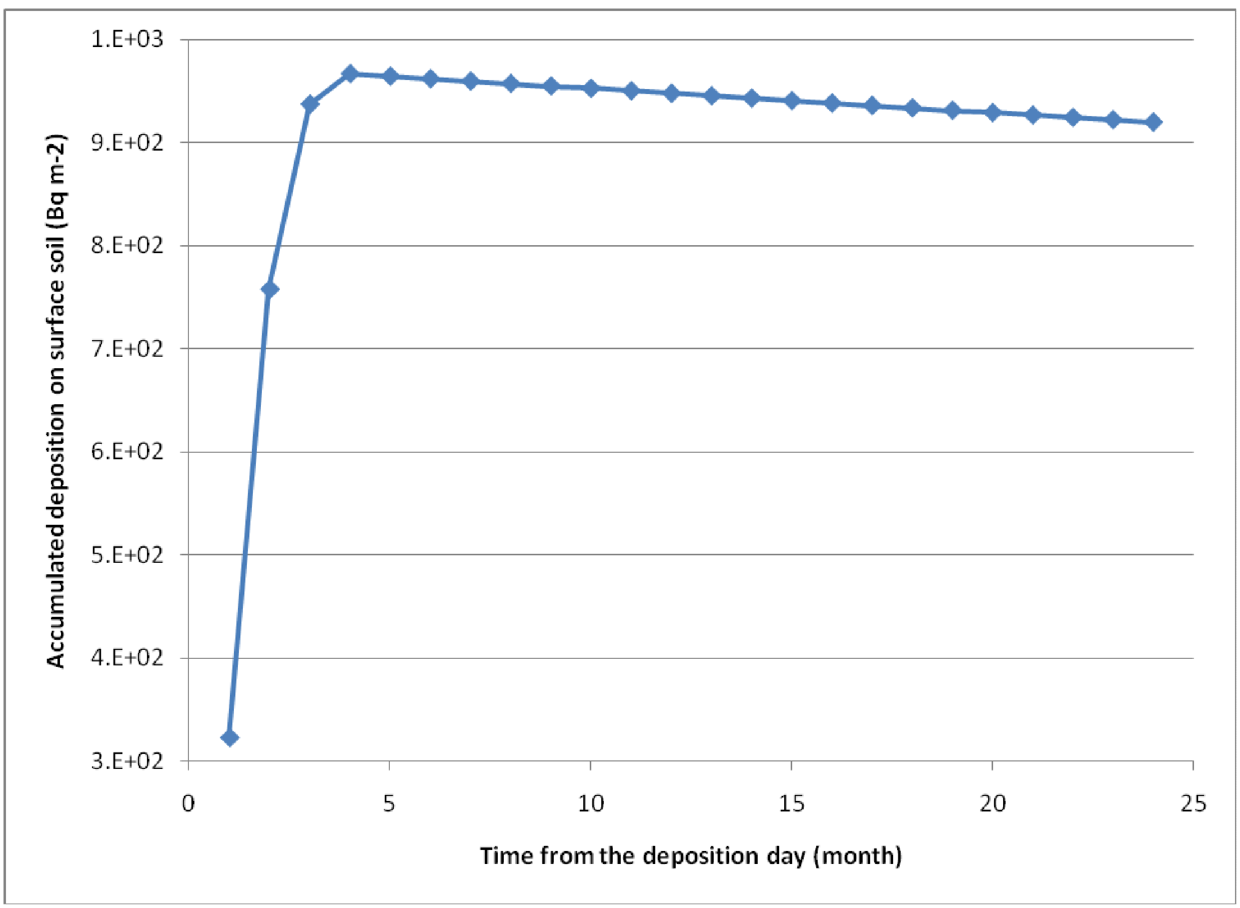

Figure 2: CHERPAC predictions of accumulated deposition on surface soil.

5.2 Agricultural plants (Figure 3)

- Seasonal differences were noticed as nothing is growing for the first: two months for the winter deposition case, and five months for the autumn deposition case.

- For Cs-137, the fruits concentrations were predicted to be the highest among all plants for the winter release. The pasture and leafy vegetables concentrations were the highest for the summer release. The greenhouse non-leafy concentrations were the lowest in the first year for the summer release.

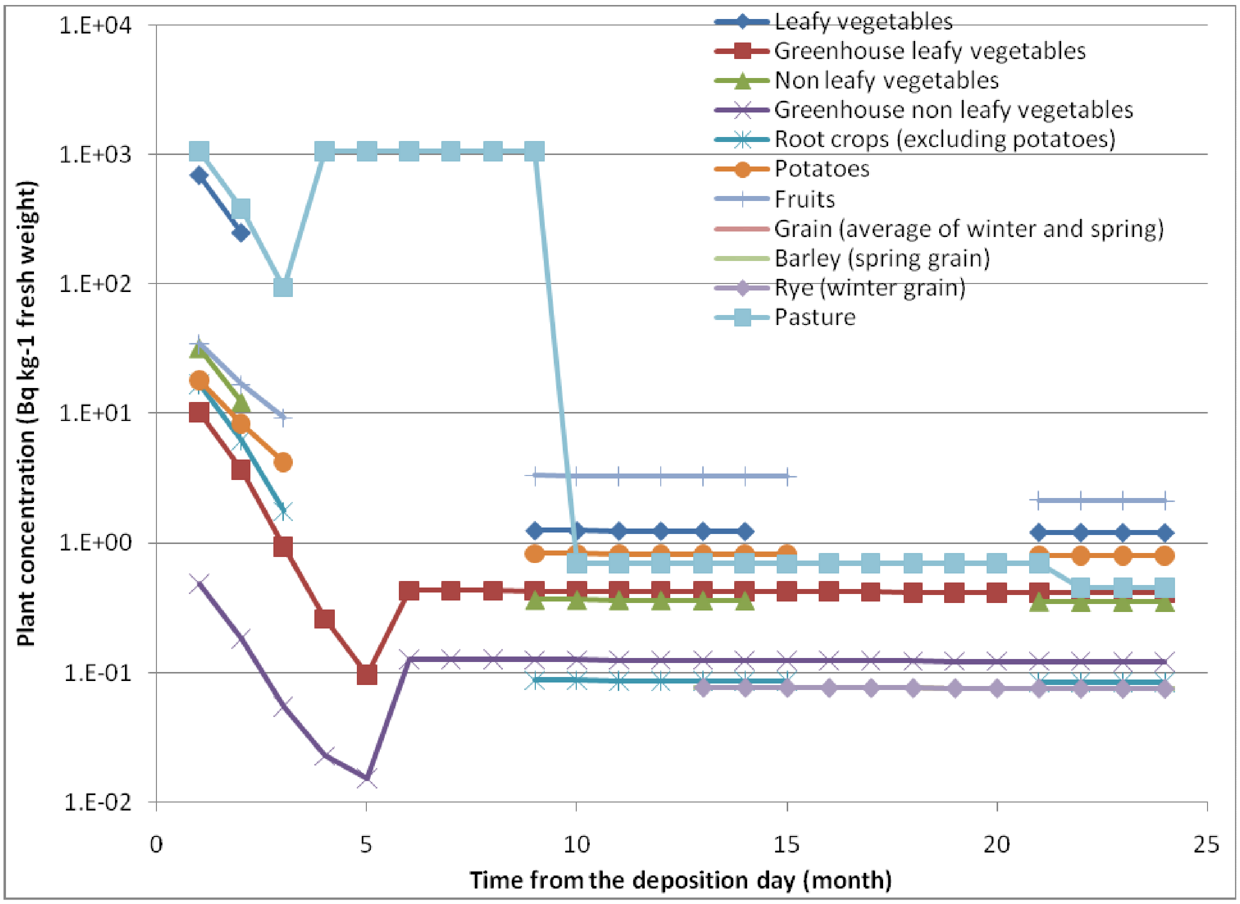

Figure 3: CHERPAC predictions of agricultural plant concentrations.

5.3 Forest plants (Figure 4)

- Mushrooms have four times higher concentrations than berries because the bulk transfer factor for mushrooms is higher than that of the berries.

- Mushrooms concentration increases for the first few years as the activity passes through the root zone, but it levels off and comes down afterward.

- Wild berries concentration are shown zero for the first 10 months because the pickup season is only June and July.

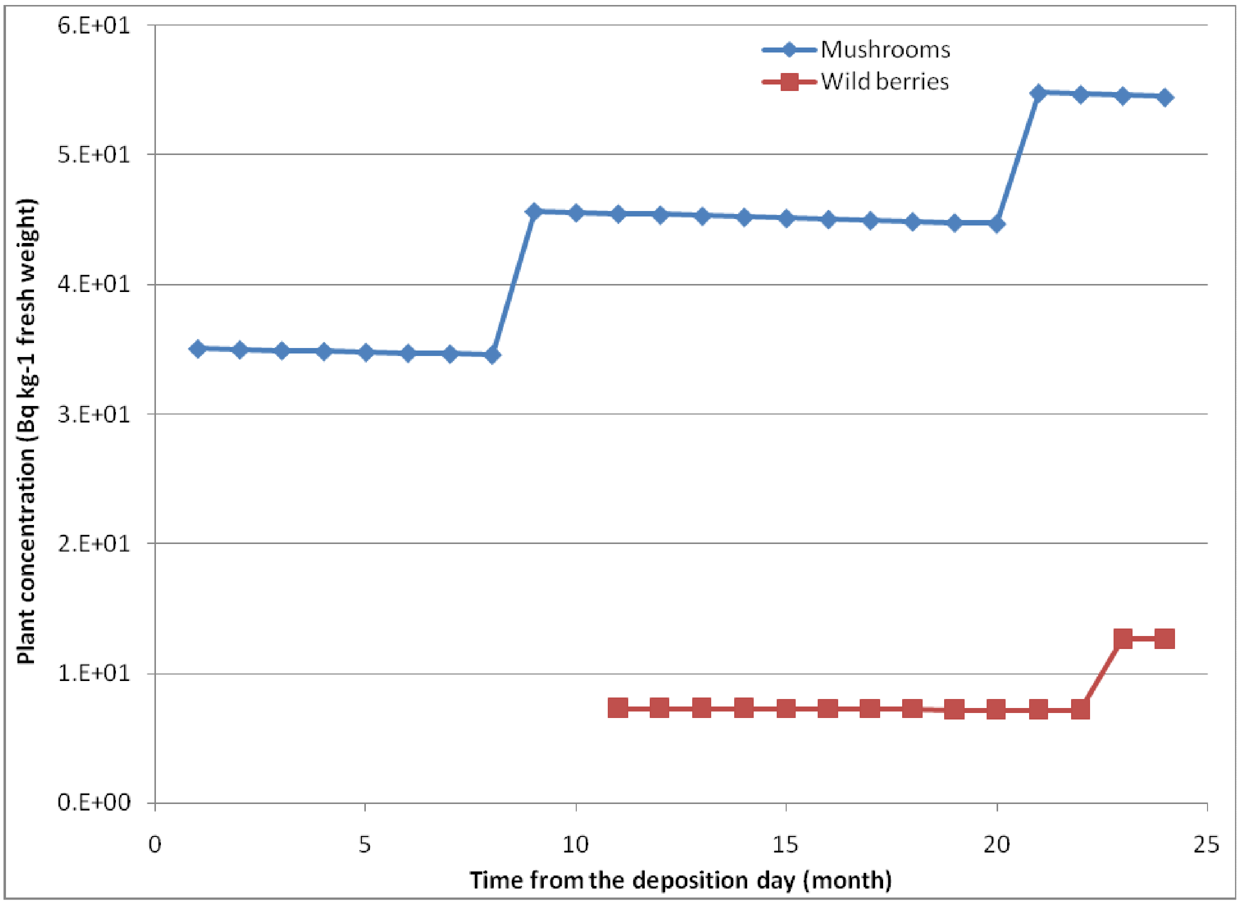

Figure 4: CHERPAC predictions of forest plant concentrations.

5.4 Agricultural animal products (Figure 5)

- Beef concentration was predicted to be highest among all animal products. Eggs concentration was predicted to be the lowest.

- Beef concentration started appearing two months later than the deposition event because these animals are not assumed to eat fresh pasture (this assumption got hard coded in CHERPAC in the past and not removed yet).

- The concentrations in chicken and eggs are driven from soil and grain concentrations. They are assumed to eat prior season (not fresh) grain, and they are outdoor only from May to October, so no transfer from soil in the winter months. Therefore, the chickens and eggs concentrations showing zero values for the winter months in the first year.

- Some blips in the animal produce concentrations are due to the facts that hay is considered to be harvested twice in a growing season in CHERPAC. The concentration is dropping with time when animals eating the first-harvest hay, and then the concentration suddenly increases when the animals start eating newer fresh second-harvest hay.

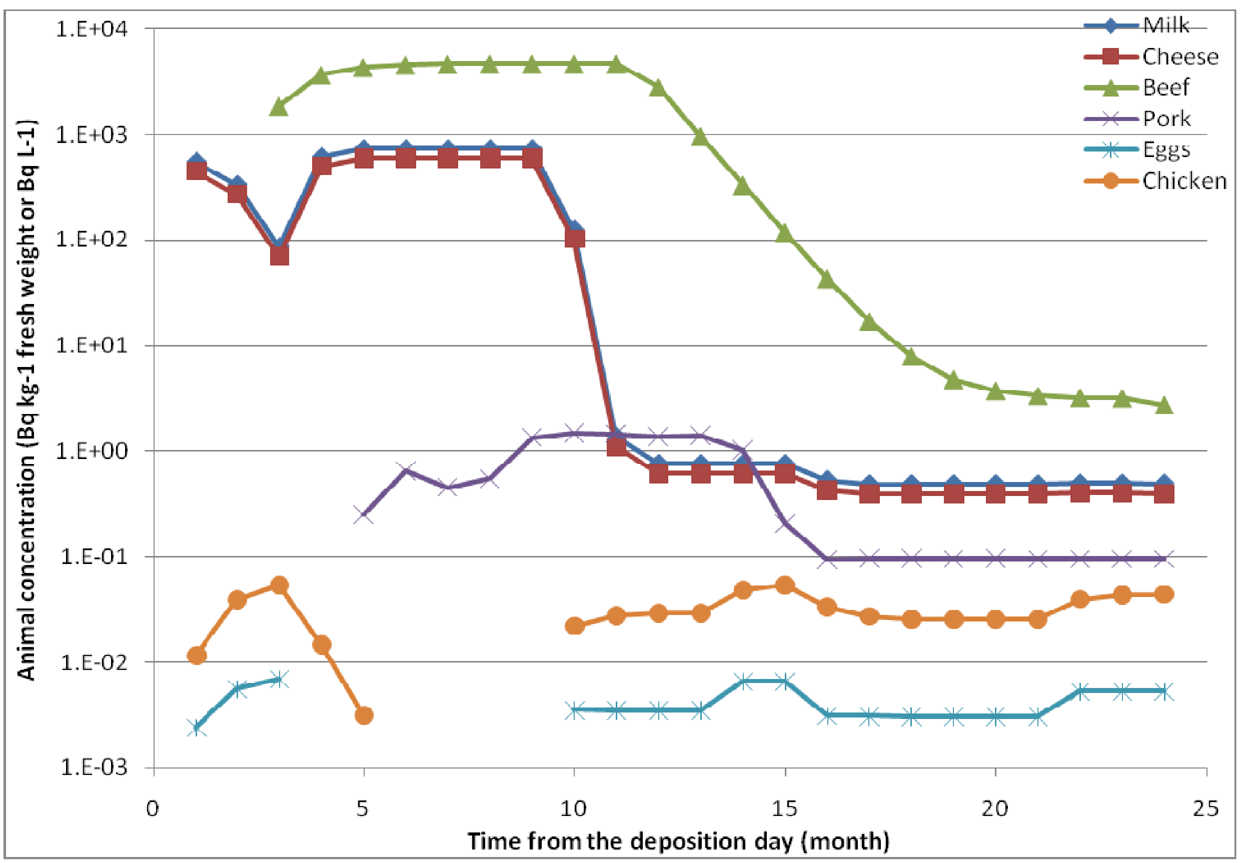

Figure 5: CHERPAC predictions of agricultural animal product concentrations.

5.5 Forest animal products (Figure 6)

- The concentrations in small game are higher than the big game because of the higher bulk transfer factor.

- The fish concentrations are higher compared to other animal products because of the higher BAF of Cs-137.

- The results also indicate that fish may give higher dose than other forest food products.

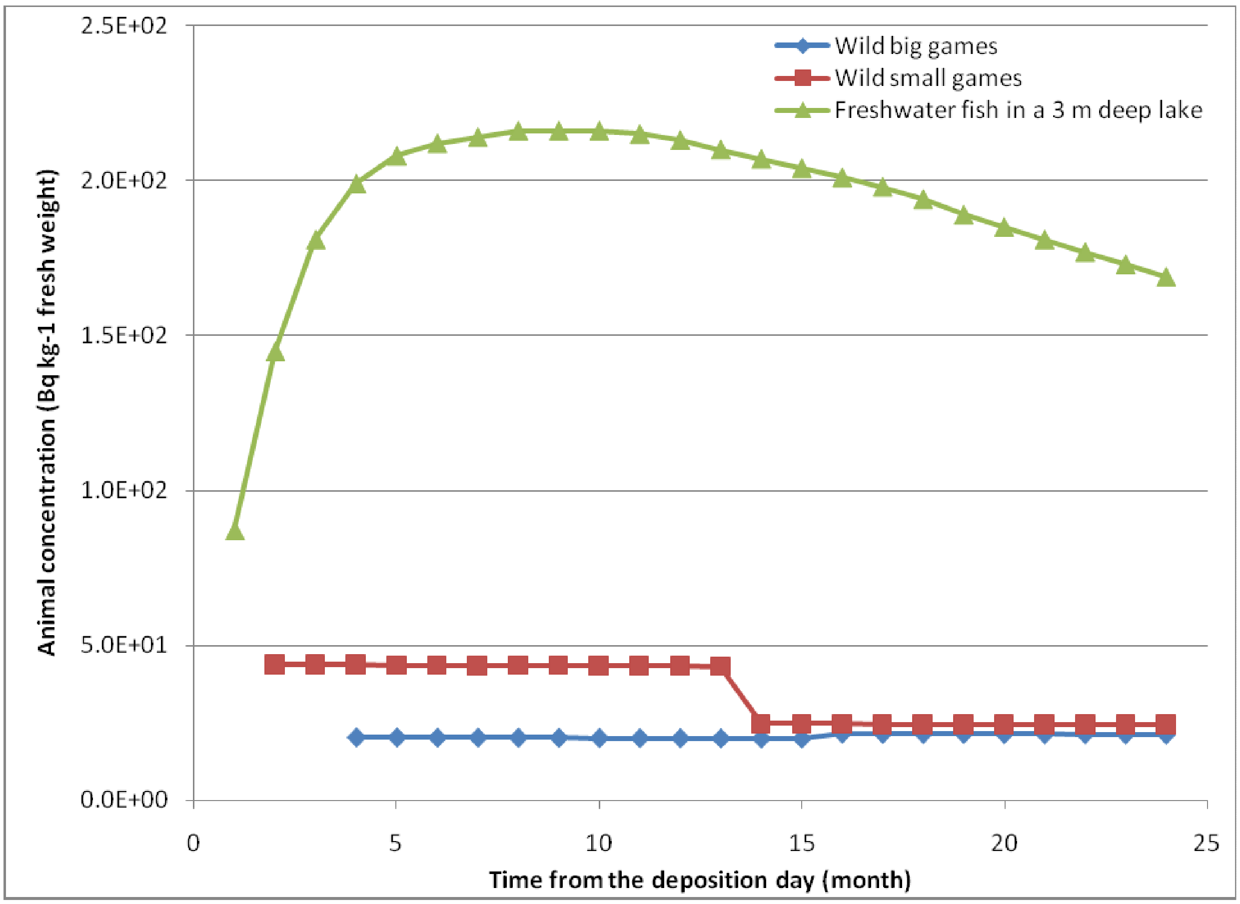

Figure 6: CHERPAC predictions of forest animal product concentrations.

5.6 Doses (Figure 7)

- The ingestions doses from the agricultural food products are predicted to be much higher compared to the groundshine doses and forest food products ingestion doses.

- Infants have lower dose from forest product because of their lower intake rates compared to the other categories.

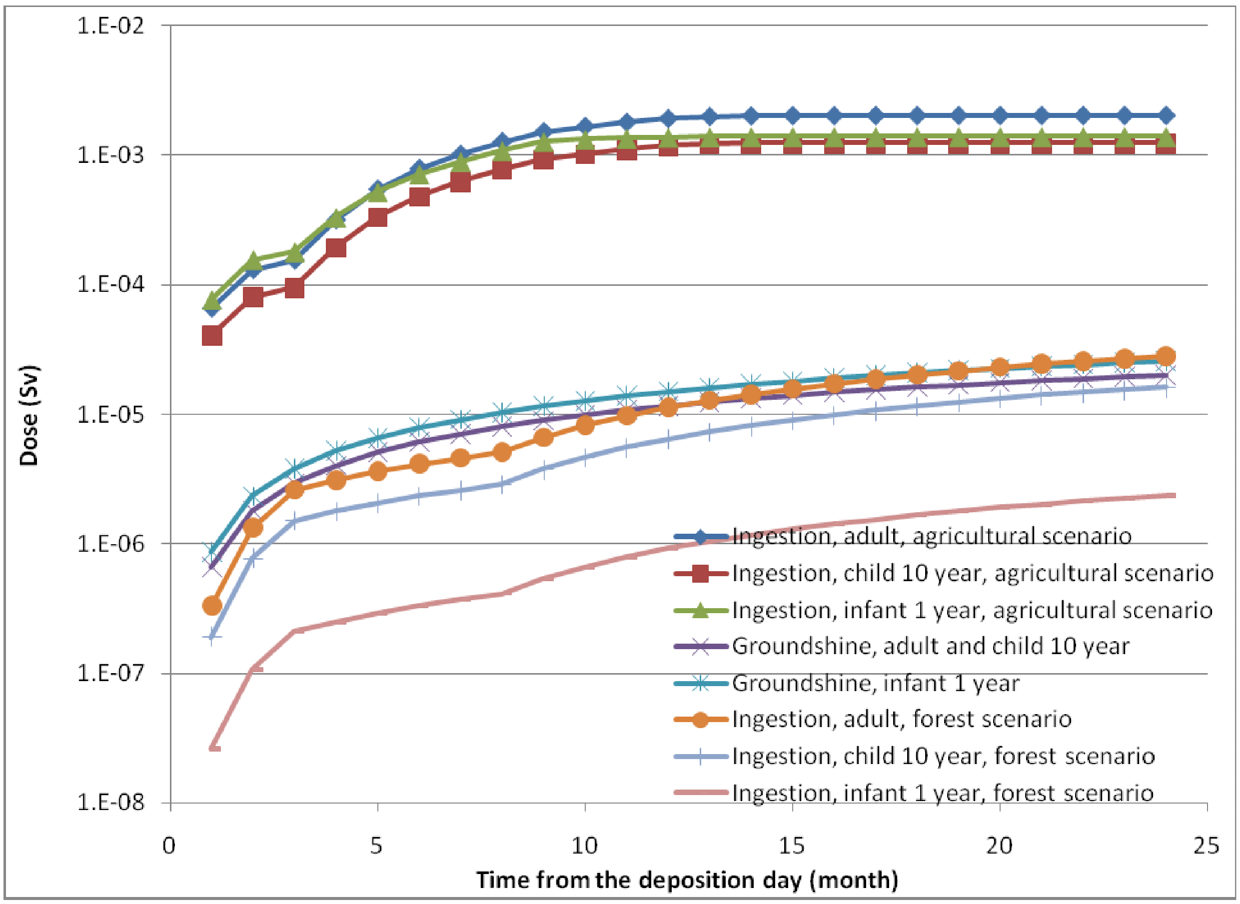

Figure 7: CHERPAC predictions of doses to humans.

6. Conclusions

To be added in the future.

7. References

To be added in the future.

8. Acknowledgements

The contribution of Ring Petersen (prior to retiring from AECL in 1998) to CHERPAC development and documentation is gratefully acknowledged. Nick Scheier's review of this document and valuable suggestions for improvements are much appreciated. David Rowan's advice about the lake and fish model is also thankfully recognized.