CANADIAN AND UNITED STATES REGULATORY MODELS COMPARED: DOSES FROM ATMOSPHERIC PATHWAYS

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INTRODUCTION

CANDU reactors sold offshore are licensed primarily to satisfy Canadian regulations. For radioactive emissions during normal operation, the Canadian Standards Association's CAN/CSA-N288.1-M87 (1) is used. This standard provides guidelines and methodologies for calculating a rate of radionuclide release that exposes a member of the public to the annual dose limit.

In some countries such as the Republic of Korea, the regulatory requirement is to calculate the annual dose to members of the critical group. To calculate doses from air concentrations, either CSA-N288.1 or the Regulatory Guide 1.109 (2) of the United States Nuclear Regulatory Commission, which has already been used to license light-water reactors in these countries, may be used. When dose predictions from CSA-N288.1 (called CSA henceforth) are compared with those from the U. S. Regulatory Guides (called RG henceforth), the differences in projected doses raise questions about the predictions. This report explains differences between the two models for ingestion, inhalation, external and immersion doses.

For compliance with nuclear regulations, emissions reported in terms of percent DRLs for CANDU reactors routinely include tritium, ^{14}C, noble gases (as Bq MeV), radioiodine (as ^{131}I) and unidentified particulates. Stack sampling provides supporting numbers during operation to a greater or lesser extent. In addition, at some sites and under some conditions, measured or estimated releases are available for other radionuclides (3, 4, 5, 6, 7). There are no data for a number of radionuclides, and many of the particulate values are single measurements or even estimates (3). These data, adjusted as emissions from a single CANDU reactor unit and averaged with extremes discarded (Table 1) are used here to calculate doses from unit releases and actual releases for both models.

Table 1
Radionuclides Released from CANDUs and Average Measured and Assumed Source Terms

	Average Measurements Bq s^{-1}	Assumptions Bq s^{-1}
H-3	7.0E+06	
C-14	1.4E+04	
Cr-51		7.1E-02
Mn-54		7.1E-02
Fe-59	2.0E-03	
Co-58	1.4E-03	
Co-60	2.3E-02	
Zn-65		7.1E-02
Sr-89		7.1E-02
Sr-90		7.1E-02
Zr-95	1.5E-01	
Nb-95	1.7E-01	
Mo-99	3.3E-03	
Ru-103		7.1E-02
Ru-106	4.6E-02	
Te-132	1.6E-03	
I-131	3.1E-01	
I-132	4.5E-01	
I-133	6.2E-01	
I-134	6.3E-01	
I-135	5.6E-01	
Cs-134	9.9E-02	
Cs-136	6.5E-03	
Cs-137	2.7E-01	
Ba-140		7.1E-02
Ce-141		7.1E-02
Ce-144		7.1E-02
Ar-41	1.5E+05	
Kr-85m	5.3E+04	
Kr-87	9.6E+04	
Kr-88	2.7E+05	
Xe-133	3.9E+06	
Xe-135	6.3E+05	

DOSES

Ingestion Pathways

In addition to real differences between the models which are due primarily to differences in parameter values, significant differences will arise because of assumptions made by the user. The aim in this intercomparison is to assure that assumptions made by the user apply equally to both models.

Assumptions Made for Comparison. The endpoints for concentrations in foodstuffs and ingestion doses are different for RG and CSA because of different definitions of vegetables and meat and different diets (Table 2). Consequently, the models should not be compared directly and nevertheless, meaningful comparison is possible if certain assumptions are made.

Table 2
Important Differences in Parameters and Model Assumptions for Rg 1.109 and CSA-N288.1

Consumption for adults and infants in kg per annum assumed

	RG* Adult	CSA** Adult	RG* Infant	CSA** Infant
Leafy vegetables	64	14		10
Fruit vegetables	108.4	55		25
Root vegetables	108.4	79		24
Fruit	114.4	55		25
Grain	124.8	[74]		[12]
Milk & milk products	310	174	330	220
Beef (meat)	110	35.5		12
Pork		35.5		12
Poultry		16		10
Eggs		14		5

* Recommended values for intake to be used for the maximum exposed individual in lieu of site-specific data RG groups fruits, vegetables, and grain: 520 kg per annum; leafy vegetable, 64 kg per annum Consumption of vegetables products defined: (on a mass basis) 22% fruit, 54% vegetables (including leafy) and 24% grain.

** Recommended average food consumption rates in lieu of site-specific data; CSA groups above-ground vegetables (fruit vegetables) and fruit, 110 kg for adult, 50 kg for infant; beef and pork, 71 kg for adult, 24 kg for infant. Numbers in square brackets are shown for diet with no guidance for how to calculate concentrations.

Days to ingestion in RG (0 days to ingestion in CSA):

Leafy vegetables	1 d to maximally exposed individual
Produce	60 d to maximally exposed individual
Unspecified vegetables	14 d to member of the general population
Milk	2 d to maximally exposed individual
Milk	4 d to member of the general population
Meat	20 days from slaughter to consumption

Fraction of food arising from a contaminated source

	CSA	RG
Leafy veg	site specific	1
Produce	site specific	0.76

In RG the following delays apply:

Pasture	0 days (assumed here for comparison)
Hay	90 days if stored

Period of long term build up in the soil in years based on lifetime of power station

RG	CSA
15	infinite

The assumptions made for this intercomparison included:

- Air concentrations at 1000 m from the elevated source are 5.4 10^{-7} Bq m^{-3}.
- The member of the critical group for whom all doses are calculated lives 1000 m from the source and is self-sufficient, i.e., raising all necessary food for a completely contaminated diet.
- For tritium, the ratio of the tritium in the plant to the tritium in the air is set at 0.5 with an absolute humidity of 0.01 kg m^{-3} for RG. This corresponds to the CSA default value of 50 m^3 kg^{-1} for the transfer from air to vegetation.
- For carbon, there are 0.16 g carbon per cubic meter of air.
- For comparison between RG and CSA, the minimum time between harvest and ingestion in RG was assumed: 1 day for all vegetables, 2 days for milk, 20 days for meat.
- When vegetable crop concentrations are compared, the single RG value is compared with a weighted average of the concentrations of CSA's four different crops based on annual adult intake of each.
- Meat concentrations from RG are compared with a weighted average of beef, pork, poultry and eggs based on annual adult intake of each in CSA.
- In CSA, it is assumed that all feed consumed by animals is equivalent to eating off pasture all year, unless the radionuclide is short-lived (< 1 month), in which case a winter non-grazing factor of 0.5 is introduced. In RG, the user can select fractions of pasture or hay that has been stored for 90 days. In order to compare the models, the RG equation for pasture was modified to account for the winter non-grazing factor for short-lived nuclides, just as in CSA.
- In RG, iodine is considered to be 50% elemental, and only this portion of the iodine released enters the food chain. In CSA, the released iodine can be fractionated between elemental, particulate and organic fractions. Since particulate iodine also deposits significantly and enters the food chain, for CSA it was assumed that the fractionation is 50% elemental, 25% particulate and 25% organic.
- No wet deposition was considered for either model.
- A factor of 5 was assumed to convert dry weight to fresh weight pasture. RG parameter values are exclusively fresh weight, but CSA forage is in dry weight. Thus CSA values had to be converted to be comparable for the discussion.

Total activity ingested per year per radionuclide is compared for the default diets of each model. However, since these diets are intended to be different (RG's maximal and CSA's average), a better comparison of ingestion dose is made with both models using the average diet described in CSA. Furthermore, since delays to ingestion in RG reduce dose from short-lived radionuclides drastically, the CSA predictions were modified on a spreadsheet to reflect the same delays and to be comparable with RG's (with CSA diet).

Comparison of concentrations in foodstuffs: To understand why ingestion doses differ, it is imperative to compare all the steps from air concentration to concentrations in forage and vegetables to concentrations in milk and meat products and to compare intake from overall diet.

In Table 3, ratios of predicted CSA concentrations divided by RG concentrations (CSA/RG) for pasture, vegetables, milk, beef and meat are compared. Pasture concentrations for CSA are consistently lower than RG's with the exception of ^{90}Sr, which has the highest soil to plant concentration ratio (CR) of the CSA nuclides. CSA's low predictions are due to the difference in yield of the two models: RG's is 0.7 kg, while CSA's is 1.4 kg (recommended generic value in fresh weight). CSA/RG ratios for vegetables mostly lie between 2.4 and 2.6. This is largely due to the lower average yield (1.3 kg m^{-2}) of CSA compared with RG's 2.0 kg fw m^{-2}. The ratios for the shorter-lived iodines, particularly ^{132}I and ^{134}I, are remarkable exceptions. These high ratios (e.g., 4.1 10^8 for ^{134}I) illustrate how important the day's delay to ingestion is for short-lived radionuclides, since when the two results are compared once CSA's have been adjusted for the delay, the ^{134}I ratio falls to 1.9, which agrees with all the other radioiodines.

For tritium, the CSA/RG ratio for concentration in fresh weight pasture is 1.3, like the vegetables. However, there is a conceptual error in CSA's treatment of the specific activity model for tritium. With the specific activity model for tritium, by definition, concentrations of tritium should be calculated on a fresh weight basis, but, in CSA, pasture is given as dry weight. Thus a calculated fresh weight concentration is defined as a dry weight quantity. In practice, either the pasture will have been dried to hay from which essentially all water (including HTO) has been evaporated, and consequently the concentration of HTO in dry weight pasture will be little or nothing, or the calculated tritium concentration in pasture must be expressed in fresh weight. This error affects concentrations of tritium in milk and meat and ultimately ingestion dose from tritium. That CSA's plant concentrations are 30% higher than RG's is due mostly to RG's assumption that 75% of the total plant is water (CSA tacitly assumes 100%).

Table 3

CSA/RG Ratios for Concentrations in Pasture*, Vegetables**, milk and Beef and Meat***

Columns labelled "no delay" compare CSA and RG as calculated by the model; columns labelled "delay" mean the CSA value has been delayed for x days to be comparable to the RG value which is based on time between harvest and ingestion

	Pasture	Vegetables		Milk		Beef		Meat	
		No delay	1 d delay	No delay	2 d delay	No delay	20 d delay	No delay	20 d delay
H-3	1.3	1.3	1.3	0.58	0.58	0.47	0.46	0.63	0.63
C-14	0.80	0.54	0.54	1.0	1.0	1.7	1.7	1.4	1.4
Cr-51	0.40	2.5	2.5	0.20	0.19	2.3	1.4	0.81	0.49
Mn-54	0.40	2.4	2.4	0.54	0.53	0.26	0.25	0.39	0.37
Fe-59	0.46	2.5	2.5	0.11	0.10	0.33	0.24	0.22	0.16
Co-58	0.49	2.6	2.5	1.4	1.4	0.45	0.37	1.4	1.1
Co-60	0.51	2.5	2.5	1.5	1.5	0.40	0.40	1.2	1.2
Zn-65	0.45	2.0	2.0	0.12	0.12	1.6	1.5	1.0	0.97
Sr-89	0.48	2.6	2.5	0.86	0.84	0.84	0.65	5.1	3.9
Sr-90	1.1	2.5	2.5	1.9	1.9	1.4	1.4	8.7	8.7
Zr-95	0.40	2.5	2.5	3.6	3.6	0.33	0.27	0.33	0.27
Nb-95	0.45	2.5	2.5	3.8	3.6	0.60	0.41	0.21	0.22
Mo-99	0.40	3.1	2.4	0.032	0.020	13	0.087	9.2	0.063
Ru-103	0.46	2.5	2.5	1.6	1.6	0.0033	0.0023	0.0024	0.0013
Ru-106	0.50	2.4	2.4	1.7	1.7	0.0026	0.0025	0.0019	0.0014
Te-132	0.39	2.9	2.3	1.4	0.92	13	0.18	11	3.9
I-131	0.32	2.1	1.9	0.62	0.52	2.2	0.39	3.5	0.64
I-132#	0.31	2.6E+03	1.9	1.2E+06	0.63	2.7E+62	0.41	4.6E+62	0.69
I-133#	0.31	4.2	1.9	2.6	0.52	2.9E+06	0.35	4.7E+06	0.57
I-134#	0.31	4.1E+08	1.9	3.9E+16	0.82	2.4E+166	0.45	4.3E+166	0.81
I-135#	0.31	23	1.9	79	0.55	1.5E+21	0.39	2.4E+21	0.65
Cs-134	0.52	2.5	2.5	0.30	0.30	3.4	3.3	5.7	5.5
Cs-136	0.42	2.6	2.5	0.21	0.19	5.9	2.0	9.9	3.4
Cs-137	0.54	2.4	2.4	0.32	0.32	3.5	3.5	5.9	5.9
Ba-140	0.42	2.6	2.5	0.42	0.38	0.038	0.013	0.58	0.31
Ce-141	0.46	2.6	2.5	0.51	0.49	1.4	0.93	0.72	0.47
Ce-144	0.51	2.6	2.6	0.48	0.48	1.0	0.99	0.52	0.50

* Pasture is compared on a fresh weight basis

** The number used for CSA is a weighted average of vegetable and fruit concentrations based on yearly adult diet

*** The number used for CSA is a weighted average of all meats and eggs based on yearly adult intake

\# Meaningless high ratios for radionuclides with half-lives less than 1 day show assumption of instantaneous ingestion to be unrealistic

CSA/RG ratios for ^{14}C in pasture and vegetables are also different even though the specific activity model is used in both models. RG has the same ^{14}C concentrations in pasture as in vegetables because all plants are assumed to have 110 g of carbon per kilogram of plant. In contrast, CSA assumes a carbon content of 60 g kg^{-1} vegetable and 440 g kg^{-1} pasture dry weight (equivalent to 88 g if fresh weight). Thus the CSA/RG ratio is slightly higher for pasture than for vegetables. CSA concentrations are lower than RG's because of the assumptions of lower carbon content in fresh weight plants.

In Table 3, concentrations are compared also for milk, beef and "meat" based on weighted averages of meat concentrations from an adult diet. A small contribution to concentration in CSA comes from the inhalation pathway to animals, which is not included in RG.

The CSA/RG ratio for milk averages about 1.0 with about half of the ratios less than 1.0. Since the intake of cows is essentially the same in both models (10 kg dw in CSA and 50 kg fw in RG) most of the difference in milk concentrations can be traced to the lower concentrations found in CSA forage which are not offset by the generally higher forage to milk transfer factors (F_m) in CSA or perhaps are made lower by CSA/RG F_m ratios of less than 1. In both models, both tritium and ^{14}C are calculated using F_m. For tritium, due to the conceptual error in CSA, the cow will ingest 10 kg of dry weight hay with a concentration calculated on the basis of fresh weight. This either overestimates the amount of tritium ingested (i.e., if the hay is dry and free of HTO) or underestimates the amount of tritium ingested by a factor of five (50 kg fresh weight is the equivalent of 10 kg dry weight). Conservatively assuming a fresh weight diet, the CSA/RG ratio for concentration in milk should be 1.9.

The "meat" in RG is supposed to include a diet of meat (unspecified) and poultry, but, the forage to meat transfer factors (F_f) used in RG are more similar to the values used in CSA for beef than they are for the pork, poultry or egg F_f values in CSA. Thus the CSA results (with delays to ingestion) are compared just for beef and for a weighted meat, as mentioned above. For the beef comparison, most ratios are within a factor of 4 except for ^{103}Ru, ^{106}Ru and ^{140}Ba, which are extremely low. If the differences in pasture concentrations were considered, the CSA value would rise by a factor of two, improving the underpredictions and raising the overpredictions. On average, when CSA weighted meat is compared with RG meat, the ratio rises by nearly a factor of two, and the ^{140}Ba CSA value then falls within a factor of three of the RG value. The rutheniums remain a problem due to the very low F_f for ruthenium in CSA (0.002 d kg^{-1} beef) compared with RG (0.4 d kg^{-1} meat).

Comparison of total diets: CSA/RG ratios are shown in Table 4 for adult and infant. Values compared are for the RG maximal adult diet or milk infant diet, the CSA diet used in RG, the CSA diet in CSA without delay corrections and the CSA diet in CSA with losses due to delays included. The contribution of each radionuclide to adult and infant CSA diets is remarkably similar (within a factor of 2) for CSA and RG. The CSA diet contributes slightly more Becquerels per annum per unit release than does RG because of higher vegetable concentrations than found in RG, which compensate for comparatively lower concentrations in milk and meat. This is true for the infant (CSA diet) too. CSA/RG ratios would be much greater for ^{51}Cr and ^{95}Zr if the CSA diet had included contributions from pork, poultry and eggs not calculated in CSA; similarly, CSA/RG ratios for ^{95}Nb, ^{99}Mo, ^{132}Te, and ^{140}Ba would be somewhat higher if the dietary contribution from pork were calculated in CSA, which it is not. For both adult and infant, the very low ^{103}Ru and ^{106}Ru ratios in the diet are accounted for by extraordinarily low concentrations in meat in CSA. Zinc-65 activity in infant's diets is low because of low concentrations of ^{65}Zn in milk (due to a low F_m) relative to RG. Niobium-95 is a bit low in CSA for the adult diet due to low concentrations in poultry and eggs.

The all milk diet in RG for infants creates some very high CSA/RG ratios, since many radionuclides are not easily transferred to milk compared with other food stuffs. In RG, milk always has the lowest concentration of vegetables, milk and meat. For CSA on average, it ranks 7 out of 9 foodstuffs, and, on average, has a similar concentration to that calculated in RG. For example, in both RG and CSA, very little ruthenium is concentrated in milk. In a total CSA infant diet, between the vegetables and meat, however, there is a lot of ruthenium concentrated, relatively. Thus for annual diet, the CSA/RG-with-milk-diet ratio is 5900 for ^{106}Ru, while the CSA/RG-with-CSA-diet ratio is only 0.12 due to the higher meat concentrations in NUREG compared with CSA.

Quantities of tritium and ^{14}C in diets of adults and infants are essentially the same for the two models.

Ingestion Doses: CSA/RG ratios are shown in Table 5 for adults and infants respectively. All comparisons are based on the use of the CSA diet in both models with delays to ingestion accounted for. For the critical organ comparisons, the highest doses from each model are compared with each other, regardless of whether the dose is highest by being the only dose (i.e., the effective dose in CSA when there is no critical organ). Also, a set of

Table 4
CSA/RG Ratios for Annual Diet for Adult and Infant

ADULT

Nuclide	Default diet	CSA diet	Decay corrected Default diet	Decay corrected CSA diet
H-3	0.48	0.84	0.48	0.84
C-14	0.49	0.80	0.49	0.80
Cr-51	0.91	1.7	0.88	1.6
Mn-54	0.93	1.7	0.92	1.7
Fe-59	0.61	0.88	0.58	0.83
Co-58	0.96	1.6	0.92	1.5
Co-60	0.92	1.5	0.92	1.5
Zn-65	0.38	0.62	0.37	0.60
Sr-89	1.0	1.9	0.98	1.8
Sr-90	1.1	2.0	1.1	2.0
Zr-95	0.61	0.88	0.60	0.86
Nb-95	0.37	0.44	0.32	0.38
Mo-99	0.65	1.2	0.49	0.90
Ru-103	0.12	0.13	0.11	0.13
Ru-106	0.09	0.11	0.09	0.11
Te-132	1.1	2.1	0.90	1.7
I-131	0.74	1.4	0.66	1.2
I-132	1.2E+03	2.2E+03	0.74	1.4
I-133	1.7	3.1	0.69	1.3
I-134	1.9E+08	3.6E+08	0.75	1.4
I-135	10.	19.	0.74	1.4
Cs-134	0.84	1.5	0.84	1.5
Cs-136	0.82	1.5	0.68	1.2
Cs-137	0.83	1.5	0.83	1.5
Ba-140	1.0	1.9	0.94	1.7
Ce-141	0.99	1.8	0.96	1.8
Ce-144	0.98	1.8	0.98	1.8

INFANT

Nuclide	Milk diet	CSA diet	Decay corrected Milk diet	Decay corrected CSA diet
H-3	1.2	0.84	1.2	0.84
C-14	1.3	0.90	1.3	0.90
Cr-51	4.7	1.8	4.6	1.7
Mn-54	24	2.1	23	2.1
Fe-59	5.4	0.96	5.2	0.92
Co-58	7.8	1.8	7.6	1.7
Co-60	8.1	1.7	8.1	1.7
Zn-65	0.30	0.37	0.30	0.36
Sr-89	8.0	2.2	7.9	2.1
Sr-90	9.8	2.3	9.8	2.3
Zr-95	1.2E+03	1.0	1.2E+03	1.0
Nb-95	6.5	0.59	5.8	0.53
Mo-99	0.57	0.67	0.43	0.51
Ru-103	5.7E+03	0.16	5.6E+03	0.15
Ru-106	5.9E+03	0.12	5.9E+03	0.12
Te-132	1.6E+02	2.7	1.3E+02	2.2
I-131	1.9	1.4	1.7	1.2
I-132	3.2E+06	3.4E+03	1.7E+03	1.8
I-133	7.8	3.6	3.0	1.4
I-134	8.5E+16	5.8E+08	2.6E+08	1.8
I-135	2.3E+02	26	15	1.7
Cs-134	0.92	1.0	0.92	1.0
Cs-136	0.97	1.0	0.80	0.84
Cs-137	0.93	1.0	0.93	1.0
Ba-140	28	2.3	26	2.2
Ce-141	57	2.3	56	2.2
Ce-144	61	2.3	61	2.3

Table 5
CSA/RG Ratios of Ingestion Dose for Adults

	ADULT					INFANT			
	Total Body		Critical Organ*			Total Body		Critical Organ*	
Nuclide		CRL DCF		CRL DCF	Nuclide		CRL DCF		CRL DCF
H-3	0.60	0.54	0.60	**0.54**	H-3	0.58	0.48	0.58	**0.48**
C-14	2.7	3.0	0.54	**0.60**	C-14	1.1	1.1	0.22	**0.22**
Cr-51	75	87	0.30	**2.6**	Cr-51	31	1.0E+2	1.1	**28**
Mn-54	4.7	5.2	0.29	**1.0**	Mn-54	1.5	5.4	0.34	**3.4**
Fe-59	1.4	1.4	0.16	**0.76**	Fe-59	0.72	2.08	0.28	**3.1**
Co-58	4.7	2.5	0.52	**1.2**	Co-58	2.7	3.2	2.7	**14**
Co-60	20	3.9	2.3	**1.8**	Co-60	8.9	6.7	8.8	**14**
Zn-65	1.3	1.3	0.58	**0.73**	Zn-65	0.46	0.73	0.21	**0.38**
Sr-89	1.9	2.0	0.05	**0.46**	Sr-89	2.0	2.0	0.056	**0.44**
Sr-90	0.13	0.11	**0.35**	**0.37**	Sr-90	0.44	0.13	0.11	**0.61**
Zr-95	4.3E+2	4.6E+2	1.6	**14**	Zr-95	1.3E+2	6.0E+2	0.18	**7.3**
Nb-95	1.1E+3	4.4E+2	2.4	**6.3**	Nb-95	1.1E+3	6.3E+2	11	**3.0**
Mo-99	5.7	2.5	**4.7**	**10**	Mo-99	1.0	0.97	0.13	**0.79**
Ru-103	4.5	4.5	0.02	**0.15**	Ru-103	1.1	5.2	**0.031**	**1.3**
Ru-106	8.3	7.9	0.02	**0.16**	Ru-106	2.3	7.4	0.04	**1.2**
Te-132	11	10	**5.4**	**1.1E+02**	Te-132	17	13	**72**	**69**
I-131	15	29	**32**	**38**	I-131	21	43	**0.92**	**1.1**
I-132	3.5	7.9	**0.93**	**0.95**	I-132	5.5	13	**1.20**	**1.5**
I-133	14	27	**33**	**40**	I-133	18	43	**0.97**	**1.3**
I-134	1.6	5.5	**0.69**	**0.58**	I-134	7.7	7.7	**1.1**	**0.90**
I-135	6.1	11	**1.0**	**1.1**	I-135	10	21	**1.3**	**1.7**
Cs-134	0.91	0.86	0.74	**0.85**	Cs-134	0.89	0.84	0.090	**0.079**
Cs-136	0.78	NA	0.56	**NA**	Cs-136	0.50	NA	0.19	**NA**
Cs-137	1.1	0.99	0.70	**0.75**	Cs-137	1.2	1.0	0.09	**0.07**
Ba-140	12	13	**4.0**	**4.3**	Ba-140	2.6	16	0.13	**8.4**
Ce-141	7.1E+3	6.5E+3	**2.4**	**2.4**	Ce-141	1.6E+3	7.5E+3	0.37	**20**
Ce-144	1.5E+3	1.3E+3	**2.7**	**2.7**	Ce-144	4.0E+2	2.0E+3	0.39	**23**

* Numbers in bold are the comparisons of critical organ to critical organ; all other comparisons are CSA effective dose/RG dose to critical organ.

revised CSA predictions using updated DCFs (8)compiled for newly calculated DRLs at Chalk River (9) are compared with RG.

For adult effective dose, the CSA/CRL predictions are always higher than or equal to RG's with the exception of tritium, ^{90}Sr, ^{134}Cs and ^{137}Cs. Doses from ^{51}Cr, ^{60}Co, ^{95}Zr, ^{95}Nb, ^{141}Ce and ^{144}Ce are greater (sometimes by an enormous amount) by at least a factor of 20. For dose to a critical organ for an adult, when the CSA value is based on a DCF for effective dose, the CSA predictions are low (very low in the case of ^{89}Sr, ^{103}Ru and ^{106}Ru) or not significantly higher than RG's. When critical organ doses are compared for adults, CSA doses are either equal to or higher than RG's except for ^{90}Sr (0.35), ^{132}I (0.93) and ^{134}I (0.69). For the comparison of critical doses for adults with updated DCFs for CSA, the results are evenly divided between CSA/RG ratios greater than and less than one.

For infants, for the CSA diet, the trend in effective doses is quite similar to that for adults. In a critical organ to critical organ comparison for radioiodines, the CSA/RG ratio is about one. When CSA predictions with new DCFs are compared with RG's, most notable are the very low CSA/RG ratios for the cesiums and the higher ratios for the ceriums.

For tritium, the total body and critical organ doses for adults and infants for CSA are lower than RG's, and the new DCFs lower them a little more, to about half. For ^{14}C, the CSA effective doses for adults and infants are higher than RG's, but CSA doses to critical organ are lower than RG's. The new DCFs raise the dose to critical organ for an adult predicted by CSA to 60% that of RG but leave the predicted infant dose to critical organ at 22%, suggesting that the RG critical organ doses are obsolete.

One major difference between CSA and RG which impacts on ingestion doses is that RG has different DCFs for all critical organs considered, with the exception of tritium where all organs have the same DCF as the total body. Since DCFs to critical organs are higher than DCFs to whole body, the doses to critical organs in RG will invariably be higher than those calculated for total body in CSA (The DCFs for total body in CSA are mostly comparable to or higher than RG's). When DCFs for critical organs are specified in CSA, the organ doses are comparable to RG. The updated DCFs used in CSA are for a complete set of critical organs, and consequently the CSA-CRL/RG ratios are higher than the CSA/RG ratios for doses to critical organs for 80% of the radionuclides.

In a model intercomparison, there can be no right or wrong answers. From experience gained from model testing (10, 11) two similar models with similar assumptions would be expected to produce similar results, certainly within a factor of $^+/_-$ 3. The reasons for large deviations from this factor should be examined. Each model has some conservativeness built in: for RG, it is the maximal diet, while for CSA, it is having no delay times to ingestion. Both models employ sets of transfer parameters that are believed to be conservative (hence much of the similarity). Only those doses that differ significantly are cause for concern and should prompt an investigation of both models. Extreme differences between the two models' dose predictions can be explained primarily on the basis of differences in DCFs coupled with smaller differences in dietary contributions.

Inhalation Pathways

The equations for modelling dose from inhalation are essentially the same in CSA and RG, since, although CSA has an occupancy factor not found in RG, the default value is 1. Breathing rates for adults are slightly different: CSA's is 8400 m^3 a^{-1}, and RG's is 8000 m^3 a^{-1}. For infants the breathing rates are identical: 1400 m^3 a^{-1}.

CSA/RG and CRL/RG ratios of inhalation doses are shown in Table 6. As with the ingestion dose comparison, effective doses from CSA and RG are compared, doses to critical organs for the two models are compared (in bold) or the effective dose of CSA is compared with the dose to critical organ of RG, and the CSA dose based on updated DCFs (CRL) is compared with RG for both effective and organ doses. Since there is so little difference in the inhalation models, the differences in results are dominated by the DCFs. The CSA effective doses are usually higher than RG's, while doses to critical organs calculated with the updated DCFs are almost always lower than RG's, and none are significantly higher.

The CSA/RG ratios for ^{14}C inhalation doses for both adult and infant for effective and critical organ doses are alarmingly small, but since ratios calculated from the updated DCFs are still tiny (although about twice as large as the CSA/RG ratio), one might assume that RG's DCFs are the ones that should be reexamined.

External Dose Pathways

Each model calculates dose from external deposition by multiplying the deposition on the ground at steady state by a series of parameter values describing default conditions.

Table 6
CSA/RG and CRL/RG Ratios for Inhalation Doses for Adults and Infants

	ADULT					INFANT			
Nuclide	Total body		Critical organ*		Nuclide	Total body		Critical organ*	
	CSA/RG	CRL/RG	CSA/RG	CRL/RG		CSA/RG	CRL/RG	CSA/RG	CRL/RG
H-3	1.0	1.8	1.0	**1.8**	H-3	0.9	1.5	0.93	**1.5**
C-14	0.047	0.058	0.0089	**0.011**	C-14	0.015	0.018	0.0029	**0.0035**
Cr-51	31	12	0.22	**1.2**	Cr-51	22	12	0.15	**1.3**
Mn-54	9.9	7.9	0.044	**0.14**	Mn-54	3.2	6.6	0.016	**0.13**
Fe-59	11	11	0.11	**0.43**	Fe-59	8.2	7.1	0.077	**0.41**
Co-58	53	32	0.12	**0.54**	Co-58	27	22	0.063	**0.52**
Co-60	1.5E+2	65	0.37	**1.8**	Co-60	79	41	0.21	**1.6**
Zn-65	3.8	1.9	0.21	**0.8**	Zn-65	2.2	2.0	0.10	**0.70**
Sr-89	46	28	0.29	**1.8**	Sr-89	28	14	0.16	**1.5**
Sr-90	2.1	0.82	**0.17**	**0.91**	Sr-90	3.8	0.80	0.17	**1.2**
Zr-95	10	7.9	**1.7**	**0.71**	Zr-95	9.4	4.9	**2.2**	**0.71**
Nb-95	13	13	0.11	**0.51**	Nb-95	8.1	8.2	**0.76**	**0.49**
Mo-99	1.4E+3	1.3E+3	0.13	**0.69**	Mo-99	7.5E+2	7.5E+2	0.18	**1.5**
Ru-103	1.3E+2	1.4E+2	0.17	**1.0**	Ru-103	84	76	0.10	**0.93**
Ru-106	5.3E+2	2.4E+2	0.50	**3.3**	Ru-106	2.6E+2	1.1E+2	0.25	**2.9**
Te-132	4.0E+2	3.5E+2	3.0	**80**	Te-132	3.8E+2	2.8E+2	5.2	**8.9**
I-131	17	11	**1.0**	**0.70**	I-131	23	19	**1.0**	**0.77**
I-132	3.5	2.5	**0.92**	**0.44**	I-132	4.1	4.0	**0.89**	**0.49**
I-133	15	10	**1.0**	**0.63**	I-133	18	17	**0.91**	**0.66**
I-134	1.6	2.3	**0.69**	**0.27**	I-134	0.58	0.29	**0.80**	**0.31**
I-135	6.2	3.9	**1.0**	**0.53**	I-135	7.9	6.9	**1.0**	**0.58**
Cs-134	0.41	0.28	0.83	**0.51**	Cs-134	0.61	0.51	0.064	**0.081**
Cs-136	0.42	NA	0.83	**NA**	Cs-136	0.42	NA	0.17	**NA**
Cs-137	0.50	0.35	0.83	**0.47**	Cs-137	0.83	0.83	0.062	**0.093**
Ba-140	19	32	0.83	**0.11**	Ba-140	7.9	14	0.014	**0.094**
Ce-141	57	77	0.83	**1.5**	Ce-141	34	31	0.13	**1.1**
Ce-144	20	9.0	0.83	**3.2**	Ce-144	13	5.3	0.23	**2.6**

* Numbers in bold are the comparisons of critical organ to critical organ; all other comparisons called "critical organ" are CSA effective dose/RG dose to critical organ

Steady-state deposition (Bq m^{-2}) of CSA and RG is compared in Table 7. CSA deposition is about 16% that of RG (except for iodine) unless the radiological half-life of the nuclide is long (> 5 years), in which case the CSA/RG ratio is larger due to the "infinite" time of accumulation in CSA compared with the 15 year accumulation half-life in RG. The CSA/RG ratio for the iodines is about 0.31 because of higher deposition in CSA due to inclusion of particulate iodine. Deposition to ground for tritium and ^{14}C, although calculated, is not needed for any calculations in the ingestion pathway, since specific activity models are used, or for the external dose pathway, since neither nuclide contributes to effective or skin doses.

CSA/RG ratios for external doses are also compared in Table 7. The CSA/RG ratios for effective external doses are slightly less than the ratios for deposition (except for ^{132}Te and ^{140}Ba, which have very high CSA/RG ratios for DCF) even though the CSA has higher DCFs. The contribution to dose of low deposition in CSA is further reduced by the occupancy factor (0.2), dose reduction factor due to non-uniformity of surface (0.7) and shielding factor (i.e., fraction of outdoor dose received indoors) (0 for β and 0.4 for γ) relative to RG (1.0, none and 0.7 for both β and γ respectively), but these are mostly compensated by the CSA's higher DCFs. When the CRL/RG ratios for effective external dose are compared to CSA/RG ratios, there is little difference except for ^{95}Zr, ^{106}Ru and ^{144}Ce which are a factor of two or more higher for CRL/RG due to revised DCFs.

For skin dose from external deposition, the effect of the larger CSA/RG for DCFs for external skin dose are reflected in the CSA/RG ratio, for these ratios are higher, sometimes much higher than the ratios for effective dose, and some are greater than one. The large difference in ^{89}Sr is due to an extremely small DCF for skin in RG. In general, the CRL/RG ratios are consistently higher than CSA/RG ratios due to revised DCFs, and half are greater than one.

Immersion Pathways

In RG, the only immersion doses calculated are those from noble gases, whereas in CSA, immersion doses from all radionuclides are calculated. CSA has an occupancy factor (fraction of time an individual spends outside exposed to the plume) of 0.2, while the assumption in NUREG is an occupancy factor of 1. CSA uses a shielding factor of 0.9 for γ and 1.0 for β, while RG's shielding factor is 0.7 for the maximally exposed individual (compared here) and 0.5 for a member of the general population.

Table 7
CSA/RG and CRL/RG Ratios for Deposition and External Doses

	Deposition	External Dose: Effective		External Dose: Skin	
	CSA/RG	CSA/RG	CRL/RG	CSA/RG	CRL/RG
H-3	0.25				
C-14	1.5				
Cr-51	0.16	0.15	0.14	0.17	0.16
Mn-54	0.16	0.13	0.13	0.16	0.15
Fe-59	0.16	0.13	0.14	0.15	0.29
Co-58	0.16	0.13	0.14	0.16	0.20
Co-60	0.18	0.14	0.15	0.16	0.21
Zn-65	0.16	0.13	0.13	0.15	0.16
Sr-89	0.16	NC		4453	6607
Sr-90	0.41	NC		1.4	2.1
Zr-95	0.16	0.14	0.29	0.17	0.54
Nb-95	0.16	0.15	0.15	0.17	0.17
Mo-99	0.16	0.16	0.18	2.0	3.7
Ru-103	0.16	0.13	0.13	0.16	0.28
Ru-106	0.16	0.13	0.25	8.7	9.7
Te-132	0.16	1.5	1.5	4.4	6.5
I-131	0.31	0.27	0.28	0.40	2.0
I-132	0.31	0.25	0.26	0.80	1.2
I-133	0.31	0.31	0.35	2.2	3.8
I-134	0.31	0.30	0.32	1.1	1.5
I-135	0.31	0.22	0.24	0.74	1.2
Cs-134	0.16	0.12	0.13	0.17	0.33
Cs-136	0.16	0.14	NA	0.17	NA
Cs-137	0.43	0.37	0.37	1.1	2.6
Ba-140	0.16	1.2	1.2	5.2	7.8
Ce-141	0.16	0.15	0.18	0.24	3.4
Ce-144	0.16	0.15	0.68	38	46

In order to use the semi-infinite cloud model and appropriate dose conversion factors, it was assumed that the air concentration at 1000 m was uniform over the attenuation distance of each radionuclide. The conditions to use the semi-infinite cloud model in both NUREG (release height less than 80 m) and CSA (release height less than 50 m, distance from release 1 km or greater) were met.

The effective argon doses per concentration in air are very close, even though the parameter values and approaches are different (Table 8). CSA skin doses from immersion are just slightly higher than RG's, except for ^{88}Kr which is higher by a factor of three due to a skin dose conversion factor that is eighteen times higher than RG's. Using the slightly revised DCFs from CRL makes little difference between the CSA/RG and CRL/RG ratios (e.g., the CRL value of ^{88}Kr is still sixteen times higher than RG's).

Table 8
CSA/RG and CRL/RG Ratios for Immersion Dose

Nuclide	Immersion Dose: Effective CSA/RG	Immersion Dose: Effective CRL/RG	Immersion Dose: Skin CSA/RG	Immersion Dose: Skin CRL/RG
Ar-41	1.0	0.81	1.3	1.3
K-85m	0.95	1.0	1.1	1.1
Kr-87	1.0	1.1	1.2	1.2
Kr-88	1.4	1.4	3.1	2.8
Xe-133	0.81	0.89	0.99	1.1
Xe-135	0.94	1.0	1.1	1.2

SUMMARY AND CONCLUSIONS

The differences that exist between RG and CSA depend strongly on the assumptions made for an assessment. Structural differences are negligible. In this paper, when comparisons were made between the models as they could be run in an assessment, many of the options which make RG adaptable to different situations were not selected. Certainly, implementation of any of these options will result in doses even lower than those calculated here for comparison with CSA. Thus large differences may seem to exist between the two models, but they are mostly due to different assumptions employed in the assessment. Once the diets and delays to ingestion have been normalized between RG and CSA, the only other significant differences are due to the use of different parameter values. Most of the differences in parameter values are due to different dose conversion factors, and the use of the latest values in both models will correct these discrepancies. In addition, once the uncertainty in the calculations and parameter values is taken into account, a difference of a factor of two between CSA and RG will be shown to be unimportant since the 95% confidence interval on an ingestion dose might be expected to be at least a factor of five.

The five most important doses (Sv a^{-1}), whether effective or to a critical organ, calculated with realistic source terms are compared for CSA and RG in Table 9. Ingestion doses are dominated by ^{14}C for both RG and CSA because of the conservative assumptions of the scenario description: that all food is grown 1000 m from the stack. Changing a very few assumptions about diet will easily reduce ingestion doses. For example, if one assumes that 100% of the vegetables are grown 1000 m from the stack but that none of the animal produce is contaminated, the ^{14}C ingestion dose to an adult will be reduced to one-fourth in the CSA model. When revised DCFs, such as in CRL, are used in CSA and RG, RG's ^{14}C doses will drop more in line with CSA's. Also, once the conceptual mistake for tritium in CSA is corrected (i.e., when more tritium is passed from forage to animals), the ingestion dose from tritium will rise and become quite comparable with RG's.

Tritium dominates inhalation dose predictions for both RG and CSA because of the amount released from CANDU reactors. Inhalation doses can be reduced by introducing a more realistic occupancy factor of less than one.

External doses may be higher than reported here by about a factor of three (the difference between the emission data estimated for these calculations and the average particulate emissions reported per CANDU unit). Nevertheless, they are low enough that they add little to overall dose.

Table 9
Top Five Ranked Doses (Sv per Annum) from RG and CSA Using Source Term Data from Table 1

Adult Ingestion				Infant Ingestion			
RG		CSA		RG		CSA	
C-14	2.1E-6	C-14	1.2E-6	C-14	9.7E-6	C-14	2.2E-6
H-3	1.8E-6	H-3	1.0E-6	H-3	2.7E-6	H-3	1.6E-6
Sr-90	8.4E-8	I-131	7.2E-8	I-131	3.1E-7	I-131	2.9E-7
Ru-106	1.8E-8	Sr-90	3.0E-8	Sr-90	8.1E-8	Nb-95	9.8E-9
Cs-137	8.1E-9	Cs-137	5.7E-9	Cs-137	3.3E-8	Sr-90	9.1E-9

Adult Inhalation				Infant Inhalation			
RG		CSA		RG		CSA	
H-3	1.3E-6	H-3	1.3E-6	H-3	6.6E-7	H-3	6.1E-7
C-14	3.7E-8	I-131	5.2E-10	C-14	5.5E-8	I-131	6.8E-10
Sr-90	1.0E-9	C-14	3.3E-10	I-131	6.7E-10	I-133	2.9E-10
I-131	5.4E-10	I-133	1.9E-10	Sr-90	4.2E-10	C-14	1.6E-10
I-133	2.0E-10	Sr-90	1.7E-10	I-133	3.2E-10	Sr-90	1.0E-10

External				Immersion			
RG		CSA		RG		CSA	
Cs-137	8.9E-9	Cs-137	9.9E-9	Kr-88	5.5E-7	Kr-88	1.7E-6
Sr-90	3.9E-9	Sr-90	5.4E-9	Xe-133	3.2E-7	Xe-135	3.3E-7
Cs-134	2.1E-9	Ce-144	5.9E-10	Xe-135	3.0E-7	Xe-133	3.1E-7
Co-60	1.6E-9	Ru-106	5.5E-10	Ar-41	2.1E-7	Ar-41	2.7E-7
Mn-54	3.0E-10	Cs-134	3.6E-10	Kr-87	2.0E-7	Kr-87	2.3E-7

Differences in doses from noble gases are slight, with the exception of ^{88}Kr with a skin dose three times higher in CSA than in RG. Immersion dose from all noble gases in general can be reduced by the use of more realistic parameter values for shielding and outdoor occupancy.

When intercomparing two models, there can be no "right" or "wrong" , "good" or "bad" answer. When models agree, it is hoped that the agreement is based on sound scientific evidence; if they disagree, the reasons for the disagreements should be found. This paper has drawn attention to important differences between CSA and RG which should be resolved. Some answers may be found in more up-to-date parameter values and in correcting some errors, but testing the models with independent data sets will be the only way to resolve which model produces predictions closest to what was measured in a real situation, using site-specific data in the models.

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