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$^{56}$Fe, $^{90}$Sr, $^{134}$Cs, $^{137}$Cs and $^{210}$Pb in the Biosphere

Radiological Health Aspects of the Environmental Contamination from Radioactive Materials in Northern Sweden

Lund 1970
To My Daughter
whose future welfare depends on our understanding of the consequences of environmental pollution.

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Lund 1970
This thesis is based on the following papers by the author:


II  $^{90}$Sr in Northern Sweden; Relationships and Annual Variation from 1961 to 1969 in Lichen, Reindeer and Man. To be published in Health Physics.


These papers will be referred to in the text by the Roman numerals given above.

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INTRODUCTION

During the past two decades scientists in the field of the radiological sciences have increased their efforts to identify and measure the radiation levels to which man is exposed. These investigations have been prompted in large measure by the introduction of radioactive materials into the environment by nuclear-weapons tests and nuclear-power plants.

Man is exposed to natural radiation partly from sources outside his body described as external irradiation and partly from internal irradiation due to radionuclides deposited in the body by contaminated food, water and air.

The most significant sources of external irradiation are cosmic-ray secondaries and γ-rays which penetrate the body and deliver relatively uniform absorbed doses to all of the tissues. The γ-radiation is due to γ-emitting radionuclides of the uranium and thorium decay-series and to ⁴⁰K which are present in the ground. The magnitude of absorbed dose-rate due to cosmic-rays in man living in "normal areas" is about 30 mrad/a and due to γ-rays in the range of 30-65 mrad/a. (UNSCEAR 1966).

The largest natural source of internal irradiation is the potassium isotope ⁴⁰K which delivers a relatively uniform absorbed dose-rate of about 20 mrad/a to all of the tissues in the human body, ²²⁶Ra, ²²⁸Ra and ²¹⁰Po, which originate from the uranium and thorium decay-series, are present in soil and ground-water and may be absorbed by plants and animals, and thus enter the human food-chain. These radionuclides are mainly deposited in bone, and because of their low concentration the absorbed dose-rate from them is only a few mrad/a. But they are α-emitters, and the α-rays have high 'relative biological effectiveness', RBE, which must be taken into account when evaluating possible biological effects. (ICRP/ICRU 1963).

²²²Rn is a radioactive gas originating from the decay of ²³⁸U. It escapes from the ground into the atmosphere and is thus inhaled by man. The irradiation of the respiratory epithelium by inhalation of ²²²Rn and its decay products is responsible for the highest absorbed dose-rate of natural origin to any specific tissue in man. The absorbed dose-rate due to the inhalation of ²²²Rn and its decay products has been estimated to be of the magnitude of some hundreds of mrad/a. (JACOBI 1964).

Another consequence of the presence of ²²²Rn in the atmosphere is the formation of its long-lived decay products ²¹⁰Pb and ²¹⁰Po which are deposited on the ground and thus enter the human food-chain. Certain ecological systems give rise to unusually high concentrations of ²¹⁰Pb and ²¹⁰Po in the human diet, which will be discussed later in this thesis.
Finally there are some minor contributions to the absorbed dose-rate in man which are mainly due to $^{87}$Rb and $^{14}$C.

The total absorbed dose-rate due to external and internal irradiation from natural sources in "normal areas" has been estimated to be about 100 mrad/a (UNSCEAR 1966). There are however also areas with much higher dose-rates due to natural irradiation. Thus the absorbed dose-rates to a population of 100,000 individuals in Kerala, India, is estimated to be about 1300 mrad/a and in one locality in Brazil an absorbed dose-rate of 12,000 mrad/a has been reported. (UNSCEAR 1966).

ENVIRONMENTAL CONTAMINATION DUE TO NUCLEAR-WEAPONS TESTS

The main sources of environmental irradiation other than the natural background experienced by the world’s population, has hitherto been the testing of nuclear-weapons in the atmosphere. The assessment of absorbed dose in man due to such testing is, however, complicated by the widely differing half-lives and elemental composition of the radionuclides which are released. (Table 1).

The $\gamma$-emitting radionuclides deposited on the ground by fallout give rise to external irradiation of man. The deposited radionuclides also give rise to an internal irradiation because they are absorbed by plants and animals and thus deposited in man through different food-chains. The concentration of certain radionuclides in different ecological systems might lead to unusually high radioactivity-concentration in man. For example high concentration of $^{137}$Cs has been found in fish from fresh-water lakes, which might be of importance to people having high consumption of such fish. (HÄSÄΝEN et al. 1963, 1967, KOEHMAINE et al. 1966, LIDÉN 1963, LIDÉN & CARLSSON 1969). Another interesting example is that people consuming great amounts of Pacific salmon have been found to have an unexpectedly high content of $^{55}$Fe. (PALMER & BEASLEY 1965, 1967). It has also been found that Lapps engaged in reindeer-breeding contain unusually high amounts of $^{137}$Cs. (LIDÉN 1961). The food-chain: lichen, reindeer and man has been found to be of great interest when studying the transport of different radionuclides from fallout to man. (SVENSSON & LIDÉN 1965). The present thesis deals with an investigation of certain problems related to the transport of $^{55}$Fe, $^{90}$Sr, $^{134}$Cs and $^{137}$Cs in this food-chain.
TABLE 1

Fission-products and activation-products from nuclear-weapons tests which contribute to environmental contamination.

<table>
<thead>
<tr>
<th>Radionuclides; Type of decay</th>
<th>Fission-products</th>
<th>Activation-products</th>
</tr>
</thead>
<tbody>
<tr>
<td>85 Kr ( \beta )</td>
<td>10.8 a</td>
<td>125 Sb ( \beta,\gamma )</td>
</tr>
<tr>
<td>89 Sr ( \beta )</td>
<td>52.7 d</td>
<td>131 I ( \beta,\gamma )</td>
</tr>
<tr>
<td>90 Sr ( \beta )</td>
<td>28.0 a</td>
<td>137 Cs ( \beta,\gamma )</td>
</tr>
<tr>
<td>90 Y ( \beta )</td>
<td>64.4 h</td>
<td>140 Ba ( \beta,\gamma )</td>
</tr>
<tr>
<td>91 Y ( \beta )</td>
<td>58 d</td>
<td>140 La ( \beta,\gamma )</td>
</tr>
<tr>
<td>95 Zr ( \beta,\gamma )</td>
<td>65.5 d</td>
<td>141 Ce ( \beta,\gamma )</td>
</tr>
<tr>
<td>95 Nb ( \beta,\gamma )</td>
<td>35 d</td>
<td>144 Ce ( \beta,\gamma )</td>
</tr>
<tr>
<td>103 Ru ( \beta,\gamma )</td>
<td>39.5 d</td>
<td>144 Pr ( \beta,\gamma )</td>
</tr>
<tr>
<td>106 Ru ( \beta,\gamma )</td>
<td>1.01 a</td>
<td>155 Eu ( \beta,\gamma )</td>
</tr>
<tr>
<td>106 Rh ( \beta,\gamma )</td>
<td>30 s</td>
<td></td>
</tr>
</tbody>
</table>
PURPOSE OF THE PRESENT INVESTIGATION

This investigation was related to members of the Lapp communities Tännäs and Mittådalen in the Northern part of Sweden (latitude 62° N) near Funäsdalen at the Norwegian border. The purpose was to investigate the transport of the fallout-radiouclides $^{55}$Fe, $^{90}$Sr, $^{134}$Cs and $^{210}$Pb + $^{210}$Po in the food-chain: lichen, reindeer and man. The transport of $^{137}$Cs in this food-chain has been investigated at this institute by Lidén and co-workers. (Svensson & Lidén 1965, Lidén & Gustafsson 1967, Gustafsson 1969, Lidén 1969). An investigation of $^{22}$Na has also been performed by Mattsson (1970).

Since lichen is the initial link in the food-chain, it is important to determine the radionuclide-content of the lichen-carpet and the rate at which these radionuclides are eliminated. Samples of Cladonia alpestris have been collected since 1961 by Lidén and co-workers in the area of Lake Rogen (62, $^{3}$° N, 12, $^{4}$° E). Because reindeer only consume the fresh top-layer of the lichen-carpet it is also of great interest to study the vertical distribution of the radionuclides in the lichen-carpet.

The reindeer-meat is the main meat-component of the Lapps’ diet and therefore it is important to determine its content of the different radionuclides. Due to the special grazing-habits of reindeer, which eat fresh green fodder in Summer and only lichen in Winter, there is a seasonal variation of the radionuclide-intake (Lidén & Gustafsson 1967). This makes it possible to study the metabolism of different radionuclides in detail.

The main purpose of this investigation was to determine the concentrations of the different radionuclides in human tissues and to calculate the absorbed dose due to them. Blood-samples were therefore collected in connection with the whole-body measurements of $^{137}$Cs in the Lapps, which were carried out by Lidén and co-workers. The author also participated in carrying out these measurements in 1964, 1965 and 1966.

ANALYTICAL METHODS AND MEASUREMENTS

The analytical and measuring methods were quite different for each of the radionuclides investigated, since they represented different chemical properties and different types of decay.
$^{55}\text{Fe}$, which decays through electron-capture (EC), emits low energy (5.9 keV) K-X rays and Auger electrons. Because this radiation is absorbed by the sample itself, $^{55}\text{Fe}$ must be separated chemically and electro-deposited on to copper planchets in a thin layer. (I). Thus the samples were reduced to ashes and leached with HCl. The iron was separated from most fission products by adsorption on a HCl-saturated anion-exchange-column and eluted with 0.1 M HCl. The iron was then precipitated with cupferron (ammonium salt of nitrosophenylhydroxylamine) in order to eliminate traces of other elements. After destruction of the cupferrate the iron was electro-deposited on to copper planchets for counting. Spectrometric measurements of the K-X rays were performed in order to identify its origin. The routine measurements were performed with an anticoincidence-shielded gas-flow (argon-ethanol) G.M. -counter.

$^{90}\text{Sr}$ is a $\beta$-emitter with a long half-life and its daughter-product $^{90}\text{Y}$ is also a $\beta$-emitter but with a much shorter half-life. Because a biospheric sample often contains a mixture of radionuclides, $^{90}\text{Sr}$ must be separated chemically before measuring. (II). Thus the samples were reduced to ashes which were dissolved in concentrated acids. Magnesium, calcium and strontium were co-precipitated as phosphates. $^{90}\text{Sr}$ was then separated from Ca and Mg with an ion-exchange method. $^{90}\text{Y}$ was allowed to grow into radioactive equilibrium with the $^{90}\text{Sr}$ present and was then co-precipitated with Fe(OH)$_3$. The $^{90}\text{Y}$-activity was measured with the same G.M.-detector as above at different time-intervals in order to identify the measured activity by its half-life. Finally, $^{90}\text{Sr}$ was precipitated as SrCO$_3$ and measured after ingrowth of $^{90}\text{Y}$.

$^{134}\text{Cs}$, which is a $\beta-\gamma$ emitter, has been measured with $\gamma-\gamma$ coincidence technique because a simple $\gamma$-spectrum is dominated by the large amounts of $^{137}\text{Cs}$ present in the samples. Details about the decay of $^{134}\text{Cs}$ and the $\gamma-\gamma$ coincidence spectrometer are given in paper III. In order to certify the origin of the peaks in the coincidence-spectrum, Cs was separated chemically and measured again. Thus the sample was wet-ashed and the solution passed through a column of asbestos mixed with microcrystalline ammonium dodecamolybdophosphate (AMP) which adsorbs Cs with great selectivity. The AMP-crystals were dissolved in NaOH, and Cs was precipitated by adding chloroplatinic acid. The precipitation was collected on a filter and measured as above.

$^{137}\text{Cs}$, being a $\beta-\gamma$ emitter, can often be measured directly in the sample with a single $\gamma$-detector. However in lichen samples complex $\gamma$-spectra were registered due to the presence of other radionuclides. Therefore $^{137}\text{Cs}$ was separated chemically as above before measuring. Other measuring techniques can also be used in this case. SVENSSON & LIDÉN (1965) resolved the registered $\gamma$-spectra into separate components with numerical data-
technique. Also high resolution $\gamma$-detectors are now available for this purpose.

$^{210}\text{Pb}$, which is a $\beta$-emitter decays to $^{210}\text{Bi}$ which successively decays to $^{210}\text{Po}$, which is an $\alpha$-emitter. The technique for determination of $^{210}\text{Pb}$ and $^{210}\text{Po}$ in biospheric material is given in detail in paper IV. The sample was wet-ashed and after the solution had been made slightly acid, a reducing agent (hydroxylamine or ascorbic acid) was added and a silver or nickel planchet was placed in the solution. The $^{210}\text{Po}$-activity which was spontaneously deposited on the planchet was measured with a high resolution surface-barrier $\alpha$-detector.

RESULTS AND DISCUSSION

Iron-55

After the intensive testing of nuclear-weapons in the atmosphere during 1961-1962, the fraction of $^{55}\text{Fe}$ in the fallout increased steadily. This radionuclide was investigated by the author in lichen and in the diet and blood of Lapps engaged in reindeer-breeding. (I). Preliminary results of this work were presented at the International Symposium on Radioecological Concentration Processes, held in Stockholm 1966. (PERSSON 1967). The $^{55}\text{Fe}$-specific activity in lichen and moss was found to be of the magnitude of 10 nCi per gram of iron in 1961, but increased to about 500 nCi/g during 1963. According to Fig.3 in paper I, the $^{55}\text{Fe}$-specific activity in reindeer-meat and -blood reached the magnitude of 500 nCi/g in Winter 1965-1967, which decreased to about 150 nCi/g in Summer 1965-1966. The retention of $^{55}\text{Fe}$ in reindeer was assumed to follow a single exponential function which adapted to the experimental values indicates a biological half‐time of 150 d. The body‐content of $^{55}\text{Fe}$ in man was estimated by analyzing blood‐samples from the Lapps. The results thus obtained indicated a higher $^{55}\text{Fe}$‐specific activity in women than in men which can be explained by the common iron deficiency in women during the fertile years which causes a higher gastrointestinal absorption of $^{55}\text{Fe}$.

Strontium-90

From the radiotoxicological point of view, $^{90}\text{Sr}$ has always been pointed-
out as being the most hazardous radionuclide in the fallout from nuclear-weapons tests. In the food-chain: lichen-reindeer-man, however, there is a natural discrimination of $^{90}\text{Sr}$ because it is concentrated in the reindeer-skeleton which is not consumed by man. This is one reason why $^{90}\text{Sr}$ has not been so thoroughly investigated in this food-chain as for example $^{137}\text{Cs}$. The author investigated $^{90}\text{Sr}$ in this food-chain (paper II) and found that there was a steady increase of the $^{90}\text{Sr}$-area-content of lichen-carpets after the nuclear-weapons tests in 1961-1962 and a maximum area content of 13 nCi/m$^2$ was reached during 1965. (II). The $^{90}\text{Sr}$/Ca-ratio was investigated in lichen, reindeer-bone and -meat, and relationships were derived from a three-compartment model. This indicated seasonal variations of the $^{90}\text{Sr}$/Ca-ratio which are in agreement with the experimental values. The $^{90}\text{Sr}$/Ca-ratio in adult Lapps has been calculated from an estimated $^{90}\text{Sr}$/Ca-ratio of their total diet.

Cesium-134/Cesium-137

The $\gamma$-spectrum registered by whole-body counting of Lapps showed not only the characteristic peak of 662 keV from $^{137}\text{Cs}$, but also a small deviation at 800 keV, which was caused by $^{134}\text{Cs}$. (LIDÉN & ANDERSSON 1962). The origin of $^{134}\text{Cs}$ in the atmosphere was, however, unknown at that time. The author investigated the $^{134}\text{Cs}/^{137}\text{Cs}$ activity-ratio in different biospheric materials such as lichen, moss, reindeer and also in man. (III). The global inventory of $^{134}\text{Cs}$ was estimated from these results.

A great many of the nuclear-weapons tests performed before 1958 were surface explosions with a total fission-energy of 92 Mton of high explosives. The $^{134}\text{Cs}$-activity released during this period was estimated to be 200 kCi, of which the main part was produced by neutron-activation of $^{133}\text{Cs}$ in soil and the bomb-material. During the last test-period 1961-1962 no surface explosions were reported and the total release of $^{134}\text{Cs}$ was estimated to be 50 kCi of which 10 kCi were formed by fission-process and the remaining 40 kCi by neutron activation.

Lead-210

In addition to the artificial radionuclides $^{55}\text{Fe}$, $^{90}\text{Sr}$, $^{134}\text{Cs}$ and $^{137}\text{Cs}$ the natural radionuclides $^{210}\text{Pb}$ and $^{210}\text{Po}$ have also been observed to have high concentrations in lichen and reindeer. (HILL 1965). Thus it was suggested that the Swedish Lapps who consume a regular diet of reindeer-meat may also have an increased body-content of $^{210}\text{Pb}$ and $^{210}\text{Po}$, and the author therefore investigated $^{210}\text{Pb}$ in this food-chain.
The main source of \(^{210}\)Pb and its decay-product \(^{210}\)Po, in the atmosphere is \(^{222}\)Rn which is exhaled from the ground. However, there are a number of investigators who have reported evidence for the presence of artificial \(^{210}\)Pb in the atmosphere as a result of nuclear-weapons tests. (STEBBINS 1961, JAWOROWSKI 1966, 1969, KREY 1967, and PEIRSON et al. 1966). But there are also others who have found no evidence for production of \(^{210}\)Pb by nuclear-weapons tests. (BIHANDARI et al. 1966, PATTERSON & LOCKHART 1964, RAMZAEV et al. 1969, BEASLEY 1969, and BLANCHARD & MOORE 1970).

The content of \(^{210}\)Pb in lichens collected in the actual area during the period of 1961-1969 has been investigated by the author. No maximum was found in 1963-1965 similar to those found for \(^{137}\)Cs, investigated by LIDÉN & GUSTAFSSON (1969) and for \(^{55}\)Fe and \(^{90}\)Sr which were investigated by the author. (I, II). Thus there was no evidence of significant amounts of \(^{210}\)Pb released by nuclear-weapons tests during 1961-1962.

The \(^{210}\)Pb-content of reindeer-bone and-meat from the district of Funäsdalen has also been investigated by the author and the results are presented in this thesis in Table 2, together with a summary of previously published data from Alaska (BEASLEY & PALMER 1966, BLANCHARD & MOORE 1970, HOLTZMAN 1966), Canada (HILL 1965), Finland (KAURANEN & MIETTINEN 1969) and the U.S.S.R. (RAMZAEV et al. 1967). There is a fairly good agreement between the values of the \(^{210}\)Pb-content of reindeer-bone and-meat from Sweden, Alaska and Finland but the values from the U.S.S.R. are about twice as high and show a greater spread. The mean values given in the table take no consideration of latitudinal and seasonal variations, which are necessary for getting an accurate comparison. These variations are, however, of less significance than the biological and sampling variability.

The \(^{210}\)Pb-activity concentration in blood from Lapps living in this area was also investigated. The samples were taken in mid-June in 1968 and 1969 and the results are given in Table 3, together with previously reported data from Alaska and Finland. (BLANCHARD 1967, BLANCHARD & MOORE 1970, KAURANEN & MIETTINEN 1969). Measurements of the \(^{210}\)Pb-activity concentration in different tissues of Alaskan residents indicate a gonad/blood ratio of 4.3 in persons having a steady diet of reindeer- and caribou-meat. The average \(^{210}\)Po/\(^{210}\)Pb-activity ratio in gonad-tissues was determined to be \(3.7 \pm 0.3\). Thus by using the estimated \(^{210}\)Pb-activity concentration in blood from living Eskimos the \(^{210}\)Po-activity concentration in the gonads was estimated to be about 100 pCi/kg w.w. The corresponding value for Finnish Lapps, which has been estimated by KAURANEN & MIETTINEN (1969) from measurements of \(^{210}\)Pb and \(^{210}\)Po in placentas from Lapps were 85 pCi/kg w.w. The \(^{210}\)Po-activity concentration in the gonads of Swedish Lapps
TABLE 2

$^{210}$Pb-content and $^{210}$Po/$^{210}$Pb-activity ratio measured in lichen and reindeer-tissues in Alaska (BLANCHARD & MOORE 1970, BEASLEY & PALMER 1966, HOLTZMAN 1966), Canada (HILL 1965), Finland (KAURANEN & MIETTINEN 1969), the U.S.S.R. (RAMZAEV et al. 1967) and in Sweden (this work). *pre-1951

<table>
<thead>
<tr>
<th>Country</th>
<th>Lichen nCi/kg d.wt.</th>
<th>Reindeer-tissues pCi/kg w.w.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>210Pb</td>
<td>210Po/210Pb</td>
</tr>
<tr>
<td>Alaska</td>
<td>16 ± 12</td>
<td>-</td>
</tr>
<tr>
<td>Canada</td>
<td>13 ± 8</td>
<td>0.96</td>
</tr>
<tr>
<td>Finland</td>
<td>3.5</td>
<td>1.0</td>
</tr>
<tr>
<td>U.S.S.R.</td>
<td>6.8 ± 0.5</td>
<td>0.94</td>
</tr>
<tr>
<td>Sweden (this work)</td>
<td>8 ± 1</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>7 ± 1</td>
<td>-</td>
</tr>
</tbody>
</table>
TABLE 3

210Pb-activity concentration (pCi/kg w.w.) in tissues of Lapms, Eskimoes and others in Alaska (BLANCHARD 1967, BLANCHARD & MOORE 1970), Finland (KAURANEN & MIETTINEN 1969), and Sweden (this work).

*Estimated values

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Group</th>
<th>Sex</th>
<th>Blood</th>
<th>Gonads</th>
<th>Bone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>210Pb</td>
<td>210Po/210Pb</td>
<td>210Pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eskimoes</td>
<td>M</td>
<td>6 *</td>
<td>1 *</td>
<td>30 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>4.4*</td>
<td>&quot;</td>
<td>20 *</td>
</tr>
<tr>
<td>Alaska</td>
<td>1968</td>
<td>non-Eskimoes</td>
<td>M</td>
<td>1</td>
<td>0.2</td>
<td>6 ± 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>2</td>
<td>0.6</td>
<td>6 ± 2</td>
</tr>
<tr>
<td>Finland</td>
<td>1966</td>
<td>Lapps</td>
<td>M+F</td>
<td>7</td>
<td>1.9</td>
<td>30 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.7</td>
<td>0.3</td>
<td>7 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-Lapps</td>
<td>M+F</td>
<td>5.3 ± 0.5</td>
<td>1.7 *</td>
<td>23 *</td>
</tr>
<tr>
<td>Sweden</td>
<td>1968</td>
<td>Lapms</td>
<td>M</td>
<td>4.5 ± 0.5</td>
<td>&quot;</td>
<td>20 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>3.2 ± 0.3</td>
<td>&quot;</td>
<td>15 *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(this work)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lapps</td>
<td>M</td>
<td>4.5 ± 0.5</td>
<td>&quot;</td>
<td>20 *</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td></td>
<td>F</td>
<td>3.2 ± 0.3</td>
<td>&quot;</td>
<td>15 *</td>
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</table>
was estimated from measurements of the $^{210}\text{Pb}$-activity concentration in blood. By using the $^{210}\text{Pb}$-gonad/blood-ratio of 4.3 and the $^{210}\text{Po}/^{210}\text{Pb}$-activity ratio of 3.7 for the gonads, the $^{210}\text{Po}$-activity concentration was estimated to be 80 pCi/kg w.w. in testes and 60 pCi/kg w.w. in ovaries of the Swedish Lapps. The $^{210}\text{Pb}$- and $^{210}\text{Po}$-activity concentrations in the skeleton of Swedish Lapps were also estimated from the corresponding values in Alaska and Finland given in Table 3. The activity-concentrations of $^{210}\text{Pb}$ and $^{210}\text{Po}$ in the skeleton of Swedish Lapps thus estimated were 100 pCi/kg w.w., and 80 pCi/kg w.w. respectively. The $^{210}\text{Pb}$-activity concentration in the skeleton of Lapps from the U.S.S.R. has been reported to be 120 pCi/kg w.w. (RAMZAEV et al. 1967).

**ABSORBED DOSE IN MAN**

**Radiological health aspects**

When considering the absorbed dose in the tissues of the subjects exposed to natural and artificial sources of radiation, some tissues are more likely to be relevant when discussing possible radiation-effects. For this purpose it is reasonable to consider the absorbed dose in the gonads (ovaries and testes) to be relevant on genetical grounds and this absorbed dose in general will be represented by the absorbed dose in the soft tissues of the body. In relation to long term somatic effects the tissues associated with bone should be given attention, both because the blood-forming tissues are contained in the bones and because some of the long-lived radionuclides are deposited preferentially in them. The absorbed dose will be calculated therefore, partly for osteocytes and the cells lining the Haversian canals, because these tissues are concerned with bone-maintenance and repair and partly for cells on or near endosteal surfaces, particularly in trabecular bone because there are grounds for considering these tissues to be sites of radionuclides. The calculations were also performed for the active bone marrow in trabecular cavities, being blood-forming tissues and thus of interest in the discussion of possible onset of leukaemia. (ICRP 1966, 1968, 1969).

The absorbed dose delivered by artificial radionuclides is usually given by the concept of "dose commitment" which is the total absorbed dose received by a significant tissue in unlimited time after a particular release of radioactive material in the environment. (LINDELL 1960). Within 50-60 years most of the "dose commitment" will have been delivered from all of the radionuclides
released by a nuclear explosion except for $^{14}$C. Only 8% of the "dose commitment" from $^{14}$C will have been delivered during this period. The contribution of "dose commitment" delivered by the year 2000 from all nuclear-weapons tests carried out before 1968 has been reported by UNSCEAR (1969).

The total absorbed dose due to nuclear-weapons tests as given in this work will be relevant for adult Lapps living during the period of 1950-2000. As the "dose commitment" is not the absorbed dose to an individual but the total absorbed dose to cells of a particular tissue within members of the present and future populations, the two concepts are somewhat difficult to compare.

**External irradiation**

The absorbed dose-rate in man due to cosmic rays at sea-level is normally about 30 mrad/a due to the ionizing component and 0.7 mrad/a due to neutrons. For the Lapps engaged in reindeer-breeding the absorbed dose-rate from the ionizing component of cosmic rays has been estimated to be about 38 mrad/a. (GUSTAFSSON 1969).

Practically all the natural environmental radiation of terrestrial origin is due to radionuclides of uranium and thorium-decay series and to $^{40}$K. This component of the absorbed dose-rate has been estimated to be about 44 mrad/a in the air in the area where the Lapps are living (GUSTAFSSON 1969). The attenuation factors given by SPIERS & OVERTON (1962) have been used to calculate the absorbed dose-rate in female and male Lapps respectively and the values thus obtained are given in Table 4.

The absorbed dose in man from external irradiation due to fallout was estimated from exposure measurements performed at Idre, a place not far from Funäsdalen. (SWEDJEMARK & HÅKANSSON 1969). In fresh fallout there were contributions from both long-lived $^{137}$Cs and short-lived radionuclides (Table 1). The division of the total exposure in contribution from short-lived radionuclides and from $^{137}$Cs, was performed according to a detailed study recently reported by GIBSON et al. (1969). The combined shielding-, screening- and conversion-factor of 0.4 was used to convert the exposure registered into absorbed dose in man. (GUSTAFSSON 1969). The absorbed dose thus obtained due to $^{137}$Cs during 1950-2000 was 58 mrad and due to the short-lived radionuclides 56 mrad.
Internal irradiation

The absorbed dose due to $^{40}$K, which is naturally present in the body, has been calculated by using the average potassium-concentrations of 2.4 g/kg in men and 1.7 g/kg in women as reported by LIDÉN & GUSTAFSSON (1967). The average absorbed dose-rate delivered to the gonads calculated from these data was 22 mrad/a for testes and 16 mrad/a for ovaries. The calculation of corresponding doses in bone and bone-marrow has been carried out according to SPIERS (1968).

The $^{210}$Po-activity concentration in gonad-tissues of the Swedish Lapps was estimated to be 60 pCi/kg w.w. in female and 80 pCi/kg w.w. in male. The dose-rate in soft-tissues having a $^{210}$Po-activity concentration of 1 pCi/kg w.w. is 0.1 mrad/a. Thus the absorbed dose delivered by $^{210}$Po to the gonads of female Lapps was 6 mrad/a and of male Lapps 8 mrad/a.

The absorbed dose-rate to different bone-tissues was calculated according to CHARLTON & CORMACK (1962) and SPIERS (1968). With an average $^{210}$Po-activity concentration in the skeleton of 80 pCi/kg w.w., the absorbed-dose-rate in the osteocytes was 8.5 mrad/a, in cells lining the Haversian canals 5.0 mrad/a and in the cells lining the surfaces of trabecular bone 1.4 mrad/a. If the $^{210}$Po-activity concentration in bone-marrow was assumed to be the same as in blood the total absorbed dose in bone-marrow was 1.0 mrad/a. The absorbed dose-rates in the gonads due to $^{210}$Po are about 10-20 times higher for Lapps than those considered for normal areas by UNSCEAR (1966) and in Haversian canals and bone-marrow about three times higher.

There are also minor contributions to the absorbed dose in man due to $^{87}$Rb, $^{14}$C, $^{226}$Ra, $^{228}$Ra and $^{222}$Rn. Because of lack of relevant information about these radionuclides in Lapps, the absorbed dose-rates due to them are assumed to be the same as those reported by SPIERS (1968).

The radionuclides released by nuclear-weapons tests are deposited in Lapps with varying efficiency after their incorporation into lichen and reindeer. The total absorbed dose to be received by the Lapps by the year 2000 from the fallout-radionuclides $^{55}$Fe, $^{90}$Sr, $^{134}$Cs, and $^{137}$Cs will be summarized here and the results are given in Table 5. In case of $^{14}$C the "dose commitment"-value given by UNSCEAR(1969) has also been used for the Swedish Lapps.

The absorbed dose in the Lapps due to $^{55}$Fe has been studied in detail by the author (II). Thus the absorbed dose to be received by the year 2000 from $^{55}$Fe in gonads and cells lining the bone-surfaces of female and male Lapps was estimated to be 5.6 mrad and 2.2 mrad respectively. Corresponding values for the osteocytes and bone-marrow were estimated to be 3.2 for female Lapps and 1.3 for male Lapps.
The absorbed dose delivered by $^{90}\text{Sr} + ^{90}\text{Y}$ was estimated by the author in paper II. The values thus obtained for the period of 1950-2000 were 80 mrad in the endosteum and 50 mrad in the active bone-marrow. The absorbed dose in the osteocytes and cells lining the Haversian canals was estimated to be 100 mrad by using the dose-rate constants given by SPIERS (1968).

The most significant internal contamination of Lapps is that due to $^{137}\text{Cs}$. The body-content of $^{137}\text{Cs}$ in Swedish Lapps has been reported by SVENSSON & LIDÉN (1965), LIDÉN & GUSTAFSSON (1967) and LIDÉN (1969). The time-integral of the $^{137}\text{Cs}$-body-content up to the year 2000 was calculated from these reported results. The values thus obtained were 140 nCi-a/kg for male Lapps and 95 nCi-a/kg for female Lapps from the area of Funäsdalen.

The absorbed dose due to $^{137}\text{Cs}$ in different tissues was calculated according to the following equation,

$$D_T = Q_{Wb} \left( \Delta \beta \cdot \frac{C_T}{C_{Wb}} + \Delta \gamma \cdot \frac{M_{Wb}}{M_T} \cdot \phi_T \right) \text{ mrad}$$

$Q_{Wb} =$ Time-integral of the $^{137}\text{Cs}$-activity concentration in the whole body (nCi-a/kg)

$C_T =$ Potassium-concentration in actual tissue

$C_{Wb} =$ Average potassium-concentration of the whole body

$M_T =$ Mass of actual tissue (kg)

$M_{Wb} =$ Mass of total body (70 kg)

$\Delta \beta =$ Absorbed dose constant for short-range radiation, (4.8 kg-mrad/nCi-a).

$\Delta \gamma =$ Absorbed dose constant for long-range radiation, (10.4 kg-mrad/nCi-a).

$\phi_T =$ Absorbed fraction: the energy due to $\gamma$-radiation from $^{137}\text{Cs}$ in the total body, which is absorbed in the actual tissue.

The dose-constant and absorbed fraction were obtained from LOEVINGER & BERMAN (1968), DILLMAN (1969) and SNYDER et al. (1969).

The time-integral of $^{134}\text{Cs}$-body-content was calculated by using the $^{134}\text{Cs}/^{137}\text{Cs}$-activity-ratios given by the author in paper III. The values thus obtained were 0.45 nCi-a/kg for female and 0.7 nCi-a/kg for male Lapps up to the year 2000, which correspond to absorbed doses in soft-tissues of 6 mrad and 9 mrad respectively.
TABLE 4

Absorbed dose-rates arising from natural irradiation given for Lapps in the investigation area.

<table>
<thead>
<tr>
<th>Radiation source and type of radiation</th>
<th>Absorbed dose-rates (mrad/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soft tissues, gonads</td>
</tr>
<tr>
<td></td>
<td>F</td>
</tr>
<tr>
<td><strong>External irradiation</strong></td>
<td></td>
</tr>
<tr>
<td>Cosmic rays:</td>
<td></td>
</tr>
<tr>
<td>Ionizing component</td>
<td></td>
</tr>
<tr>
<td>Neutrons</td>
<td></td>
</tr>
<tr>
<td>Terrestrial irradiation</td>
<td></td>
</tr>
<tr>
<td><strong>Internal irradiation</strong></td>
<td></td>
</tr>
<tr>
<td>$^{40}$K $\beta + \gamma$</td>
<td>16</td>
</tr>
<tr>
<td>$^{87}$Rb $\beta$</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{14}$C $\beta$</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{226}$Ra $\alpha$</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{228}$Ra $\alpha$</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{210}$Po $\alpha$</td>
<td>6</td>
</tr>
<tr>
<td>$^{222}$Rn + decay products in air</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>87</td>
</tr>
<tr>
<td>Radiation source and type of radiation</td>
<td>Absorbed dose (mrad)</td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Cortical bone</td>
<td></td>
</tr>
<tr>
<td>Trabecular bone</td>
<td></td>
</tr>
<tr>
<td>Soft tissues, gonads</td>
<td></td>
</tr>
<tr>
<td>Osteocytes</td>
<td></td>
</tr>
<tr>
<td>Cells lining the Haversian canals</td>
<td></td>
</tr>
<tr>
<td>Cells lining bone-marrow</td>
<td></td>
</tr>
</tbody>
</table>

External irradiation

<table>
<thead>
<tr>
<th>External irradiation</th>
<th>( {^{131}I} )</th>
<th>( {^{137}Cs} )</th>
<th>( {^{55}Fe} )</th>
<th>( {^{89,90}Sr} )</th>
<th>( {^{90}Sr} )</th>
<th>( {^{131}I} )</th>
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<tbody>
<tr>
<td>( \beta )</td>
<td>13</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Total</td>
<td>910</td>
<td>1270</td>
<td>760</td>
<td>1000</td>
<td>760</td>
<td>760</td>
</tr>
</tbody>
</table>

Internal irradiation

<table>
<thead>
<tr>
<th>Internal irradiation</th>
<th>( {^{131}I} )</th>
<th>( {^{137}Cs} )</th>
<th>( {^{55}Fe} )</th>
<th>( {^{89,90}Sr} )</th>
<th>( {^{90}Sr} )</th>
<th>( {^{131}I} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>770</td>
<td>1130</td>
<td>760</td>
<td>1000</td>
<td>760</td>
<td>760</td>
</tr>
</tbody>
</table>

Cumulative absorbed dose from fallout released by nuclear-weapon tests done prior to 1969, calculated for Lapps in the investigation-area up to the year 2000.
CONCLUSION AND SUMMARY

The total absorbed dose to be received by the Swedish Lapps from natural sources is estimated in this work to be 4400 mrad during the 50 year-period of 1950-2000, which is somewhat lower than the value of 5000 mrad proposed for "normal areas" by UNSCEAR (1966). Because of the higher $^{210}$Po-content in Lapps, a greater fraction of the absorbed dose, $D$, in them is due to $\alpha$-rays which have a high relative biological effectiveness (ICRP/ICRU 1963). For radiation-protection purposes a quality factor, $QF$, of 10 should be used for $\alpha$-particles when calculating the dose-equivalent, $DE$, : $DE = D \times QF$ (ICRU 1968, ICRP 1966). This means that the dose-equivalent for Lapps is about the same as for people in normal areas according to SPIERS (1968) when cells lining the bone-surfaces and bone-marrow are considered, but slightly higher when the gonad-tissues and cortical bone-tissues are considered.

The average absorbed dose-contribution in Lapps due to fallout from the nuclear-weapons tests should be about 1100 mrad for men and 800 mrad for women during this 50 year-period.

It is very difficult to estimate possible biological effects from the small absorbed dose due to artificial fallout. One way to illustrate the effect is in terms of 'comparative risk' which is the period of time during which the normal natural background (100 mrad/a) would deliver an absorbed dose corresponding to that due to fallout by the year 2000. Thus for the Swedish Lapps this time interval is 12 years for men and 9 years for women in respect to the gonads and bone-marrow which receive the highest absorbed dose. Corresponding values for the whole world-population estimated by UNSCEAR (1969) are 11 months for gonads, 26 months for cells lining bone-surfaces and 18 months for bone-marrow.

Another method for judging possible effects from low irradiation-levels is to estimate the range within which effect may be expected. This is done by defining "order of risk"; a sixth order of risk thus implies that the probability of a somatic injury to any individual is in the range of $1 \times 10^{-6}$-10$\times 10^{-6}$, that is to say 1 to 10 events could be expected per million exposed persons. For a normal-background radiation-level (100 mrad/a) the probability of somatic injury is of the sixth order based on the hypothesis that risk for somatic effects is linearly related to the absorbed dose also at very low absorbed dose-values. (ICRP 1966). This means that hypothetically 0-2 cases of somatic effects due to normal-background radiation might be expected in the entire population of about 3000 Swedish Lapps engaged in reindeer-breeding during the 50 year-period of 1950 to 2000. Additional contributions to the absorbed dose in Lapps stemming from radionuclides produced by nuclear-weapons tests and from atmospheric $^{210}$Pb will not add any further cases to those 0-2 hypothetically due to normal background-irradiation.
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