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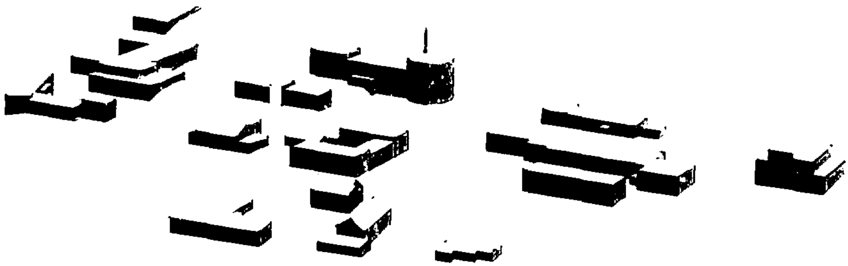

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FRESHWATER EXPOSURE PATHWAYS IN THE NORDIC COUNTRIES

by

Ulf Tveten

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ABSTRACT

The study reported here was partially funded by the Nordic Council of Ministers, via the Nordic Liaison Committee for Atomic Energy.

The project is part of a larger project "Large reactor accidents: Consequences and mitigating actions". The purpose of the project has been to summarize the information available, primarily in the Nordic countries, on the freshwater exposure pathways, with particular emphasis on aspects relevant in connection with large reactor accident consequence calculations.

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C O N T E N T S

1. INTRODUCTION

This subproject (REK-1:11 "Freshwater exposure pathways") is part of the project REK-1 "Large reactor accidents; Consequences and mitigating actions", which is a Nordic project, partially financed by the Nordic Council of Ministers.

The purpose of REK-1:11 is to attempt to summarize the information available in the Nordic countries on the freshwater exposure pathways, particularly seen in connection with calculation of consequences of large reactor accidents.

Initially one would expect the freshwater pathways to be of equal importance in the four Nordic countries, because of the similarities in climate. The geographical area is one of abundant precipitation, evenly distributed over the year. But it is found that conditions in Denmark are quite different from conditions in the other three countries, and that the freshwater exposure pathways are of no importance in Denmark.

All four countries also experience a relatively long winter, though the length and severeness of the winter varies much with latitude and distance from the ocean. The radiological impact of winter is, however, to a large degree unknown. Winter conditions is the subject of another of the subprojects under REK-1.

2. THE FRESHWATER PATHWAYS

It is not easy to give a logical definition of freshwater exposure pathways. The expression is usually meant to cover internal exposure via drinking water and freshwater fish; and external exposure due to swimming, boating, contact with fishing utensils, use of beach areas. But migration of radioactive materials in soil or rock is really also part of the freshwater pathways. And one might also argue that the whole biosphere is part of the freshwater pathways, as all uptake to and transport in the biosphere requires the presence of water.

In this subproject it has been chosen to start the freshwater pathways from the moment deposition upon ground or a freshwater surface has happened, in the case of an atmospheric release. Since the project concentrates upon large reactor accidents, liquid releases are not of concern.

The traditional exposure pathways, mentioned earlier in this chapter, are included. In addition is included exposure via irrigation. Accordingly the irrigated agricultural products will have to be considered, although they have traditionally not been considered part of the freshwater exposure pathways.

3. CONDITIONS IN DENMARK

Since conditions in Denmark differ so much from those in the other three countries, it has been chosen to treat them quite briefly in a separate chapter.

The major difference is that the surface water supply is very limited in Denmark. Accordingly drinking water as well as irrigation are quite insignificant as exposure pathways. Drinking water istaken from ground water, pumped up from considerable depths; meaning that contamination via migration of radioactive materials deposited upon ground will also be insignificant. An exception is Copenhagen, where surface water is being used as drinking water to an increasing extent.

Lakes are relatively few in Denmark, and they are not large. The lakes cover only 1.3% of the total land area. There are no rivers, but a number of creeks. The ocean is not very far off from any position in Denmark, and swimming and recreational use of beaches mostly takes place by the ocean; while similar use of freshwater areas is quite limited. Accordingly swimming and shoreline exposure to sediments in connection with the freshwater pathways is also insignificant.

Neither will exposure via freshwater biota be an important pathway in Denmark, except possibly where maximum individual exposure is concerned.

In conclusion the only important freshwater pathways in Denmark are the ones involving agricultural products, including milk; but as discussed in chapter 2, it is doubtfull whether these exposure pathways should be regarded as belonging among the freshwater pathways.

More detailed information about the freshwater pathways in Denmark is found in (Ref. AA79), from which the information in the present chapter has been taken.

4. DEPOSITION AND RUN-OFF

4.1 Deposition

Deposition upon ground from a cloud containing radioactive material is routinely calculated by reactor accident consequence calculation models. In connection with the freshwater pathways, however, one is also interested in deposition upon water surfaces.

Deposition may take place during wet and dry conditions. During wet conditions the deposition per unit area will be the same upon a water surface as upon a ground surface. But during dry conditions deposition will be smaller upon a water surface than upon a ground surface, because water is a smooth surface. To a certain degree, one will expect deposition upon a water surface to depend upon wave characteristics. Higher waves would lead to higher deposition. With a few exceptions, the highest air concentrations of an atmospheric release occur when the wind velocity is low and there are stable atmospheric conditions, and accordingly when the deposition upon water is lowest. If waves are rougher, and deposition higher, the air concentrations will also be lower; the last effect probably more than counteracting the first.

Available data for dry deposition upon water surfaces are quite limited. Some measurements of the deposition velocity of sulfurdioxide gas on water are, however, referred to in a survey from the Norwegian Air Research Institute (Ref. GO78). The individual measurements are described in (Ref. GA77, GO77, SH74 and WH74). In SH74 it was found that the deposition velocity was 1/1000 of the wind velocity. WH74 reports deposition velocities of 0.16 cm/s for stable weather conditions, 2.2 for neutral and 4.0 for unstable. The other two references give deposition velocities of 0.3 and 0.4 cm/s.

Most measurements of cesium and strontium behavior in the environment are measurements upon nuclear weapons fallout. Deposition of nuclear weapons fallout, at least in climates like the Nordic, is almost entirely wet deposition. This is also shown in work performed at the Norwegian Defence Research Establishment (Ref. HV66 and LI82). Fallout in Norway has been measured since 1956. Fig. 4.1 is shown in (Ref. HV66), and demonstrates a close to linear relationship between fallout and precipitation for the years 1959 to 1965, for seven different geographical positions around the country. This means that the major part of deposition is wet deposition, and that deposition accordingly is the same per unit area upon ground and water surfaces.

Because measurements are often designed to give information on both deposition characteristics, run-off, and behavior in soil, lakes and rivers, it is difficult to keep a clear distinction between these subjects; and information on deposition may also be found in the chapters on the other phenomena.

4.2 Run-off

Radioactive materials deposited upon the ground will to a certain extent be washed away with run-off water; either in solid or dissolved form, and will eventually reach a lake, a river or the sea. The phenomenon of water running from a land surface is called run-off.

Vertical migration in soil may also take place, leading to release to rivers or lakes via ground water. This process is, however, too slow to be of concern in connection with calculation of severe reactor accidents.

Extensive measurements giving information about run-off have been performed in Finland (Ref. SA84). The catchment areas of five larger Finnish rivers have been studied. The five areas do not cover the whole country. In table 4.1 are shown some of the characteristics of the areas.

Sr-90 and Cs-137 from nuclear weapons tests have been monitored in deposition upon ground, in the five largest rivers, and in certain lake and river systems in Finland since the midsixties. These observations have shown an even distribution of Sr-90 and Cs-137 deposition over the country, but regional differences were found in their concentrations in surface water. These observations give a basis for determining the total removal from Finnish ground of these isotopes, and also for describing some aspects of their behavior in the environment.

In (Ref. SA84) are reported comparisons of the amounts of Sr-90 and Cs-137 deposited in Finland and removed from Finland up to 1981. It was found that the average removal by water was 41% for Sr-90 and 7% for Cs-137. As the water surface is about 9% of the Finnish area, these results indicate that Sr-90 is significantly removed from ground by run-off, while Cs-137 is not. It is even indicated that part of the Cs-137 deposited directly upon water surfaces is trapped in sediments in rivers and lakes.

In large parts of Finland, the percentage of the total area which is freshwater surfaces, is much larger than in most other parts of the Nordic countries. It will probably not be possible to ignore the contribution from run-off of Cs-137 from ground surfaces in most parts of the Nordic countries. One possible exception in addition to Finland (or much of Finland) is the middle part of Sweden, where there are a number of very large lakes.

There is probably also a link between run-off and the type of terrain. Most of Norway is very hilly or mountainous, and so are the Northern parts of Finland and Sweden. This type of terrain is often combined with special ground conditions; where the bedrock is covered with only a thin layer of soil and sparse vegetation. Under these conditions one would expect run-off to be much more pronounced than in typical agricultural areas or in dense forest areas.

These assumptions actually seemed to be supported by some measurements performed in Norway in the years 1957 and 1958 (Ref. BE59). However, it was later found that the calculations performed in this reference were based upon outdated information on the size of the reservoir itself. The calculations were repeated, using the correct information (Ref. LU62), and the following conclusions could be drawn: Direct fallout on the water surface accounts for 50 - 60% of the Sr-90 found in drainage, while direct fallout on the water surface accounts for almost all the Cs-137 found in the drainage. When drawing these conclusions, it is assumed that sedimentation in the reservoir is of little importance, where mass balance is concerned. This assumption is also supported by measurements performed in Finland, and referred to elsewhere in this report (Ref. SA84). However, if a large fraction of the catchment area is lake surface, this assumption does not hold for Cs-137. In this case as much as 10-20% of the Cs-137 deposited in the catchment area may be contained in the sediments; while Sr-90 contained in the sediments will still only be a small fraction.

In (Ref. LU62) are also reported some other measurements of special interest in connection with winter conditions. These measurements were performed in the Møsvatn area, a mountain region in Norway. This is an area used previously by the Norwegian Watercourse and Electricity Board for hydrological studies. The elevation ranges from 1100 meters above sea level to 936 meters above sea level, the latter being the elevation of the lake with the single water outlet. The area is dish-shaped with lakes at different levels. The total area is 5.91 km^2, and the lakes cover 6.9% of the area.

In the Mesvatn area there are three distinct seasonal periods: summer, winter and the snow-melting flood season. The snow acts as a reservoir from which the precipitation is drained into the lake, and the frozen ground may prevent absorption of the fallout before the melting water arrives at the lake.

As a matter of fact, it was found that during summer, the concentration in the lower lake of Sr-90 and Cs-137 corresponded to deposition onto the water surfaces of the lakes, with no contribution from runoff from the surrounding ground surfaces. In winter and the melting season the conditions are quite different. It was found that there was a peak in the activity concentration in the lake during spring, as expected. There were also peaks during winter, and these coincided with time periods with above-freezing temperatures. The activity content in the snowcover of the lake surfaces is not high enough to explain the magnitude of the peaks. It was concluded that there was a significant contribution from runoff from the surrounding ground area. Under special conditions during winter, as much as 50% of the activity deposited in the catchment area could reach the lake. During the spring flood the amount of fallout brought into the lake corresponds to twice the amount stored in the snow stored on the lakes alone. These conclusions are drawn for Sr-90 as well as Cs-137.

In (Ref. LU62) are also reported measurements performed in another catchment area, called the Ski area. This is an area in the South-eastern part of Norway, in which the area of lakes and rivers is a very small percentage of the total area; only 0.4%. In this area it was found that the concentrations in the outlet from the area varied much less than concentration in the precipitation. This indicates that only a smaller part of the radioactive materials in the outlet water was deposited directly upon water surfaces.

4.3 Soil

The measurements reported in (Ref. SA84) indicate that run-off is quite different for different types of soil, and that run-off is much stronger for strontium than for cesium in all types of soil. The typical soil in South-Western Finland is clay soil. Strontium deposited upon this type of soil does to a large degree run off, while cesium almost completely stays where it is deposited originally. Peat soil is the common type of soil in most other parts of Finland. This type of soil is also the most common in Norway, and there is reason to believe that data from these catchment areas in Finland are valid for much of Norway, and probably for much of Sweden.

Typical of two of the Finnish catchment areas is large proportions of bog. In these areas of low clay content, run-off of Cs-137 was found to be somewhat larger than in the other areas; but still only 6-8% of the total amount deposited in the catchment area.

The vertical distribution of Cs-137 in soil also gives an indication of the mobility, and how easily the material can be washed out. Measurements have been performed in Norway (Ref. LU62 and LI82). The results are given in table 4.2. Unfortunately the older and newer measurements are not performed on the same type of soil, and not on layers of the same thickness. The older measurements were performed on peat bog, while the newer measurements were performed on soil from an agricultural area in Southeastern Norway. Care was taken, however, to choose soil which has not been cultivated during the period over which weapons fallout has been deposited. The measurements clearly show that Cs-137 is not very mobile in either type of soil.

Measurements of the vertical distribution of Cs-137 in soil have also been performed in the other Nordic countries. In figure 4.2, from (Ref. PR82), are given results from measurement of the vertical distribution in some types of soil in Denmark, Finland and Sweden. These measurements also show low mobility of Cs-137, though the variation with soil type is relatively strong. It should be added that the curve in fig. 4.2 for Finland is not typical of Finnish soil. A more typical curve is taken from (Ref. AI83), and is shown in figure 4.3. Measurements of the vertical Cs-137 and Sr-90 concentrations in five different Finnish soils are also reported in (Ref. HÄ68). These measurements also show that most of the activity is contained in the vegetation and upper layers of soil (even where Sr-90 is concerned); although a significantly deeper penetration is found in Sphagnum peat.

Uptake in plants can also give an indication of the mobility of Sr-90 and Cs-137 in different soil types (Ref. RA82). Measurements in Finland and Sweden have shown that Cs-137 becomes unavailable to plants after a few years in soils with sufficiently high clay content. Organic matter in the soil, on the other hand, keeps Cs-137 mobile (Refs. ER77 and KU72). High organic matter content in soil reduces root absorption of Sr-90. This may, however, be due to other factors than reduced mobility in the soil. Sr-90 in soil is otherwise available for root uptake for many years after deposition.

5. RIVERS AND LAKES

The content of radioactive materials, originating from an atmospheric release, in a water body will consist of material deposited upon the water surface, run-off of freshly deposited material in the catchment area, and run-off (desorption and erosion) of older deposited material in the catchment area.

5.1 Water in rivers and lakes

(In ref. YA63, JA72 and KA74) it has been shown that the concentration of a radionuclide of weapon-test origin in a river can be described by the following equation:

$$C_w = c_1 F_a + c_2 F_c$$

where

C_w is the concentration in the water in the river (Ci/m^3)

c_1 and c_2 are correlation coefficients

F_a is the deposition rate ($Ci/m^2 month$)

F_c is the cumulative deposition (Ci/m^2)

This expression can not be true for all rivers, of course, but is an expression often referred to in radioecology. Even though this expression is meant to describe the conditions in a river, it will give a reasonable description of the conditions in a lake, if the residence time of the water in the lake is of the same time scale as variations in deposition rate. Water concentrations of Cs-137 have been measured in the Ulkesjön lake in Sweden over the years 1963 to 1974 (Ref. CA76). A good correlation was found with the following expression of the above type:

$$C_w = (0.97 \quad 0.22)\, F_a + (0.015 \quad 0.003)\, F_c$$

The contribution from run-off of activity deposited upon ground at earlier time periods is apparently not unimportant, though the contribution from activity deposited at the time of measurement, or relatively recently, dominates. The expression does not differentiate between activity deposited upon the water surface and run-off of freshly deposited activity in the catchment area. In connection with an atmospheric release caused by a nuclear accident, it can be argued that this expression will still describe the situation. But in this connection, the two parts of the expression will mean something else. The first part of the expression will describe the conditions a short time after deposition has taken place, while the second part will describe the long-term conditions. Numerically (though they have different dimensions) Fc can clearly not be greater than Fa in this case, meaning that the first part of the expression will be much larger than the second part. Also the water concentration on the lefthand side of the equation is the water concentration in the upper layer.

Lake Ulkesjön is a type of lake which is quite common in the Nordic countries. It is a moderately-sized lake (roughly 90.000 m^2) in a forest area. A few streams run into the lake, and one runs out of the lake. The lake bottom is mostly covered with a semi-liquid black mud. The water has a rather dark brownish color. There is no local pollution. The lake is not deep, with a greatest depth of 8 meters. Annual precipitation is 770 mm. The catchment area is 1.3 km^2.

In (Ref. SA79) measurements on two Finnish rivers are reported. Here it is also found that the concentration in river water is an almost linear function of the deposition rate, while the accumulated deposition is less important.

Deposition upon water surfaces in most areas in the Nordic countries will almost entirely be upon lake surfaces, since very few Nordic rivers are wider than one hundred meters across. One of the larger lakes in Norway is Tyrifjorden with an area of 136 km^2. The river Drammenselva runs from Tyrifjorden to the sea, and it is one of the widest rivers in Norway. It is 275 km long. The width of the river varies from its source to its outlet to the ocean, but even at the widest it is only some 200 meters across. In order to have a surface area equal to the surface area of Tyrifjorden, the river would have to be 500 meters wide all the way. Most rivers in Norway are considerably narrower, and it seems safe to assume that most of the deposition upon freshwater surfaces takes place upon the lake surfaces.

Finnish measurements and measurements in the USSR (Ref. LA83) show that the Sr-90 concentration in river water is higher in large rivers than in small rivers. This is the way the results are presented in the report. No explanation is given. The larger water surface can not explain this fact. The reason may rather be that there is a stronger interaction with material on the river bottom in a small river. But the observed differences may on the other hand not be connected to the size of the river, but to other characteristics, like lake surface fraction in the catchment area or soil type. Generally, the content of Cs-137 in river water was much lower than that of Sr-90.

5.2 Sediment

Rivers and lakes contain the radioactive materials in solution or fixed on solid particles. In the latter case the particles may be in suspension or settle on the bottom of the river or lake. A systematic examination of the Cs-137 concentrations in a lake in Southern Sweden was performed up to 1975 (Ref. CA76). Among the measurements performed were some in which the activity concentrations in filtered as well as unfiltered lake water were measured. These were found to be almost identical, indicating that only an insignificant fraction of the Cs-137 in the lake water was fixed on plankton or suspended material. In a river, however, one must expect a much larger portion of the activity to be in suspension. In the following parts of this chapter, it will become evident that a significant part of the deposited activity may be contained in the sediments on the lake bottom. And this seems to indicate that a <u>not</u> insignificant part of the activity is fixed on plankton or suspended material. This apparent conflict has not been resolved at the time of writing.

There is a continous settling of sediment on the lake bottom. A typical velocity of sediment buildup is somewhat less than 1 cm per year (1-2 mm per year may be a realistic value). The content of radioactive materials in sediments may give some information about the behavior of nuclear weapons fallout in the environment. If the total content in sediment per unit area is more than 100% of the accumulated fallout (corrected for radioactive decay) per unit area, run-off from the catchment area is clearly significant. Such a result would also indicate that resuspension from the sediment probably is insignificant. Measurements in Norway (Ref. AU78) performed upon three sedimentation cores fetched from the bottom of lake Årungen, show that 98%, 87% and 47% respectively of the accumulated Cs-137 fallout per unit area in the district was found in the sediment samples. The estimated turnover of the water in this lake is once every fourth month. The results seem to indicate that the contribution from run-off from the catchment area is not significant. But this can not be know for certain, without information on how much Cs-137 leaves the lake via the river outlet and evaporation. This information was not collected in this case.

Measurements performed in Finland upon sediment indicate that sediment contains much more cesium than strontium. Also, the amount of strontium in the water column above sediment in a lake is roughly equal to the amount of strontium in the sediment; while for cesium, the amount in the water column is much less than in the sediment. In a mass balance, the sediment is often of little importance; meaning that the amount of radioactive material remaining on ground surfaces and the amount going with the freshwater into the sea is much larger than the amount being trapped in the total of all sediments in the freshwater compartments. This is, however, not always true if the fraction of water surface is large. In Finland it is often 10-20%, and the Cs-137 content in sediment per m^2 water surface area may be larger than the amount of accumulated Cs-137 per m^2 on land. For more information see table 5.1, taken from (Ref. SA83).

Swedish measurements in lake Ulkesjön (Ref. CA76) gave as result that the cesium content per unit area in sediment was 67% of the cumulative deposition per unit area in the catchment area, which agrees well with the Norwegian measurements. But it is also said in (Ref. CA76) that the value is low compared to other findings (Refs. RI72 and MC73).

The above-mentioned Swedish and Norwegian measurements indicate that more than half of the activity deposited upon the water surface is trapped in sediment. As the total water surface, in different parts of the Nordic countries, may range from somewhere about 1% to 20% of the total area, this would indicate that a maximum of about 10% of all cesium deposited in the area may be trapped in sediment. The Finnish findings referred to in the above and in table 5.1, however, indicate a maximum of more than 20%.

Vertical migration of cesium and strontium in the sediments has also been investigated. The Norwegian measurements (Ref. AU78) were performed with the intention of using measurement of the Cs-137 content for dating of sediment. This is only possible if the sediment, once it is deposited, remains largely undisturbed. There should be little or no biological disturbance of the sediment, no significant resuspension, and no significant vertical migration of the radionuclide concerned. The measurements indicate that these conditions are fulfilled for the Norwegian lake investigated. It was, however, found in Finnish measurements in a lake beside the town of Tampere, that the vertical distribution was quite different. The Cs-137 was found to be homogenously distributed over the top 20 cm of sediment. Tampere is an industrial town, and there are large releases to the lake as well as considerable traffic on the lake. In undisturbed lakes, measurements in Finland also indicate that all Cs-137 is found in the top 5 - 10 cm, with a strong gradient. Similar Swedish results are found in figure 5.1, taken from (Ref. CA76), which shows the vertical Cs-137 distribution in in sediment in the lake Ulkesjön; both measured and calculated by a mathematical model developed in (Ref. CA76), and described there.

From a population exposure point of view, an accumulation of radioactive materials in sediment is an advantage. The sediment will act as a sink. Only in relatively infrequent situations do persons come in contact with sediment. The bulk of the sediment will be situated on lake bottom, and is inaccessible. After hundereds or thousands of years, the sediment may, however, once more be exposed, but this is not an important concern, in connection with large reactor accidents.

Temporary exposure of sediment may, however, occur during dry periods. And the critical areas will, of course, be the shores of lakes and rivers. Use of these areas can lead to radiation exposure directly from the radioactive materials on the ground, and via inhalation of resuspended sediment.

The Cs-137 content in sediment may vary strongly, even quite locally. As could be expected, the concentration is higher in sediment in deep tranquill lakes. The variation in concentration is particularly strong in rivers, where the high concentrations are often found on the inner side of river bends. This aspect is of some significance in connection with population exposure, as these same places often are the most popular places for swimming, sunbathing and camping. The concentrations in sediment are in Finland found to vary up to a factor of 100 quite locally.

6. *DRINKING WATER*

The effect of water purification plants upon strontium and cesium concentrations is found in Finnish investigations to be quite unimportant. The strontium concentration is hardly affected, and the reduction of cesium concentration is at the most 50%.

A lot is said about the concentration of fallout Cs-137 and Sr-90 in freshwater, in chapter 5.1. In the present chapter we will rather view exposure via drinking water after an accident, with the aid of a rough calculation, borrowed from (Ref. TH82).

Figure 6.1 shows a drinking water reservoir, upon which deposition takes place. The water concentration will then be

$$C_w(t) = (X\ v_d\ /\ d)\ e^{-\lambda t}$$

where

C_w is the concentration in the water (Ci/m^3)

X is the time-integrated concentration in air $(Ci s/m^3)$

v_d is the deposition velocity (m/s)

d is the depth of the reservoir (m)

λ is the effective decay factor (d^{-1})

t is the time since deposition (d)

The individual dose commitment will be

$$D = \int_0^\infty dt\ U\ DF\ C_w(t)$$

where

U is the individual water usage (liter/d)

DF is a dose conversion factor (dose per unit intake)

The effective decay factor depends upon radioactive decay, sedimentation and water turnover. If we consider the two nuclides I-131 and Cs-137, the effective decay factor will be dominated by radioactive decay in the first case, and water turnover in the latter. Sedimentation will be important in neither, except in the latter case if turnover is very slow.

The two equations above can be combined and solved, to give the following expression for individual dose commitment:

$$D = U\ DF\ X\ v_d\ /\ (d\ \lambda)$$

In (Ref. TH82) a rough calculation is carried out, based upon the following assumptions:

The release is 6×10^{7} Ci of I-131 and 2×10^{6} Ci of Cs-137. This corresponds roughly to the release PWR1 from the American Reactor Safety Study (Ref. RE75).

For unit release a time-integrated air concentration of 10^{-7} Cis/m^{3} has been chosen. This is typical of a distance of 10-30 km for many ordinary combinations of meteorological conditions.

A deposition velocity of 0.001 m/s is chosen. This may be somewhat low, but this is on the other hand deposition upon a water surface, with small roughness.

Depth of the reservoir is assumed to be 10 m.

Dose conversion factors (dose per unit activity intake) of 2×10^{6} and 5×10^{4} rem/Ci are used for I-131 (thyroid dose) and Cs-137 (whole body dose) respectively.

The resulting doses calculated, using these rather conservative assumptions, are ca. 10 rem (0.1 Sv) to the thyroid from I-131 and 0.1 rem (0.001 Sv) whole body from Cs-137. These doses are very small compared to doses via other exposure pathways when such a severe accident is postulated.

7. FISH

The total amount of Cs-137 contained in the total amount of freshwater fish in a typical lake is reported to be as low as 1% of the content in the total amount of water in the lake (Ref. CA76). On the other hand, the concentration in fish is much higher than in the water. The Cs-137 concentration in fish has been extensively studied, and Nordic measurements are reported in (Refs. CA76, KO66, KO68 and KO70) among others. Typical concentration factors are 200 - 10000.

In the fish exposure pathway strontium is less important than cesium, as strontium concentrates in bone. Most of the freshwater fish consumed are of species where most of the bones are easily removed, and it must be valid to assume that less than 10% of the fish bone will be consumed. In (Ref. FL71) it is claimed that aquatic food loses 20-50% of its activity during preparation and processing prior to consumption, without reference to any particular nuclide.

The concentration of Cs-137 in fish depends, among other factors, upon the concentration of stable cesium and potassium in the water, and the feeding habits of the fish. The latter varies with age and size of the fish, as well as with species, and there are large individual differences. The differences in concentration between fish from different lakes are in a Finnish investigation reported to be larger than that between fish from different parts of the Baltic Sea (Ref. SX84).

It is found that the concentration in fish is higher in oligotrophic lakes than in eutrophic ones. This is not surprising, but can be seen from another point of view: Eutrophic lakes, lakes with abundant nutrition, are now usually the same as relatively polluted lakes, while oligotrophic lakes are usually unpolluted ones. The latter are rarely found near larger population concentrations. Accordingly most of the freshwater fish consumed will be from eutrophic lakes. Concentrations or concentration factors valid for oligotrophic lakes can, for this reason, not be used as a basis for determining the collective doses from freshwater fish, and doses determined in this manner will be higher than the ones that are really to be expected.

A study of liquid pathways after reactor accidents was performed some years ago in the US (Ref. NI81). Much interesting and detailed information is given, but much of it is irrelevant for Nordic conditions. One such piece of information is that more than half of the commercial fish catch (salt- and fresh-water) is used for industrial purposes, such as production of pet food, bait, oil, solubles and glue. This is hardly true in the Nordic countries, but it has not been possible in the present study to obtain the relevant statistical material.

In a Swedish report (Ref. MA70) the contributions to average individual dose in Sweden from various foodstuffs for the years 1962 to 1968 are given. The information is reproduced in table 7.1 of the present report. It was found that in 1968 freshwater fish contributed 15% of the dose. The consumption of freshwater fish is in this report assumed to be almost 20% of the total fish consumption, a figure which according to the Swedish reviewers of the present report is realistic also for presentday conditions.

The Finnish reviewers have found that a 15% contribution from freshwater fish consumption to the nutrition dose may even be somewhat low for Finnish conditions (Ref. RA84).

For Norwegian conditions it seems clear that the freshwater fish exposure pathway can not contribute as much as 15% of the nutrition dose. The consumption of freshwater fish in Norway is quite limited, and the species of freshwater fish available for the ordinary consumer, are much too expensive to be part of the everyday diet.

Information upon the conditions in Norway was found in a report from the Directorate of Game and Freshwater Fish (Ref. IN82). Similar information for Finland and Sweden respectively may be obtained from:

Jord- och Skogbruksministeriet, Fiskeri och jaktavdelningen
Regeringsgatan 3A
SF-00170 Helsingfors 17

Fiskeristyrelsen
Box 2565
S-40317 Göteborg

It has not been possible, for economic reasons, to collect and process the Finnish and Swedish information in the present study.

Regarding freshwater fish in Norway, there is a complicating factor. Some of the most popular species live only part of the time in freshwater. This applies to salmon, sea-trout and sea-char. On one hand this means that the fish potentially is exposed to freshwater containing radioactive materials only part of the year. On the other hand it means that fish caught in the sea may well have been previously exposed to radioactive materials in freshwater.

In (Ref. IN82) is given information on recreational fishing and commercial fishing; fishing in freshwater and in the sea; though some of the information is incomplete. Nevertheless it is possible to draw firm conclusions on the basis of this information. The commercial catch of sea-trout and salmon is less than double the recreational catch. The recreational catch of inland fish (which does not include salmon, sea-trout and sea-char) is more than ten times the commercial catch. In the same reference it is estimated that the total catch of freshwater fish in Norway is 11500 metric tonnes, based mainly upon information from the year 1980.

No information is supplied in this reference on the use of the fish caught. It may, however, safely be assumed that very little, if any, goes to industry. Almost all the fish caught is of species regarded as very good and rather expensive, fish for eating.

Average freshwater fish consumption in Norway is estimated at about 10% of the total fish consumption, which is given as 30 kg per person and year (Ref. IN82). In the Swedish report referred to in the above (Ref. MA70) an estimate for freshwater fish consumption in Sweden of 2.5 kg per person and year is given. The Swedish reviewers of the present report say that the total fish consumption is 15 kg fish meat per person and year, and that 20% of this is freshwater fish. This indicates that the freshwater fish consumption in the two countries is quite similar.

It is, however, not easy to believe in these numbers as a basis for cumulative dose calculations. For one normal fish dinner one would buy about 250 grams of fish filet per person. This amount will also include some waste. Probably about 10% will be thrown away with the remainder of the bones. 30 kg per person and year means more than two such dinners per week, as an average over the whole population.

8. IRRIGATION

Contamination after an accident in a nuclear power plant via irrigation water is similar to contamination via rain in some respects, and different in other respects. The most important difference is the following: Contamination via rain can only take place during the time it takes the cloud containing radioactive materials to pass over the area in question. Contamination via irrigation water can continue as long as there are radioactive materials present in the water body from which the irrigation water is drawn. Accordingly, although the concentration in irrigation water may be much lower than in rain water, the accumulated deposition may nevertheless approach a comparable level. In the following a rather rough estimate of the relative importance of exposure via irrigation is carried out, based upon Norwegian agricultural statistics. There is no reason to believe that conditions in the other Nordic countries are sufficiently different to make the conclusions drawn invalid.

Table 8.1 gives some information about irrigation in Norwegian agriculture (Ref. IN83). The areas cited here are for the country as a whole. The geographical distribution is very uneven. Table 8.2 contains the areas by county, and the areas cover all plants in existence in 1979 (Ref. CE79). Most irrigated land is found to be located in the central parts of South- East Norway, including the counties along the Oslo Fjord. Table 8.1 shows that there has been a sharp decline in the building of new irrigation plants since 1978. This may be due to favorable weather or to less favorable government subsidies.

More detailed information could probably be obtained, but in the present context, it is felt that rough calculations based upon the information in table 8.2 will suffice. It is desired to obtain a rough estimate of the rainfall which would be equivalent to irrigation. In table 8.2 the plants are grouped by pumping capacity (in m^3/h). The table also gives the total area covered by all plants. Since it is not known what area is covered by the plants in each of the capacity groups, it is not possible to perform more than a rough estimate, but at least one can obtain a relatively reliable estimate by basing it upon counties where the highest group contains a proportionately low number of plants. It is assumed that the middle groups are represented by their midpoints, and that the lower group is represented by 5 m^3/h. But it is not possible to tell from the material what value should be chosen to represent the upper group. That is why it is desirable to be able to exclude it from the estimate. Furthermore it is assumed that the irrigation plant is run at full capacity 100 days in one growing season. This will be conservative, even for a very dry summer in Norway.

The counties having the smallest proportion of plants in the upper capacity group are Oppland, Telemark, and Møre and Romsdal. From these it is found that a rainfall corresponding to irrigation would be roughly of intensity 0.3 mm/h. The variation among the different counties is surprisingly small. Over a whole growing season, using the assumtion in the preceding paragraph (100 hours per season at full capacity), this corresponds to 30 mm precipitation. For comparison, typical persistent, rather strong rain in Norway has an intensity of roughly 1 mm/h.

Now let us see what the above means in connection with large reactor accidents. We assume that a plume containing radioactive materials pass over an area of land and lake, while it is raining. This means that deposition per unit area is the same over land and lake. In other words, what is deposited upon 1 m^2 land area is distributed over 10 m^3 water in the lake, if the lake is 10 m deep. 30 mm of this water sprayed on the land will obviously add very little to the activity concentration on land. In this situation, irrigation can not be an important exposure pathway.

9. FRESHWATER PATHWAYS IN CONSEQUENCE MODELS

All the experimental information presented in this report concerns the nuclides Sr-90 and Cs-137, for obvious reasons. Only in one chapter (Drinking water) is another nuclide (I-131) mentioned, and then in connection with a calculation; not experiments. It should, however, be mentioned that measurements of I-131 behavior in water purification processes have been performed by the Finnish Radiation Protection Institute. But in connection with the long-term consequences of a reactor accident, Sr-90 and Cs-137 are very often the most important nuclides.

9.1 Run-off

Few of the accident consequence models in common use take run-off into account; and the few models that do, take it into account only as a reduction factor upon the dose from radioactive materials deposited upon ground. And it is usually taken into account only in urban areas.

Under summer conditions it seems reasonable to assume that run-off of Sr-90 is roughly 40%, while run-off of Cs-137 is negligible, based upon available information. Run-off during winter conditions in agricultural areas is probably similar to run-off during summer conditions. In mountain areas, however, it seems to be reasonable to assume a run-off of 50% of both Sr-90 and Cs-137 during winter conditions.

The radiological impact of taking run-off into consideration is, however, limited; except in urban areas. Various examinations of these problems are being carried out, also as part of the present project; and one report is available (Ref. QV83) and another one under preparation (Ref. RO84).

9.2 Soil

Strontium is much more mobile in soil than cesium. But in connection with calculation of the consequences of large reactor accident, exposure via ground water transportation will be of no importance for either of these elements.

The only connection in which mobility in soil of a nuclide may be of importance, is in connection with exposure to direct radiation from radioactive materials deposited upon ground. Vertical migration may reduce the direct radiation dose, due to the shielding effect of overlying layers of soil. In all consequence models in common use, this effect is described by an equation from (Ref. GA63):

$$D(t) = 0.63\ e^{-\lambda_1 t} + 0.37\ e^{-\lambda_2 t}$$

where

- $D(t)$ is the relative dose rate (dose rate at time zero being one) 1 meter above an infinite surface at time t (measured in years) after deposition upon the surface.
- λ_1 is an experimentally determined "decay constant" given a value corresponding to a "half life" of 0.60 years.
- λ_2 is like the above, but describing a slower portion of the "decay", corresponding to a "half life" of 22.7 years.

The equation was determined upon the basis of measurements of plots of grass-covered land contaminated with Cs-137, and with a surface concentration significantly higher than the one resulting from deposition of cesium from nuclear weapons fallout.

The Nordic measurements of vertical distribution of Cs-137 in soil, referred to elsewhere in this report, are all measurements of cesium of weapons fallout origin. Accordingly the deposition is virtually continous, and it is difficult to relate them to an accident situation. But at least there is nothing in the results from these measurements indicating that the equation above does not adequately describe variation in time of the dose rate above a surface contaminated with Cs-137, even for rather differing types of soil.

9.3 Concentration in water

The concentration of radioactive materials in freshwater is not calculated in most consequence models in general use. For reasons of completeness such a calculation ought to be included.

It is suggested that the equation given in chapter 5.1 is used to calculate the water concentration in a typical lake or river in the Nordic countries, when better or more site-specific data are not available. It must, however, be used with some care, especially with regard to the deposition conditions (dry or wet deposition), and the type of area (percentage of the area which is freshwater surface, and type of soil). In areas where the percentage of freshwater surface is particularly small, the concentrations in freshwater may be larger than calculated by the equation.

9.4 Swimming and use of beaches

These exposure pathways are not included in consequence models in common use.

If the content of radioactive materials in sediment was evenly distributed, the surface concentration in an area of exposed sediment could not be significantly larger than the surf e concentration of radioactive materials deposited upon ground in the vicinity. It is found, however, that the concentration in sediment varies strongly; and that there is reason to assume that sites attractive from a recreational point of view have the higher concentration. A probable explanation is that the concentration factor of algae etc. is significantly higher than the concentration factor of the non-organic parts of sediment, and that sediment on the shore consists of a higher portion of the organic parts of sediment.On the other hand, both the size of the potentially exposed population and the exposure time over a year will be quite limited in the Nordic climate. Table 9.1 is taken from a report in the Safety Series published by the International Atomic Energy Agency (Ref. GE82). It gives default values for occupancy rates, but the rates are of a generic nature, and will certainly be too high for Nordic conditions. Furthermore they refer to a critical population group; while the collective dose more than the individual dose is of interest in this connection.

It is concluded that these exposure pathways are of minor importance, where population doses are concerned, but individual doses may perhaps be of importance. A more through investigation need to be performed before it can be decided whether or not this exposure pathway should be included in an accident consequence calculation model meant for use in the Nordic countries.

9.5 Boating and fishing

Compared to the other possible exposure pathways, boating and contact with fish utensiles will be quite unimportant, in connection with a large reactor accident. These exposure pathways are not included in the reactor accident consequence models in common use.

See table 9.1 for values for occupancy rates, recommended by the International Atomic Energy Agency (Ref. GE82) for use if location-specific data are not available. These rates are, however, not for Nordic conditions, and refer to a critical population group. They are not neccessarily valid for Nordic conditions.

9.6 Drinking water

This exposure pathway is not included in consequence models in common use today.

Compared to the other exposure pathways, this exposure pathway is of minor importance after a large reactor accident. In the example calculated in chapter 6, the dose from cesium was actually found to be of the same order of magnitude as the annual natural background dose. In this calculation, one of the largest postulated releases (PWR1) was assumed, and it accordingly difficult to imagine situations where the drinking water pathway might be important.

9.7 Fish as food

This exposure pathway is also not included in present-day consequence models in common use.

Swedish and Finnish results indicate that the dose via freshwater fish might contribute more than 10% of the collective nutrition dose. It might be worth while to pursue this point further; e.g. using some rough calculations. Nevertheless, even at 20%, this exposure pathway would be one of the less important exposure pathways; particularly since it constitutes a rather small part of the average diet. Although it is outside the scope of the present report, it may be mentioned that the same Swedish reference (Ref. MA70) finds the contribution to the nutrition dose via saltwater fish to be roughly half that via freshwater fish, in spite of the fact that the amount of saltwater fish consumed is considerably larger.

9.8 Irrigation

Exposure via irrigation is not calculated in most consequence models in common use.

In chapter 8 in the present report, it is shown by rough evaluations that the irrigation exposure pathways will normally be quite unimportant in connection with large reactor accident consequences; when individual as well as collective doses are concerned.

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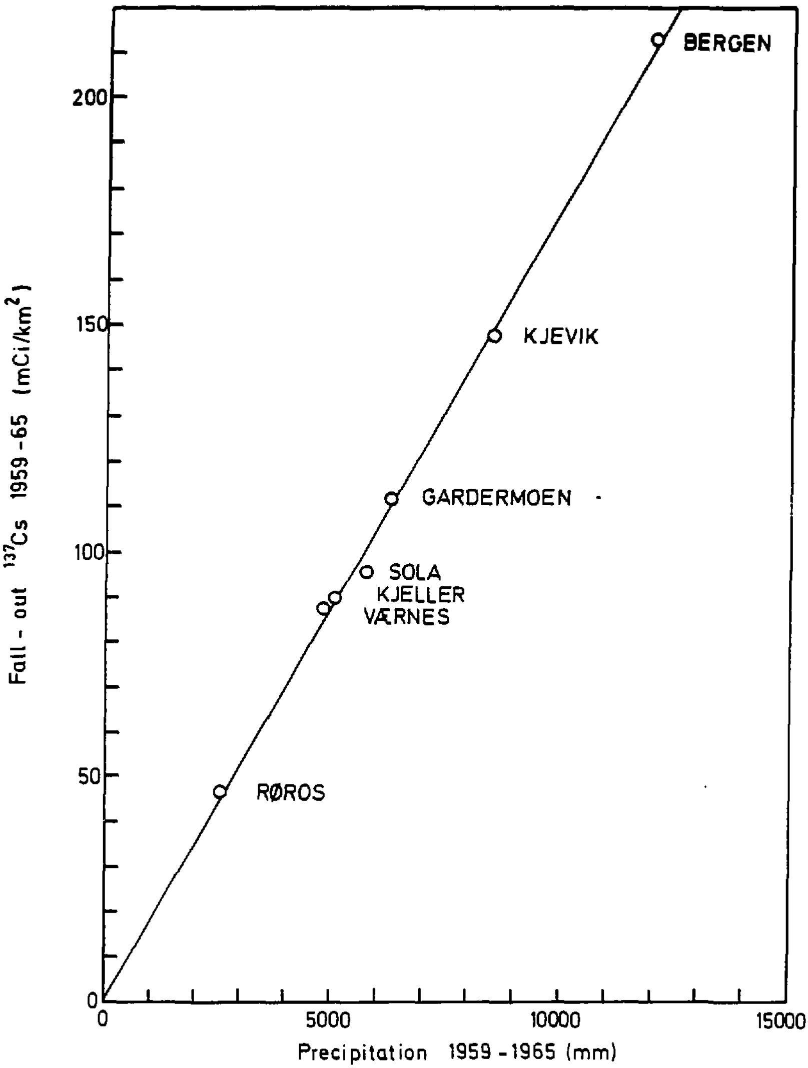

Fig. 4.1 Correlation between yearly precipitation and fall - out for seven locations in Southern Norway.

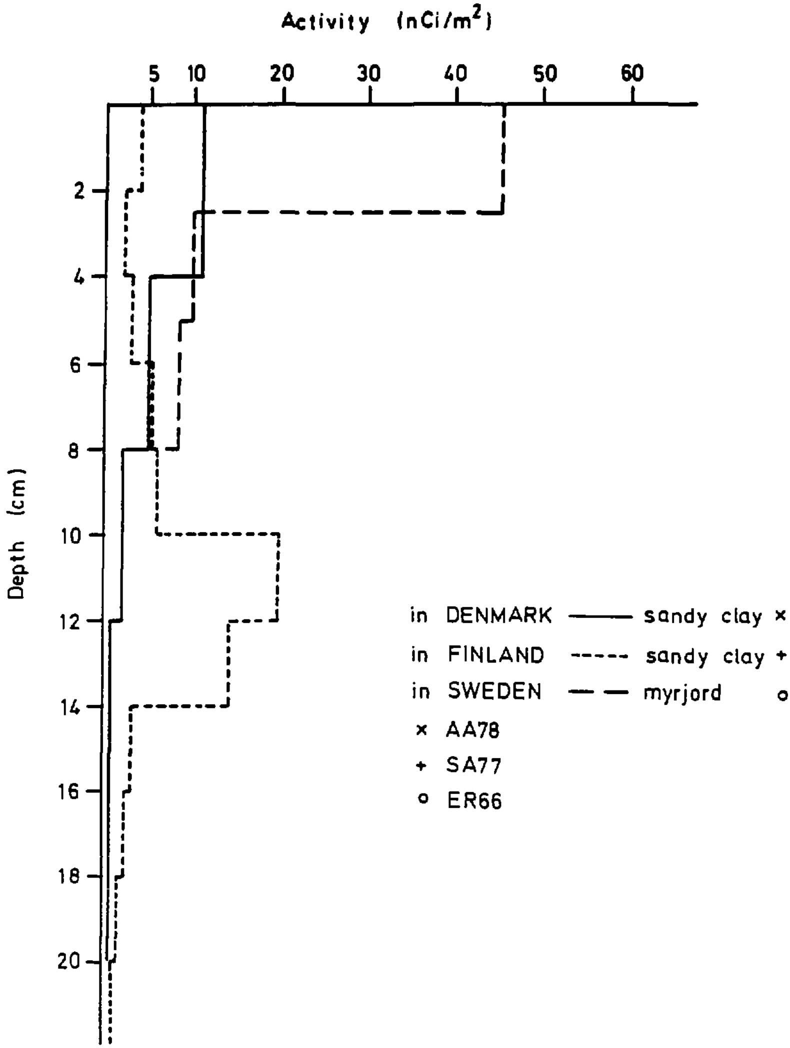

Fig. 4.2 Vertical distribution of Cs - 137 in some types of soil.

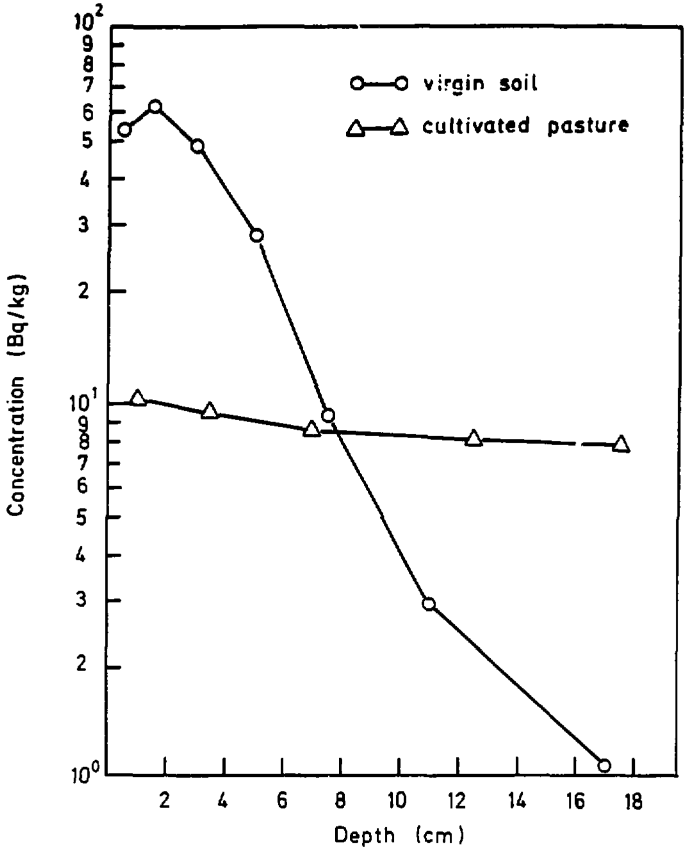

Fig. 4.3 Vertical distribution of Cs-137 in soil in Finland. (Ref. AR83)

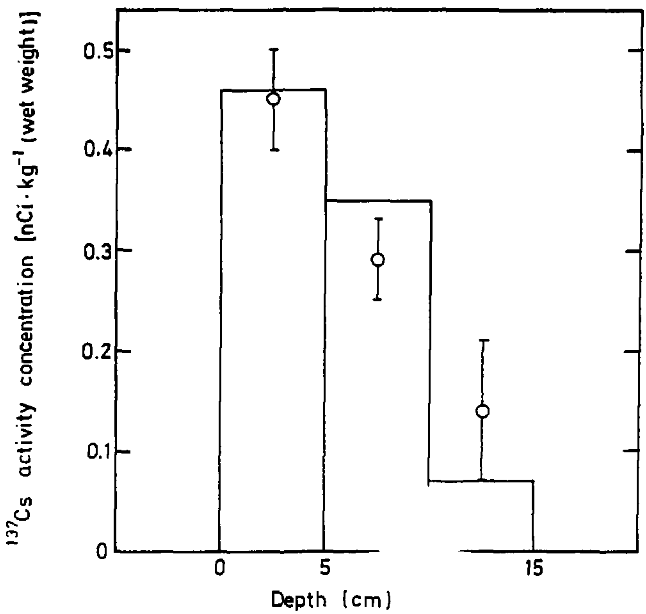

Fig. 5.1. Depth distribution of ^{137}Cs in the sediment as calculated from the mathematical model described in the text. Observed values are also indicated with an uncertainty of 1 S.E. of the mean. (Ref. CA76)

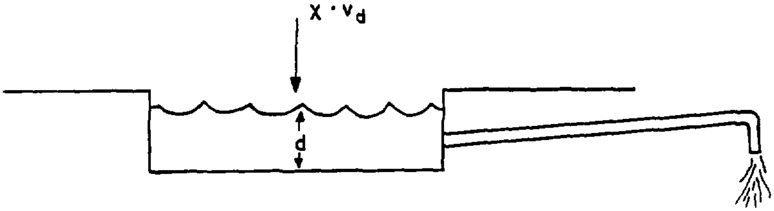

Fig. 6.1 Deposition upon a drinking water reservoir.

River basin	Drainage area (km2)	Lake percentage (%)	Discharge (km3/a)
Kemijoki (KE)	51400	2.9	17
Kokemäenjoki (KO)	27100	11.7	6.8
Kymijoki (KY)	37235	19.1	9.6
Oulujoki (OU)	22925	11.4	8.4
Tornionjoki (TO)	40010	4.9	12

Table 4.1. Data of Finish river basins (Ref. HY80)
(The discharge is the mean discharge 1961-1975)

Time period	Layer			
	0-5cm	5-10cm	10-15cm	15-20cm
Oct. 1960	90%		10%	
1966 - 1967	92%	8%		
1978 - 1979	61%	27%	9%	3%

Table 4.2 Average vertical distribution of Cs-137 in Norwegian soil.

Lake and river system / Lake or river	Cumulative deposition nCi/m²			Cumulative retention nCi/m²			Estimated mean radionuclide amounts in sediment nCi/m²			Estimated radionuclide amounts in the mean water column nCi/m²	
	1969		1978	1969		1978[1]	1969		1978		
	Observed in 1969	Decay-corr. to 1978		Calculated in 1969[1]	Decay-corr. to 1978		Observed in 1969[2]	Decay-corr. to 1978[3]		1969	1978
Cs-137											
Kemijoki	64	52	56	60	49	52					
Kemijärvi							75	61	180	1.1	0.6
Kemijoki							1100	890	430	-	-
Oulojoki	64	52	56	59	48	50					
Ontojärvi							68	56	65	1.5	1.0
Oulojärvi							78	63	76	1.3	0.86
Kokemäenjoki	64	52	56	62	51	55					
Näsijärvi							42	34	91	1.6	1.0
Pyhäjärvi							270	220	340	0.84	0.54
Kymijoki	64	52	56	59	48	52					
Päijänne							37	30	46	4.0	2.6
Sr-90											
Kemijoki	39	31	35	29	24	26					
Kemijärvi							7.0	5.6	7.7	2.9	1.7
Kemijoki							29	23	5.5	-	-
Oulojoki	39	31	35	23	18	20					
Ontojärvi							8.8	7.0	7.5	6.4	3.0
Oulojärvi							4.8	3.8	5.6	5.3	2.5
Kokemäenjoki	39	31	35	25	20	22					
Näsijärvi							5	4	11	17	8.5
Pyhäjärvi							12	9.6	26	9.3	4.6
Kymijoki	39	31	35	20	16	17					
Päijänne							5.5	4.4	7.7	31	16

[1] The outflos subtracted from the deposition
[2] Cs-137 corrected for the relation between leachable and total amount
[3] Corrected for radioactive decay

Table 5.1 Cs-137 and Sr-90 deposition, retention, and amounts in sediments and water column, in some Finnish lakes and rivers (Ref. SA83).

Year	1962	1963	1964	1965	1966	1967	1968
Dairy products	23.0 (41%)	35.1 (37%)	33.8 (25%)	23.7 (30%)	13.4 (29%)	9.7 (30%)	7.4 (29%)
Meat	18.2 (33%)	28.8 (30%)	38.4 (28%)	22.1 (28%)	11.0 (24%)	4.3 (13%)	4.3 (17%)
Grain	- -	13.4 (14%)	33.7 (25%)	13.6 (17%)	5.6 (12%)	2.8 (9%)	1.8 (7%)
Lake fish	2.5 (4%)	2.5 (3%)	6.3 (5%)	6.3 (8%)	6.3 (14%)	5.6 (17%)	3.8 (15%)
Salt water fish	1.6 (3%)	1.6 (2%)	1.6 (1%)	1.6 (2%)	1.6 (3%)	1.6 (5%)	1.6 (6%)
Reindeer meat	5.1 (9%)	5.1 (5%)	11.7 (9%)	6.0 (7%)	4.2 (9%)	6.0 (18%)	5.1 (20%)
Total in-take, incl. "others"	56	87	137	80	46	32	26

Table 7.1. Summary of annual cesium-137 diet intake from various foodstuffs. Sweden. Nationwide averages (nCi/person).

Additional information:

Milk consumption 175 kg (From Nat. Swed. Inst. of Pub. Health)
Cheese " 18 kg (")
Meat " 48 kg (")
Grain " 88 kg (")
(Estimated that 50% in flour and consumption of harvest of the preceding year.)
Reindeer meat consumption 0.3 kg.
Fish consumption 17.6 kg (Estimated that 2.5 kg is lake fish, and the rest salt water fish. About half the lake fish estimated to be from oligotrophic lakes.)
"Others" is estimated to be 10% of the total intake excluding reindeer meat.

Year	Number of new installations	Area served by new installations (decares) (1 decar is 1000 sqm)
1974	-	21,198
1975	-	30,439
1976	671	58,980
1977	1112	151,812
1978	1017	105,740
1979	706	75,107
1980	409	35,316
1981	342	29,804
1982	252	17,055

Table 8.1. Investments in irrigation equipment in Norway.

County	Number of plants	By capacity in m^3/h				Area covered (decares)
		<10	10-24	25-49	>50	
The whole country	10,624	4,175	3,344	1,885	651	703,030
Østfold	578	123	209	177	48	69,768
Akershus and Oslo	544	219	136	106	51	49,986
Hedmark	1,077	332	287	254	158	138,257
Oppland	2,322	703	856	516	142	148,846
Buskerud	1,014	332	304	224	71	74,016
Vestfold	792	258	345	130	26	56,688
Telemark	506	291	107	50	10	17,931
Aust-Agder	677	392	200	47	15	24,343
Vest-Agder	455	254	124	41	16	17,844
Rogaland	460	118	142	113	51	29,810
Hordaland	411	263	115	11	6	10,961
Sogn og F.	1,180	564	366	140	48	41,250
Møre og Roms.	237	144	40	27	2	8,481
S-Trøndelag	86	51	24	4	-	3,234
N-Trøndelag	198	87	68	36	5	8,277
Nordland	51	28	12	8	1	2,338
Troms	24	12	2	1	1	302
Finnmark	12	4	7	-	-	698

Table 8.2. Irrigation plants in Norway up to and including 1979.

Pathway	Occupancy rates (h/a)	Modification factor	
		γ	β
Working over contaminated sediments	2000	1	1
Sunbathing	1000	1	1
Handling fishing gear	2000	0.1	1
Swimming	300	2	1
Boating	2000	1	1

Figure 9.1. Values for occupancy rates recommended by IAEA (Ref. GE82).

Institute for energy technology

«The Institute's mandate is to conduct research and development, analyses etc. within the field of energy, including nuclear research, and other fields particularly suited to the Institute's competence».

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- Process development
- Process modelling and -simulation
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- Fluid- and gas flow technology
- Process control and -supervision
- Nuclear fuel technology
- Safety analyses
- Materials technology
- Radioisotopes for medical- and industrial application
- Physical- chemical analyses
- Radiation instruments and -recording

The Institute is the owner and operator of the Halden Boiling Water Reactor. R & D work connected to the operation of the reactor started in 1958 and is sponsored through an OECD international agreement.

The Institute has 500 employees, 300 at Kjeller and 200 in Halden.

Institute for energy technology
Box 40
N-2007 Kjeller
Norway
Telephone (02) 71 25 60
Telex 76361 energ n

Institute for energy technology
Box 173
N-1751 Halden
Norway
Telephone (031) 83 100
Telex 76335 energ n