EMRAS Tritium/C14 Working Group

THE PIG SCENARIO

Final Report
September 2008

1. INTRODUCTION

At the 2005 EMRAS plenary meeting in Vienna, the Tritium/C14 Working Group decided to adopt a scenario to test models that describe the transfer of tritium in large farm animals. As a world average, meat, milk, eggs and fish supply 16% of human food energy and 36% of protein. Pig meat consumption ranks first among various meats and is predicted to increase. Pigs are not very economic in terms of land requirements but they are efficient in terms of water consumption per unit energy or protein produced. As a consequence, we chose to base the animal scenario on pigs.

2. SCENARIO DESCRIPTION

The scenario was split into two parts. The first part was based on unpublished observational data and provided a blind test of the models. Participants were asked to predict the dynamics of total tritium in urine and faeces and the concentrations of tritiated water (HTO) and organically bound tritium (OBT) in organs for a pregnant sow fed an OBT diet for 84 days before delivery. The genotype and initial mass of the sow were given, as well as the composition, OBT concentration and intake dynamics of the diet.

The second part of the scenario was a model intercomparison exercise based on hypothetical data. This exercise was necessary because the sow considered in the blind test was about 200 kg in weight, much heavier than animals used for human consumption, which are normally sacrificed near 110 kg. In the absence of relevant experimental observations, two exercises were proposed. In the first, the pig was fed a diet contaminated with HTO for 50 days between 55 and 105 days of age, the mid period between weaning and sacrifice. The diet at early and later times was uncontaminated. Modellers were asked to predict the total tritium in urine, HTO and OBT concentrations in faeces, and the OBT concentration in muscle from the time the pig was 55 to 155 days old. The second exercise considered a short-term OBT intake at various ages of the pig. Modellers were asked to predict the meat and liver OBT concentrations at sacrifice for different pig genotypes.

The scenario descriptions are discussed briefly below and are given in full in Appendix A.

2.1 Blind Test

Data for the blind test were obtained from experiments carried out by M. van Hess and colleagues at SCK-CEN, Belgium. Results from one of these experiments, in which a pregnant sow was fed OBT during gestation, delivery and lactation, were published (van Hess et al., 1986). However, data from a prior experiment involving a sow that was slaughtered just before delivery were not published. These data were provided by van Hess in the form of a personal communication to N. Beresford (CEH, UK) as the basis for the scenario. Concentrations of total tritium in urine and OBT in fecal dry matter are given as a function of time in Table 1. HTO and OBT concentrations in various organs of the sow at slaughter are given in Table 2. This study pre-dated the publication on the sow that was allowed to live through delivery (van Hess et al., 1986) and records on the experimental protocol were only partially recovered.

Table 1. Concentrations of total tritium in urine and OBT in faeces for a pregnant sow

Days after start of contamination	Total tritium in urine		OBT in faeces	
	(nCi/ml)	(Bq/ml)	(nCi/g dry wt)	(Bq/g dry wt)
7	1.53	56.6	43.91	1624.7
14	2.09	77.3	54.08	2001.0
21	1.88	69.6	57.44	2125.3
28	2.41	89.2	57.26	2118.6
36	2.73	101.0	58.44	2162.3
42	2.79	103.2	61.71	2283.3
49	2.55	94.4	53.95	1996.2
56	2.83	104.7	55.83	2065.7
63	2.91	107.7	51.70	1912.9
70	3.08	114.0	50.43	1865.9

Table 2. HTO and OBT concentrations in sow organs at delivery

Organ	Dry weight	HTO concentration		OBT concentration	
	(% fresh wt)	(nCi/ml)	(Bq/ml)	(nCi/g dry wt)	(Bq/g dry wt)
Heart	21.70	1.31	48.5	6.52	241.2
Lungs	23.45	1.26	46.6	4.79	177.2
Liver	26.09	1.37	50.7	8.22	304.1
Jejunum	22.40	1.31	48.5	5.26	194.6
Ileum	20.16	1.25	46.3	5.97	220.9
Colon	24.26	1.21	44.8	4.07	150.6
Kidney	23.68	1.36	50.3	6.17	228.3
Muscle	26.98	1.33	49.2	2.70	99.9
Brain	22.16	1.32	48.8	3.10	114.7
Little brain	26.23	-	-	5.67	209.8
Blood	-	1.13	41.8	5.14	190.2

We observe from Table 2 that the organs differ in OBT concentration by a factor 3, with the lowest value in muscle and the highest in liver, and an average value that is close to the OBT concentration in blood.

The modellers were given the composition and total amount of the diet, but no information on water intake, urine production or the number of piglets in the litter. From the published paper (van Hess et al., 1986), we deduce a piglet number of 8-9, which was normal for livestock practices of the early 1980s. Literature values for sow water intake start from a low of 6-8 L/d (perhaps at the start of gestation) to 20 L/d (at delivery and lactation); water intake also increases with feed intake (NAC, 1998). The water intake range suggested in the scenario might be an underestimate and this might influence model results.

Pregnant sows increase food intake for purposes of maintenance, activity, pregnancy (gestation and development of mammary glands) and maternal growth (body reserves to be used later in lactation). This information was not known and had to be assessed by the modellers, or at least considered in estimating the uncertainties in their predictions. Intake and partition is most conveniently addressed in terms of metabolisable energy (ME). The ME intake can be estimated from the diet composition and amount. Values for dry potato and dry milk are included in many nutritional tables, and values for algae can be obtained by assuming similarity to grass or alfalfa. Considering the nutritional tables from Romania (Stoica 1995), the UK (McDonald 1995), the USA (NAC 1998) and France (INRA, 2008), we obtain an average value of 16.5 MJ/kg dry mass, with about 5% variability. Uterine energy deposition (ME_{preg}) can be assessed using the literature (Noblet 1997) and is given in Figure 1. The maintenance energy of the sow depends on body weight and an agreed value is $ME_{main} = 0.43 \cdot BW^{0.75}$. Here we can ignore any thermal stress, as we are discussing a controlled experiment. An approximate value for the activity energy need of the sow (ME_{act}) is available in Noblet (1997). The potential maternal growth of the sow (ME_{growth}) can be estimated as the balance between ME intake and the sum of ME_{main}, ME_{act} and ME_{preg}. The intake and partition of metabolisable energy for this scenario, as well as the mass gain of the sow, is summarized in Table 3.

Table 3. Metabolisable energy (ME) intake and partition to maintenance, activity, pregnancy and growth

Day of gestation	Days after start of contamination	ME intake (MJ/d)	ME_{main} (MJ/d)	ME_{act} (MJ/d)	ME_{preg} (MJ/d)	ME_{growth} (MJ/d)	Mass gain (kg/d)
30-51	0-21	30.7	21.1	1.33	1.4	6.84	0.18
52-76	22-46	34.0	21.6	1.35	2.2	8.88	0.23
77-109	47-79	38.1	22.3	1.40	3.2	11.2	0.29
110-114	80-84	49.6	23.1	1.45	4.4	20.6	0.57

A gain in mass immediately before delivery is not realistic, as at this moment feed intake is increased to allow for milk production. The values in Table 3 imply that the sow will have a maternal weight gain close to 20 kg, in agreement with the range of 20-30 kg found in the literature. Most of the mass gain will be in adipose tissue, but the weight of the visceral organs will also increase to reflect the increased intake (Noblet, 1997).

As a conclusion of this short analysis of processes in the gestation period, we expect that muscle mass will not change significantly, but some weight gain will occur in the viscera, which should be taken into account in the models. The uncertainty in the sow water intake will influence model results for total tritium concentration in urine. Similarly, the modelers were required to estimate the digestible fraction of the diet in order to predict the OBT concentration in faeces. According to recent French work (INRA, 2008), this fraction has a value of about 0.85.

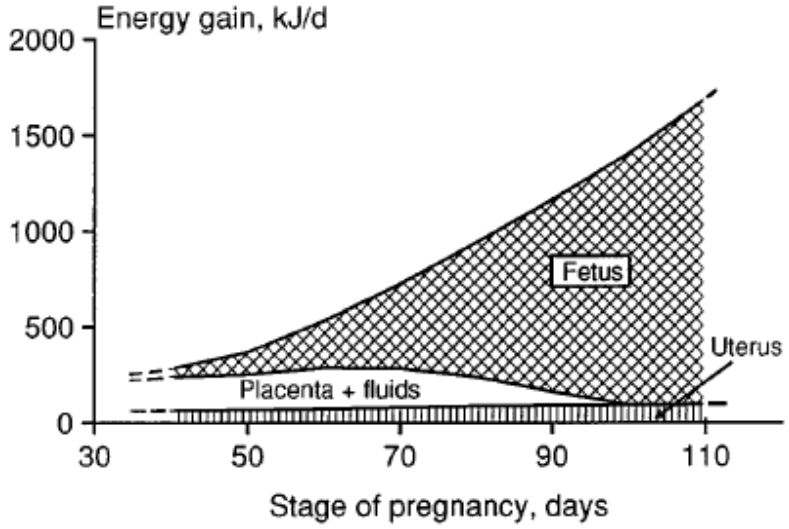


Figure 1. Uterine energy deposition in a sow bearing 12 piglets

The prediction of tritium concentrations in urine and faeces requires knowledge of pig waste. Some relevant information is available from the FAO (1980):

> "The production of solid pig waste ranges from 0.6 to 1.0% of dry matter per day calculated on body weight. Low-digestibility rations yield relatively more manure. With an increase of body weight, the quantity of pig waste decreases significantly. Faeces represent about 46% and urine 54% of wastes on a fresh weight basis, but on a dry basis faeces represent 77% and urine 23%. The pH of pig manure is in the range 7.2–8.3."

This reference indicates that waste fresh mass is given by $1.4 \cdot BW^{0.25}$ and provides an idea of the mass and composition of urine and faeces.

2.2 Model Intercomparisons

The blind test was not particularly applicable for normal radiological assessments of tritium transfer through the food chain because the sow was much heavier than is usual for pigs at slaughter. Intercomparison exercises involving smaller animals were added to make the scenario more useful. The first exercise, which involved HTO intake over a period of 50 days, was promoted as an example of a waste management scenario in which the contamination arises from drinking water from a well. The second exercise had two goals: to consider tritium dynamics following a short-term intake of OBT; and to consider the influence of pig genotype on the tritium concentrations in meat and liver. The exercises were built without experimental data but both incorporated hypothetical data on pig growth following the modeling results of van Milgen and Noblet (2003) and Noblet (1997).

3. MODEL DESCRIPTIONS

The models used to calculate results for the Pig Scenario varied in complexity. The simplest model (STAR-H3) was one of the oldest, being formulated in 1995-1998. STAR-H3 has a single organic compartment representing the slow turnover of OBT, with a turnover rate for all animals of 0.03 d^{-1} (half-time of 23 d). In STAR-H3, the animals are assumed not to grow over time. The model is implemented on a software platform (AMBER) that allows only pasture as intake. STAR-H3 was not applied in this scenario by the model developers but by a combination of participants from the National Institute of Physics and Nuclear Engineering - Horia Hulubei (IFIN-HH) and Lawrence Livermore National Laboratory (LLNL). At LLNL, STAR-H3 was applied as prescribed, with the given pig diet replaced by pasture. AT IFIN, the model was reconstructed from references and judgement to allow more realistic inputs. The modified model, termed STAR-H3(DG), was used to execute the LNLL examples with the same pasture intakes to ensure the accuracy of the reconstruction. The model was then run with the diet as given in the scenario description for the blind test. STAR-H3(DG) does not allow for pig growth and was not used in the model intercomparison exercises.

Electricité de France (EDF) also used a simple model (OURSON) with a single organic compartment. OURSON assumes that all OBT in the diet enters the organic compartment. A dynamic equation is derived for the specific activity (SA) in the compartment, taking into account growth dilution and the difference in feed and compartment concentrations. The rate of transfer to HTO in the body is given by the digestible intake per unit body dry weight. There is no transfer from body HTO to body OBT. The HTO concentration in urine is assumed to be the same as that in the body; similarly, the OBT concentration in urine urea is taken to equal that in the body. Faeces OBT corresponds to the OBT in the non-digestible fraction of food, where it is assumed that the OBT SA is identical in the digestible and non-digestible fractions. The whole body OBT is considered to be representative of the muscle compartment. Concentrations in other organs are derived from the concentration in muscle using correction factors based on the fat and protein contents of each organ, the fat and protein turnover rates, and the hydrogen contents of fats, proteins and carbohydrates.

Atomic Energy of Canada Limited (AECL) carried out the calculations using the animal model from the ETMOD code, a process-oriented code that considers the detailed dynamics of HTO. ETMOD does not have an animal organic compartment, assuming that all tritium in the animal is in the form of HTO. Accordingly, AECL submitted results for the total tritium concentration in urine only.

Two of the models participating in the Pig Scenario, MCT and PRISM, were of moderate complexity. MCT is a model with two organic compartments, one with a fast turnover rate (half-life 30 days) and one with a slow turnover (half-life 450 days). The model also includes an inorganic compartment representing body water. MCT was developed initially for humans but was modified for these calculations to reflect the mass of the sow. In the pig version, organically bound hydrogen is split equally between the two organic compartments. About 70% of OBT intake enters the fast OBT compartment and the rest is converted immediately to HTO and enters the body water compartment. There is no transfer from the fast to the slow OBT compartment.

The PRISM software is a modeling platform for probabilistic applications in which specific models for tritium and C-14 have been implemented. The current standard version is PRISM HC (Maul et al., 2005). This version was extended for the Pig Scenario to treat the urine and faeces endpoints (Walke and Thorne, 2007). PRISM HC uses a simplified model of the gastrointestinal tract. OBT intake is partitioned between body water and two organic compartments, one of which is labile (fast turnover) and the other non-labile (slow turnover). A fraction 0.79 (range 0.61-0.94) of the OBT is immediately converted to HTO and distributed to body water. The rest enters the organic compartments, with twice as much going to the labile compartment as to the non-labile compartment. Similarly, the hydrogen content of the labile compartment is twice that of the non-labile compartment on average, but the range is very large (from 1/9 to 9). The loss rate from body water is 0.13 d^{-1} (0.06-0.19 d^{-1}), higher than in MCT (0.077 d^{-1}), but the range includes the MCT value. The loss rate from the labile organic compartment is $1.1x10^{-3}$ d^{-1} ($5.5x10^{-4}$ - $2.2x10^{-3}$ d^{-1}) whereas from the non-labile compartment it is $7.32x10^{-5}$ d^{-1} ($3.66x10^{-5}$ - $1.46x10^{-4}$ d^{-1}). Note that these rates are much lower than in MCT and the transfers are directly to faeces and urine and not through body water as an intermediate pathway.

It was observed that the PRISM results submitted by the Food Standards Agency (FSA) differed substantially from the experimental observations and from the predictions of the other models. To clarify this, IFIN used available documentation (supplied by the model developers and FSA) to independently reconstruct the model under the ModelMaker platform. The reconstructed model was run with average values of the PRISM HC transfer parameters, and results are reported as PRISMDG.

The MAGENTC model (**Ma**mmal **GEN**eric model for **T**ritium and **C**arbon transfer) was developed by IFIN over the last three years with inputs from Japan (H. Takeda, NIRS) and the U.K. (N. Beresford, CEH; N. Crout, Nottingham University). The model starts with the basic assumption that the turnover rates of organically bound tritium and carbon in organs can be assessed using net maintenance energy turnover rates. The model has six organic compartments and distinguishes between organs with high transfer and metabolic rates (viscera), storage organs with very low metabolic rates (adipose tissue), and ‘muscle’ with

intermediate metabolic and transfer rates. Dry matter intake is partitioned to metabolisable and excreted fractions. The former, in the case of tritium, distinguishes exchangeable and non-exchangeable fractions. The exchangeable fraction is converted to HTO and transfers directly to body water compartments, whereas the non-exchangeable fraction is absorbed in the systemic circuit (blood plasma) after digestion. While MAGENTC is a research grade model, two major simplifications are included: a single respiration rate and a single metabolic rate for all organs. Model parameter values were established independently of any tritium or C-14 experimental data. Generic values were used in the blind scenario, but more refined values for pig nutrition, growth, metabolism and physiology were used in more recent applications. The biokinetic rates for muscle and viscera used in the Pig Scenario are shorter than those for the labile and non-labile compartments in PRISM HC.

A summary of the participating models and users is shown in Table 4. Full descriptions of all the models are presented in Appendix B.

Table 4. Participating models and users

Model	User	Affiliation	Designation
MCT	M Saito	Kyoto, Japan	MCT
STAR-H3	D Galeriu,	National Institute of Physics and Nuclear Engineering – Horia Hulubei (IFIN-HH), Romania	STAR-H3(DG)
	R Peterson	Lawrence Livermore National Laboratory (LLNL), U.S.A.	
MAGENTC	D Galeriu, A Melintescu	IFIN, Romania	IFIN
PRISM HC	P Kennedy	Food Standards Agency (FSA), U.K.	FSA
PRISM HC reconstructed	D Galeriu, A Melintescu	IFIN, Romania	PRISMDG
OURSON	F Siclet	Electricité de France (EDF), France	EDF
ETMOD	V Korolevych	Atomic Energy of Canada Limited (AECL), Canada	AECL

4. RESULTS OF THE BLIND TEST

Predicted and observed concentrations of total tritium in urine for the blind test are shown in Table 2, and predicted-to-observed (P/O) ratios are given in Table 5. FSA overestimates by many orders of magnitude whereas most other predictions lie within a factor 10 of the observations. Because the reconstructed version of PRISM (PRISMDG) gives good results, the FSA overestimate may be due to inappropriate use of the model by the user, most likely in matching the model output to the scenario requirements. The overestimate of a factor 4-6 by STAR-H3 is explained by the fact that, in this model, all OBT intake is distributed to body water and the excretion rate assumed is too high for a pig. The underestimate in MCT is due

to the low excretion rate and the partition of intake OBT to the body water compartment. The underestimate of a factor 3-10 in the EDF results is due to the model assumption that all OBT input appears in the body organic compartment. The IFIN and AECL predictions agree well (within 20% at most times) with the experimental data.

Table 5. Predicted-to-observed ratios for total tritium in urine

Days after start of contamination	MCT	IFIN	STAR-H3(DG)	FSA	PRISMDG	EDF	AECL
7	0.02	0.64	6.26	17675	1.34	0.09	0.81
14	0.11	0.85	4.88	34495	1.39	0.14	0.92
21	0.24	1.20	5.46	82942	1.73	0.23	1.21
28	0.28	1.06	4.27	98812	1.41	0.24	1.07
36	0.30	1.02	3.77	123077	1.26	0.27	1.01
42	0.36	1.04	3.70	146154	1.24	0.30	1.01
49	0.46	1.18	4.05	199568	1.37	0.37	1.16
56	0.43	1.09	3.66	212098	1.23	0.37	1.09
63	0.47	1.08	3.56		1.20		
70	0.56	1.03			1.14		

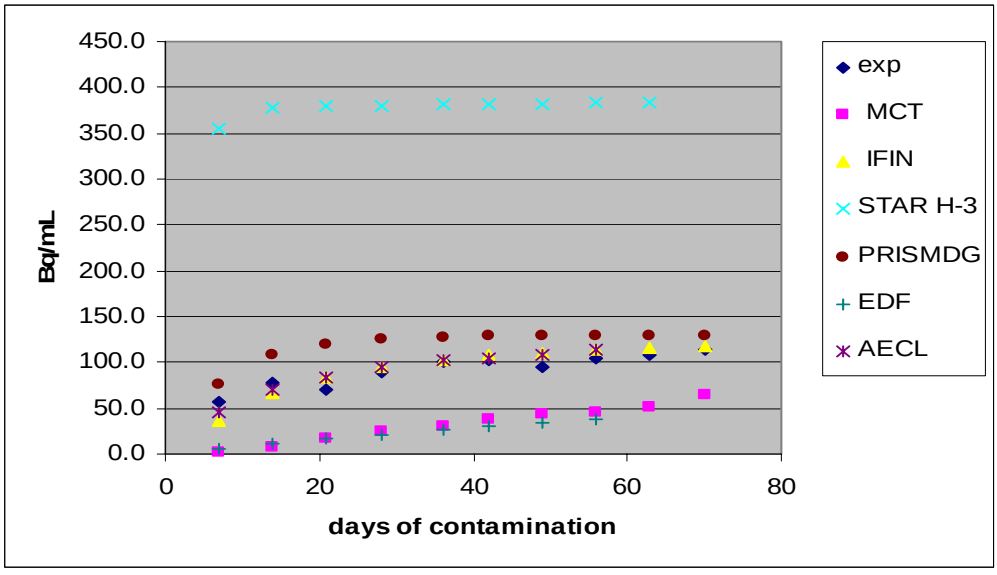


Figure 2. Predictions and observations of total tritium concentrations in urine. Results for FSA are very high and are not shown.

The concentration of OBT in faeces was predicted only by MCT, FSA, EDF and IFIN; the P/O ratios for this endpoint are given in Table 6. Faeces contamination is expected to be similar to the contamination of undigested feed, but in fact it is four times higher than the average concentration in the diet (Table 1). This explains the underprediction by MCT, EDF and IFIN. The overprediction by FSA remains to be explained.

Table 6. Predicted-to-observed ratios for OBT in faeces

Days after start of contamination	MCT	FSA	IFIN	EDF
7	0.69	2.46	2.20	3.60
14	0.42	3.93	1.10	1.80
21	0.33	4.86	0.73	1.20
28	0.28	5.64	0.55	0.90
36	0.23	6.31	0.43	0.70
42	0.21	6.62	0.37	0.60
49	0.19	7.14	0.31	0.51
56	0.17	7.51	0.28	0.45
63	0.16		0.24	
70	0.17		0.22	

The sow was fed a mixture of dry potato, dry cow milk and dry algae. It is known that the composition of faeces differs from that for feed, as shown in Table 7. It is possible that the inhomogeneity of feed compound activity and fibre enhancement in pig faeces explains the enhanced activity in the faeces.

Table 7. Composition of pig feed and faeces (from FAO, 1980)

Constituent	Unit	Feed	Faeces	Faeces/feed ratio
Gross energy	MJ/kg	18.0	17.9	-
Ether extract (crude fat)	%	5.27	4.72	0.90
Ash	%	6.7	17.4	2.59
Crude fibre	%	5.7	18.2	3.19
Acid detergent fibre	%	6.8	24.3	3.57
Neutral detergent fibre	%	20.6	44.6	2.17
Lignin	%	1.1	4.9	4.45
Cellulose	%	5.2	16.9	3.25
Hemicellulose	%	13.8	20.3	1.47

Predictions of organ HTO and OBT concentrations were supplied by FSA, MCT, EDF and IFIN (using STAR and PRISM as well as MAGENTC). The P/O ratios for HTO are given in Table 8. With the exception of FSA, all models give good predictions, although EDF underestimates by a factor 5. Table 9 gives the P/O ratios for OBT in organs. STAR-H3(DG), as expected, underestimates by a factor 10 due to the model assumption that OBT intakes enter the high turnover compartment (body water). The EDF predictions, which were obtained on the assumption that all OBT in the diet enters the organic compartment, are close to the observations, although the concentration in muscle is overestimated by a factor of 3. The reasons for this are not clear and should be investigated further. MCT overestimates by a factor between 2 and 4, and IFIN (using generic parameter values) by a factor 2. We note the large range of overestimation in the FSA results, which are unexplained. The reconstructed version of PRISM overestimates by only 50%.

Table 8. Predicted-to-observed ratios for HTO in organs (84 days after start of contamination)

Organ	MCT	FSA	IFIN	PRISMDG	STAR-H3(DG)	EDF
Heart	0.54	33.4	2.17	1.31	0.81	0.19
Lungs	0.56	11.7	2.25	1.36	0.84	0.20
Liver	0.51	5.39	2.07	1.25	0.77	0.18
Jejunum	0.54	11.2	2.17	1.31	0.81	0.19
Ileum	0.56	38.4	2.27	1.37	0.85	0.20
Colon	0.58	5.89	2.35	1.42	0.88	0.21
Kidney	0.52	29.2	2.09	1.26	0.78	0.18
Muscle	0.53	0.42	2.13	1.29	0.80	0.19
Brain	0.53	7.70	2.15	1.30	0.80	0.19
Blood	0.62	2456	2.51	1.52	0.94	0.22

With the exception of FSA and STAR, all models give reliable predictions of HTO and OBT concentrations in organs. STAR was developed assuming pasture intake and the model structure must be changed if performance is to improve. The poor FSA results are likely due to user error and not to any deficiency in the model. The results of the blind test give confidence that both simple and complex models can be used to predict tritium concentrations in pig meat if only OBT intake is considered.

Table 9. Predicted-to-observed ratios for OBT in organs (84 days after start of contamination)

Organ	MCT	FSA	IFIN	PRISMDG	STAR-H3(DG)	EDF
Heart	2.05	9.89	1.40	1.51	1.29	1.29
Lungs	2.79	4.11	1.90	2.06	0.13	1.30
Liver	1.92	1.04	1.11	1.20	0.08	0.84
Jejunum	3.00	3.23	1.73	1.88	0.12	1.09
Ileum	2.24	13.0	1.53	1.65	0.10	0.96
Colon	3.28	2.23	2.24	2.42	0.15	1.40
Kidney	2.17	8.46	1.48	1.60	0.10	1.17
Muscle	4.44	0.23	1.90	3.65	0.23	3.11
Brain	3.91	4.69	-	3.17	0.20	1.65
Blood	3.04	970	1.27	1.92	0.12	1.22

5. RESULTS OF THE INTERCOMPARISON EXERCISES

Only four models (IFIN, MCT, FSA and AECL) participated in the intercomparison exercises. Moreover, AECL submitted results for the urine concentrations only, and the FSA results are suspect given the poor performance of this model in the blind test. The conclusions that can be drawn from such little information are limited. Predictions for the first exercise, in which the diet of a growing pig was contaminated with HTO for 50 days starting when the pig weighed 20 kg, are given in Table 10. Concentrations in urine are expected to be slightly less than those in drinking water (10 Bq/ml) because of dilution with metabolic water. This is the case for IFIN, MCT and AECL but the FSA results are much higher. Once the contamination stops at day 50, the urine concentrations should decay. This was again the case for IFIN, MCT and AECL, but not for FSA. Similar results were obtained for HTO in faeces.

Table 10. Total tritium concentration in urine for the intercomparison exercise involving 50 days of HTO intake

Days after start of contamination	Total tritium concentration in urine (Bq/ml)			
	FSA	IFIN	MCT	AECL
7	9.55E+04	8.20	3.45	8.15
14	2.48E+05	8.90	5.23	9.077
21	4.76E+05	8.90	6.27	9.204
42	1.13E+06	8.80	7.72	9.254
50	1.33E+06	8.70	8.00	9.261
60	1.48E+06	1.00	3.50	1.302
70	1.53E+06	0.20	1.55	0.17
100	1.56E+06	0.01	0.15	0.0005

Table 11 shows the model predictions for OBT concentrations in meat for the first intercomparison exercise. There are orders of magnitude difference between models, with FSA showing the highest results. The decay in meat, after the contamination stops at day 50, is slower in FSA than in IFIN or MCT. Kirchmann (1977) indicates a half-time in urine near 4 days, based on an experiment in which pigs were offered tritiated water for 28 days starting from the age of 8 weeks; in contrast, van Hess (1986) observed a half-time of about 100 days for muscle after OBT intake. At the end of Kirchmann's experiment, muscle OBT made up 0.6% of the total activity intake. The IFIN prediction at the end of HTO intake (0.49 %) is closest to this value (Table 11). The FSA result is higher by a factor 10, whereas that for MCT is lower by a factor 5.

Table 11. OBT concentration in meat for the intercomparison exercise involving 50 days of HTO intake

Days after start of contamination	OBT concentration in meat (Bq/kg fresh weight)		
	FSA	IFIN	MCT
7	9.21E+03	7.50E+01	3.9E+00
14	1.58E+04	1.65E+02	1.2E+01
21	2.33E+04	2.27E+02	2.1E+01
42	3.90E+04	3.19E+02	4.8E+01
50	4.16E+04	3.35E+02	5.8E+01
60	3.91E+04	2.85E+02	6.2E+01
70	3.69E+04	2.23E+02	5.8E+01
100	3.19E+04	1.22E+02	4.0E+01

HTO concentrations in faeces were predicted by FSA, MCT and IFIN (Table 12). The FSA results are again unexpected high. At the end of the contamination period, the MCT predictions for HTO in urine and feces indicate a half-time of 8 days, double the experimental result for a similar pig (Kirchmann, 1977). Here and elsewhere in the first intercomparison exercise, there is a need to clarify the FSA results. Also, more model predictions are needed before useful conclusions can be drawn.

Table 12. HTO concentration in faeces for the intercomparison exercise involving 50 days of HTO intake

Days after start of contamination	HTO concentration in faeces (Bq/ml)		
	FSA	IFIN	MCT
7	354	10.0	5.41
14	929	10.0	6.66
21	1810	10.0	7.39
42	4480	10.0	8.40
50	5350	10.0	8.60
60	6130	1.20	5.45
70	6560	0.20	4.09
100	7390	0.01	3.11

For the second intercomparison exercise, in which pigs of different genotypes were fed OBT for one day at different stages of their growth, only IFIN and FSA supplied predictions (Table 13). Two contrasting genotypes were considered but FSA preserved the same organ partitioning for both types, whereas IFIN used a conventional and obese one. Both models showed that the genotype has little effect on OBT concentrations in meat, but the IFIN results suggest that genotype is more important for concentrations in liver. There are significant differences between the model predictions that remain to be explained.

Table 13. OBT concentrations in meat and liver after short-term OBT intake at various stages of growth

Mass at intake (kg)	OBT concentration in meat at sacrifice (Bq/kg fresh weight)				OBT concentration in liver at sacrifice (Bq/kg fresh weight)			
	Genotype 1		Genotype 2		Genotype 1		Genotype 2	
	IFIN	FSA	IFIN	FSA	IFIN	FSA	IFIN	FSA
20	575	263	617	269	62	3621	48	3708
40	1775	408	1380	381	170	5521	93	5226
60	2851	529	2078	452	350	7291	126	6221
80	3982	647	2800	517	1192	8925	168	7128
100	5001	739	3900	581	6000	10187	1330	7751

6. CONCLUSIONS AND RECOMMENDATIONS

The two simple models, STAR-H3 and OURSON, differ in terms of their partitioning of tritium following intake and their transfers from HTO to OBT and OBT to HTO (Figure 3). In STAR, OBT taken in with feed enters only the fast (body water) compartment, while in

OURSON it enters only the slow (body OBT) compartment. The metabolisation of OBT from body HTO is modeled in STAR but is ignored in OURSON.

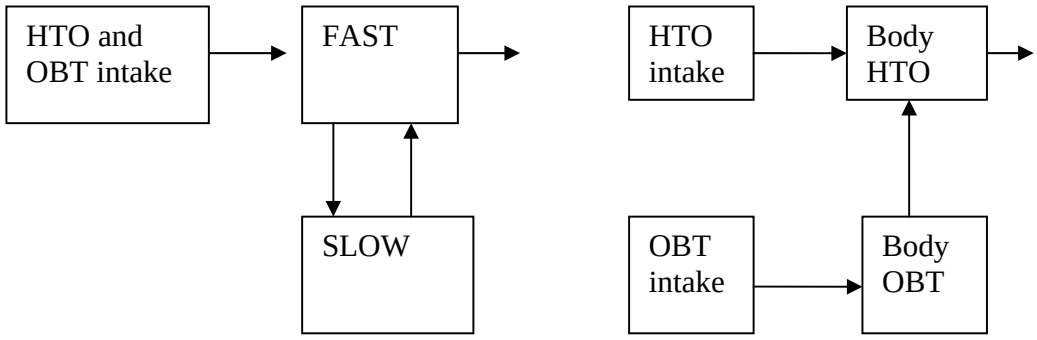


Figure 3. Flowchart of the simple models STAR (on the left) and OURSON (on the right)

The scenario gives the intake of tritium as OBT, a fraction of which will be in exchangeable form. There are processes in animal digestion that increase the fraction of exchangeable OBT (mostly from carbohydrates), and the stomach and intestines will contain not only non-exchangeable OBT but also tritiated water, which is absorbed and distributed to body water. Thus, in reality, organic tritium taken in with feed is distributed between body OBT and body HTO, and not entirely to one or the other, as in STAR and OURSON. Because STAR sends all organic intake to body water, it overpredicts total tritium concentrations in urine and underpredicts OBT concentrations in pig organs. In contrast, because OURSON sends all organic intake to the body OBT compartment, it underestimates total tritium concentrations in urine and HTO concentrations in meat, and overestimates OBT concentrations in organs.

The biological half-life of OBT is comparable in both models. There are experimental data showing the existence of OBT in organs after an HTO intake, a transfer pathway that is not considered in OURSON, or in the AECL model. The above analysis suggests changes that could lead in the future to an improved simple model for tritium transfer in large animals.

Two of the participating models, MCT and PRISM, consider two organic compartments (Figure 4). The transfer pathways and many transfer rates differ between the models but both give predictions that are relatively close to the observations. (This statement is based on the results obtained with the reconstructed version of PRISM and not on those obtained by FSA, which appear to be incorrect.) MCT does not consider the fraction of input organic tritium that is directly absorbed in the body OBT, which explains the underprediction in urine. Both models have fast and slow OBT compartments but MCT transfers catabolic OBT to body water, whereas PRISM transfers it out of the body, which is perhaps an oversimplification. The parameter values used in MCT reflect human properties and should be adapted more to pig metabolism. However, it is premature to designate either MCT or PRISM as the better model, as the blind test covered a single situation only.

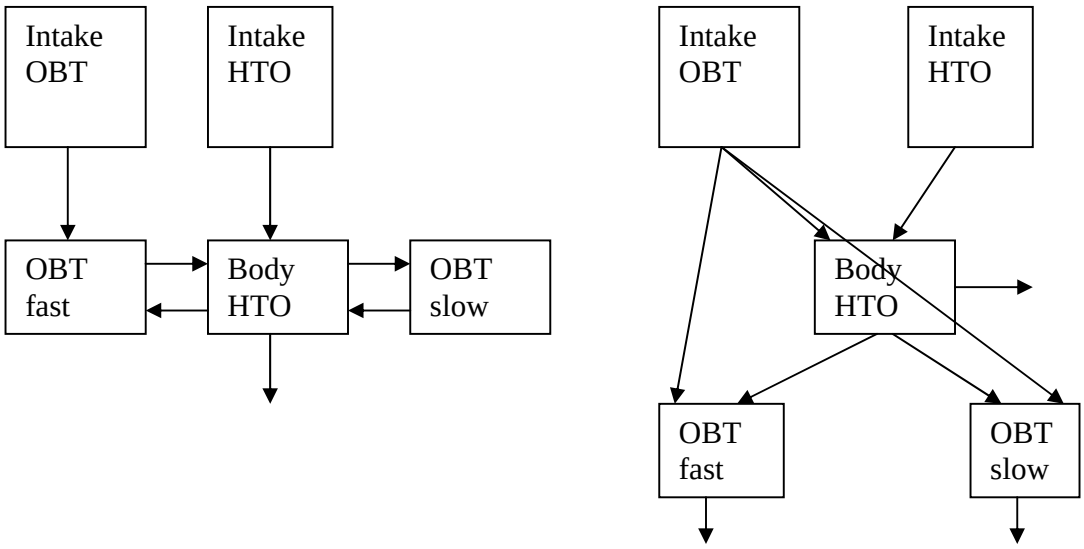


Figure 4. Flowchart of the models MCT (on the left) and PRISM (on the right)

MAGENTC was developed as a research model and is more complex than the other models in the scenario. Its performance is marginally better than that of MCT and PRISM for the blind test, and gives results that are closer to observations in similar experiments involving HTO intake in pigs.

Few models participated in the intercomparison exercises and, because the FSA results are likely incorrect, no firm conclusions can be drawn. For the case of prolonged HTO intake, the IFIN model seems to give reliable predictions based on the available experimental data for pigs. In the second intercomparison, only FSA and IFIN participated. The results of MAGENTC compare favourably with data from many other experiments, so we conclude that genotype is not important for the radiological assessment of tritium in meat (although it may be in liver).

To the best of our knowledge, this scenario was the first to attempt a limited blind test and model intercomparison for tritium transfer in large farm animals. More tests and intercomparisons are needed in order to define the best operational model. Also, in practice, we must be aware of the influence that the user has on model performance. The results presented here give hope that a simple operational model can soon be developed that is based on parameter values reflecting pig metabolism and that satisfies the requirements of robustness needed today in radiological assessments.

REFERENCES

FAO. 1980. Feed from animal wastes: state of knowledge. FAO Animal Production and Health Paper 18, http://www.fao.org/DOCREP/004/X6518E/X6518E00.HTM

INRA. 2008. http://www.inapg.fr/dsa/adz/tables/; http://www.inapg.fr/dsa/afz/tables/fichiers/FeedMix2004.pdf; http://www.inapg.fr/dsa/afz/tables/fichiers/jn233.pdf.

Kirchmann R. et al. 1977. Distribution of tritium in the different organs of calves and pigs after ingestion of various tritiated feeds. Curr. Top Radiat. Res. Q 12, 291.

Maul, P.R., C.E. Watson and M.C. Thorne. 2005. Probabilistic modelling of C-14 and H-3 uptake by crops and animals. Qunitessa Report QRS-1264A-1 Version 3.0.

McDonald, P., R.A. Edwards, J.F.D. Greenhalgh and C.A. Morgan. 1995. Animal Nutrition, Fifth Edition. Longman Scientific and Technical Publishers, Harlow.

NAC. 1998. National Academy of Sciences. Nutrient Requirements of Swine. Tenth Revised Edition. National Academy Press, Washington D.C.

Noblet, J., J.Y. Dourmad, M. Etienne and J. Le Dividich. 1997. Energy metabolism in pregnant sows and newborn pigs. J. Anim. Sci. 75, 2708–2714.

Stoica, I. 1997. Animal Nutrition and Feeding (in Romanian). Ed Coral-Sanivet, Bucharest.

van Hess, M. et al. 1986. Retention in young pigs of organically bound tritium given during pregnancy and lactation. Radiation Protection Dosimetry 16, 123.

van Milgen, J. and J. Noblet. 2003. Partitioning of energy intake to heat, protein and fat in growing pigs. J. Anim. Sci. 81(E. Suppl. 2), E86–E93.

Walke, R. and M. Thorne. 2007. EMRAS model comparisons *Adaptation of PRISM H-3 Model to Partition Excretion.* Quintessa Report QRS-3004B-TN1, Version 1.0.

APPENDIX A

Pig Scenario Description

1. Model-Data Scenario

A pregnant sow of the Belgische Landras strain, weighing about 180 kg, was given feed contaminated with organically bound tritium (OBT) for 84 days before delivery. The food had an average concentration of 577 Bq/g dry matter (dm) and was composed of a mixture of milk powder, potato powder and dried algae, as shown in Table 1.

Table 1. Composition of the sow diet

Food composition	Milk powder	Algal powder	Potato powder	Minerals
Amount (%)	41	2.3	51	5.7
Activity (%)	45.2	12.3	42.5	0
Concentration (Bq/g dm)	636.1	3085.7	480.8	0

As the pregnancy progressed, the amount of food given to the sow increased as shown in Table 2. Throughout the period, water was offered *ad libitum* but intake was not monitored. Literature values for pregnant sows indicate a water consumption of 6-8 L/d. The sow was sacrificed at birth and the tritium activity in various organs was measured. In the 84-day contamination period, urine and faeces were also monitored for tritium content.

Table 2. Amount of feed given to the sow

Time interval (days after start of contamination)	Amount of feed (kg dm/d)
0 - 21	1.86
22 - 46	2.06
47 - 79	2.31
80 - 84	3.01

Modellers are asked to predict the following:

1. Total tritium concentration in urine and HTO and OBT concentrations in faeces at the times shown in Table 3.

Table 3. Times at which predictions in urine and faeces are requested.

Day following start of contamination	Urine (Bq/ml total tritium)	Faeces	
		HTO in water fraction (Bq/ml)	OBT in dry fraction (Bq/g dm)
7			
14			
21			
28			
36			
42			
49			
56			

2. HTO and OBT concentrations in the organs shown in Table 4 at delivery (84 days after the start of contamination)

Table 4. Organs for which predictions are requested at delivery.

Organ	Dry Matter (%)	HTO (Bq/ml)	OBT (Bq/g dm)
Heart	21.70		
Lungs	23.45		
Liver	26.09		
Jejunum	22.40		
Ileum	20.16		
Colon	24.26		
Kidney	23.68		
Muscle	26.98		
Brain	22.16		
Blood	18.54		

Modellers are also asked to provide

(i) estimates of the 95% confidence intervals on all predictions, and
(ii) descriptions of the models they used following the EMRAS template.

2. Model Intercomparisons

The above test is not appropriate for animals used for human consumption since pigs are sacrificed near 110 kg. In the absence of other experimental observations, two exercises based on hypothetical data are proposed:

2.1 Exercise 1: Long-term HTO Intake

A pig of conventional strain was given uncontaminated food and water for the first 55 days of its life, at which point it weighed 20 kg. It was then fed food and water contaminated with HTO at a level of 10,000 Bq/L for 50 days. Its feed was uncontaminated for the next 50 days, at which point it was 155 days old and weighed 110 kg, and was sacrificed. At no time was any of the feed given to the pig contaminated with OBT. Modellers are asked to predict the total tritium in urine, HTO and OBT in faeces and OBT in muscle from the time the pig was 55 to 155 days old (50 days of contaminated diet and 50 days of clean) for the times given in Table 5. Estimate also the 95% confidence intervals of all predictions.

Table 5. Times at which predictions in urine and faeces are requested.

Day following start of contamination	Urine (Bq/ml total tritium)	Faeces HTO in water fraction (Bq/ml)	Faeces OBT in dry fraction (Bq/g dm)	Meat OBT (Bq/kg fw)
7				
14				
21				
42				
50				
60				
70				
100				

2.2 Exercise 2: Short-Term OBT Intake

All animals on a large pig farm are fed OBT-contaminated food for a single day at a level of 1 MBq/kg dm. Modellers are asked to predict the meat and liver OBT concentrations at sacrifice (body mass 110 kg) for the following pig mass on the day of contamination: 20, 40, 60, 80 and 100 kg.

One of the aims of Exercise 2 is to determine if accurate results can be obtained by considering a single generic pig or if the specific strain and diet of the pig must be taken into account. Accordingly, the modellers are asked to assess the influence of growth rate and genotype on their results by carrying out calculations for their default pig (and default diet) and for slow-growth and fast-growth pigs, as defined below:

- A slow growth genotype needs about 165 days to grow from 20 to 110 kg. For a moderate fatness, the adipose mass is near 30% of empty body mass and the meat near 25%. (Empty body mass is the live body mass minus the content of the gastrointestinal tract.)

- Modern commercial pigs needs about 110 days to grow from 20 to 110 kg. Depending on genotype, muscle mass can be high (63%) or low (45%). Accordingly, the adipose mass fraction can vary between 15 and 28%.

Generic intakes for slow-growth and fast-growth pigs are shown in Table 6. These intakes assume an *ad libitum* diet based on barley (20%), corn (60%) and soybean meal (20%) that contains 21% crude protein, 1% lysine and 14.4 MJ metabolisable energy per kg on a dry mass basis.

Table 6. Generic feed intake

	Intake (kg dm/d)				
Body mass (kg)	20	35	50	80	110
Intake for slow growth	1	1.4	1.66	1.9	2
Intake for modern commercial growth	0.95	1.48	1.9	2.35	2.7

Total water intake is $0.3BM^{0.71}$ L/d, where BM is body mass in kg.

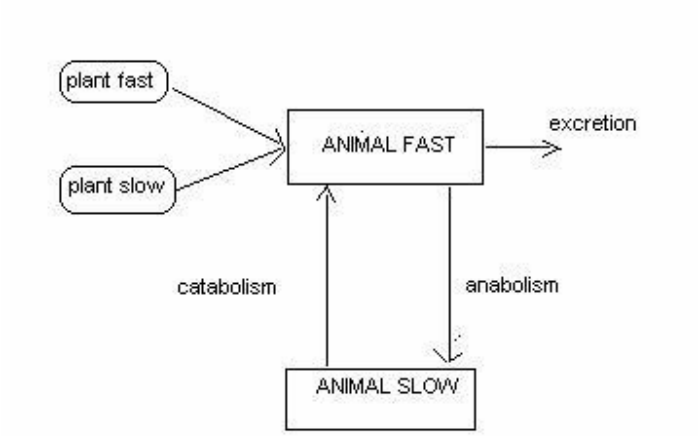
All assumptions regarding pig genotype, diet and intake rates should be fully documented in the model descriptions.

APPENDIX B

MODEL DESCRIPTIONS

STAR-H3
(Used by LLNL and IFIN-HH)

STAR was the first model used in the UK for assessing tritium and ^{14}C contamination of plants and animals. In the original version (Smith, 1995), only cows (beef) were considered for UK conditions, implying that the animal diet consisted of fresh pasture all year. Pasture (and all other plants) is modeled as a two-compartment system: a fast-turnover compartment (water) and a slow-turnover compartment (organic material). Animals are also assumed to have a fast and a slow compartment, the former for HTO and labile organically bound hydrogen and the latter for non-labile organically bound hydrogen. The rate of loss of tritium from the non-labile OBT compartment (catabolism) is an input parameter of the model, as is the rate of excretion from the fast compartment. Both fast and slow compartments represent one kg of "meat" with 70% water. Hydrogen in the fast compartment is presently set at 700/9 g. The amount of non-labile organically bound hydrogen in the slow compartment is fixed at 24 g. All intakes (from drinking and respiration water, as well as from the fast and slow plant compartments) enter the fast animal compartment only. A flowchart of STAR-H3 is given below.



The model was extended (Watkins, 1998) to sheep, pigs and chickens with the same assumptions but different amounts of feed intake. The intake of food and water for all animals is divided by the "carcass mass" to give the input to the animal fast compartment. All animals are considered to eat pasture. STAR-H3 ignores animal growth and has the same hydrogen content in all animals. Animal hydrogen intake is given below.

Animal	Carcass mass (kg)	Intake (kg fw/d)	Specific intake (kg fw/kg)	Specific intake (gH/kg/d)	Inhalation (m^3/d)	Inhalation (gH/kg/d)
Cow	230	115	0.5	52.44	130	0.50
Sheep	25	7	0.28	29.37	8.64	0.31
Pig	100	30	0.3	31.47	12	0.11
Chicken	2	0.5	0.25	26.22	0.24	0.11

For all animals, the slow and fast turnover rates are 0.03 d^{-1} and 0.4 d^{-1}, with the exception of the lactating cow, for which the fast turnover rate is 0.5 d^{-1}. In reality, the slow turnover rate varies with animal type. From all this information, the hydrogen contents in the slow and fast compartments and the transfer rates in the model can be assessed:

Compartment or Transfer rate	Units	Cattle	Sheep	Pig	Chicken
Slow compartment	gH kg^{-1} meat	22	22	22	22
Slow turnover	d^{-1}	0.03	0.03	0.03	0.03
Fast turnover	d^{-1}	0.5	0.4	0.4	0.4
Growth	-	0	0	0	0
Excretion	d^{-1}	0.492	0.392	0.392	0.392
Intake	gH kg^{-1} d^{-1}	52.4	29.4	31.4	26.2
Fast compartment	gH kg^{-1}	77.8	77.8	77.8	77.8
Anabolism	d^{-1}	0.00849	0.00849	0.00849	0.00849
Catabolism	d^{-1}	0.03	0.03	0.03	0.03

There are some inconsistencies in the model with respect to the assumed hydrogen intake and mass balance.

References

Smith, G.M., P.C. Robinson and M.J. Stenhouse. 1995. H-3 foodchain modelling following short-term release to atmosphere. Intera Environmental Division Report IE3947-1.

Watkins, B.M., P.C. Robinson and G.M. Smith. 1998. Update of models for assessing short-term atmospheric releases of C-14 and tritium in the light of new information and experimental data. Quantisci – MAFF-5044-1.

MCT Model
(M. Saito, Japan)

1. Introduction

The MCT model was initially developed for humans, particularly Japanese (Saito, 1992). Assuming that humans are a good surrogate for pigs, the model was used with minimal changes since the hydrogen metabolism in the pig is expected to be similar to that of humans. In the MCT model, two OBT compartments and one free water tritium (FWT) compartment are assumed.

2. Assumptions and Parameter Values

2.1 Rate constants for hydrogen transfer

Excretion from body water	0.077 d^{-1}
Transfer from body water to fast OBT	0.000270 d^{-1}
Transfer from body water to slow OBT	0.000345 d^{-1}
Transfer from fast OBT to body water	0.022482 d^{-1}
Transfer from slow OBT to body water	0.001443 d^{-1}

2.2 Body weight and feed intakes

Days after start of contamination	Body weight (kg)	Feed consumption (kg dm d^{-1})	Water intake (kg d^{-1})
0-21	180	1.86	7
22-46	200	2.06	7
47-79	220	2.31	7
80-84	240	3.01	7

Efficiency of dry matter digestion: 70%

2.3 Hydrogen balance

Body water content of soft tissues: 60% of body weight
Dry matter content of soft tissues: 30% of body weight

2.4 Hydrogen content of the sow body

Free water hydrogen (FWH): 12000 gH
Organically bound hydrogen (OBH): 6000 gH

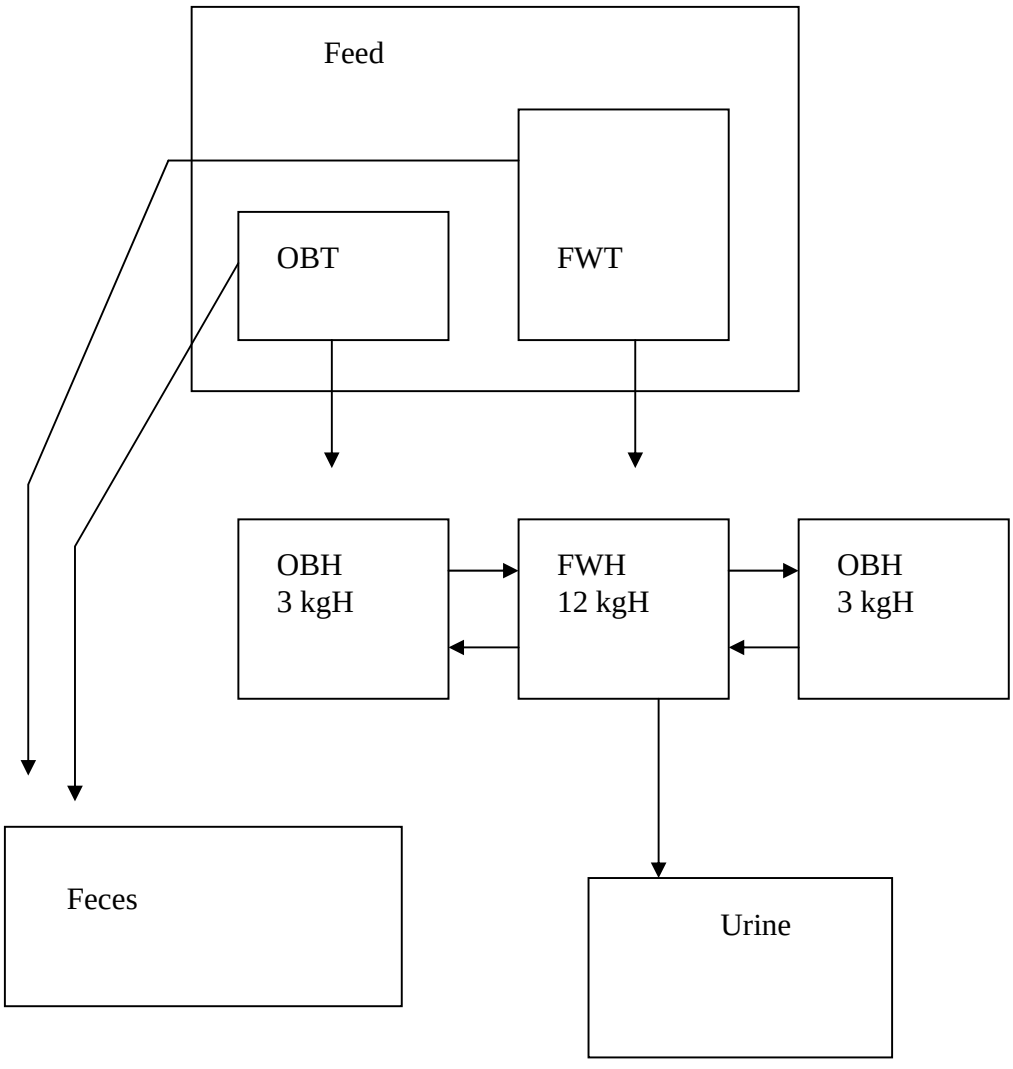
2.5 Body composition

Water content of the sow whole body: 108 kg water, or 60% of the body weight including hard tissues.
Dry matter of the sow body: 72 kg

2.6 Fecal excretion

The feed material contains 10% by weight of exchangeable organically bound water. The percent availability of the dry component as nutrient taken up in the GI tract is 70%. The rest of the dry component is excreted as feces.

3. Model Structure

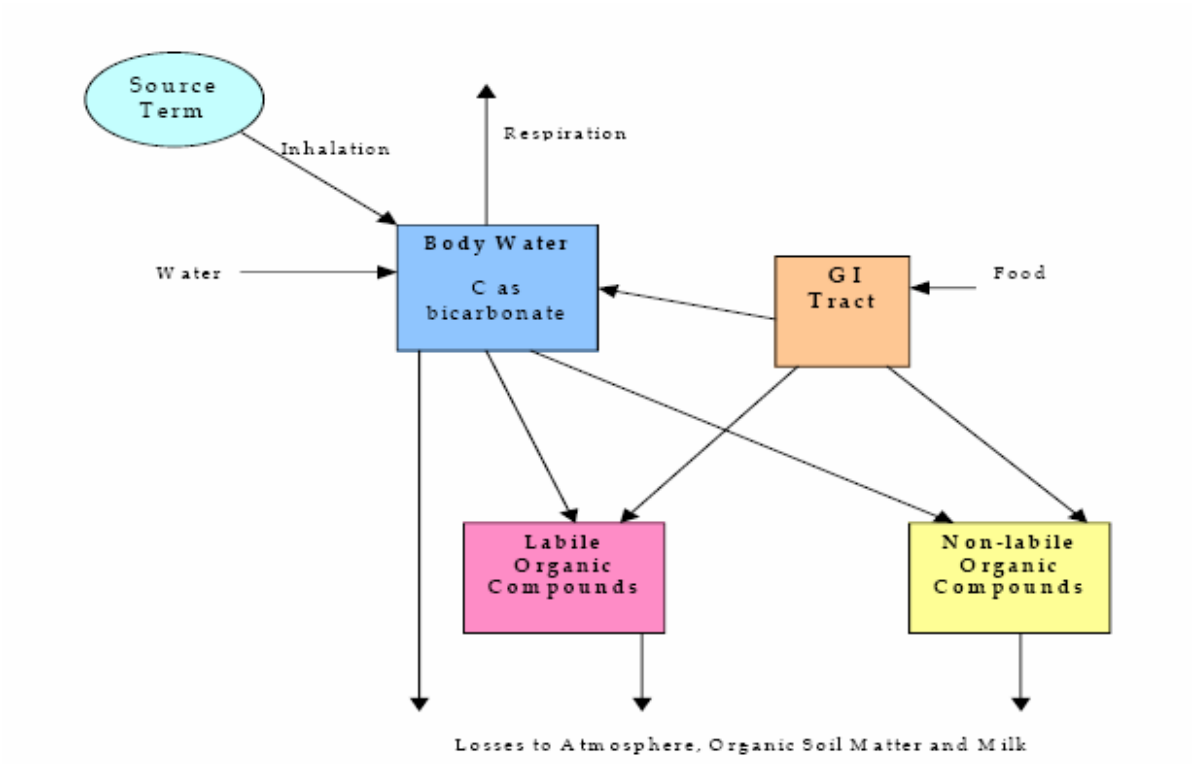


Reference

Saito, M. 1992. A modified three-compartment model for tritium metabolism in man. Radiation Protection Dosimetry 42, 17.

FSA Model
(PRISM)

Model Name: Prism 3.0 (H-3/C-14 Model) implemented on the software platform AMBER 5.
Purpose of Model: Regulatory Assessment; Conservative
Type of Model: Dynamic; Numerical; Compartmental



Compartments Considered:
The animal is assumed to consist of four compartments: GI Tract [GI], body water [BW], labile organics [LO] and non-labile organics [NO]. The use of a single compartment to represent the GI tract is a much simpler approach than is usually taken for other radionuclides. The model also includes an environmental sink compartment [SN]. Losses to this compartment by respiration, evaporation, transpiration and parts of the plant not normally harvested are taken into account.

Transport Processes Considered:
PRISM considers transfer to the animal via inhalation and food and water intake, transfer among the various animal compartments, and losses to the sink.

Endpoints:
The model calculates the concentration in a given compartment by dividing the activity in that compartment (as determined by transfers to and from the compartment) by the mass of the compartment. In the animal model, there is no distinction between concentrations in different animal tissues. OBT and HTO concentrations in urine and faeces cannot be reported directly because it is assumed that all activity from the GI tract and respiration are retained in body water.

Key Assumptions

- The GI tract is represented by a single compartment since tritium uptake from the tract is complete and rapid.
- Other parts of the system are represented by labile and non-labile compartments rather than by specific organs or tissues.
- Tritium in the aqueous phase of the plant is transferred directly to body water; any loss of water from stored fodder can be neglected.
- Consumed organic plant material enters the GI compartment and is transferred rapidly to the other three animal compartments (body water, labile organics and non-labile organics) according to prescribed partitioning fractions, which are required to sum to 1.0.
- Transfer rates from the body water compartment are expressed in terms of a total loss rate and partitioning fractions f_{BWLO}, f_{BWNO} and f_{BWSN}.
- All tritium taken in with feed is in the form of HTO in contaminated fodder.
- Organ masses (apart from meat, liver and kidney, which are expressed explicitly in the output file) are adapted from ICRP 23 values for Reference Man using the "0.75 Power Rule".
- The time of feeding of contaminated fodder is from midnight on the day of contamination to midnight the following day.
- In all cases, the pigs were assumed to have a mass of 20 kg at the start of the run. This avoided the excessively complicated scenario in which the pig first received clean fodder, then contaminated fodder, and then clean fodder again. It also got around the fact that the model does not accept growth scenarios that start before weaning takes place.

Temporal and spatial discretization of the model:
There is no spatial discretization in PRISM. Where the exposure is via the atmosphere, the user can define the source term as a continuous air concentration, a spike (a discrete, short-term exposure) or a complex exposure (a series of spikes). Where the exposure is via contaminated feed, the daily concentration of activity in fodder can be defined, as well as the duration of the feeding regime. Output is normally reported every three days unless otherwise specified. Experience with the pig scenario suggests that the default interim output times between start and finish should be replaced with the specific times at which results are required.

Parameter Values:
Most parameters were assumed to be uniformly distributed. The maximum and minimum values of the distributions for each parameter, and the best estimates, are shown in the following table.

Parameter	Units	Best estimate	Range
Fraction transferred from body water to labile organics	-	0.02	0.002-0.1
Fraction transferred from body water to non-labile organics	-	0.01	0.001-0.05
Fraction transferred from body water to sink	-	0.97	0.85-0.99
Fraction transferred from GI tract to labile organics	-	0.14	0.04-0.26
Fraction transferred from GI tract to non-labile organics	-	0.07	0.02-0.13
Transfer rate to body water	d^{-1}	0.13	0.06-0.19
Transfer rate from labile organics to soil organic layer	d^{-1}	0.0011	0.00055-0.0022
Transfer rate from labile organics to sink	d^{-1}	0*	
Transfer rate from non-labile organics to soil organic layer	d^{-1}	7.32×10^{-5}	3.66×10^{-5} - 1.46×10^{-4}
Transfer rate from non-labile organics to sink	d^{-1}	0*	
Mass fraction of organic matter	-	0.035	0.0175-0.07
Mass fraction of labile organic compartment	-	0.36	0.1-0.66

*amended on remodelling to 10 d^{-1}

Uncertainties:
The uncertainties in the model predictions were estimated using a probabilistic approach based on sampling the distributions for the various parameters. Concentrations at the 95% level were a factor 7-10 higher than those obtained using best estimate values. Losses to the sink appear to be quite low.

Application of the Model to the Scenario:
For the model-data comparison, four feeding regimes were modelled to take into account the different quantities of fodder fed to the sow. In the first instance, the given concentration of activity was scaled to Bq/kg dry weight and input. The growth curve was edited to take into account the final mass of the sow, and the organ masses, at delivery. Additional calculations were carried out to test different combinations of growth curves and activity concentrations in the feed.

The first model intercomparison exercise involved long-term HTO contamination of the feed and water fed to the pig. Since PRISM cannot handle liquid intakes, the contaminated water was replaced in the model with an equivalent amount of contaminated fodder. In the first instance, the given concentration was input and two feeding regimes were set up to model the contaminated and uncontaminated periods. As in the case of the model-data scenario, the growth curve was edited to take into account the final mass of the pig at slaughter. Additional

calculations were carried out to test different combinations of growth curves and activity concentrations in the feed.

Some initial runs gave very similar results for both the 110-day and 165-day growth scenarios. Subsequent investigations suggested that this was because the generic growth curve parameters were the same for the two runs, and that the amount of fodder fed in the contamination part of the scenario was also the same (a normal PDF in the range 1.9-2.9 with a best estimate of 2.4 kg d^{-1}). In subsequent model runs, the growth curve was adjusted to take into account the final masses and different rates of growth. The mass of feed was adjusted to take into account the different rates quoted in the scenario.

References

Maul, P., M.C. Thorne, C. Watson and R. Walke. 2006. Prism food chain modelling software: Version 3.0 Technical Guide. Quintessa Report QRS-3004A-2.

Watson, C., and P. Robinson. 2006. The Prism food chain modelling Software: Version 3.0 User Guide. Quintessa Report QRS-3004A-3.

Walke, R., M.C. Thorne and C. Watson. 2006. The Prism food chain modelling software: Version 3.0 Testing and Verification Report. Quntessa Report QRS-2004A-4.

Ould-Dada, Z. 2005. A demonstration of SPADE and AMBER. Notes from the European Crop Protection Association meeting “Dietary Risk Assessment Workshop”, Brussels.

Xu, X.G., T.C. Chao and A. Bozkurt. 2000. VIP-Man: An image-based whole-body adult male model constructed from colour photographs of the Visible Human Project for multi-particle Monte Carlo calculations (for Reference Man organ masses). Health Physics 78, 476-486.

Walke, R. and M.C. Thorne. 2007. Adaptation of Prism H3 to partition excretion. Quntessa Report QRS3004B.

IFIN-HH Model

MAGENTC (MAmmal GENeric model for Tritium and Carbon transfer)

The MAGENTC model was developed gradually over the last three years as a research tool for the transfer of C-14 and H-3 in mammals, based on energy metabolism. It is the result of an international collaboration led by IFIN-HH with contributions from researchers from the UK and Japan. In its initial form it was used for wild mammals (Galeriu et al., 2005a) and the human dosimetry of tritium (Galeriu et al., 2005b). A full description will be released soon (Galeriu et al., 2008).

For adult mammals, the model for the transfer of tritium and ^{14}C in the body is based on the following ideas:

- The most important body organic compartments are the viscera (including the heart), muscle, adipose tissue, blood (plasma and RBC) and the remainder (including the brain). The mass and composition of these organs are well known.
- Tritium in body water equilibrates rapidly and a single body water compartment suffices when modelling tritium.
- The loss rate from organic compartments is similar for intakes of HTO or OBT and can be assessed directly from the energy turnover rate (net maintenance).
- Net maintenance can be considered the sum of the energy needs of basal metabolism and activity, neglecting thermal stress.
- The basal metabolic need is the sum over all organs of the product of the organ specific basal metabolic rate and the organ mass.
- The specific metabolic rate (SMR) for organs in adult mammals varies marginally, except for muscle, compared to the basal state. The basal SMR shows a dependence on the mature mass of the animal.
- Values of SMR have been obtained experimentally for a few mammals only and a zero-order approximation, dependent on mature mass, is normally used.
- There is metabolic conversion of HTO to OBT. The equilibrium value of the OBT/HTO ratio derived from ingested HTO or OBT does not vary across mammals.
- The energy (heat) and accompanying matter lost in transforming the metabolisable input in net requirements is considered a single, fast process.

Under these hypotheses, the model gives reliable predictions with no calibration. A flowchart of the model is given in Figure 1 below.

For growing mammals, the model needs a clear definition of maintenance energy need, which is difficult to obtain because of the complexity of processes in growing mammals. In a few cases, the experimental data give a reliable definition.

Generic, default parameter values were used in calculations for the blind test of the Pig Scenario. For the model inter-comparison exercises with growing pigs, the model assumes that growth and intake in the various model compartments are driven by the growth rates of

each organ (or group of organs) and depend on changes in composition. Experimental data from French researchers (van Milgen and Noblet, 1999, 2003, 2005; van Milgen et al., 2000; Ouiniou and Noblet, 1995) have been used to test the model as they permit a good distinction between maintenance and growth needs.

Three distinct pigs were analyzed: a conventional genotype (SL), a lean genotype with low visceral mass (PP), and a fat genotype (MS). These pigs differ in respect to body mass and MEI intake dynamics, as well as in their adipose and visceral tissues (Figures 2-5). Muscle mass differs also (Figure 6). All growth data are extracted from the French papers referenced above. We selected this data partly because they describe the time dependence of muscle and adipose mass. The concentrations in muscle show moderate sensitivity to the SMR in viscera and remainder organs (Figures 7-8). Using the same starting body composition and same relationship for body water as a function of body protein for each genotype, and a constant OBT concentration in the diet (1Bq/kg dry matter), we obtained the results in Figure 9. From this figure, we can deduce that genotype is not of peculiar importance for continuous intake and that whole body concentrations overestimate muscle concentrations by a factor that depends on pig obesity.

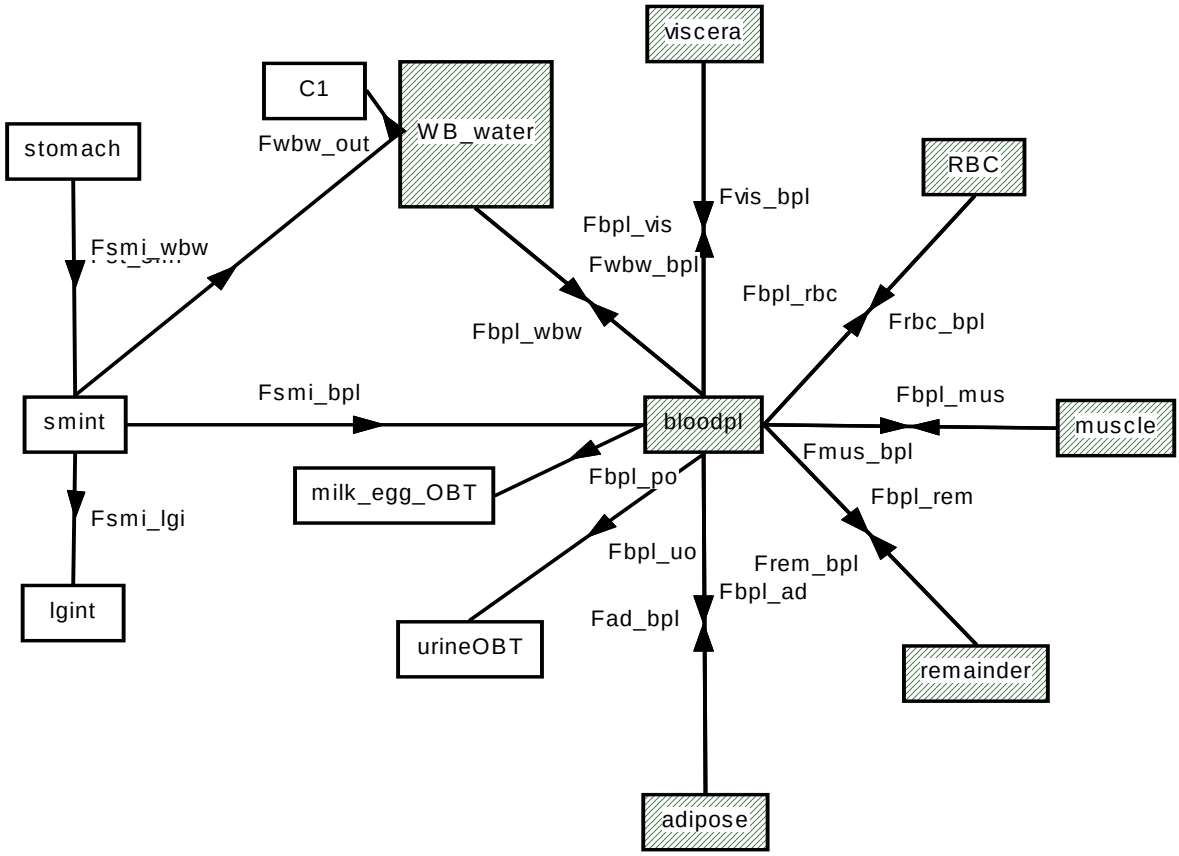
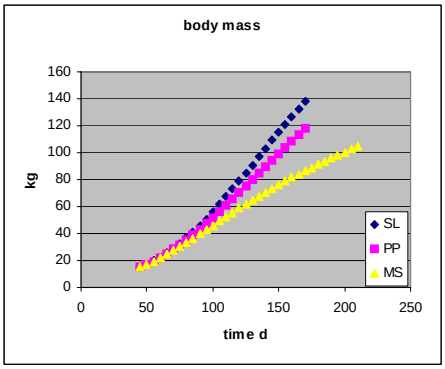
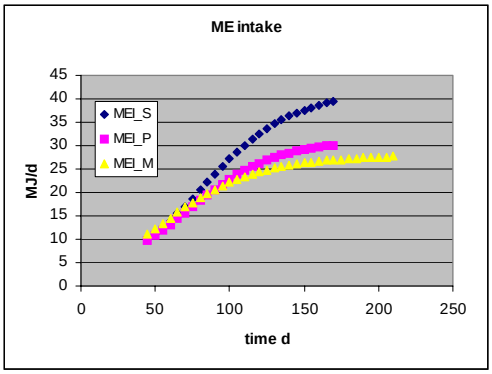
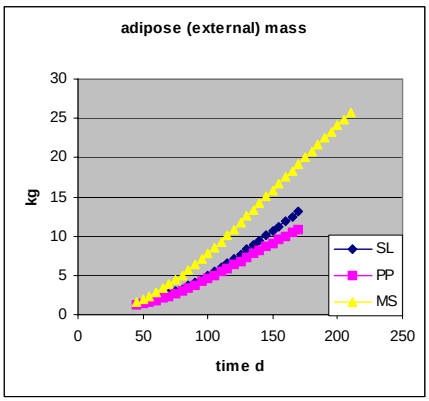


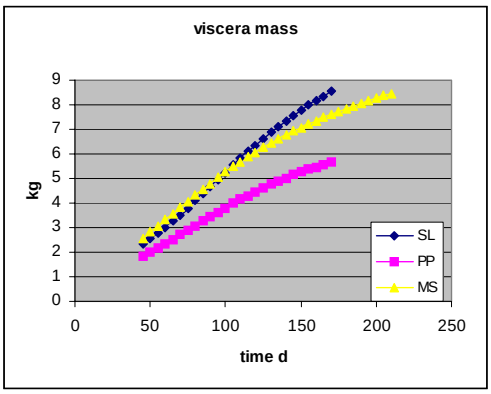
Figure 1. Flowchart of the MAGENTC model





Figures 2 and 3. Dynamics of pig body mass and MEI intake for different pig genotypes.





Figures 4 and 5. Dynamics of adipose and viscera mass for different pig genotypes.

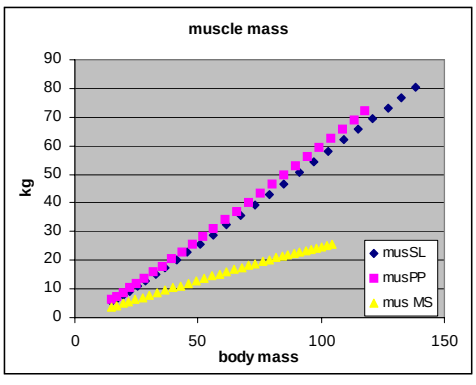


Figure 6. Muscle mass as a function of body mass for different pig genotypes.

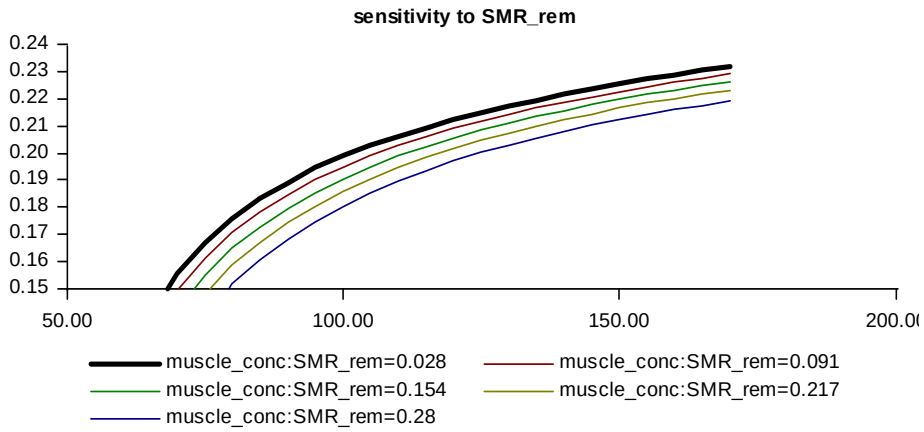


Figure 7. Sensitivity of muscle concentration to SMR in remainder organs.

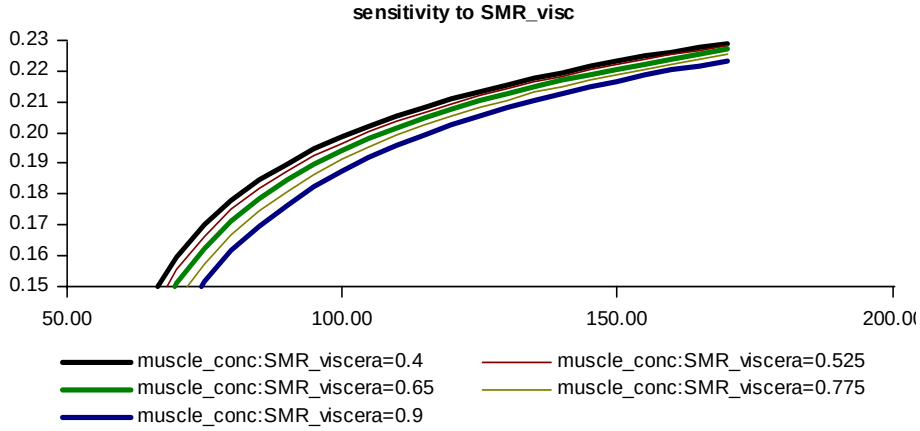


Figure 8. Sensitivity of muscle concentration to SMR in viscera

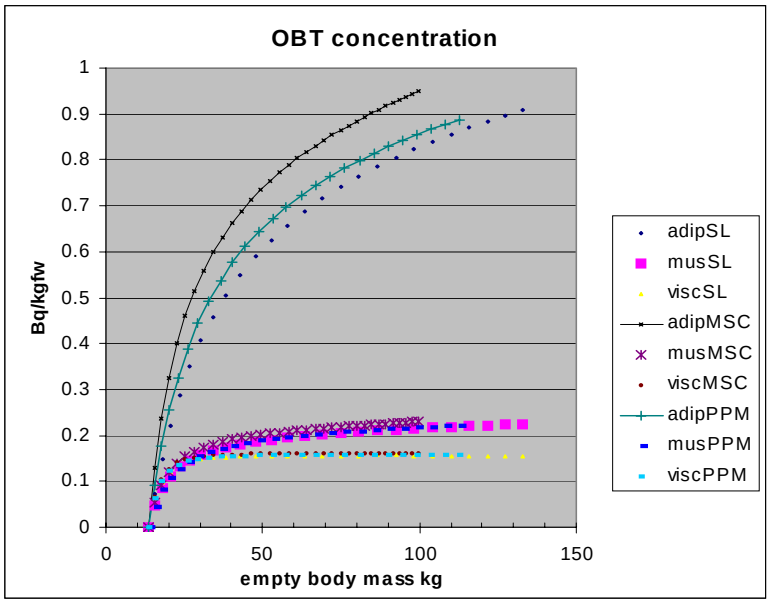


Figure 9. OBT concentration in muscle, viscera and adipose tissue for three pig genotypes fed 1 Bq/kg dry matter.

References

Galeriu, D., N.A. Beresford, A. Melintescu, N.M.J. Crout and H. Takeda. 2005a. ^{14}C and tritium dynamics in wild mammals: a metabolic model. Radioprotection, Suppl 1, Vol 40 S351-357.

Galeriu, D., H. Takeda, A. Melintescu and A. Trivedi. 2005b. Energy metabolism and human dosimetry of tritium. Fusion Science and Technology, Vol 48, 795-798.

Galeriu, D., A. Melintescu, N.A. Beresford, H. Takeda and N.M.J. Crout. 2008. The dynamic transfer of ^{3}H and ^{14}C in mammals – a proposed generic model. Radiation and Environmental Biophysics. DOI: 10.1007/s00411-008-0193-9.

Quiniou, N. and J. Noblet. 1995. Prediction of tissular body composition from protein and lipid deposition in growing pigs. J. Anim. Sci. 73, 1567-1575.

van Milgen, J., J. Noblet, A. Valancogne, S. Dubois and J.Y. Dourmad. 2005. InraPorc : un modèle pour analyser les performances et évaluer les stratégies alimentaires chez le porc en croissance. Journées de la Recherche Porcine en France 37, 291-298.

van Milgen, J. and J. Noblet. 2003. Partitioning of energy intake to heat, protein and fat in growing pigs. J. Anim. Sci. 81(E. Suppl. 2), E86–E93.

van Milgen, J. and J. Noblet. 2000. Modelling energy expenditure in pigs. In : Modelling nutrient utilisation in farm animals. Ed J.P. McNamara, CAB International.

van Milgen, J. and J. Noblet. 1999. Energy partitioning in growing pigs: The use of a multivariate model as an alternative for the factorial analysis. J. Anim. Sci. 77, 2154–2162.

EDF Model

The EDF calculations are based on the OURSON model, a dynamic model that evaluates radionuclide concentrations in the aquatic and terrestrial environment resulting from liquid discharges, in order to estimate doses to humans. Consequently, only dose-relevant compartments are included in the model. Milk and meat are the two animal compartments taken into account. Both HTO and OBT are described by single compartment metabolic models.

The pig scenario involves the calculation of tritium concentrations in urine, in faeces and in different body organs. None of these compartments are included in the OURSON model. Therefore it was necessary to make some adaptations.

The HTO concentration in urine was assumed to equal the concentration in body water. The same assumption is used for HTO in cow's milk. Thus the HTO concentration in urine was calculated according to Equation (1). The concentration depends on the HTO activity in the diet, on the turnover of OBT in meat tissue, and on the water intake rate in food and drinking water.

$$\frac{dC_{urine}^{HTO}(t)}{dt} = -\lambda_w C_{urine}^{HTO}(t) + \frac{1}{H_2O_{pig}}\left(HTO_{diet} + k_{ing}.OBT_{pig}(t)\right) \quad (1)$$

with

$$\lambda_w = \frac{\text{water consumption (L/day)}}{H_2O_{pig}(L)}$$

where

HTO_{diet} = HTO activity in the diet (drinking water plus food) (Bq/day)

k_{ing} = OBT turnover rate (d^{-1}) (see Equation 2)

W = animal dry weight (kg)

$OBT_{pig}(t)$ = total OBT in the pig (Bq)

$OBT_{pig}(t)$ was calculated according to the OURSON equation for OBT in meat, where the turnover rate is governed by the relative rate of ingestion of food and the food digestibility:

$$\frac{dA_{meat}^{OBT}(t)}{dt} = -k_{ing} A_{meat}^{OBT}(t) + k_{ing}.\frac{H_{food}}{H_{meat}}.A_{food}^{OBT}(t) \quad (2)$$

with

$$k_{ing} = \frac{I \cdot D}{W}$$

where

A_{meat}^{OBT} = OBT specific activity in meat (Bq/g H)
A_{food}^{OBT} = OBT specific activity in food (Bq/g H)
I = food intake (kg dry weight d^{-1})
D = digestibility (unitless)
W = animal dry weight (kg)
H_{food} = average food organically bound hydrogen (g/kg dry matter)
H_{meat} = average meat organically bound hydrogen (g/kg dry matter)

Urea is another source of tritium in urine. The OBT specific activity in urea was assumed to equal the average OBT specific activity in the pig.

Faeces OBT corresponds to the OBT in the non-digestible fraction of food. It was assumed that the OBT specific activity was identical in the digestible and non-digestible fractions. Faeces HTO was considered to originate from microbial decomposition of the non-digestible food fraction; thus HTO and OBT specific activity in faeces were identical.

To estimate OBT concentrations in the various organs, OBT in the pig was calculated according to Equation 2. It was considered that this value was representative of the muscle compartment. Concentrations in other organs were derived from the concentration in muscle using a correction factor based on the fat and protein contents of each organ, the turnover rate of fats and proteins, and the hydrogen content of fats, proteins and carbohydrates.

The HTO concentration was assumed to be the same in all organs, and was calculated with Equation 1.

Parameters
Noblet et al. (2003) provide digestibility coefficients (for energy) for a pregnant sow for different types of foods (Table 1). However, no value for algal powder was available. The value for alfalfa with a protein content of less than 16% was attributed to algal powder.

Food hydrogen contents and the organically bound hydrogen (OBH) content of pigs were calculated from water equivalent factors (Peterson and Davis, 2002). The sow dry weight was 90 kg, based on a dry matter content of 50% (Peterson and Davis, 2002).

Table 1. Digestibility coefficients and organically bound hydrogen contents of different foods

Food	Digestibility coefficient	OBH content (% dry matter)
Whole milk powder	0.930	7.43
Whole potato powder	0.925	6.44
Alfalfa powder, proteins<16% (surrogate for algal powder)	0.48	5
Pig		10.04

Human data were used to estimate the OBH content of urea (0.066 g/g; Richardson and Dunford, 2003) and the urea concentration in urine (25 g/L). The same reference was used for the contents of carbohydrates, fats (two types) and proteins in different organs, and the turnover rates of fats and proteins. Calculated turnover rates relative to those in muscle are given in Table 2.

Table 2. Calculated relative turnover rates in different organs.

organ	Heart	Lungs	Liver	Jejunum	Ileum	Colon	Kidney	Muscle	Brain	Blood
OBT turn over rate relative to muscle	1	0,80	0,83	0,62	0,62	0,62	0,83	1	0,51	0,80

References

Noblet J., V. Bontems and G. Tran. 2003. Estimation de la valeur énergétique des aliments pour le porc. INRA Prod.Anim., 16(3), 197-210.

Peterson S.R. and P.A. Davis. 2002. Tritium doses from chronic atmospheric releases: a new approach proposed for regulatory compliance. Health Physics 82, 213-225.

Richardson R.B. and D.W. Dunford. 2003. A biochemical-based model for the dosimetry of dietary organically bound tritium. Part 2: Dosimetric evaluation. Health Physics 85, 539-552.

AECL Model

1. Model Description

The AECL calculations were carried out with the animal subroutines of the ETMOD code, an environmental tritium code used for predicting the consequences of accidental tritium releases to the atmosphere from tritium-handling facilities at Chalk River Laboratories and other sites (Chouhan, 2004; Russell and Ogram, 1992; Thompson et al., 1992). ETMOD simulates the behaviour of tritium in the biosphere, covering many transport and exposure pathways including atmospheric dispersion, deposition and migration in soil, re-emission from soil, and transfer to vegetation, animals and animal products. It can handle releases of either tritium gas (HT) or tritiated water vapour (HTO) and addresses organically bound tritium (OBT) formation in plants. As its main endpoint, ETMOD predicts ingestion and inhalation (including skin absorption) doses to humans.

The animal subroutines of ETMOD calculate HTO concentrations in animal products using the HTO taken in by the animal through inhalation and ingestion of water, feed and soil. The dynamics of the HTO concentration in animal body water, C_H, is driven by the concentration gradient between HTO in intake water and in body water, as described by the following equation:

$$dC_H/dt = (H/W_t - C_H)\, W_t/W_b \qquad (1)$$

where W_t = total water intake from all sources (L/d)
W_b = body water content (kg)
H = total daily amount of tritium intake (Bq/d), including OBT

Now $W_b = C_{bwf}\, BM$, where C_{bwf} is the body water fraction and BM is body mass (kg). Also,

$$W_t = W_i + C_{wf1}I_{r1} + (1- C_{wf1})W_mI_{r1} + C_{wf2}I_{r2} + (1- C_{wf2})W_mI_{r2} + 1000R_oI_{inh} + \theta_wI_s \qquad (2)$$

where C_{wf1} and C_{wf2} = water fractions in grain and other food types, respectively (unitless)
I_{r1} and I_{r2} = ingestion rates for grain and other food types (kg/d)
W_m = metabolic water fraction in dry matter (identical for all food types, unitless)
R_o = air specific humidity (g/m^3)
I_{inh} = inhalation rate (m^3/d)
θ_w = soil water content (L/kg)
I_s = soil ingestion rate (kg/d)

In general, H is given by

$$H = C_w W_i + C_{f1} C_{wf1} I_{r1} + C_1^{OBT} (1- C_{wf1}) W_m I_{r1} + C_{f2} C_{wf2} I_{r2} + C_2^{OBT} (1- C_{wf2}) W_m I_{r2} + 2 C_{air} I_{inh} + C_s \theta_w I_s \quad (3)$$

where C_w = HTO concentration in water (Bq/L)
C_{f1} and C_{f2} = HTO concentrations in grain and other food types, respectively (Bq/kg)
C_1^{OBT} and C_2^{OBT} = OBT concentrations in grain and other food types, respectively (Bq/kg)
C_{air} = HTO concentration in air (Bq/m^3). Skin absorption of HTO is assumed equal to inhaled HTO, which is reflected in the multiplier 2 in Eq. (3)
C_s = HTO concentration in soil (Bq/kg)

OBT is not modeled explicitly in the animal in the current version of ETMOD.

2. Assumptions and model parameterization

2.1. Model-Data Comparison

a) Total water intake consists of inhaled water vapour, ingestion of water in food, formation of metabolic water following food ingestion, and directly ingested water. The ingestion rate of water (W_i) and of the water in food (W_f) are assumed to be constant throughout the period of the experiment. Two cases are considered:

i) W_i = 6.0 L/d and W_f = 1.0 L/d;
ii) W_i = 8.0 L/d and W_f = 1.2 L/d.

b) Food intake follows the rates prescribed in the scenario description, as shown in the following table:

Day after start of exposure	1	22	47	80
Food intake (kg/d dry matter)	1.86	2.06	2.31	3.01

60% of the dry matter in the diet is combined with 15% of the food water; the remaining 40% of the dry matter is combined with 85% of the food water. The average food water content equals 70%. One kg of dry weight food yields 0.56 l of metabolic water for all food types.

c) The soil ingestion rate is 125 g/d with a water content of 30%.

d) The inhalation rate equals 35.9 m^3/d. The air absolute humidity is 12 g/m^3.

e) The pig gains 0.5 kg/d from a weight of 180 kg at the start of the exposure.

f) The body water content is 65%.

2.2. Model Intercomparison Exercise

a) Total water intake consists of inhaled water vapour, ingestion of water in food, formation of metabolic water following food ingestion, and directly ingested water. The ingestion rate of water (W_i) is assumed to obey the following regression:

$$W_i = 0.3\ BM^{0.71}\ \text{L/d},$$

where BM is body mass in kg.

b) Food intake corresponds to generic intake rates for slow-growth genotypes, as shown in the following table:

Body mass (kg)	20	35	50	80	110
Food intake (kg/d dry matter)	1	1.4	1.66	1.9	2

60% of the dry matter in the diet is combined with 15% of the food water; the remaining 40% of the dry matter is combined with 85% of the food water. The average food water content equals 70%. One kg of dry weight food yields 0.56 l of metabolic water for all food types.

c) The soil ingestion rate is 125 g/d with a water content of 30%.

d) The inhalation rate (I_r) is scaled by the water ingestion rate:

$$I_r = 4.2\ W_i\ \ m^3/d$$

The air absolute humidity is 12 g/m^3.

e) The growth of body mass, BM, is approximated by the following regression:

$$BM = \boldsymbol{a}_0 + \boldsymbol{a}_1 t + \boldsymbol{a}_2 t^2 + \boldsymbol{a}_3 t^3 \quad \text{kg},$$

where t is time (d)

and $\boldsymbol{a}_0$=21.104, $\boldsymbol{a}_1$=1.92, $\boldsymbol{a}_2$= -1.57e-02, $\boldsymbol{a}_3$= 5.0e-05

f) The body water content of the pig is W_{bwf} = 65%.

The dynamics of body mass, inhalation rate and food intake are plotted on Figures 1-3, respectively.

References

Chouhan, S.L. 2004. Addendum computer program abstract and theory manual for ETMOD 2. AECL Report RC-2901, Vol. 2, Revision 0., 123p.

Russell, S.B. and G.L. Ogram. 1992. ETMOD: A new environmental tritium model. Fusion Technology 21, 645-650.

Thompson, J.W., J.A. Kennedy and J-M. Lina. 1992. ETMOD software quality assurance documentation, Volumes 1-3. CFFTP P-9205. Prepared by Atlantic Nuclear Services Ltd. for CFFTP, 2700 Lakeshore Road West Mississauga, Ontario L5J 1K0.

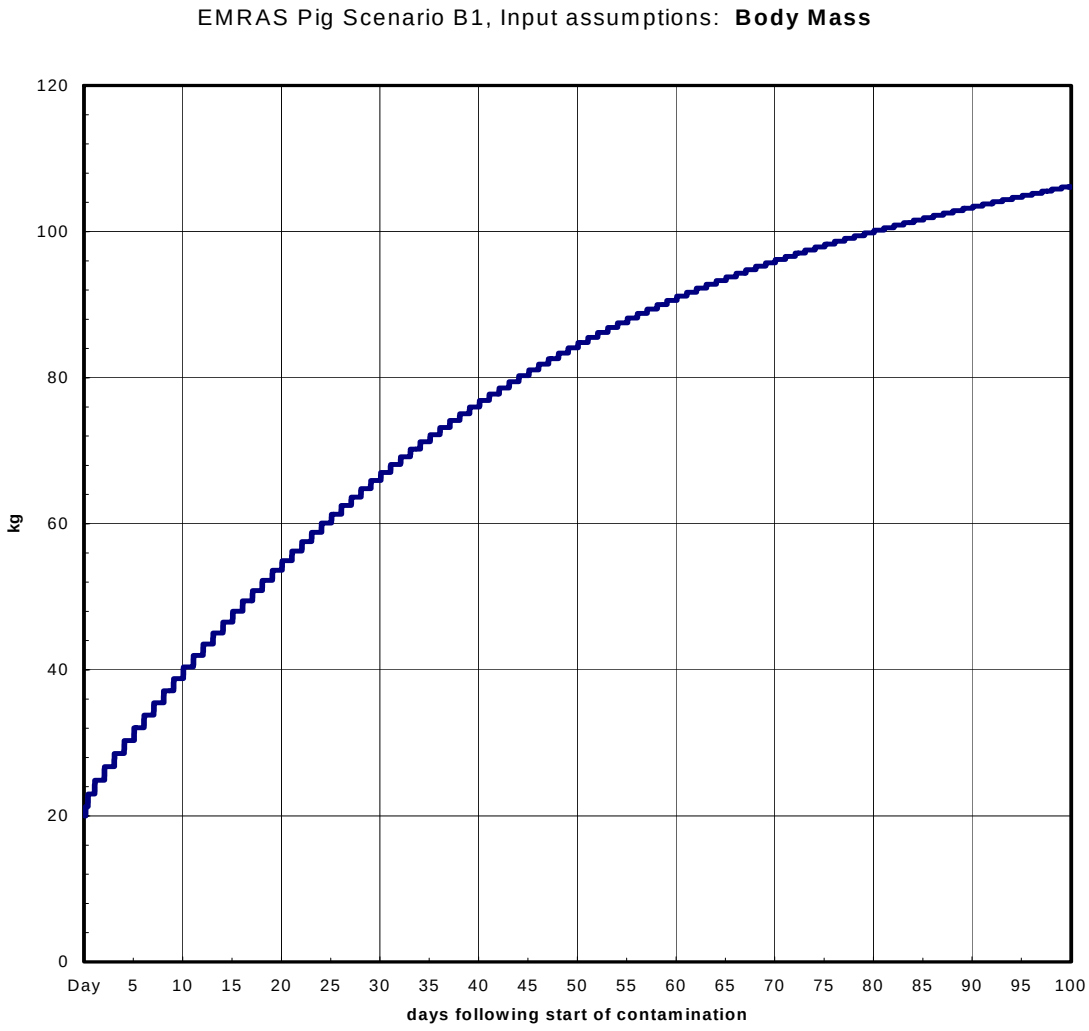


Figure 1. Dynamics of body mass for the model intercomparison exercise.

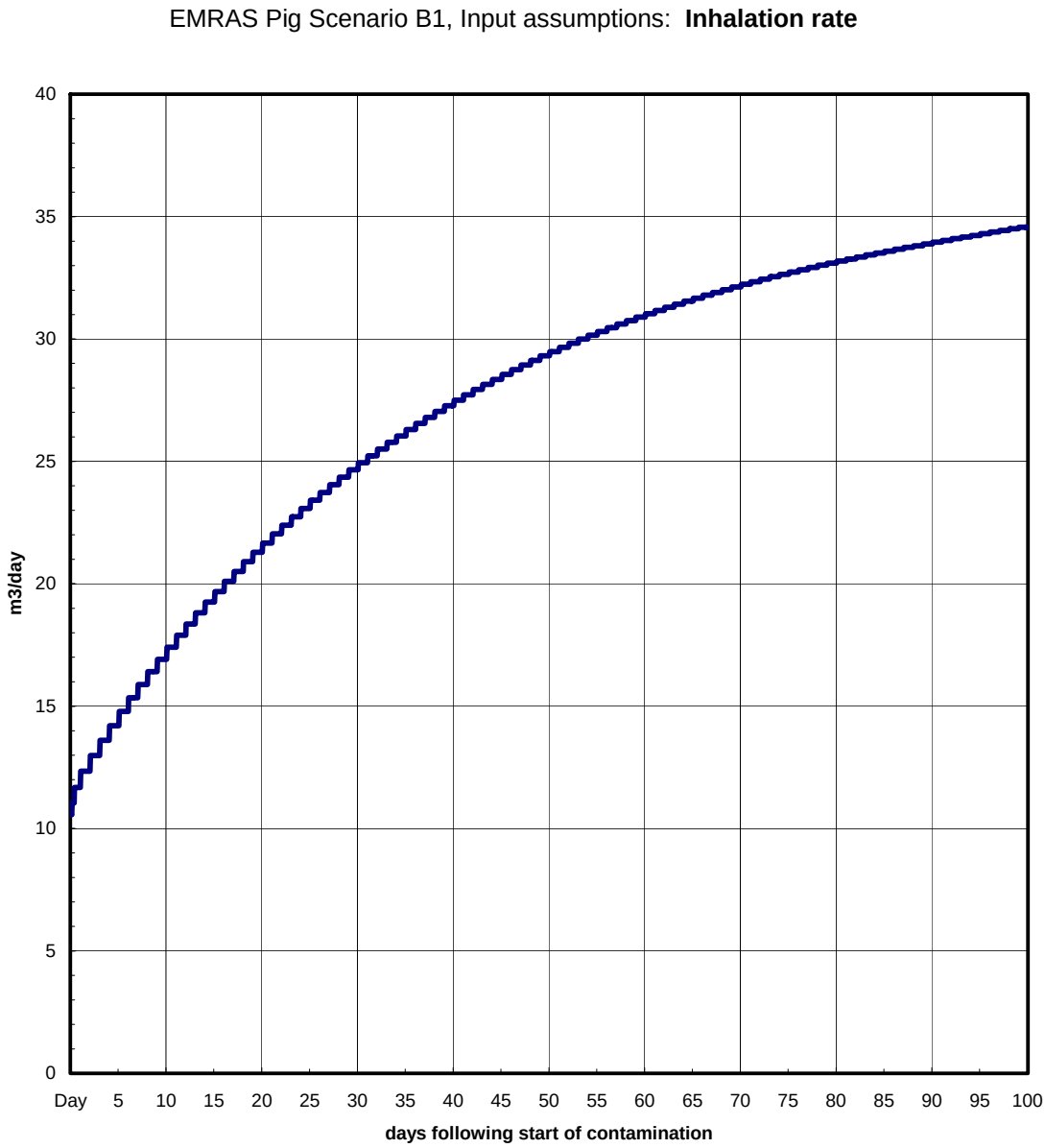


Figure 2. Dynamics of inhalation rate for the model intercomparison exercise.

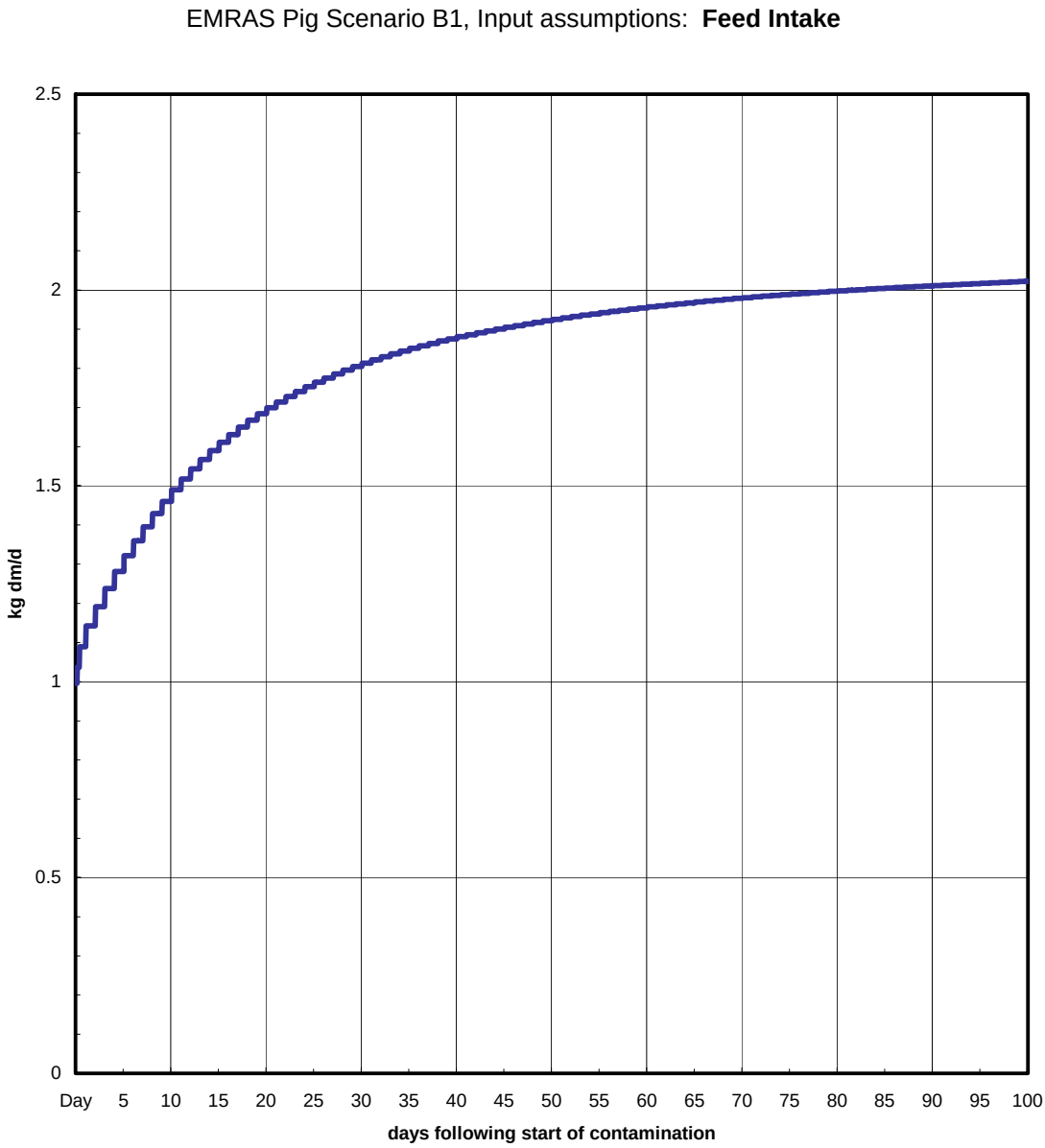


Figure 3. Dynamics of food dry matter intake for the model intercomparison exercise.