COMPUTER SIMULATION OF ^{131}I TRANSFER FROM FALLOUT TO MAN

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(Received 16 July, 1974; revised 27 September, 1974)

Abstract. A compartment model has been constructed to depict the principal routes of ^{131}I transfer from fallout to man. Thyroid accumulation and excretion have been modelled for cow and for man. A simulation is carried out of the major fallout during the fall of 1962, following tests of nuclear weapons, and the results are compared with experimental data for southern Scandinavia.

1. Introduction

The assessment of the ecological impact of pollutants can be significantly assisted by the construction of compartment models of the pollutant (Odum, 1971). A computer simulation calculation can contribute to ensuring consistency among the assumed flow mechanism and the parameters involved (Patten, 1971), and the calculation may furnish prognoses on the future effects of various policies of regulation (Sørensen, 1973). As an example of such model building we present a description of the radioactivity levels in humans, resulting from inhalation and transfer to the human food chain of ^{131}I-fallout which follows the detonation of a nuclear weapon. This isotope has a half-life of about one week, and one major pathway to man is known to involve milk from cows grazing on contaminated grass acres (Berry and Chamberlain, 1963; Hungate *et al.*, 1963). By using numerical integration there are no limitations on the nature of couplings that can be introduced in the compartment model. This is in contrast to the restriction to single chains of accumulation that were used earlier for studying the biological effects of fallout-iodine, in order to arrive at closed expressions for the radioactivity levels (Bergström, 1967; Ng, 1967).

The intensive monitoring of activity levels following incidents of atmospheric fallout makes radioisotopes suitable as the first examples for model building. Few non-radioactive pollutants have been measured regularly over extended periods of time and in several compartments along the food chains. One may hope that the basic parameters of a model for suitably selected radioisotopes may be applicable for chemically similar non-radioactive pollutants, allowing for modifications according to differences in physical and chemical nature of the releases.

Figure 1 shows the general structure of the compartment model used in the present study. The complete set of system equations and parameters is listed in Appendix B and the structure of equations and choice of parameters are discussed in detail in the following sections.

Water, Air, and Soil Pollution **4** (1975) 65–87. *All Rights Reserved*

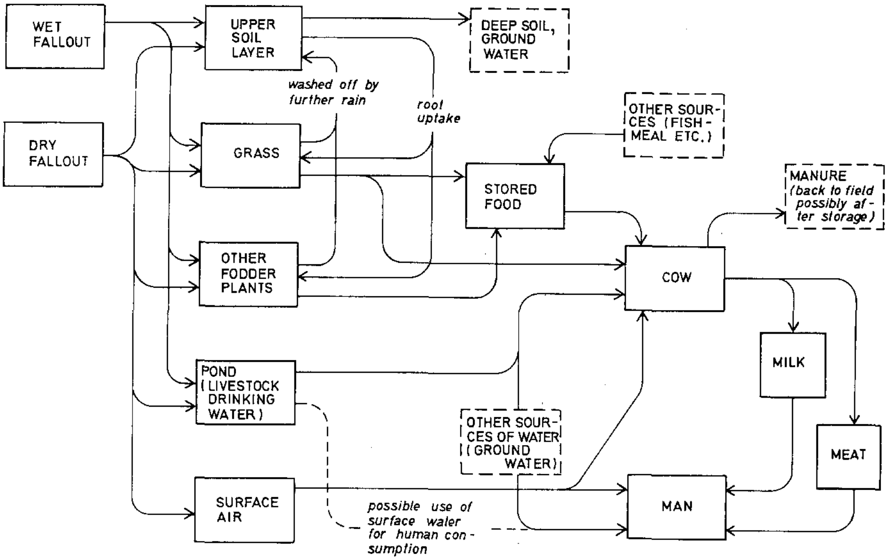


Fig. 1. Gross structure of ^{131}I model, from fallout to man. Dashed compartments are considered unimportant, due to the one-week half-life of ^{131}I.

2. Fallout Data

During the Fall of 1962 the specific activity of ^{131}I in rainwater was measured every week at Risø, Denmark (Aarkrog *et al.*, 1963). Combined with precipitation data one obtains the weekly fallout. The distribution of I on precipitation days cannot be derived from the analysis of weekly samples, but we assumed that the fallout was proportional to the amount of precipitation each day, thereby defining a wet deposition rate, RWET (Ci m^{-2} h^{-1}), which is non-zero only on precipitation days and which is consistent with the measured weekly averages.

Total β-activity in the air was measured daily during the Fall of 1962 by Aarkrog *et al.* (1963) as well as by the Danish Defense (1963), which also determined the age of the particulate matter activity. By combining these data with the fraction that ^{131}I is estimated to constitute of the total β-activity at a given number of days after the detonation of a fission-fusion weapon, one obtains the ^{131}I air concentration, Co (Ci m^{-3}). The ^{131}I fraction as a function of time after detonation, is given by Teller *et al.* (1968). The filter efficiency of 0.7 quoted by Aarkrog *et al.* (1963) has been corrected for.

In order to obtain a dry deposition rate, RDRY (Ci m^{-2} h^{-1}), a deposition velocity was introduced (see Equation (B.11) in Appendix B). According to the discussion in Slade (1968), experimental determinations of the deposition velocity, VDEP, of ^{131}I on grass give average maximum values around 72 m h^{-1}, with deviations of at least a factor of 2 depending on topography, meteorological conditions and possibly on the history of the airborne ^{131}I. The latter dependence is derived from the assumption that the I, which is originally released as a vapor, may – to a varying degree – become adsorbed on condensation nuclei, in particular the small Aitken particles. Experimentally derived deposition velocities for other gases with adsorbing properties (ThB, SO_2) also lie in the range from 25 to 100 m h^{-1} (Chamberlain, 1966; Owers and Powell, 1974). As an average deposition velocity we have used VDEP = 50 m h^{-1}.

3. Surface Air Layer

The air activity, CSURF (Ci m^{-3}), in breathing height is given by (B.1). In addition to Co a term proportional to RDRY is added, describing the reemission of I (possibly vapor) from the deposited activity. This reemission is tentatively put at 10% from grass (entering cows breathing air) and 20% from city surface (largely representing mans breathing air). Due to the uncertainty of VDEP, the influence of which will be checked, the exact value is not very important. The accumulation of activity in the surface air layer is gradually lost to higher air layers. The relative, vertical loss of activity is taken as LAIR = 0.5 h^{-1}. This is about six times slower than the average vertical removal rate for water vapor, which is known from the water balance (Odum, 1972). The ratio six is roughly chosen as the ratio of VDEP to an average vertical diffusion velocity in the atmosphere, in order to represent the slower upward admixture just above the ground, where the wind velocity is small and the surface roughness eliminates large eddies. We believe that this gives an upper limit estimate of the increase of the surface air activity. It should be emphasized that a horizontally uniform wind and fallout field has been assumed, so that horizontal transport is not considered to change the activity level.

4. Grass Acre and Stored Fodder

The radio-I which falls on plants edible to man or livestock is going to play an important role in the evaluation of I levels in man. Some experimental ^{131}I levels in grass are available (Aarkrog *et al.*, 1963), although they have been sampled on different locations on different days. In our model the primary origin of ^{131}I is the dry or wet deposition on the grass surfaces. Due to the short half-life of ^{131}I the growth and withering of grass need not be modelled in detail. The possibility of interior grass contamination from root uptake of I is investigated, and the removal by cows grazing is included. Equations (B.2, B.3) show the model equations for surface and interior of the grass plant. The total activity level by fresh weight is then given by (B.17) or (B.16), either for the whole plant or for the top (edible) part. The relation between a given amount of edible grass and the area of pasture from which this is derived depends strongly on the type of soil, weather conditions and grazing method. The average value attributed to Danish farming practice is derived from a quoted net removal by grazing of 0.45 Danish fodder units (per m^2 per season) (Sørensen *et al.*, 1965). This is about 60% of the maximum grass yield that can be obtained by harvesting. For the conversion it has been assumed that one Danish fodder unit corresponds to 1.4 kg dry matter and 7 kg fresh weight of grass (Petersen, 1973). If grass cover is sparse, the area that will furnish 1 kg edible grass, GVOL, becomes larger, and the specific radioactivity in the edible portions may increase. It has been assumed that the grass cover is dense enough to make the bulk deposition take place on the leaves, rather than on the ground. The ratio of the two, expressed through the parameter GDEPD, is chosen as 30:1, which is the approximate ratio of effective surface areas. The dry deposition comprises I vapor, which may enter the grass leaves through the stomata, according to Bucovac *et al.* (1965). We include this in the surface component, CGRASS.

Also the wet deposition has been assumed to be suspended on the grass leaves at first (GDEPW = 1). Later on, however, contamination can be removed from the grass surface by washoff. This process takes place during heavy rainfalls only, and it will remove part of the earlier deposits, dry as well as wet deposits from which the water has evaporated and left the I behind, and finally the washoff process will continuously remove part of the wet deposition from the same rainfall. The functional form for the washoff process is given in (B.13), implying exponential removal of I from grass surfaces during rainfalls of intensity PREC ($\mathrm{m\,h^{-1}}$) above a certain threshold PRECo. The influence of varying the washoff parameters will be discussed in Section 8.

In order to investigate the importance of root uptake of ^{131}I, a term was incorporated into (B.3), proportional to the average water uptake rate through the grass roots, R_2 (see (B.15) and Appendix A). The uptake of the radioisotope then depends on the soil contamination, CDSOL, which will be discussed in the next section, and on whether or not there is a discrimination against I at the root entrance or during the transport inside the plant. Such discrimination has been observed for other radioactive contaminants, e.g. Sr and Cs (Krieger *et al.*, 1967; Andersen, 1967). However, assuming that there is no discrimination against I (RETENT = 1), we obtain an estimate of the maximum contribution of root uptake to the grass activity, which turns out to be at most 4.6%, and over 80% of the time the root contribution is below 1%.

The description of the cows intake of grass during the autumn period must include a model for the transition from predominantly deriving the food from grazing to being predominantly fed with stored fodder. The model for the decrease in fresh grass intake is given by (B.12). The remaining food requirement (B.19) is satisfied by a number of products (soy-cakes, pulse, beets, hay, etc.), which are lumped together in a quantity with specific ^{131}I concentration CHAY (B.18). If fresh grass was the only source of food, the average requirement would be GCO = 3.39 kg fresh grass per hour. This number is derived from the actual Danish figure for cows consumption of fresh grass (Samvirkende Danske Landboforeninger, 1971) together with the fact that this constituted 40% (in nutritional value) of the total food consumption by cows (Statistical Department, 1972). According to Aarkrog *et al.* (1963), the fresh grass constituted two thirds of the food requirement in September 1962, at the location where ^{131}I levels in milk were measured (thus GCO4 = 0.66). Further the grazing starts decreasing about October 1. (TBEG = week#5) and has ceased completely by November (TFACT = 0.04).

It is to be noted that even during summer a fraction of the food is not of fresh origin. This fraction we consider free from radio-I contamination, since it has probably been stored for some time. We incorporate in the stored fodder ^{131}I activity (B.18) two different crops harvested at different times during 1962. These could be hay (after probably being exposed to fallout while drying) and beets. The soy-cakes are imported and presumably do not contain ^{131}I. The times, from which the ^{131}I in the two stored fodder components are shielded and start to decay exponentially, are taken at the beginning and end of October (TIX and TIX1). The activities at these times are approximated by those of grass. No information on the actual dates of harvest in the region of interest is available, but of the two dates chosen the first one precedes a bump in the ^{131}I milk level at the location (Risø), which is absent in other parts of the country. The second one corresponds to a bump which is present in most of the milk data from various parts of Denmark, but apparently weak or absent in the Risø data (Aarkrog *et al.*, 1963). The general choice of these two dates is not inconsistent with Danish farm practice (Sørensen *et al.*, 1965), neither are the fractions GCO5 = 0.4 and GCO6 = 0.2, which the two fodder components are assumed to constitute (Statistical Department, 1972).

5. Soil and Drinking Water Sources

Although ^{131}I deposited on the ground may contribute to the health hazard of fallout by direct γ-radiation, the dose that could result from such exposure would be small compared to the thyroid dose from ingested ^{131}I, that may result from incorporation into mans food-chain. We shall therefore look at soil contamination mainly to allow an upper estimate to be made of the root uptake contribution to grass contamination. The soil profile is assumed to consist of a plowlayer and below it a more tight layer of clay or sand type. The use of a plowlayer zone for grass is relevant for Danish conditions, because 60% of the grass fields are in rotation and only few are natural (Statistical Department, 1972).

We distinguish between soluble and insoluble I (CDSOL and CDINS), for which the model equations are given in (B.4) and (B.5). The soluble part includes I adsorbed to water droplets, the insoluble part includes I which may in principle be soluble, but which is temporarily attached to soil particles. This mechanism, in which the I downward flow is slower than that of water, due to the attachment and delay in being again dissolved or adsorbed to the water, is incorporated into the equations by means of the terms involving ATTACH and DDRY. The root uptake rate (R_2-term) is discussed in the previous section and in Appendix A, as far as the water budget is concerned. The loss to deeper soil is represented by the R_3-term, which basically represent the average rate of water flow derived from the yearly balance, modified for I by the delay in transport. No seasonal effects were included. The deep soil is considered as a sink, so no detailed modeling was made. This is justified by the long periods of time (relative to the ^{131}I half-life) involved in reaching drinking water wells.

The parameters involved in the slow-down process for I flow in soil are not known.

The values chosen have the property of reproducing the rate of ^{90}Sr penetration that can be obtained by studying concentrations in different depths following fallout or experimentally deposited radioactivity (Andersen, 1967).

The only source of radio-I in (cows) drinking water that could be important is the use of shallow ponds for watering the livestock. Little surface water is used for human consumption in Denmark. The equation for a typical livestock watering pond is given in (B.6). Both dry and wet deposition contributes ^{131}I, and removal by sedimentation was put at a negligible rate in order to obtain an upper limit for the I contribution. Consistent with the assumption of a non-local fallout, no inflow or outflow was considered. Even under the extreme conditons the contribution of pond water to the cows ^{131}I-intake remained at or below 1% of the intake through fresh grass.

6. Cow

The sources by which a diary cow may intake ^{131}I are given by (B.23). The grass and stored fodder sources have been discussed in Section 4, the surface water contribution follows from the pond ^{131}I-content by (B.22), which partly involves the average fraction (OVFLG$=$0.7) that such water sources are estimated to constitute during grazing periods, partly a factor which reduces this source as grazing time diminishes. The implication is that when the cows are kept indoors, they are given tab water. The direct water intake required depends on the amount of water in the fodder. The total water requirement is 4.48 kg h^{-1} (Pedersen, 1973). If the cow eats fresh grass only, it receives an average of 2.71 kg water h^{-1} from the grass. Thus the additional requirement is INTWCO$=$1.77 kg h^{-1}. Finally the intake through inhalation (or submersion through skin) is given by BRETCO, which is the fraction (21%) of the cows average respiration rate that is taken up by the body. ICRP (1959) quotes this fraction as being up to 25% for man.

The model for retention of I in the cow is schematically illustrated in Figure 2 (adapted from Alexander *et al.*, 1971), the corresponding equations being (B.7), (B.8), (B.24) and (B.25). Two compartments are distinguished. One, with a rapid turnover, may represent the blood stream, the other one, representing the thyroid storage section, has the slowest turnover and a substantial accumulation. Essentially the same model will be used for cow and man.

The fraction of the intake that is taken up and entering the blood stream, is taken as unity (ECOW$=$0), in accordance with ICRP (1959). If the diet is rich in non-radioactive I, the ^{131}I isotope may be less than fully uptaken. However, the total amounts in question are small compared to the cows daily I requirement (7 mg) (see Long, 1961). The I is cleared from the blood stream by transfer to the thyroid (fraction ECOW1) or to milk (fraction $(1-\mathrm{ECOW1}) * \mathrm{USAGE}$), or by excretion (B.14). In our model 75% (ECOW1) of the iodine cleared from the blood goes to the thyroid (Alexander *et al.*, 1971) and the blood clearance rate is LABC2$=$0.5 h^{-1}. The similar fraction that goes to milk (USAGE) is chosen to fit the data in the beginning of the fallout period (where thyroid ^{131}I level is still insignificant and that route

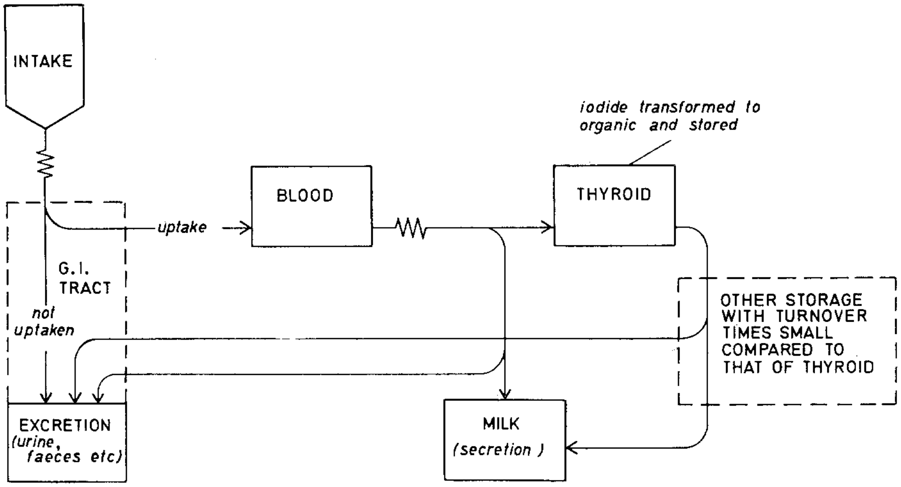


Fig. 2. Mammalian subsystem, used for cow and man. A zig-zag line denotes delay. The compartment denoted 'other storage' gives rise to additional I transport via blood. However, this flow is essentially of I containing hormones which are 'labelled' and which do not interfere with the flow of simple I explicitly included in the model of blood I transport.

does not contribute much). Estimates in the literature of I secretion in milk are also based on milk to diet ^{131}I ratio (Ng, 1967), rather than on biochemical studies. In the thyroid the I, which is likely to be inorganic (iodide) at the uptake level, is transformed to organic and stored (Alexander *et al.*, 1971). The secretion from the thyroid is represented by a biological decay constant (LABC3) taken from Colard *et al.* (1965). The secretion into milk (MILKC) is again adjusted to data, now in the early winter period, where the intake has almost ceased. Secretion into meat (MEATC) is neglected, and the fate of thyroid secretions used in other parts of the body is an excretion, with a turnover time which is small compared to that of the thyroid, and therefore neglected.

A total retention function for ^{131}I in the cow can be obtained from the intake and excretion expressions (B.23) and (B.14).

The ^{131}I concentration in cow's meat is derived from the blood level. For an even distribution over the body the proportionality factor (USAGEM in (B.25)) would be the inverse weight of the animal, but to account for loss of blood when the cow (which in this case need not be a diary cow) is eventually slaughtered, the value USAGEM$=$ $=0.001$ kg^{-1} has been used to represent the concentration in meat for human consumption.

7. Man

The present model aims at describing I levels in an average, adult man with no milk secretion. As mentioned the model for the man and the cow is essentially the same (Figure 2), adapted from Alexander *et al.* (1971). The ^{131}I intake rates follow from the food and water intake rates, which are again taken from the survey of Danish dietary habits quoted by Aarkrog *et al.* (1963). They are similar to the values used by ICRP (1959) to within about 20%. In particular the inhalation of air is strongly dependent on whether the person is at rest or working (0.4 to 2.4 m^3 h^{-1} according to Altman and Dittmer, 1964). The fraction of inhaled air which is deposited in the lower respiratory tract (lungs) is about 25% (ICRP, 1959). By using the possible accumulation of I in the air layer near the ground, which for city breathing air includes the shelter effects of building structures (B.29), we probably obtain an upper limit for the contribution of inhalation to the human ^{131}I concentration.

The central parameter governing the ^{131}I retention is the biological clearance rate LABM3 of the slowest compartment, the thyroid gland. The value used, $3.125 \times \times 10^{-4}$ h^{-1} (Colard *et al.*, 1965) is somewhat larger than the one, 2×10^{-4}, calculated by ICRP (1959). A more detailed discussion of the change in the newer interpretation is given by Roedler *et al.* (1972). A still larger deviation from ICRP (1959) is found in the parameters describing the transfer from blood to thyroid. The value for the fraction of ^{131}I cleared from the blood, that reaches the thyroid gland, is quoted as 0.3 in ICRP (1959), whereas we used the value 0.75 (Alexander *et al.*, 1971). We use two successive compartments, (B.9) and (B.10), whereby we get a ^{131}I build-up curve for the thyroid, which would be S-shaped for constant intake, rather than starting linearly as the one-compartment ICRP-model. The equilibrium value, however, would be the same, and the precise value of LABM2 is not important, as long as it is small compared to the times associated with fluctuations in the intake level. A very likely explanation for the different values used for EMAN1 emerges from the I flow model of Alexander *et al.* (1971). They find that a number of I transfers among the compartments of interest take place in both directions. Each day 125 μg, usually of iodide, is transfered from blood to thyroid. However, here the transformation to organic only yields 57 μg day^{-1}, sending 68 μg day^{-1} back to the bloodstream, still as inorganic. Further the loss from blood to urine is (still on the average and for a normal man) 80 μg day^{-1}. Finally, the blood stream receives 64 μg day^{-1} of organic iodine from organs other than the thyroid, mainly products of thyroid hormones that have been in use elsewhere for a few days. Now, if the net blood-to-thyroid transfer is compared to the net blood clearance, one obtains a ratio of EMAN1 = 0.75. If, on the other hand, it is compared to the gross outflow from the blood compartment (neglecting reentrance of I of thyroidal and extra-thyroidal origin), one obtains ICRP's value of 0.3.

As discussed earlier, the time required for I to reach ground water, that is the main source of man's drinking water in Denmark, is too long to lead to any significant level of ^{131}I, which hence has been set equal to zero (B.26).

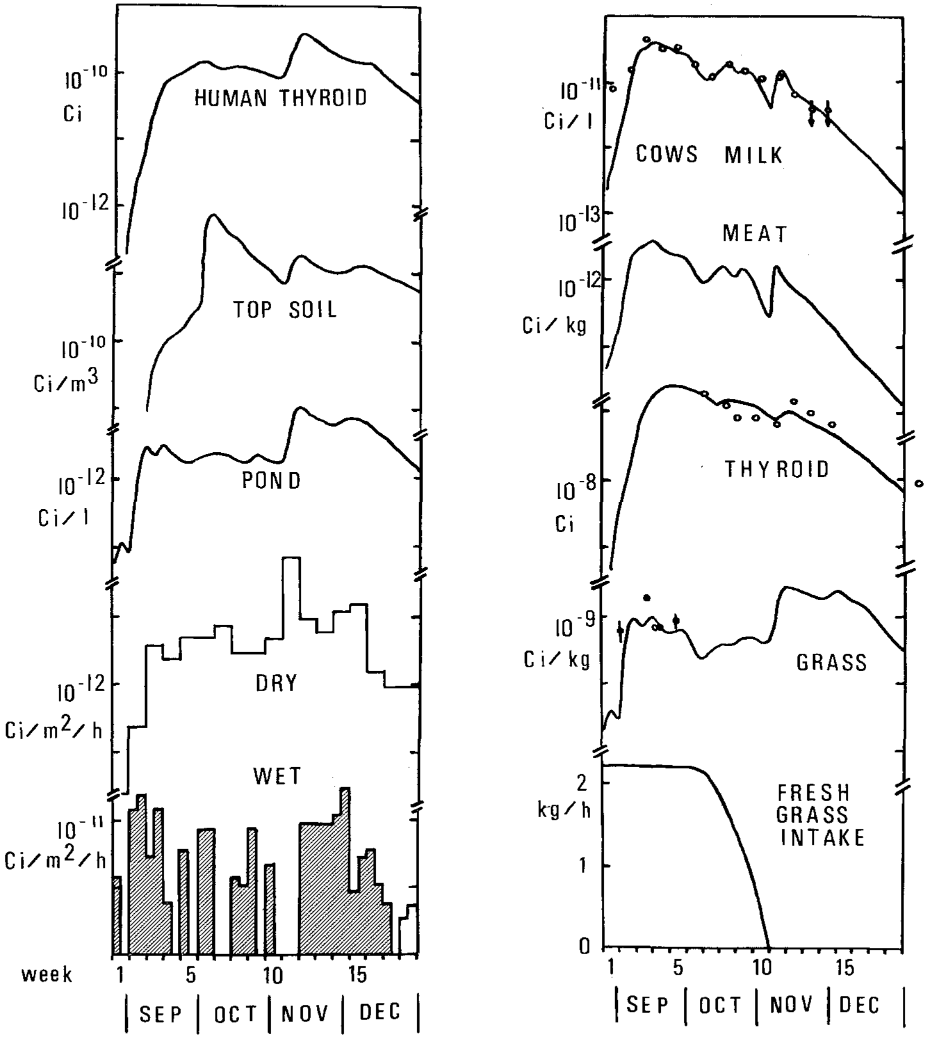
Potentially a number of other food sources except milk and meat could lead to ^{131}I intake, e.g. berries and vegetables. In principle they would be modelled exactly as the grass compartment, and the human intake would be direct instead of indirect *via* the dairy cows products. Due to the lack of experimental data no detailed calculation was performed, but assuming that the specific ^{131}I activities would reach the same levels as for grass, and that no radioactivity would be lost by storage, washing or by preparing the fruits, berries and vegetables (this assumption appears reasonable e.g. for I-vapor that has entered the stomata of leafy vegetables), one would at the peak activity levels in September and November 1962 reach the following average ^{131}I intake rates: 7×10^{-12} Ci h^{-1} from vegetables (September) and 2×10^{-11} Ci h^{-1} from fruits (November). The intake food rates in 1962 for Denmark were taken as 7.9×10^{-3} kg h^{-1} (vegetables) and 7.1×10^{-3} kg h^{-1} (fruits) (Aarkrog *et al.*, 1963).

This may be compared to the maximum ^{131}I intake rate *via* the grass-cow-milk chain, which according to the calculation was 9.4×10^{-13} Ci h^{-1} (September). Despite the crudeness in the estimate of activity levels that might occur in fruits and vegetables, the finding of human intake figures one to two orders of magnitude larger than those from milk strongly suggests the conclusion, that the potentially most dangerous ^{131}I-pathways were not monitored at the time. Furthermore, the fact that some of the relevant vegetables and fruits may have been in season during the fallout, make it highly possible that the consumption by several individuals may have far exceeded the yearly average values used in the above estimate.

8. Discussion

We have treated a number of pathways for ^{131}I from fallout to man, using a general computer simulation, the model equations being formulated as coupled differential equations. Most of the parameters were found to be reasonably well fixed from first principles or from data unrelated to the present problem. A few parameters had to be determined by fitting the ^{131}I-data, although they were in principle amenable to independent experimental determination. The reliability of such a phenomenological determination of parameters depends on the strength of and nature of couplings. We find that the possible feed-back loops are generally of very minor importance, so that the model reduces more or less to a simple chain model, in which case each step with associated data for the compartment in question allows for the determination of one more parameter at a given time. The interesting phenomenon is that the availability of a time-extended body of data makes it possible to determine more than one parameter for each compartment, due to the richness of structure in the time-variation.

In Figure 3 we show the results of the model simulation for Risø (Denmark), for the last part of 1962. The initial ^{131}I levels were taken at zero, which they probably were not. However, due to the short half-life and the intense fallout during the Fall of 1962, the simulation is independent of the initial conditions after 1 to 2 weeks. Figure 3a shows the input wet and dry fallout (half-week averages are shown, the dry deposition rate is estimated as discussed in Section 2), the top soil (plowlayer) and pond (cows drinking water) compartments. On Figure 3b the grass ^{131}I levels are shown together with some data (Aarkrog *et al.*, 1963). Only one data point (open circle) is from Sealand, the same island on which Risø is located, but about 50 km south of Risø. The other data points are from other parts of Denmark, from Jutland to Bornholm. Since the precipitation varies considerably (in 1962 it was about 50% larger in



(a) (b)

Fig. 3a–b. Results of the model simulation and measured ^{131}I levels near Risø, Denmark. For clarity, dry and wet deposition rates are shown as half week averages. Full circles (grass) indicate data from other regions of the country. From left to right these are Jutland, Funen, Lolland and Bornholm. The open circle is from Næstved on Sealand.

the western part of the country than at Risø), one might assume that variations in ^{131}I fallout exist, and that these data points for grass therefore are inapplicable for a detailed comparison with the Risø calculation, although the general magnitude may serve as an indication. This situation leaves little possibility to directly investigate the mechanism by which radio-activity on the grass surface may be washed off onto the soil, i.e. the two parameters LAW and PRECo in (B.13), or the appropriateness of the deposition velocity VDEP used in estimating the dry contribution to the fallout (B.11).

The single data-point for grass may be used to choose one of these parameters.

The more extensive data for cows milk and thyroid (Figure 3b) allow a more thorough study of the parameter dependence. In order to reproduce the first data points for cows thyroid (assuming that the mammalian I retention model, Figure 2, is adequate) one must have a decrease after the first maximum caused by the september peak fallout. This decrease must occur before the fresh grass intake starts to decrease (Figure 3b bottom). Such a decrease will not be possible if VDEP is increased above its current value of 50 m h^{-1}, in which case dry deposition will dominate over wet from the middle of September and cause ^{131}I concentration in cows thyroid as well as milk to raise, in contradiction to data.

The present rather high value of the threshold for washoff, PRECo, makes washoff effective only during the most intensive rainfall period in October. This explains the drop-in milk concentration (data from Aarkrog *et al.*, 1963) in the beginning of October, when in addition the milk secretion of I is dominated by the fast turnover compartment (blood) and not by the thyroid. If a smaller value of PRECo were used, a stronger drop in milk concentration would follow the first peak in September, in contradiction to the data. Under the circumstances, the value of LAW is simply determined by the data point for grass. If VDEP were to be taken smaller than the present, LAW would also have to be decreased.

As mentioned, the wiggles in the milk concentration data require that little of the milk ^{131}I is secreted via the thyroid. In fact, the parameter USAGE can be determined from the height of the first peak (week # 3) of the milk concentration, a value that is not affected by the possible ambiguity in dry deposition or washoff, as long as the existing grass data point is reproduced.

It is found that the cows inhalation of ^{131}I and ingestion by drinking pond water (even exclusively) gives contributions which are negligible (less than 1%) compared to those from grass at all times of the simulation. The contribution from root uptake to the grass ^{131}I concentration is small, as mentioned in Section 5, even if 100% of the radio-iodine in the water entering the roots is retained (RETENT = 1). It is therefore not possible to further investigate the soil contamination (Figure 3a), for which no data exist.

Returning then to the milk and cows thyroid data (Figure 3b), a bump in the milk concentration can be identified at about week # 8, another one perhaps at week # 11 in milk and certainly at week # 12 in the thyroid. The latter bumps definitely require sources of ^{131}I intake other than intake of fresh grass. Since we have also excluded inhalation and drinking water, the only remaining possibility seems to be to introduce a contaminated component in the non-fresh fodder. A number of components, harvested and brought into shelter from direct fallout at different times, are present in the fodder. Lacking detailed information on the practice at the Risø-neighboring farm, we have simply chosen the time (TIX1), at which the new fodder component is added to the diet, and have adjusted the magnitude of the intake of that component (GCO6), to roughly reproduce the position and magnitude of the November bump. The GCO6-value found (20%) appears to be of a reasonable magnitude.

In order to understand the previous bump in milk concentration (week #8), it should be noted that this is followed by a period with relatively low fallout (Figure 3a). It seems therefore excluded that it can be caused by fresh grass and one is tempted to introduce another newly harvested fodder component, which together with the strong increase in stored fodder consumption around week #8 will cause the bump to appear (fodder fraction GCO5$\approx$40% added at TIX$=$week #7). No corresponding increase appears in the thyroid data, and it should be mentioned that these were collected at the Copenhagen meat market (Danish Defense, 1963), which receives cattle from many farms and therefore reflects only those feeding practices that are common to a larger number of farms. The conclusion would then be, that the week #8 peak in milk from the Risø farm is a result of a local introduction of a contaminated fodder component at the time where grazing ceases. This point of view is strongly supported by the absence of the milk concentration structure around week #7–8 in data from other parts of the country, including that of major distributors in Copenhagen (Aarkrog *et al.*, 1963; Danish Defense, 1963).

A further question of importance is whether the cows milk receives radio-I from the large thyroid storage. This would be answered by the slope of the milk concentration after week #12, to the extent the data are significant enough. The thyroid clearance rate is well determined by the final slope (note the data point in January 1963), and in excellent agreement with the value of Colard *et al.* (1965)). The blood (see meat) concentration slope is much steeper and it appears that the milk slope is not, implying a contributing transfer from thyroid to milk, the magnitude of which (MILKC$=$2% of thyroid clearance) is poorly determined.

The assumption that the I retention models for man and cow are similar (i.e., have same biological half-lives and transfer coefficients) allows us to calculate the thyroid level for man during the important period of fallout in 1962. The result is given at the top of Figure 3a. The human thyroid level is governed by milk intake and inhalation, according to the present model. Meat intake is a negligible source. The reason for inhalation to be important relative to other sources for man but not for cows is that the cows food directly accumulates the fallout, whereas only a small fraction of the fallout reaches milk and later on man. In September and October the inhalation contributes a fair fraction of mans ^{131}I uptake, but at the November peak it strongly dominates in air concentration. It should be noted that considerable uncertainty exists regarding the accumulation of I in the surface air, which in the present model leads to an enhancement factor of six at the November peak. This enhancement factor is regulated by the parameters GDEPSD (accumulation) and LAIR (removal rate to higher air masses), for which no I measurements were found available. However, even if no enhancement were present, the contribution to mans ^{131}I intake from inhalation during the November maximum of air concentration would be four times the contribution from milk. It must therefore be emphasized that the forage-to-cow-to-milk pathway is not the only one of importance to man. Inhalation of radio-I must also be considered. Further the investigations in Section 7 indicated that food sources which pass directly from growing place to man (vegetables, fruits) could contribute one or two orders of magnitude more than milk, in which the major part of I entering the cow is not found.

In view of the preceding conclusions it may appear unjustified that the milk pathway has been given high priority in earlier investigations. It turns out, however, that the relative unimportance of milk in the simulated example may be associated with the intense-farming practice characteristic of Danish milk producers. To demonstrate this we show in Figure 4 the measured dry and wet fallout at Studsvik (Sweden, the dry deposition rate is calculated from air concentration using VDEP = 50 m h^{-1}) and measured ^{131}I concentrations for milk from a neighboring farm (Bergström, 1967). Although the fallout rates are no larger than at Risø (the wet fallout is smaller, the dry one similar), the milk concentrations are found to be more than ten times larger. Bergström (1967) remarks that the cows are feeding entirely on fresh grass (which gives a 50% increase over Risø), and that the grass cover was very sparse. We interpret this by presuming that the cows now will have to graze a much larger area to satisfy their needs, and assuming that the bulk deposition is still on grass leaves rather than

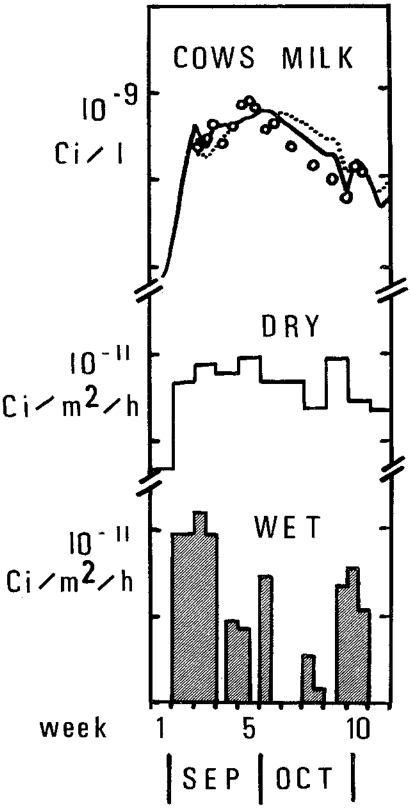


Fig. 4. Results of the model simulation (only milk levels shown) and measured ^{131}I levels near Studsvik, Sweden. The parameters used in the calculation were the same as for Risø except for the input deposition and precipitation rates and for GVOL = 3.8 (full line) or 0.6 (dotted line) m^2 kg^{-1}. For the dotted line in addition VDEP was changed to 500 m h^{-1}.

on the soil below, we would then increase the parameter GVOL by a factor 12 to reproduce the Studsvik measurements. This implies that an average of 12 m^2 will have to be grazed per hour, which is indeed the figure Bergström (1967) indicates, and is consistent with the range of values quoted by Koranda (1965) for the Western U.S.A.

The magnitude agreement between the air ^{131}I concentrations measured at Studsvik and the ones we calculated in Section 2 tends to support our method of evaluation. It is possible that the Studsvik air data are underestimated (Falk, 1973), due to low detection efficiency for I gas. It is also possible that the deposition velocity is different due to the difference in roughness length between Risø and Studsvik. In order to test both of these possibilities we increased the deposition rate by a factor of 10 (in which case GVOL can be taken within a factor of 2 of that for Risø). The results, which are shown on Figure 4 (dotted curve), seem to be in poorer agreement with the time variation of the milk data, indicating that these effects are probably of minor importance relative to that of the sparse grass cover. This leads us to the conclusion that farming practice is a major ingredient in evaluating pollutant transfer within the agricultural food chain.

The computer simulation performed in the present study has demonstrated the power of compartment model technique in discussing the transfer of a specific, undesired element from its injection into the environment to its reaching man. It appears that even though sections of the model may depend on parameters that have to be chosen more or less phenomenologically, then the use of the computer simulation technique offers a very useful tool for finding parameter sets that are consistent with the dynamical properties of the model. Hence, if the model is well conceived, it is a tool for actual determination of unknown parameters, through their influence on the time-variations of measured levels on other compartments, eventually in entirely different regions of the system.

Appendix A: Water Cycle

The inclusion of the water cycle in the modeling of I transfer is required in the investigation of root uptake. The ^{131}I present in the fraction of rainwater (from direct fallout or from washing off deposits made earlier on plant leaves or soil surface), that reaches the plant roots may become totally uptaken by the plant.

Our model of the water flow for a grass acre uses four compartments, the water in the surface air layer, on the grass/soil surface, in the grass interior and in the top soil layer,

$$\begin{aligned}\text{ASURF}\,(\text{kg water m}^{-3}\text{ air}) = \int_{\text{ASURFI}} \mathrm{d}t\,\{(R_8 + R_9)/\text{DSURF} - \\ - \text{LAC} * \text{ASURF} * \text{SOL}\}\end{aligned} \tag{A.1}$$

$$\text{APD}\,(\text{kg water m}^{-2}\text{ acre}) = \int_{\text{APDI}} \mathrm{d}t\,\{\text{RHOW} * \text{PREC} * \text{REEVAP} - R_9\} \tag{A.2}$$

$$\text{AP}\,(\text{kg water m}^{-3}\text{ plant}) = \int_{\text{API}} \mathrm{d}t\,\{R_2 - R_8/\text{GCOVER}\} \tag{A.3}$$

$$\mathrm{AD}\ (\text{kg water m}^{-3}\ \text{soil}) = \int_{\mathrm{ADI}} \mathrm{d}t\,\{(1-\mathrm{REEVAP}) * \mathrm{RHOW} * \mathrm{PREC}/\mathrm{DEPT} - R_2 * \mathrm{GCOVER} - R_3/\mathrm{DEPT}\} \tag{A.4}$$

$$R_8 = \mathrm{RPEVAP} * \mathrm{AP} * X_2 * (1 - \exp\{(\mathrm{APC}-\mathrm{AP})/\mathrm{APDD}\}) * \mathrm{GCOVER} * \mathrm{SOL} * \mathrm{VIND} \tag{A.5}$$

$$R_9 = \mathrm{RPDEVAP} * \mathrm{APD} * X_2 * \mathrm{SOL} * \mathrm{VIND} \tag{A.6}$$

$$X_2 = 1 - \exp\{f_3 * (\mathrm{ASURF} - \mathrm{ASURFS})/\mathrm{ASURFS}\} \tag{A.7}$$

R_2 and R_3 are given in (B.15) and (B.21). Parameters not listed here are found in Appendix B.

ASURFI = 0.012 (kg m^{-3}), initial water content in surface air (Danish Meteorological Institute, 1972).
LAC = 2.6 (h^{-1}), removal rate of water vapor from surface air to higher layers.
SOL, solar energy flux through horizontal surface at ground level, relative to yearly average. SOL is estimated from weekly temperature averages and their average relation to energy flux (Kristoffersen, 1974).
APDI = 1 (kg m^{-2}), initial water residing on vegetation/soil surface (results are insensitive to this value).
PREC, amount of precipitation (m^3 water m^{-2} acre h^{-1}).
REEVAP = 0.2763, fraction of precipitation which remains on grass/soil surface, to be reevaporated later (derived as total average evapotranspiration (Odum, 1972) minus transpiration from plant interior).
API = 800 (kg m^{-3}), initial grass plant water content (taken as yearly average (Sørensen *et al.*, 1965)).
ADI = 160 (kg m^{-3}), initial top soil water content (taken as yearly average for typical soil (Geiger, 1966)).
RPEVAP = 0.0125 (h^{-1}), evaporation rate of water from plant interior (Geiger, 1966; see also Penman, 1970).
APC = 700 (kg m^{-3}), lower critical water content in plant, the value at which *stomata* will be closed.
APDD = 70 (kg m^{-3}), width of drop in water content over which *stomata* closure will take place.
VIND, wind dependence of evaporation process, relative to evaporation at an average wind velocity of 21 km h^{-1}.
RPDEVAP = 0.01761 (h^{-1}), evaporation rate of water from grass/soil surface (Jensen, 1954).
f_3 = 10, parameter for change of evaporation with changing surface air humidity.
ASURFS, surface air saturation humidity, taken for normal average temperature as function of season.

The external factors for the part of the water cycle modeled are precipitation rate and the rate by which water sieves down to deeper soil (joining ground water flow towards waterways and open sea, which by excess evaporation completes the cycle). Runoff along surface is unimportant for most Danish grass acres. The root uptake rate was determined from the amount of water needed (Geiger, 1966) to produce the average grass yield of Danish pastures (Sørensen *et al.*, 1965). The most sensitive part of the model is that of evaporation. The general form of the evaporation rate may be written (Högström, 1968):

$$R = F\left(v, \mathrm{d}v/\mathrm{d}z, T, \mathrm{d}T/\mathrm{d}z, h, \mathrm{d}h/\mathrm{d}z\right), \tag{A.8}$$

where z is the height above the ground (or above the roughness length), v is the wind speed, T the temperature and h the humidity. We factorize this function and first extract the dependence on wind speed, suggested by Jensen (1954) from the analysis of experiments on evaporation from grass that was artificially kept wet,

$$\mathrm{VIND} = (1 + 1.93 \times 10^{-4} * v^{(2-\mathrm{n})/(2+\mathrm{n})})/1.554. \tag{A.9}$$

Here the parameter n, describing the velocity profile ($v(z) \sim z^{\mathrm{n}/(2-\mathrm{n})}$), was kept fixed at an average value of $n = 0.222$, and the constant in the denominator was chosen so that VIND would equal unity for an average wind speed of $v = 21000\ \mathrm{m\ h^{-1}}$.

The dependence on temperature was considered to be a dependence on the heat energy available, estimated as a function (SOL, taken relative to yearly average) of observed weekly average temperature by using existing measurements of the variation of solar energy input at Malmö, about 40 km from Risø (Kristoffersen, 1974), relating the data to the average temperature of each month. The dependence on stability class ($\mathrm{d}T/\mathrm{d}z$) is weak according to Högström (1968), and it was left out. The dependence of evaporation on air humidity is often taken as linear, proportional to $(1-h)$ (Jensen, 1954). We regard this as a first approximation to an exponential function X_2 (A.7), and we choose a fairly large value of the parameter f_3, which implies that the evaporation from a surface is considered not to be seriously limited by existing vapor in the air until the air is nearly saturated. The total evaporation rate from grass/soil surface (A.6) is now determined, apart from an overall constant, RPDEVAP, which is chosen so that the evaporation agrees with the one determined by Jensen (1954) for an average humidity of 82%.

The evaporation from plant interior is more complex due to the opening and closing of *stomata*. This mechanism has the purpose of preventing water content in the plant to drop too much. We have modeled the *stomata* regulatory function by means of a factor in R_8, which is chosen to prevent a drop of more than about 10% from the average water content. After the water vapor has reached the surface air layer, it must be removed to higher air layers (disregarding on average horizontal transport), a process governed by the parameter LAC. If yearly average flows were inserted everywhere, the water balance would require a value of $\mathrm{LAC} = 3.4\ \mathrm{h^{-1}}$. However, the actual dependence is far from linear, and the measured humidity variations indicate that accumulated vapor may sometimes be removed over very short times, implying a lower removal rate between these meteorological situations. We found by comparing the model results with detailed data from the Danish station Højbjerg (Danish Meteorological Institute, 1972), treating LAC as a parameter, that the best agreement was obtained using LAC $= 2.6\ \mathrm{h}^{-1}$.

Figure 5 shows the result of the simulation of the water cycle, using the fall 1962 precipitation data for station Højbjerg shown at the bottom. Since the model does not include hourly variations of input functions (solar energy etc.), the results are averages over intervals of the order days. We thus show only half-week averages of the calculated results as well as of the data. The gross behavior of the absolute humidity (ASURF) is reproduced, but not the details. The dependence on the wind speed is found to be small, but if v was kept at the yearly average value of $21\ \mathrm{km\ h}^{-1}$ throughout, the humidity during weeks #2.5 and 6 would suffer a relative drop, in

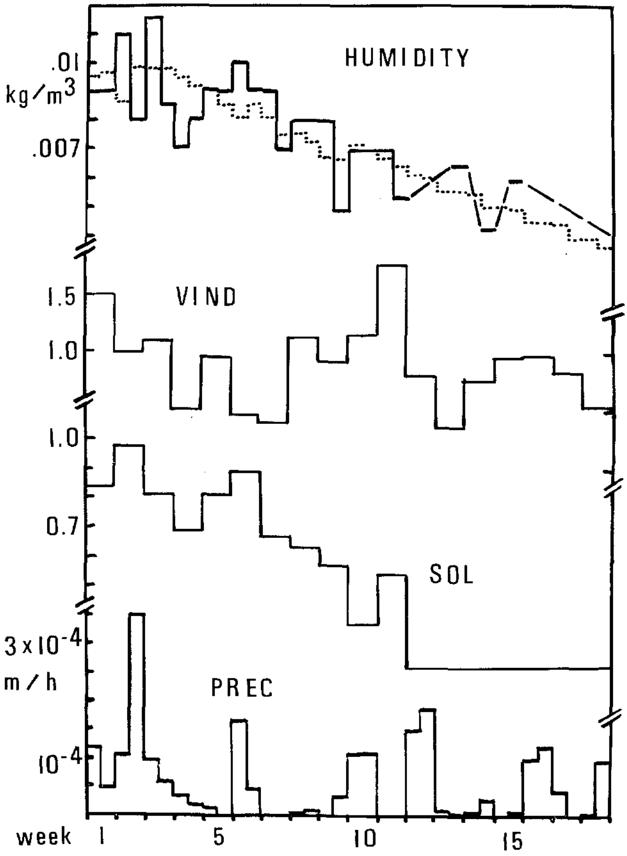


Fig. 5. Input functions PREC, SOL and VIND for the water cycle calculation and a comparison between measured and calculated (dotted line) absolute humidities. Weekly or half-weekly averaging has been performed. The humidity data after week # 12 were in some cases difficult to derive from the dry and wet bulb thermometers, due to snow or frost. All the data are for station Højbjerg, Denmark.

further disagreement with the data. The dependence on the solar heat available is also relatively weak. In this case the time variation does not improve with inclusion of the SOL-function. A strong dependence is found on LAC. For small LAC the humidity exhibits a structureless decrease throughout the time period, the larger LAC the more structure, but as LAC increases the absolute value of the humidity keeps dropping, which is understandable since the water produced by evapo-transpiration is removed faster. The value LAC = 2.6 is about the largest value which will prevent the calculated curve from being systematically below the observed one.

In order to check the influence of the incomplete description of the surface air humidity on the iodine flow calculation, the calculation was repeated using the measured humidities for ASURF. The generated variations of the remaining water levels, (A.2)–(A.4), are insensitive to this modification, and the soil and grass iodine levels remain unchanged to within the accuracy of the graphical plot. We therefore conclude, that the water cycle is sufficiently well described to allow a meaningful conclusion about the influence of root uptake on the ^{131}I levels, which – as argued earlier – leads to the disregard of root uptake as a major pathway for radio-I.

Appendix B: Model Equations

We first list the differential equations of the model, then a number of auxilliary relations and finally the parameter values (of the standard run) in the order in which they appear in the equations*.

$$\begin{aligned}\mathrm{CSURF}\,(\mathrm{Ci\ m^{-3}}) = {} & \mathrm{Co} + \int \mathrm{d}t\,\{(\mathrm{GDEPSD} \ast \mathrm{RDRY} - \mathrm{NCOW} \ast \mathrm{BRETCO} \ast {} \\ & \mathrm{CSURF})/\mathrm{DSURF} - (\lambda + \mathrm{LAIR}) \ast (\mathrm{CSURF} - \mathrm{Co})\}\end{aligned} \tag{B.1}$$

$$\begin{aligned}\mathrm{CGRASS}\,(\mathrm{Ci\ m^{-2}\ acre}) = {} & \int \mathrm{d}t\,\{(1 - \mathrm{GDEPSD}) \ast \mathrm{GDEPD} \ast \mathrm{RDRY} + {} \\ & + \mathrm{GDEPW} \ast \mathrm{RWET} - (\lambda + \mathrm{GVOL} \ast \mathrm{GCOW} \ast \mathrm{NCOW} + {} \\ & + \mathrm{LAWASH}) \ast \mathrm{CGRASS} - \mathrm{LDEATH} \ast \mathrm{CGRASS}\,(t - \mathrm{DDGRASS}) \\ & \ast \exp\{-\lambda \ast \mathrm{DDGRASS}\} + (\mathrm{FWET} \ast \mathrm{GDEPW} + (1 - \mathrm{FWET}) \\ & \ast \mathrm{GDEPD}) \ast \mathrm{WGTC} \ast \mathrm{NCOW} \ast \mathrm{REXCR}\}\end{aligned} \tag{B.2}$$

$$\begin{aligned}\mathrm{CP}\,(\mathrm{Ci\ m^{-3}\ plant}) = {} & \int \mathrm{d}t\,\{\mathrm{RETENT} \ast R_2 \ast \mathrm{CDSOL}/\mathrm{AD} - (\lambda + \mathrm{GVOL} \ast \mathrm{GCOW} \ast {} \\ & \mathrm{NCOW}) \ast \mathrm{CP} - \mathrm{LDEATH} \ast \mathrm{CP}\,(t - \mathrm{DDGRASS}) \ast \exp(-\lambda \ast {} \\ & \mathrm{DDGRASS})\}\end{aligned} \tag{B.3}$$

$$\begin{aligned}\mathrm{CDSOL}\,(\mathrm{Ci\ m^{-3}}) = {} & \int \mathrm{d}t\,\{[(1 - \mathrm{GDEPW} - \mathrm{RUNOFF}) \ast \mathrm{RWET} + \mathrm{LAWASH} \ast {} \\ & \mathrm{CGRASS} + \mathrm{FWET} \ast (1 - \mathrm{GDEPW}) \ast \mathrm{NCOW} \ast \mathrm{WGTC} \ast \mathrm{REXCR} - {} \\ & - \mathrm{RETENT} \ast \mathrm{GCOVER} \ast R_2 \ast \mathrm{CDSOL}/\mathrm{AD} - R_3 \ast \mathrm{RETEN2} \ast {} \\ & \mathrm{CDSOL}\,(t - \mathrm{DSIEV}) \ast \exp\{-\lambda \ast \mathrm{DSIEV}\}/\mathrm{AD}]/\mathrm{DEPT} - (\lambda + {} \\ & + \mathrm{ATTACH}) \ast \mathrm{CDSOL} + \mathrm{DDRY} \ast \mathrm{CDINS}\,(t - \mathrm{DDETR}) \ast {} \\ & \exp\{-\lambda \ast \mathrm{DDETR}\}\}\end{aligned} \tag{B.4}$$

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* Integrand time variable is *t* unless specifically indicated.

$$\begin{aligned}\mathrm{CDINS}\,(\mathrm{Ci\ m^{-3}}) = \int \mathrm{d}t\,\{&[(1 - \mathrm{GDEPSD}) * (1 - \mathrm{GDEPD}) * \mathrm{RDRY} + \\ &+ (1 - \mathrm{FWET}) * (1 - \mathrm{GDEPD}) * \mathrm{NCOW} * \mathrm{WGTC} * \mathrm{REXCR}]/ \\ &\mathrm{DEPT} - \lambda * \mathrm{CDINS} + \mathrm{ATTACH} * \mathrm{CDSOL} + \mathrm{LDEATH} * [\mathrm{CGRASS} \\ &(t - \mathrm{DDGRASS}) + \mathrm{GCOVER} * \mathrm{CP}\,(t - \mathrm{DDGRASS})] * \exp\{-\lambda * \\ &\mathrm{DDGRASS}\}/\mathrm{DEPT} - \mathrm{DDRY} * \mathrm{CDINS}\,(t - \mathrm{DDETR}) * \exp\{-\lambda * \\ &\mathrm{DDETR}\}\}\end{aligned} \tag{B.5}$$

$$\begin{aligned}\mathrm{CPOND}\,(\mathrm{Ci\ l^{-1}}) = \int \mathrm{d}t\,\{&(\mathrm{RDRY} + \mathrm{RWET})/\mathrm{DEPL}/\mathrm{RHOW} - (\mathrm{RSED} + \lambda) * \\ &\mathrm{CPOND}\}\end{aligned} \tag{B.6}$$

$$\begin{aligned}\mathrm{CCOW2}\,(\mathrm{Ci}) = \int \mathrm{d}t\,\{&(1 - \mathrm{ECOW}) * \mathrm{COWINT}\,(t - \mathrm{DCOW2}) * \exp\{-\lambda * \\ &\mathrm{DCOW2}\} - (\lambda + \mathrm{LABC2}) * \mathrm{CCOW2}\}\end{aligned} \tag{B.7}$$

$$\begin{aligned}\mathrm{CCOW3}\,(\mathrm{Ci}) = \int \mathrm{d}t\,\{&\mathrm{LABC2} * \mathrm{ECOW1} * \mathrm{CCOW2}\,(t - \mathrm{DCOW1}) * \exp\{-\lambda * \\ &\mathrm{DCOW1}\} - (\lambda + \mathrm{LABC3}) * \mathrm{CCOW3}\}\end{aligned} \tag{B.8}$$

$$\begin{aligned}\mathrm{CMAN2}\,(\mathrm{Ci}) = \int \mathrm{d}t\,\{&(1 - \mathrm{EMAN}) * \mathrm{MANINT}\,(t - \mathrm{DDMAN2}) * \exp\{-\lambda * \\ &\mathrm{DDMAN2})\} - (\lambda + \mathrm{LABM2}) * \mathrm{CMAN2}\}\end{aligned} \tag{B.9}$$

$$\begin{aligned}\mathrm{CMAN3}\,(\mathrm{Ci}) = \int \mathrm{d}t\,\{&\mathrm{LABM2} * \mathrm{EMAN1} * \mathrm{CMAN2}\,(t - \mathrm{DDMAN}) * \exp\{-\lambda * \\ &\mathrm{DDMAN}\} - (\lambda + \mathrm{LABM3}) * \mathrm{CMAN3}\}\end{aligned} \tag{B.10}$$

$$\mathrm{RDRY} = \mathrm{VDEP} * \mathrm{Co}\,(\mathrm{Ci\ m^{-2}\ h^{-1}}) \tag{B.11}$$

$$\mathrm{GCOW} = \mathrm{GCO} * \mathrm{GCO4} * \begin{cases} 1 & \text{if } t < \mathrm{TBEG} \\ 0 & \text{if } t > \mathrm{TBEG} + \\ & + \mathrm{TFACT}^{-1/2} \\ 1 - \mathrm{TFACT} * (t - \mathrm{TBEG})^2 & \text{otherwise} \end{cases} \tag{B.12}$$

$$\mathrm{LAWASH} = \begin{cases} \mathrm{LAW} & \text{if } \mathrm{PREC} > \mathrm{PRECo} \\ 0 & \text{otherwise} \end{cases} \tag{B.13}$$

$$\begin{aligned}\mathrm{REXCR} = \{&(1 - \mathrm{ECOW1}) * \mathrm{LABC2} * (1 - \mathrm{USAGE}) * \mathrm{CCOW2}\,(t - \mathrm{DCOW1}) * \\ &\exp\{-\lambda * \mathrm{DCOW1}\} + \mathrm{LABC3} * (1 - \mathrm{MILKC}) * \mathrm{CCOW3}\}/\mathrm{WGTC} \\ &(\mathrm{Ci\ kg^{-1}\ h^{-1}})\ \text{(see Section 6)}\end{aligned} \tag{B.14}$$

$$\begin{aligned}R_2 = \mathrm{RROOT} * (1 - \exp\{&f_5 * (\mathrm{AP} - \mathrm{APS})/\mathrm{APS}\}) * \mathrm{AD} \quad (\text{kg water m}^{-3} \\ &\text{plant h}^{-1})\ \text{(see Appendix A)}\end{aligned} \tag{B.15}$$

$$\mathrm{CPLANT} = \mathrm{FRAC} * \mathrm{CP} + \mathrm{GVOL} * \mathrm{CGRASS} \quad (\text{Ci kg}^{-1}\text{ edible plant}) \tag{B.16}$$

$$\mathrm{GRASS} = \mathrm{FRAC} * (\mathrm{CP} + \mathrm{CGRASS}/\mathrm{GCOVER}) \quad (\text{Ci kg}^{-1}\text{ plant}) \tag{B.17}$$

$$\begin{aligned}\mathrm{CHAY} = (&\mathrm{GCO5} * \mathrm{CPLANT}\,(\mathrm{TIX}) * \exp\{-\lambda * (t - \mathrm{TIX} * 168)\} + \mathrm{GCO6} * \\ &\mathrm{CPLANT}\,(\mathrm{TIX1}) * \exp\{-\lambda * (t - \mathrm{TIX1} * 168)\})/\mathrm{SHRINK} \\ &(\mathrm{Ci\ kg^{-1}})\end{aligned} \tag{B.18}$$

$$\mathrm{GCOW2} = \mathrm{SHRINK} * (\mathrm{GCO} - \mathrm{GCOW}) \quad (\mathrm{kg\ h^{-1}}) \tag{B.19}$$

$$\mathrm{CDTOP} = \mathrm{CDSOL} + \mathrm{CDINS} \quad (\mathrm{Ci\ m^{-3}}) \tag{B.20}$$

$$R_3 = \mathrm{RSIEV} * \mathrm{AD} \qquad (\text{kg water m}^{-2}\text{ interface h}^{-1}) \tag{B.21}$$

$$\begin{aligned}\mathrm{CWC} = {} & \mathrm{OVFLG} * \mathrm{GCOW}/\mathrm{GCO4} * \mathrm{CPOND}\,(t - \mathrm{DPOND}) * \exp(-\lambda * \mathrm{DPOND}) \\ & + \text{negligible ground water contribution} \qquad (\mathrm{Ci\,l}^{-1})\end{aligned} \tag{B.22}$$

$$\begin{aligned}\mathrm{COWINT} = {} & \mathrm{GCOW} * \mathrm{CPLANT} + \mathrm{GCOW2} * \mathrm{CHAY} + \mathrm{INTWCO} * \mathrm{CWC} + \\ & + \mathrm{BRETCO} * \mathrm{CSURF} \qquad (\mathrm{Ci\,h}^{-1})\end{aligned} \tag{B.23}$$

$$\begin{aligned}\mathrm{CMILK} = {} & \{\mathrm{USAGE} * \mathrm{LABC2} * (1 - \mathrm{ECOW1}) * \mathrm{CCOW2}\,(t - \mathrm{DCOW1}) * \\ & \exp\{-\lambda * \mathrm{DCOW1}\} + \mathrm{MILKC} * \mathrm{LABC3} * \mathrm{CCOW3}\}/\mathrm{YIELD} \\ & (\mathrm{Ci\,l}^{-1})\end{aligned} \tag{B.24}$$

$$\mathrm{CMEAT} = \mathrm{USAGEM} * \mathrm{CCOW2} + \mathrm{MEATC} * \mathrm{CCOW3} \qquad (\mathrm{Ci\,kg}^{-1}) \tag{B.25}$$

$$\mathrm{CSUF} = \mathrm{CSURF} \text{ using } \mathrm{GDEPSD} = 0.2 \text{ (city)} \qquad (\mathrm{Ci\,m}^{-3}) \tag{B.26}$$

$$\begin{aligned}\mathrm{MANINT} = {} & \mathrm{INTAKE} * \mathrm{CMILK}\,(t - \mathrm{DDMILK}) * \exp(-\lambda * \mathrm{DDMILK}\} + \\ & + \mathrm{INTMT} * \mathrm{CMEAT}\,(t - \mathrm{DMEAT}) * \exp\{-\lambda * \mathrm{DMEAT}\} + \\ & + \mathrm{BREATH} * \mathrm{CSUF} + \mathrm{INTW} * \mathrm{CW}\,(\mathrm{Ci\,h}^{-1})\end{aligned} \tag{B.26}$$

VDEP = 50 ($\mathrm{m\,h}^{-1}$), deposition velocity.
GDEPSD = 0.1, fraction of deposition reevaporated.
NCOW = 2.5×10^{-4} (m^{-2}), density of cows on grass acre.
BRETCO = 1.75 ($\mathrm{m}^3\,\mathrm{h}^{-1}$), amount of air from which iodine will be absorbed in cows lungs (total respired volume is 6 $\mathrm{m}^3\,\mathrm{h}^{-1}$) (Altman and Dittmer, 1964).
DSURF = 2 (m), height of surface air layer.
$\lambda = 3.589 \times 10^{-3}$ (h^{-1}), radiological decay constant of ^{131}I.
LAIR = 0.5 (h^{-1}), vertical removal rate of iodine from surface air.
GDEPD = 0.967, fraction of dry deposition on grass acre suspended on grass leaves.
GDEPW = 1, fraction of wet deposition on grass acre suspended on grass leaves.
GVOL = 0.3175 (m^2 acre kg^{-1} edible grass), average area which a cow grazes to get 1 kg (fresh weight) of grass at average Danish grazing practice (Sørensen *et al.*, 1965).
GCO = 3.39 (kg grass h^{-1}), cows average maximum fresh grass requirement.
GCO4 = 0.66, summer fraction of cows food requirement derived from grazing.
TFACT = 0.04 (wk^{-2}), autumn grazing decline parameter.
TBEG = 5 (wk), decline of grazing start time.
LAW =0.05 (h^{-1}), grass leaves wash-off rate during heavy rainfalls.
PRECo = 3×10^{-4} ($\mathrm{m\,h}^{-1}$), threshold for wash-off.
LDEATH = 1.6×10^{-4} (h^{-1}), grass withering rate.
DDGRASS = 300 (h), average growth time of grass plant (before withering process sets in).
FWET = 0.86, fraction of cows excretions which are fluid.
WGTC = 530 (kg), average weight of Danish milk cow (Pedersen, 1973).
RETENT = 1, retention fraction for I in water entering through roots.

RROOT = 0.0823025 (m^3 soil from which water is taken m^{-3} plant h^{-1}), average root water uptake parameter (Geiger, 1966).

AD, soil (plow layer) water content, yearly average 160 kg m^{-3}, cf. Appendix A.

$f_5 = 10$, parameter for change of root uptake with changing plant water content.

AP, water content of grass plant, yearly average 800 kg m^{-3}, cf. Appendix A.

APS = 900 (kg water m^{-3} plant), saturation water content of grass plant

FRAC = 1.1765×10^{-3} (m^3 plant kg^{-1} plant), inverse density of wet grass plant.

GCOVER = 4.176×10^{-3} (m^3 plant m^{-2} acre), average standing crop grass volume, incl. roots.

GCO5 = 0.4, fraction of constituent #1 in stored fodder.

TIX = 7 (wk), harvest date of constituent #1.

GCO6 = 0,2, fraction of constituent #2 in stored fodder.

TIX1 = 10.2 (wk), harvest date of constituent #2.

SHRINK = 0.235, hay shrinkage factor upon drying (Sørensen *et al.*, 1965).

RUNOFF = 0, average surface runoff from grass acre.

RSIEV = 1.78125×10^{-4} (m h^{-1}), average water flow velocity to deeper soil (Odum, 1972).

RETEN2 = 0.8, plowlayer-deep soil interface retention of iodine.

DSIEV = 20 (h), average time needed for I to penetrate plowlayer (lower estimate).

DEPT = 0.2 (m), depth of plowlayer.

ATTACH = 0.004 (h^{-1}), rate at which dissolved I gets attached to surface of soil particles.

DDRY = 10^{-5} (h^{-1}), rate at which I particles or soil-attached I gets dissolved or freely moving.

DDETR = 500 (h), average time in which I may be attached to soil

DEPL = 1 (m), depth of livestock drinking pond.

RHOW = 1000 (kg m^{-3}), density of water.

RSED = 10^{-5} (h^{-1}), rate of I sedimentation in pond (lower limit)

OVFLG = 0.7, fraction of cows drinking water derived from surface sources during grazing period.

DPOND = 2 (h), half average time interval between cows watering (lower estimate).

ECOW = 0, fraction of cows I intake not uptaken.

DCOW2 = 24 (h), average delay between intake and uptake from gastro-intestinal tract (ICRP, 1959).

LABC2 = 0.5 (h^{-1}), clearance rate for fast turnover of I in cow.

ECOW1 = 0.75, average fraction of I, processed in cows fast compartment, that is transfered to thyroid (Alexander, 1971)

DCOW1 = 3 (h), average transfer time from fast compartment to thyroid storage (including transformation to organic in the thyroid).

LABC3 = 3.125×10^{-4} (h^{-1}), clearance rate from thyroid storage (Colard *et al.*, 1965)

USAGE = 0.04, fraction of I secreted into milk by fast turnover.

MILKC = 0.02, fraction of thyroid excretion reaching milk.

YIELD = 0.5146 ($1\ h^{-1}$), average milk yield from Danish cows (Samvirkende Danske Landboforeninger, 1971; Statistical Department, 1972).

USAGEM = 0.001 (kg^{-1}), fraction of iodine from fast turnover present in meat, per kg meat.

MEATC = 0 (kg^{-1}), fraction of I from thyroid excretion reaching meat, per kg meat.

INTWCO = 1.77 ($1\ h^{-1}$), cows water intake when fed on fresh grass.

INTAKE = 0.024 ($1\ h^{-1}$), mans average milk intake (Aarkrog *et al.*, 1963).

DDMILK = 24 (h), delay in milk processing (lower estimate).

INTMT = 0.002 ($kg\ h^{-1}$), mans average meat intake (Aarkrog *et al.*, 1963).

DMEAT = 1000 (h), delay in meat reaching consumer.

BREATH = 0.25 ($m^3\ h^{-1}$), amount of air from which I will be absorbed in mans lungs (total respired volume is about $1\ m^3\ h^{-1}$, depending on excercise) (Altman and Dittmer, 1964).

EMAN = 0, fraction of mans I intake not uptaken.

INTW = 0.044 ($1\ h^{-1}$), man's average water intake, in addition to water content in food and water produced in lungs by oxidation (Aarkrog *et al.*, 1963).

CW = 0 ($Ci\ l^{-1}$), ^{131}I activity in mans drinking water.

DDMAN2 = 24 (h), average delay between intake and uptake from G.I. tract (ICRP, 1959).

LABM2 = 0.5 (h^{-1}), clearance rate for fast turnover of I in man.

EMAN1 = 0.75, average fraction of I processed in mans fast component (blood) that is transfered to thyroid (Alexander *et al.*, 1971).

DDMAN = 3 (h), average transfer time from fast component to thyroid storage (including transformation to organic in thyroid).

LABM3 = 3.125×10^{-4} (h^{-1}), clearance rate from thyroid storage (Colard *et al.*, 1965).

References

Aarkrog, A., Lippert, J., and Petersen, J.: 1963, *Risø Report,* No. 63.

Alexander, W., *et al.*: 1971, *Dynamical Studies with Radioisotopes in Medicine,* IAEA, Vienna, p. 179.

Altman, P. and Dittmer, D. (eds.): 1964, *Biology Data Book,* FASEB, Washington.

Andersen, A.: 1967, *Risø Report,* Nos. 170 and 174.

Bergström, S.: 1967, in B. Åberg and F. Hungate (eds.), *Radioecological Concentration Processes,* Pergamon Press, London, p. 159.

Berry, P. and Chamberlain, A.: 1963, *Health Phys.* **9**, 1149.

Bucovac, M., *et al.*: 1965, in E. Fowler (ed.), *Radioactive Fallout, Soils, Plants, Foods, Man,* Elsevier, New York, p. 82.

Chamberlain, A.: 1966, *Proc. Royal Soc. (London)* **A290**, 45

Colard, W., Berly, W., Henry, J. and Boulenger, R.: 1965, *Health Phys.* **11**, 23.

Danish Defense Research Board: 1963, *Report,* No. 18.

Danish Meteorological Institute: 1972, private communication.

Falk, R.: 1973, private communication.

Geiger, R.: 1966, *The Climate Near the Ground,* Harvard University Press, Cambridge.

Högström, U.: 1968, *Tellus* **20**, 65.

Hungate, F., Cline, J., Uhler, R., and Selders, A.: 1963, *Health Phys.* **9**, 1159.

ICRP (International Commission on Radiological Protection): 1959, in K. Morgan (ed.), *Report of Committee II,* Pergamon, New York.

Jensen, M.: 1954, *Shelter Effect,* dissertation, Danish Technical University.

Koranda, J.: 1965, *University of California Report*, UCRL-12479.

Krieger, H., Kahn, B., and Cummings, S.: 1967, in B. Åberg and F. Hungate (eds.), *Radiological Concentration Processes*, Pergamon Press, London, p. 59.

Kristoffersen, L.: 1974, *Proceedings of the RIFO Conference on Energy*, held March 1974 in Stockholm, to be published.

Long, C. (ed.): 1961, *Biochemist's Handbook*, E. Spon, London.

Ng, Y.: 1967, *University of California Report*, UCRL-71833.

Odum, H.: 1971, *Environment, Power and Society*, Wiley, New York.

Odum, E.: 1972, *Ecology*, Holt-Reinhardt and Winston, New York.

Owers, M. and Powell, A.: 1974, *Atmos. Environment* **8**, 63.

Patten, C. (ed.): 1971, *Systems Analysis and Simulation in Ecology* **1**, Academic Press, New York.

Penman, H.: 1970, *Scientific American* **223**, 99.

Petersen, D.: 1973, private communication.

Roedler, H., *et al.*: 1972, *Assessment of Radioactive Contamination in Man*, IAEA, Vienna, p. 515.

Samvirkende Danske Landboforeninger: 1971, *Landøkonomisk Oversigt*, Axelborg, Copenhagen.

Slade, D. (ed.): 1968, *Meteorology and Atomic Energy*, USAEC, Washington.

Sørensen, B.: 1973, *Naturens Verden* **8**, 281.

Sørensen, E., *et al.*: 1965, *Agerdyrkningslaere*, **2**, Andelstrykkeriet, Odense.

Statistical Department: 1972, *Statistical Yearbook, Denmark 1971*, Government Press, Copenhagen.

Teller, E., Talley, W., Higgens, G., and Jolinson, G.: 1968, *The Constructive Uses of Nuclear Explosives*, McGraw-Hill, New York.