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FOREWORD

As a result of nuclear accidents, nuclear weapons tests and the long term activities of a range of nuclear installations, radionuclides have been deposited in regions where there is a significant forest industry. The best-known examples are the forests in the countries of the Former Soviet Union (FSU), as well as forests in some Nordic countries, which were contaminated with long lived radionuclides such as ^{137}Cs, ^{90}Sr and ^{134}Cs after the Chernobyl accident in 1986.

Inhabitants of radioactively contaminated areas receive direct radiation exposure when visiting forests because of radionuclide retention in the tree canopy and soil litter. They may also be exposed as a result of the consumption of game, wild mushrooms and berries containing elevated levels of radionuclides, especially caesium. Another important exposure pathway results from the harvesting, processing and use of timber and wood products from contaminated forest areas; the timber and wood products become sources of potential external and internal exposure for humans.

It was foreseen soon after the Chernobyl accident that contaminated forests could become significant long term contributors to human radiation exposure and for this reason, studies of forest radioecology and associated radionuclide transfer modelling were accelerated. This resulted in notable progress in the field during the 1990s. For instance, the IAEA developed a Forest Model (FORM) in 1995–1999 for decision aiding support relevant to contaminated forests. This model, and several other radioecological forest models from different countries, were assessed and compared within the framework of the IAEA Programme on BIOsphere Modelling and ASSessment (BIOMASS) in 1998–2000.

An important application of these models is in relation to the potential use by members of the public of commodities, in this instance those based on wood, which may have been contaminated by radionuclides. Such models can be used to derive the relationship between the concentration of the radionuclides in the wood product and radiation dose, which would result from their use. The modelling results, in the form of dose conversion coefficients, can then be used for the purpose of screening level dose assessment and for the derivation of standards for wood contamination, expressed in terms of limiting activity concentrations, which can be applied to assure public protection. Such standards would be particularly useful at the international level in view of the transboundary trade in these materials. This report describes a methodology for calculating both the conversion coefficients and standards of radionuclide concentrations in wood. The report also presents a set of numerical values of the dose conversion coefficients and recommendations on their use in country specific conditions.

This work was initiated following a request in 1999 to the IAEA from the United Nations Development Programme (UNDP) in the Russian Federation and from the Federal Forestry Service of the Russian Federation. It was implemented through a series of consultants meetings in 2000. The IAEA officers responsible for this publication were M. Balonov, C. Torres and F. Gera of the Division of Radiation and Waste Safety.

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1. INTRODUCTION

1.1. Background

In the event of a nuclear accident involving the release of radionuclides to the biosphere the radioactive contamination of forests can become a significant potential source of public radiation exposure. Two of these accidents — the Kyshtim accident, Urals, USSR (now Russian Federation) in 1957 and the Chernobyl accident, USSR (now Ukraine), in 1986 — resulted in significant contamination of thousands of square kilometres of forested areas with mixtures of radionuclides including long lived fission products such as ^{137}Cs and ^{90}Sr[1]. Measurements and modelling of forest ecosystems after both accidents have shown that, following initial contamination, the activity concentration of long lived radionuclides in wood gradually increases over one to two decades and then slowly decreases in the subsequent period. The longevity of the contamination is due to the slow migration and persistent bioavailability of radionuclides in the forest soil profile, which results in long term transfer into wood through the root system of the trees.

Another source of contamination is from global radioactive fallout after nuclear weapons tests, but the level of contamination is much lower than that from, for example, the Chernobyl accident. For instance, the level of ^{137}Cs in wood in Sweden is about 2–5 Bq kg^{-1} from global fallout. Global values are very similar to the Swedish levels. In contrast, the level of ^{137}Cs in Swedish wood due to Chernobyl is around 50 Bq kg^{-1}. Levels in wood from some contaminated areas located in countries of the Former Soviet Union (FSU) are about one to two orders of magnitude higher than this.

The data on ^{137}Cs soil contamination within European territories, originating mainly from the Chernobyl accident, illustrate the scale of the problem and are presented in Table I. For comparison, residual ^{137}Cs soil deposition in Europe from global radioactive fallout was in the range 1–4 kBq m^{-2} [1]. Table II, based on statistical data of the Food and Agricultural Organization [2], illustrates the scale of international trade in timber in which some of the countries with contaminated forest areas are involved.

There is concern in several countries about the potential radiation exposure of people from radionuclides in wood, especially after the Chernobyl accident. In the Former Soviet Union countries, provisional standards for long lived radionuclide levels in wood used for different industrial and domestic purposes have been established since 1986 and regularly updated. Some national scenarios of timber processing and use were modelled to substantiate these standards. In January 1996, a system of certification of commodities was implemented in the Russian Federation whereby the activity concentration of ^{137}Cs and ^{90}Sr in timber to be exported has to be measured and specified. According to this system, any portion of timber released from contaminated areas must meet national standards.

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[1] In the context of this publication, which is devoted to radiation protection of the public against current exposure, the term "long lived radionuclide" is applied to ^{137}Cs and ^{90}Sr with half-lives of about 30 years contrary to usual waste safety terminology where this term is usually used for radionuclides with half-lives of about thousand and more years.

TABLE I. THE AREAS IN EUROPEAN COUNTRIES WITH SIGNIFICANT (ABOVE 40 kBq m^{-2}) SOIL DEPOSITION OF ^{137}Cs IN MAY 1986 [1]

Country	Surface area, km^2 (× 10^3)	Areas (km^2 × 10^3) with ^{137}Cs soil deposition (kBq m^{-2}) in the range: 40–100	100–185	185–555	555–1480	> 1480
Austria	84	11	0.08			
Belarus	210	21	8.7	9.4	4.4	2.6
Finland	340	19				
Norway	320	7.1	0.08			
Russia (European part)	3800	44	7.2	5.9	2.2	0.46
Sweden	450	23	0.44	<0.01		
Ukraine	600	29	4.3	3.6	0.73	0.56
Total in Europe	9,700	160	25	20	8.1	2.8

TABLE II. EXPORT OF FOREST INDUSTRIAL PRODUCTS (m^3 × 10^3) FROM SOME EUROPEAN COUNTRIES IN 1997 [2]

Wood product	Finland	Sweden	Russian Federation	Norway	Ukraine	Belarus
Industrial roundwood	10 161	8210	17 845	1940	465	513
Sawnwood	7535	10 922	5026	704	243	295
Newsprint and other paper (1000 Mt)	1753	2884	1447	532	55	3.1
Wood pulp (1000 Mt)	1195	397	985	258	0.5	0.5
Plywood, hardboard, veneer sheets, etc	640	1393	974	467	38	377
Wood fuel	161	251	908	191	14	0.15
Chips and particles	4	NR	554	–	–	NR
Total costs, USD×106	10 406	10 258	3009	1641	117	73
Major importing countries	Sweden, Egypt, Japan, United Kingdom, Germany	Norway, Hungary, Denmark, United Kingdom, Germany, Netherlands, France	Japan, Finland, Sweden, China, Egypt, United Kingdom, Switzerland, Hungary	Sweden, Denmark Germany, Netherlands, United Kingdom	Hungary, Turkey, Slovakia, Germany, Italy	Finland, Lithuania, Norway, Germany, Netherlands

Mt = metric tonne; NR = no record

However, at present, there is no universal radiological standard that is being applied in all countries. Such an international standard, if adopted, could facilitate the free trade of wood and wood products between countries and at the same time provide reassurance to national regulators and users of the wood products. The work described in this report is intended to provide a technical basis for the development of such standards, whether national or international.

In this publication, a generic methodology has been developed which can be used both for screening and specific level assessments of the dose to the public caused by industrial treatment and/or domestic use of wood contaminated with long lived radionuclides in natural conditions of areas historically affected by major radioactive releases. The methodology can be also applied to determine the long lived radionuclide activity concentrations in wood, which would not result in public exposure exceeding appropriate radiological standards.

1.2. Objectives

The objectives of this report are the following:

(a) to develop a generic methodology to determine:

- the dose to members of the public resulting from the presence of long lived radionuclides such as ^{137}Cs and ^{90}Sr in wood used for industry and household applications;
- reference levels of ^{137}Cs and ^{90}Sr in wood for commercial and household use which correspond to a specified radiological standard;

(b) to calculate a set of generic dose conversion coefficients and develop guidance for their application to assess the dose to the public and to derive reference levels for ^{137}Cs and ^{90}Sr in wood;

(c) to test this methodology for forested areas in the Russian Federation contaminated with radionuclides.

The ultimate goal of the dose assessment procedures described in Sections 4, 5 and 6 of this report, is to check that radiation exposure of the public, associated with the treatment and use of wood contaminated with radionuclides, is in compliance with established radiological standards. The data obtained from radiation monitoring, e.g. measurement of radionuclide concentrations in wood, or data obtained from radioecological modelling can be used as input data for such dose assessments. It is envisaged that the approach used to develop the dose assessment methodology, as well as the system-specific example, could also be used in training activities.

1.3. Scope of application

In developing the methodology presented in this report the following conceptual restrictions were assumed.

- Only issues of dosimetry and radiation protection of humans associated with radionuclide presence in wood and wood products are considered. Models of radionuclide transfer in the forest ecosystem and of the human exposure in conditions of a forest contaminated with radionuclides are presented in other IAEA technical publications, i.e. in [3] and [4], correspondingly.
- Even though the scenarios and the dosimetric models are generic, parameter values are given and calculations are performed for ^{137}Cs and ^{90}Sr only. Wherever necessary, the list of radionuclides could be extended;
- Wood processing technologies and uses are based on present day industrial practices in developed European countries located in Nordic or temperate climate zones. To apply the developed methodology in the countries located in tropical zones, or countries where other technologies are traditionally used, changes of parameter values and/or some scenarios could be necessary prior to application of the proposed framework;
- Deterministic models that utilize the best and moderately conservative (i.e. health protective) estimates of default parameter values are used in this guidance. Many parameters are highly uncertain, but their stochastic nature is not explicitly considered in our calculations. This approach may be acceptable for screening dose assessment

procedures if assessed doses are well below established dose criteria. If the assessed doses caused by the presence of radionuclides in wood approach or exceed the dose criterion, selection of more appropriate site specific scenarios and/or substitution of more realistic site specific parameters is recommended.

1.4. General approach

The approach used in this study is based on a safety assessment methodology previously developed and applied to a variety of safety assessment cases [5]. This approach allows derivation of conversion coefficients and reference concentrations in wood in a relevant, adequate, understandable and credible manner. The key components of the safety assessment approach addressed in this study are:

specification of an assessment context;

(1) system description;

(2) development and justification of conceptual scenarios;

(3) mathematical model formulation and implementation;

(4) calculation of dose conversion coefficients (DCC) aimed at dose assessment and derivation of reference activity concentrations of radionuclides in wood.

Each of these components forms a step in the development of the final methodology. The same steps should be followed when applying the methodology to a specific case.

1.5. Structure

The key aspects of the approach to develop the generic methodology which are described in this report are the 'assessment context' (Section 2), the 'system description' (Section 3), the 'development and justification of scenarios' (Section 4), the 'model formulation and implementation' (Section 5), the 'application of the developed methodology' (Section 6), and the case study 'application of the methodology to the Russian Federation' (Section 7).

2. SPECIFICATION OF THE ASSESSMENT CONTEXT

The context of an assessment may play a key role in defining relevant assessment endpoints, the system to be represented in the assessment, and in defining both the temporal and spatial boundaries of models to be used. An assessment context is usually described in terms of the following components [5]:

(1) assessment purpose;

(2) radiological protection criteria;

(3) generic methodology;

(4) assessment philosophy;

(5) calculation endpoints;

(6) time frame and societal assumptions.

These components of the assessment context are discussed below.

2.1. Assessment purpose

The purpose of this assessment is to develop a generic methodology based on a safety assessment approach [5] that can be used to determine either the dose to members of the public and industrial (non-radiological) workers resulting from a given radionuclide activity concentration in wood, or to derive reference levels (activity concentrations) for radionuclides in wood which would correspond to a given radiological protection criterion expressed in units of annual effective dose [6, 7].

2.2. Radiological protection criteria

A detailed discussion of radiological protection criteria appropriate for use in relation to standards for trade in commodities is beyond the scope of this report. At the time of writing, international discussions were taking place for the purposes of establishing agreed international criteria for the movement of commodities between countries. For national applications of contaminated wood, appropriate national dose standards should be applied. Appropriate reference activity concentrations of radionuclides in wood could be calculated based on the models developed in this report.

2.3. Generic methodology

In this study, a methodology is developed for dose assessment, based on monitoring or modelling data, and for the determination of derived levels of long lived radionuclide concentrations (mainly ^{137}Cs and ^{90}Sr) in exported/imported wood and its products. For major industrial types of wood and wood products, the main industrial processing technologies in different sectors of the wood industry were identified. It is assumed that the industrial processes under consideration would be carried out in countries or regions importing wood, and that these processes are technologically advanced. Operations implied by the selected technologies which would lead to the exposure, both external and internal, of industrial (non-radiological) workers to radionuclides contained in the wood, are identified and used to describe conceptual exposure scenarios based on the treatment of the wood or wood products.

These scenarios are used to formulate mathematical models of human exposure. Generic, default parameter values are entered into the formulas, whereafter the annual effective dose in workers is calculated for screening purposes. In assessing the exposure of the workers, the activity concentrations of radionuclides in wood and the geometry of the contaminated product are considered in order to calculate external exposure. The volume of inhaled air is considered in order to calculate internal exposure. The time spent in the conditions under consideration is also considered. The total annual dose is determined as the sum of the external dose received during the year and committed internal dose received via the inhalation of radionuclides during the same period. The ratio of the total annual effective dose to radionuclide activity concentration in the wood is defined as the Dose Conversion Coefficient (DCC). The unit of DCC is $mSv \cdot Bq^{-1} \cdot kg$.

For members of the public, different scenarios of utilization of the products made from imported wood are considered (e.g. residence in a timber house, use of furniture, etc.). These scenarios are used for the development of mathematical models of human exposure, both external and internal, and the calculation of the dose to members of the public considered in each particular scenario in which wood is used. In contrast to worker exposure scenarios, the age dependence of the dose coefficients is accounted for in the assessment both of inhalation and ingestion of radionuclides by members of the public of different ages. The total annual effective dose originating from different uses of wood products by the general public and the relevant DCC values are calculated for further dose assessment and determination of derived ^{137}Cs and ^{90}Sr activity concentrations in wood.

The values of DCC are calculated in this publication for timber and major wood products and technologies used in the hypothetical wood producing and/or importing country, separately for workers and for members of the public. In all the generic scenarios developed below and provided with default parameters it is conservatively assumed for screening purposes that all the timber or wood products, either processed under industrial conditions or utilized under domestic conditions, contain elevated levels of long lived radionuclides. This is similar to the "no dilution model" applied for screening purposes in [8, 9].

However, depending on the particular purpose of the dose assessment, the selected radiological criteria and on the radiation conditions, the multi-stage assessment procedure may or may not account for the following important modelling factors or for combinations of these:

(1) Site specific scenarios versus generic scenarios;

(2) Site specific model parameters versus default parameters;

(3) Dilution of contaminated wood with non-contaminated wood in industrial or domestic conditions.

The appropriate multi-stage procedure of the dose assessment as well as derivation of reference levels of radionuclides in wood are described in detail in Section 6. In this section only general formulae and definitions are presented.

2.3.1. Dose assessment methodology

The suggested dose assessment methodology is a multi-stage procedure with different number of steps applied at regional, national and international levels.

Step 1 in any dose assessment procedure is the screening step. It involves the application of a generic model supplied with default, moderately conservative parameters as developed below in this publication. In the simplest case of the generic assessment of annual effective dose (E_r) due to radiation emitted by a specific radionuclide *(r)* detected in wood samples the largest value of DCC_r for each kind of wood product, determined separately for workers and for members of the public, is conservatively selected and used in the following calculation:

$$E_r = DCC_r \cdot C_{wr}, \text{ mSv}, \quad (2.1)$$

where:

C_{wr}, $Bq \cdot kg^{-1}$ is the mean activity concentration of the radionuclide *(r)* in the wood product under consideration.

If several radionuclides are present in a particular wood product, the annual effective dose (E) from all the radionuclides detected should be calculated by summation of the doses from each radionuclide:

$$E = \sum_r DCC_r \cdot C_{wr} \text{ , mSv.} \quad (2.2)$$

If the dose to workers and/or members of the public, calculated using such a simple but conservative generic model (2.2), is substantially (by an order of magnitude or more) below an appropriate individual dose criterion (IDC), this result may be considered as an indicator of compliance of monitoring data with established radiological criteria. If public doses, assessed according to (2.2), approach or exceed an established IDC, then a more detailed dose assessment is recommended prior to making any decision on the restriction of wood product usage. This may involve further steps in the assessment procedure depending on whether the dose assessment is relevant to the national or international context.

At the regional or national dose assessment level, **Step 2** of the dose assessment procedure, see Figure 1, implies the selection of site specific (region specific or country specific) scenarios for the industrial treatment and/or domestic application of timber and wood products from the list of scenarios considered in the present report. This means, first of all, removal from the list of relevant scenarios those which are not typical for the specific country or region under consideration. After removal of scenarios which are non-relevant for local regional or national conditions, the dose assessment procedure according to (2.2) should be repeated. In addition, it should also be considered possible that some additional site specific scenarios, not considered in this report, will have to be developed and applied.

If, after implementation of Step 2, the ratio of the assessed dose to workers and/or members of the public still remains close to the IDC, i.e. is substantially larger than one tenth of the IDC, **Step 3** in the modification of the model should be the adjustment of model parameters to represent local technologies. In practice, this means the assessment and justification of the applicability of generic model parameters (such as the size of the source, dust concentrations in air, occupation times, etc.) which are specific to local regional or national conditions, technologies and human habits. After removal from consideration of non-relevant scenarios (step 2) and specification of model parameters for local conditions (Step 3), the dose assessment according to (2.2) should be repeated.

Step 4, which should be applied if, after implementation of Steps 2 and 3, the assessed doses to workers and/or members of the public still approach or exceed an established IDC, should account for dilution of contaminated wood with non-contaminated wood. In the derivation of dose conversion coefficients below and the dose assessment according to (2.2) it is explicitly assumed that all the wood under consideration is contaminated with radionuclides under environmental conditions.

In reality such conditions exist only in areas significantly[2] affected by a major radiation accident(s). Currently, this is the case in some regions of Belarus, Russia and Ukraine affected by the radioactive fallout due to the Chernobyl accident and, to a lesser extent, in some other European countries. However, even after such a large accident as the Chernobyl accident, relatively small fractions of the total area of the affected countries were significantly contaminated with radionuclides. Most of the territories of even significantly affected countries remained relatively contamination-free[3], and wood produced in these areas has not been contaminated with radionuclides.

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[2] Usually areas contaminated with ^{137}Cs above 40 $kBq\cdot m^{-2}$ (about 1 $Ci\cdot km^{-2}$) are considered as significantly contaminated with this radionuclide, see Table I.

[3] Excluding Belarus, of which 23% of the territory was contaminated above 40 $kBq\cdot m^{-2}$ due to the Chernobyl accident [1].

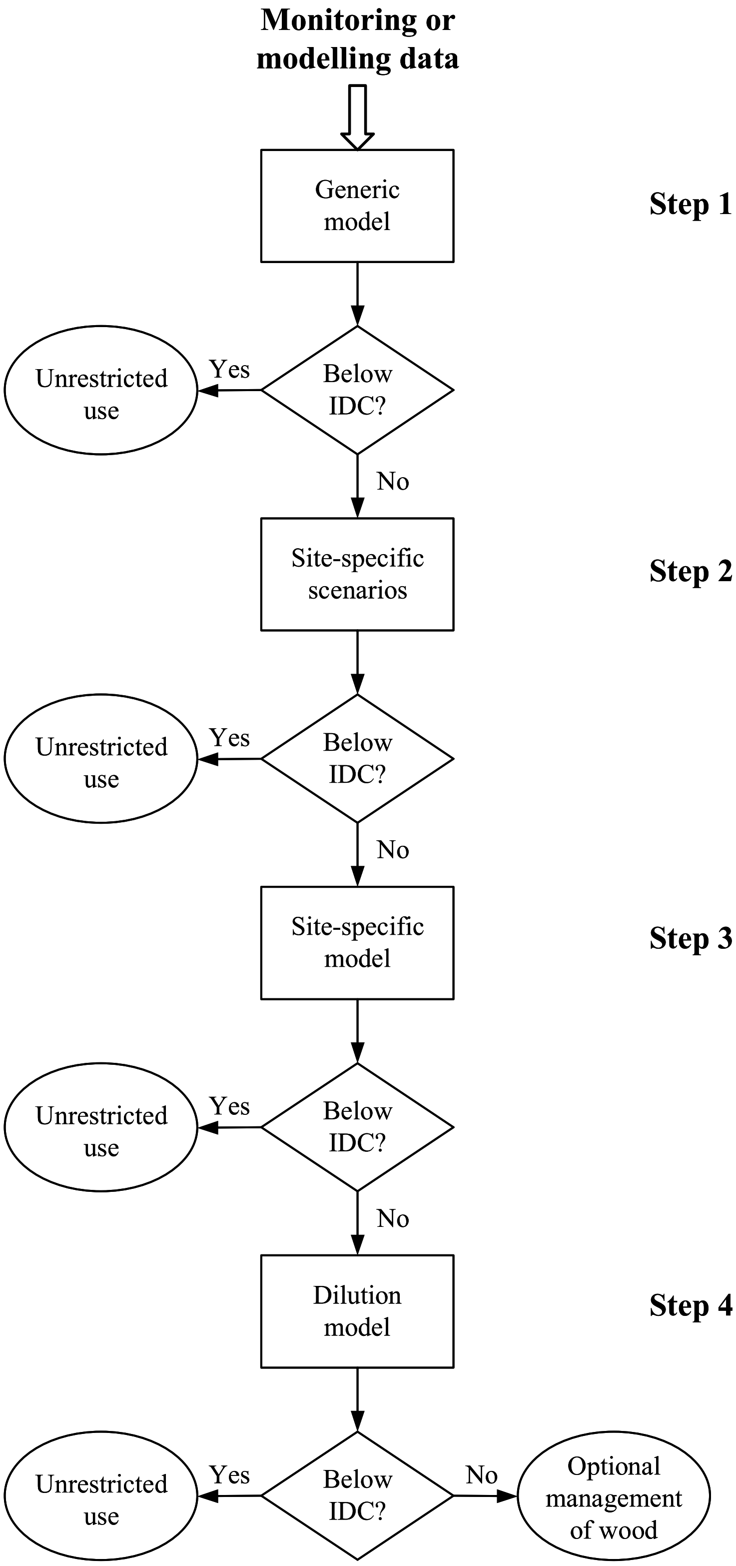

FIG. 1. Illustrative scheme for the assessment of the dose to humans that is associated with the treatment of wood containing radionuclides at the regional or national level.

For conditions of the treatment of wood in the regions of an affected country located outside of areas contaminated with radionuclides, as well as for international trade of wood and wood products, it is recommended that dilution of contaminated wood with non-contaminated wood is accounted for at the last stage of the dose assessment procedure. If the dose assessed according to "non-dilution model" (2.2) approaches or exceeds the established IDC, appropriate Dilution Factors (DF, dimensionless) should be introduced. These should be site specific and based on local production statistics. The region specific or country specific DF values can be estimated as the ratio of the amount of timber and wood products imported per year from areas contaminated with long lived radionuclides to the total amount used annually in the region or country under consideration.

Calculation of the values of the annual effective dose (E) from all the radionuclides (*r*), detected in a specific wood product, accounting for the dilution of contaminated wood with non-contaminated wood, is similar to formula (2.2):

$$E = DF \cdot \sum_{r} DCC_r \cdot C_{wr} \text{ , mSv.} \tag{2.3}$$

where:

Df, dimensionless, is the dilution factor depending on national or international conditions of wood import and treatment (see default values in Section 6.2.3);

DCC_r mSv·Bq^{-1}·kg, is the largest dose conversion coefficient for the radionuclide under consideration (*r*) from the relevant set of scenarios and parameters;

C_{wr} , Bq·kg^{-1}, is the mean activity concentration of the radionuclide under consideration (*r*) in a wood product.

At the international dose assessment level, there are fewer opportunities for modification of the dose assessment procedure than at the national level. Thus, selection of site specific scenarios/models and model parameters is non-applicable. The set of generic scenarios/models supplied with default parameters has been developed in the present publication mainly for international dose assessment and derivation of reference levels of radionuclides in wood moving in international trade.

However, when considering the international trade of wood the dilution of contaminated wood with non-contaminated one should be introduced as **Step 2** of the procedure, see Figure 2. The dilution factors used at the international level should be based on worldwide or continental production and trade statistics. They can be estimated as the mean worldwide or continent specific ratio of the amount of timber and wood products exported per year from areas contaminated with long lived radionuclides or at least from countries with substantial contaminated areas to the total amount of wood used annually in the whole world or a continent with radioactively contaminated areas. The internationally applicable default values for dilution factors are suggested in Section 6.2.3 below.

The results of multi-stage dose assessment carried out according to formulas (2.2) or (2.3) should be compared with the appropriate IDC. If the assessed dose, associated with the industrial or domestic treatment of wood contaminated with radionuclides, is substantially below the IDC, the unrestricted import of timber and wood products is recommended. However, when assessed dose approaches or exceeds the IDC, different options for the management of contaminated wood should be considered.

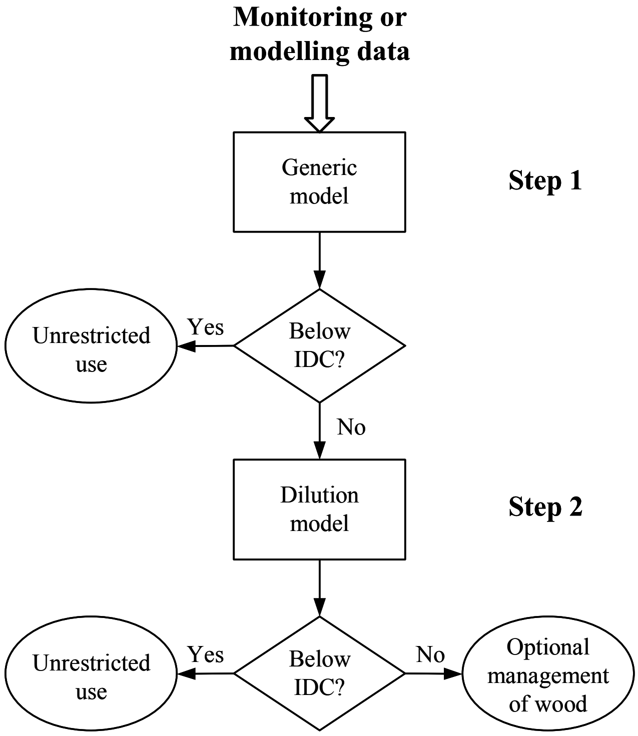

FIG. 2. Illustrative scheme for the assessment of the dose to humans that is associated with the treatment of wood containing radionuclides at the international level.

2.3.2. Determination of reference levels for radionuclides in wood

The results of the development of generic dosimetric models and the calculation of corresponding sets of dose conversion coefficients (see Sections 4 and 5) can be used to obtain values of Derived Concentrations (DC_r) of specific radionuclides (*r)* in a wood product ensuring that radiation safety requirements are met when treating wood containing radionuclides in the industrial and/or the domestic contexts. As explained above, appropriate Derived Concentrations should, where necessary, be calculated using site specific models and parameters, taking account of dilution of the contaminated material (see above and Section 6).

In cases in which dose assessment has demonstrated that "no dilution" generic or site specific models are sufficient to prove radiation safety of operations with contaminated wood, these can be also applied for calculation of Derived Concentrations, see formula (2.4) below. If a model which accounts for mixing of contaminated wood with non-contaminated wood had to be applied for dose assessment in order to avoid unnecessary restrictions on wood treatment, then the same model is recommended for the calculation of Derived Concentrations, see formula (2.5) below:

$$DC_r = IDC / DCC_r \text{, Bq· kg}^{-1}\text{ ;} \tag{2.4}$$

$$DC_r = IDC / (DCC_r \cdot DF) \text{ , Bq· kg}^{-1}\text{ ,} \tag{2.5}$$

where:

IDC, mSv, is the relevant national or international individual dose criterion;
DCC_r and *DF* are defined in (2.3).

An assessment according to (2.4) or (2.5) could be performed to establish both an international standard and a national or regional standard for radionuclide activity concentrations in wood used in any particular country or its region with specific radiation conditions, i.e. area contaminated with long lived radionuclides.

When establishing standards for international trade, the relevant international individual dose criterion IDC should be applied in combination with the most generic models of the human exposure accompanying treatment of wood containing radionuclides in the industrial and the domestic contexts. The calculation of internationally applicable DC_r should account for international conditions of mixing portions of wood produced in different countries and their regions via the use of appropriate dilution factor values, see Sections 2.3.1 and 6.3.1.

In the case of determination of a national DC_r, the national dose criterion relevant to the exposure from contaminated commodities should be used as the IDC. Most appropriate generic or national, country-specific models and parameters should be applied in combination with national dilution factor values. If national dose standards for non-radiological workers and for members of the public are different, two sets of appropriate permissible concentrations would be determined and the lowest value selected for radiological control of wood imports.

The regional standards for radionuclide concentration in wood might be useful in conditions of substantial areas contaminated with long lived radionuclides. In order to justify regional standards, appropriate national dose criterion for intervention should be applied in combination with national or site specific models and their parameters for conditions without dilution of contaminated wood with non-contaminated one inside the contaminated region.

2.4. Assessment philosophy

To provide a “cautious” approach to the radiological protection of both workers and members of the general public, scenarios, conditions of exposure and model parameters are selected which may lead to higher external and internal doses. In fact, this is the way in which critical groups of people are selected which, according to their working or living conditions, are subject to higher external and internal exposures to radionuclides contained in wood and products made from this wood. As further calculation of the derived radionuclide activity concentrations in wood and wood products is based on scenarios of exposure of critical groups both of workers and general public, the cautious approach to radiological protection is observed.

Taking into account dilution of radioactively contaminated wood with non-contaminated wood in dose assessment procedures and/or the derivation of reference levels of radionuclides in wood, both in industrial and domestic contexts, ensures adequate protection of the average member of the general public. However, application of the “dilution approach” does not take into account cases in which imported wood contaminated with radionuclides is occasionally used at a particular production facility or by a particular consumer without substantial dilution with non-contaminated wood. The probability of the use of non-diluted contaminated wood is relatively low. It might be, however, worth detailed consideration in case of the long term use of large wooden products in domestic conditions, e.g. furniture, imported wooden houses, etc. In this case each large wooden piece of furniture or part of a house might become a single source of long term consumer external exposure.

In order to maintain the “cautious “ approach in the framework of this publication, the following two restrictions are recommended with regard to the application of the dilution approach to dose assessment and derivation of reference levels for radioactively contaminated wood:

- Not to apply for dose assessment and standardisation purposes dilution factor values (DF) less than 0.01 even if site specific, region specific or country specific statistical data justify application of substantially lower values.
- Not to apply the "dilution approach" for dose assessment and standardisation purposes relevant to import and long term use of large wooden commodities, such as furniture sets, wooden houses, etc.

Both external and internal doses may depend on age. For external exposure of members of the public, occupational factors for different age groups will be considered. In the case of internal exposure, the age-specific properties of incorporated radionuclides are accounted for by considering inhalation rates and appropriate dose coefficients for different age groups. For ^{137}Cs, the internal doses to different age groups due to inhalation or ingestion are of similar magnitudes, thus using dose calculations for adults can be considered as a cautious approach. However, the internal doses to children and teenagers due to the intake of ^{90}Sr may be significantly higher than in adults. Thus the dose to children and teenagers should be calculated as part of the cautious approach.

For both workers and members of the public inhaling radionuclides in smoke and ash from burning wood, dose coefficients as derived by ICRP for particles with fast solubility in the respiratory tract (type F) and AMAD equal to one micrometer [10] were selected. As for inhalation of sawdust by workers, the dose coefficients should be cautiously selected for conditions of slow solubility (type S) and AMAD equal to five micrometers recommended by ICRP for occupational conditions [11].

2.5. Calculational endpoints

In most safety assessments the impact on humans and/or the environment is the desired calculational endpoint, and the activity concentrations in the source term are the starting point. Assessed doses are usually compared with appropriate dose limits. However, there is no universal standard or set of dose limitations that apply to trade in commodities between countries (see discussion in Section 2.2), therefore the major endpoints chosen for this study are dose conversion coefficients (DCC) which can be used to calculate a dose from the activity concentration of radionuclides in wood determined as a result of monitoring or modelling, or *vice versa*, i.e. to calculate a derived activity concentration (DC) in wood which would correspond to a specified dose criterion.

For the purposes of this study, the annual individual effective dose to an adult worker and to members of the public of different ages involved in the exposure scenarios under consideration is used as the primary measure of impact. Major human exposure pathways are accounted for in the assessment of DCC values. Thus a set of DCC values is developed for two radiologically important radionuclides, ^{137}Cs and ^{90}Sr, as a function of various exposure pathways, which, in turn, are a function of the use of the imported wood both in industry (workers) and in the domestic situation (public).

2.6. Site context

The methodology developed in this report considers only radiation exposures from timber and related products obtained from contaminated forests and subsequently exported from the site of origin to areas in the same country or to another country. In this respect, the doses incurred are entirely outside of the forest system itself; in other words ex situ doses. In situ doses, incurred as the result of the use of forest products on site, i.e. in the forest contaminated with radionuclides, are beyond the scope of the report and have been considered by IAEA forest model FORM [4].

The site context may have a bearing on the practicalities of wood export/import. For instance, the relatively high cost of transporting raw wood means that it will be mainly exported to neighbouring regions or countries. On the other hand, processed wood products such as furniture could be transported over longer distances without the costs being prohibitive; therefore these goods may be exported to countries situated far from the country of origin. Secondary export is also possible, i.e. unprocessed wood may be imported into a country that processes the wood and exports the processed product to another country, with no indication to the end-user that the raw material originated from a contaminated forest.

2.7. Time frames and societal assumptions

Due to the nature of the problem addressed in this study, the time span is relatively short (in the order of tens of years, rather than hundreds or thousands). Radioactive decay between harvesting of the wood and the final time of use of the end product is not considered, as this time span could range from days to years. Present day habits and industrial processes relating to the processing of wood are assumed.

3. SYSTEM DESCRIPTION

The system under consideration, i.e. the utilization of timber and wood products contaminated with the long lived radionuclides ^{137}Cs and ^{90}Sr, can be defined as shown in Figure 3. For the purpose of this report 'utilization' includes transportation, storage, processing, production of commodities, usage of these commodities and disposal of used commodities and relevant by-products. Figure 3 indicates that timber and wood products can be transported from the forest or from the site of primary processing to the site, where further treatment and/or utilization (including export to other countries) can be, in the form of:

(1) raw timber (round wood with and without bark),

(2) sawn wood,

(3) wood pulp for paper manufacture, or

(4) waste wood in the form of both wood and bark chips.

Following delivery of timber and wood products, these four basic products can be used in a variety of ways, in both industrial and domestic situations. Five primary industrial uses can be identified, as follows:

(1) processing of raw timber in a sawmill;

(2) use of raw timber and /or sawn wood in construction;

(3) use of sawn wood in furniture manufacturing;

(4) use of raw timber and wood pulp in paper and cardboard manufacture;

(5) use of waste wood and bark chips in bio-fuel plants.

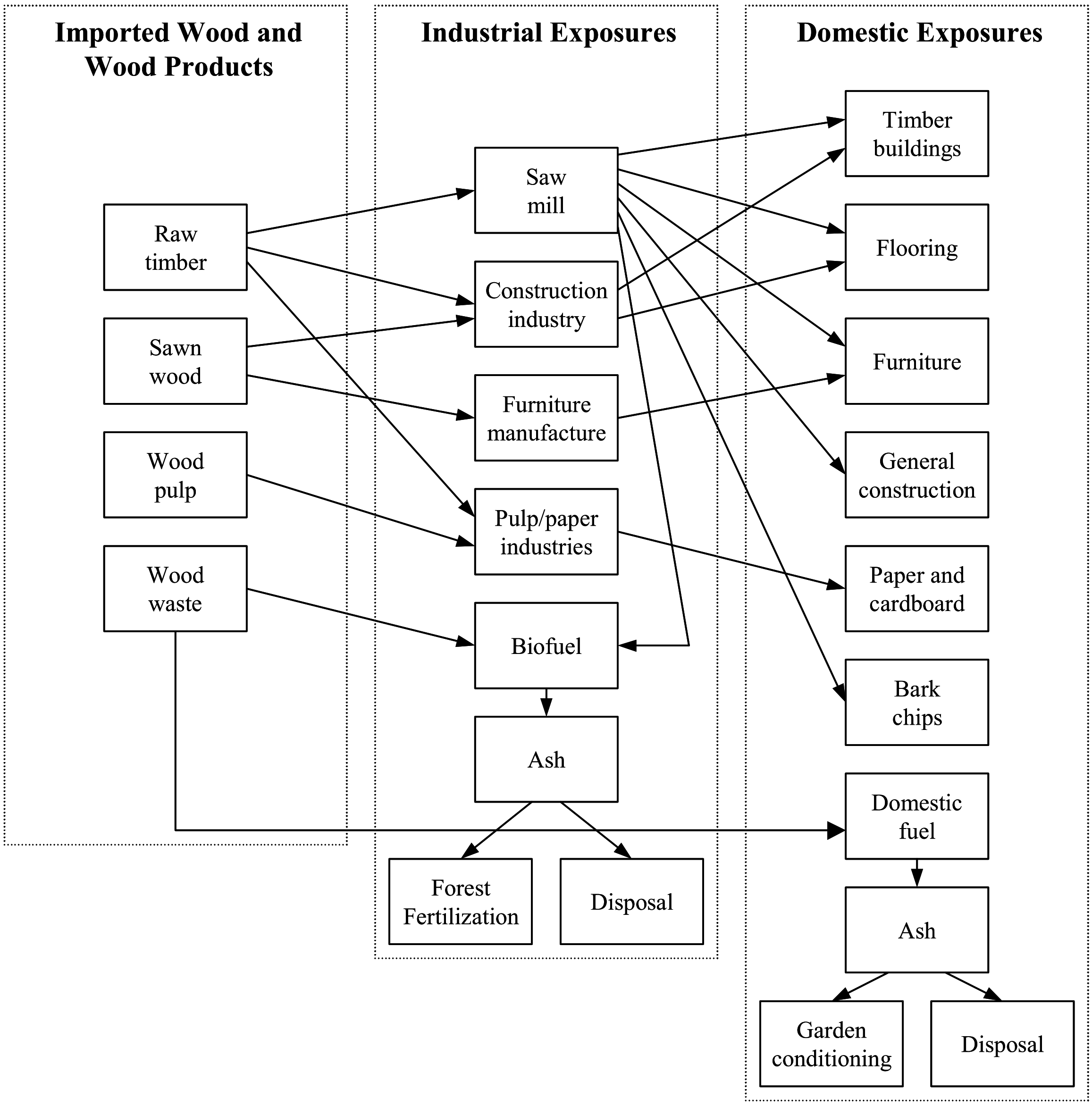

FIG. 3. Major fluxes of imported wood and wood products.

An important by-product of the use of wood and pulp for paper production, as well as waste wood and bark chips for bio-fuel energy generation, is wood/bark ash in which radionuclides (such as ^{137}Cs) can become significantly concentrated. The use of ash for forest soil fertilization and its disposal, usually to landfill, is a problem that should also be considered within the industrial context [12, 13]. Hence, there are six distinct radiological exposure scenarios which can be identified under the broad heading of 'industrial exposures', as shown in Figure 3.

Following industrial processing of wood and associated products such as wood pulp, a variety of finished products is produced, each of which has the potential to cause radiological exposures to end-users in the domestic situation, as described below:

(1) Domestic timber houses constructed from sawn wood and manufactured construction materials such as plywood and chipboard;

(2) Wooden floors constructed from sawn wood and manufactured materials;

(3) Furniture constructed from sawn wood and manufactured materials;

(4) Other buildings constructed from raw timber, sawn wood and manufactured materials;

(5) Paper and cardboard manufactured from wood pulp;

(6) Bark chips, used in domestic gardens and children's play areas;

(7) Processed wood chips manufactured from waste wood and used for domestic heating.

Some of these products, particularly the relatively high value products such as furniture, floors, pulp and paper, may even be exported to a third country, thus extending the potential geographical range over which radiological exposure may occur.

Use of waste wood for domestic heating produces significant amounts of ash with elevated activity concentrations of radionuclides compared with the original wood. In the domestic context, wood ash is usually used for soil conditioning in gardens or disposed of at communal dumps. The radiological consequences of ash utilization should be considered along with the seven major scenarios of the domestic use of imported wood. Hence, the system to be considered in any generic methodology to calculate ex situ doses deriving from contaminated wood encompasses its industrial and domestic utilization in a country importing contaminated wood. One feature of the system to be considered is that all potentially exposed people, whether in an industrial or domestic situation, are not registered radiation workers and, in radiological protection terms, are to be considered as members of the public.

The exposure that a person receives is a function of the use of the wood or wood product. The radiological significance of each technology and relevant exposure pathways, whether industrial or domestic, needs to be considered individually. To achieve this, detailed scenarios of human exposure must be defined and appropriate dosimetric models developed for each technology and corresponding exposure pathways.

4. DEVELOPMENT OF SCENARIOS FOR EXPOSURE ESTIMATES

4.1. Rationale for the development of scenarios

In Section 3 a general description of the system under consideration was given and major scenarios of wood and wood product treatment were identified within (a) the industrial context and (b) the domestic context. In this section, each of the individual scenarios is described separately and consideration is given to the information required for the development of dosimetric models of human exposure relevant to conceptual scenarios for which a detailed treatment is required. Human exposure pathways within each scenario are the prime consideration and, in this study, the annual individual effective doses to an adult worker and to members of the public of different ages are used as the primary measure of radiological impact. These doses are an indicator of the impact which might arise from various exposure pathways, which, in turn, are a function of the specific end uses of the contaminated wood ex situ. Thus, the rationale in developing scenarios is to identify specific exposure pathways associated with the possible end uses of delivered wood (raw and processed) identified below. Thereafter, in Section 5, a set of idealized conceptual dosimetric models is developed based on these end uses and processes, each taking into account the associated exposure pathways.

Based on experience in radiation monitoring, for some of the scenarios under consideration human exposure is greater for a given radionuclide content in wood, compared with other scenarios in which the exposure is known to be lower for the same radionuclide content. In this report, in so far as detailed scenario description and modelling are concerned, priority is given to the higher exposure scenarios. The lower exposure scenarios will not be considered in detail because, at this stage of standardization, only the highest dose conversion coefficients are used.

4.2. Development of industrial exposure scenarios

4.2.1. Sawmill industry

The assumptions and calculations of radiation exposure associated with sawmills are based on conventional, modern sawmills in Europe. As a cautious assumption, radiation exposures resulting from the processing of both barked and debarked wood will be considered within this scenario. Prior to processing, raw timber is stockpiled and kept wet by sprinkling to prevent cracking of the wood during processing. After processing, dried wood is also stockpiled. These stockpiles are arranged into individual stacks of approximately 100 m^3, each representing a mass of approximately 50 tonnes. Processing of raw wood involves only sawing which, nevertheless, can represent an additional exposure pathway through the generation and inhalation of sawdust. Thus, a worker in the sawmill industry may receive a dose due to:

(1) external radiation exposure from timber stockpiled in the yard;

(2) external radiation exposure from handling the wood;

(3) internal radiation exposure from inhaling wood dust.

These exposure pathways are to some extent mitigated in a modern sawmill. Efficient dust extraction systems maintain atmospheric dust loadings at a minimal level. Furthermore, in a modern sawmill, there is very little manual handling of wood as the process is highly mechanized. The dose from handling wood is therefore likely to be much lower than the dose from stockpiled wood. Example reference levels based on external irradiation from handling of wood are therefore not calculated.

Waste wood (in the form of wood chips) and bark can be used for bio-fuel heating to provide energy to the sawmill. Possible exposure from this practice is discussed in Section 4.2.5. Waste wood is also sold to pulp plants and is covered under Section 4.2.4. There is also an increased use of wood pellets for the heating of houses. Such pellets are produced from waste wood. Laminated wood, chipboard and particleboard manufactured from waste wood are important as construction materials both for furniture and within the building industry. The fluxes of wood and wood-based materials within the sawmill and associated industries are shown in Figure 4.

4.2.2. Construction industry

Wood is used in the construction of both houses and civil engineering structures. In the case of house construction, many parts (particularly roofs and floors) are built from prefabricated components, while in civil engineering; concrete structures are made in moulds which are fabricated from sawn timber and plywood. The quantity of wood used in these applications is smaller than the quantities processed within a sawmill and, as a result, exposure from external radiation is smaller. In modern factories in which prefabricated building structures are made saw dust is aspirated from the work place to keep ambient dust levels low, consequently inhalation and internal contamination and doses are limited.

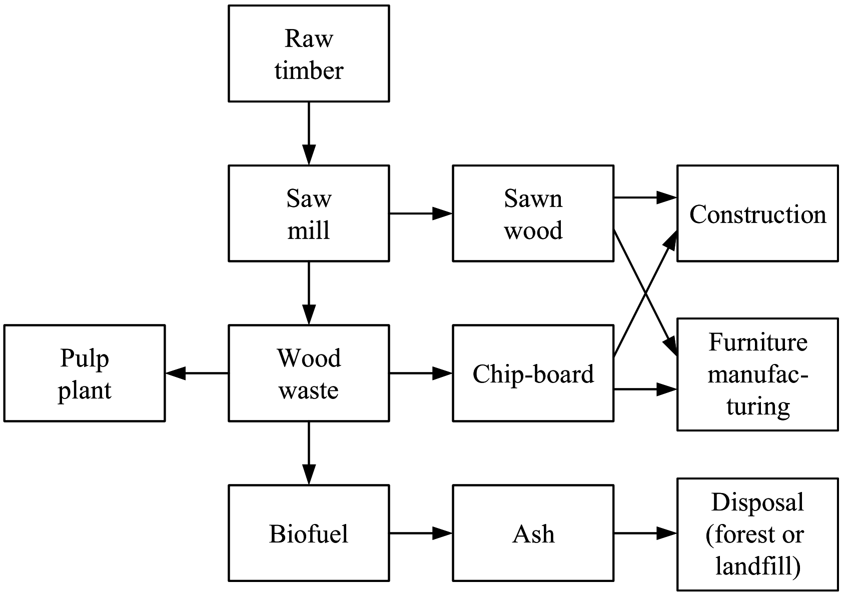

FIG. 4. Fluxes of materials associated with the sawmill industry.

4.2.3. Furniture manufacturing

Workers at a furniture factory could receive a dose due to external irradiation during handling of sawn wood or manufactured construction materials such as plywood and chipboard, as well as from inhalation of dust particles during the furniture manufacturing process. However, these exposures are likely to be similar or less than the exposures received by a worker at a sawmill, therefore this scenario is not considered further.

4.2.4. Wood pulp and paper industry

Assumptions and calculations concerning radiation exposures in the wood pulp industry in this study are based on a conventional modern European pulp mill. The radiation doses to which individuals in the pulp industry are potentially exposed are controlled to a large extent by the activity concentrations of radionuclides within the raw material (raw timber or waste wood) used by the industry, but also by very significant technological enhancement of the activity concentrations following treatment of the wood during the pulping process [12].

Wood pulp can be produced from both coniferous and deciduous wood. Coniferous wood is usually imported into countries with pulp mills with the bark already removed in order to prevent transfer of plant diseases and insects. The bark of deciduous trees is usually left on the tree. Since the bark of trees generally has a higher activity concentration of radionuclides than the wood, the presence or absence of the bark has a bearing on the radiation doses received by individuals working within the pulp industry. However, to understand fully the pathways of radiation exposure within the pulp industry it is necessary to consider the flux of materials within the pulp-making process. Figure 5 shows this flux of materials.

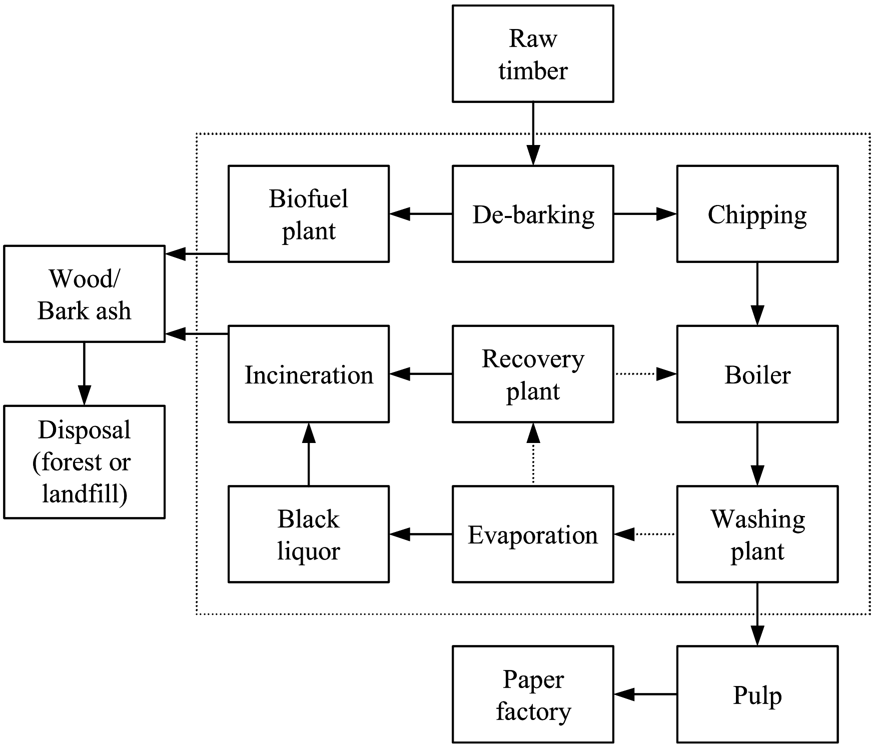

FIG. 5. Fluxes of materials within the wood pulping industry. The large box with the broken line indicates the boundaries of processes within the industry while the broken arrows indicate recycling of materials within the pulping process.

When raw timber is received at a pulping plant the first task is to remove the bark, if it is present. The bark, once removed, is directed to a bio-fuel plant where it is incinerated to provide energy for the operation of the plant (i.e. bio-fuel heating). The remaining wood is mechanically reduced to wood chips and then further processed to liberate the cellulose fibres by one of the following processes:

- alkaline extraction (Kraft process);
- acidic extraction; or
- mechanical pulping (wood is not chipped in this process).

Both the alkaline and acidic extraction processes involve recycling of materials. During both processes, a ‘black liquor’ is produced as a by-product. This is a mixture of process water, soluble products in wood and process chemicals. Economic and environmental considerations dictate that chemicals are recovered for re-use and the black liquor is obtained by evaporation of the process water (using bio-fuel energy) as part of the recycling process. Following evaporation, the black liquor is incinerated. There is, therefore, a technological enhancement of activity concentrations of radionuclides such as ^{137}Cs and ^{90}Sr a) in the black liquor, b) in the sludge resulting from the recovery process and b) in the ashes which are obtained after incineration of the black liquor. Radionuclides are also concentrated in the ash produced during burning of bark chips to provide bio-fuel energy for the evaporation of process water. The finished product, processed wood pulp consisting of cellulose fibres, contains a relatively minor fraction of the total original activity contained within the wood.

During the mechanical pulping process there is no technological enhancement of radionuclide activity concentrations and, therefore, the levels of radioactivity in the processed cellulose are similar to the levels in the wood.

Thus the major human exposure sources during the pulping process are the liquor holding tanks and the ash derived from incineration of bark and liquor sludges. The only exposure pathway from the liquor holding tanks is external irradiation; individuals spending a part of their working day standing in close proximity to these tanks will receive an external gamma radiation dose from this source. The main exposure pathway from the bark and liquor ashes is also external irradiation, but inhalation of re-suspended ash particles may also be significant. Further exposure to radionuclides in ash depending on the method of utilization and/or disposal is described separately in Section 4.2.6.

Wood pulp produced from contaminated wood is further used for production of paper and cardboard. The activity levels in pulp are generally much lower than those in wood, by a factor of about 50 for bleached pulp. During the production of paper different (uncontaminated) materials are added to the pulp. Cardboard is often made of recycled paper. Radiological exposure in this industry is not considered to be significant.

In spite of the relative large amount of paper used in the publishing industry the exposure from radionuclides contained in paper may be considered to be negligible for the same reasons as within the paper manufacturing industry.

4.2.5. Bio-fuel plants

Within bio-fuel plants, different types of wood can be used, such as waste wood from the sawmill industry, wood from short rotation coppice (*Salix* spp.), waste wood collected from the forest after thinning or harvesting, or other kinds of wood such as scrap wood remaining after demolition of buildings or other constructions. Such wood is sometimes imported and a blend of different woods can be used at the plant. In bio-fuel plants a relatively large fraction of bark and leaf litter is used in the combustion process since thinning wood and coppiced *Salix* have a high bark:wood ratio and often include the remains of leaves. The wood is normally dried in the field, if it is not already dry, and converted into chips before being transported to the bio-fuel plant.

Exposure pathways are associated with the handling and incineration of the wood and eventual transport of the ash to a waste dump. Because wood for bio-fuel plants usually originates from different areas and enterprises, the contaminated fraction is usually significantly diluted with non-contaminated wood and the corresponding external exposure is lower than at sawmills. Exposure due to ash treatment and disposal is discussed in the next section.

4.2.6. Ash utilization and disposal

Contaminated ash is produced in large quantities at wood pulp factories and at bio-fuel plants. Further human exposure to radionuclides in ash will depend on the method of its utilization or disposal. Ash is usually deposited in stockpiles prior to final use or disposal. Under current practices, ash can be applied to forests as a fertilizer or, alternatively, landfilled or used as a fill material for the maintenance of roads. Ash waste dumps might be specifically associated with a pulp or bio-fuel plant, but in some cases a lack of available space dictates that a municipal waste dump is used.

If the ash is used as fertilizer in a forest, forest workers may receive an additional dose due to external irradiation from the ash, as well as from inhalation of re-suspended particles, particularly during application of the ash. These exposure pathways are considered in detail in Section 5.2.6.

If the ash is disposed to landfill or used in road construction, possible exposure scenarios depend on the environment and the characteristics of the landfill/road, as well as on events and processes which might initiate release of contaminants from the ash, or influence their transport to the human environment. Generally, scenarios affecting landfilled ash can be considered under the following two headings: a) natural processes and events, b) waste and disposal facility and human activities.

4.2.6.1. Natural processes and events

Contaminants can be leached from ash by rainwater, with the possibility that adjacent groundwater will become contaminated. The main environmental transfer pathway to humans would be through the use of contaminated groundwater for domestic purposes, irrigation of crops and watering of animals. Thus the main exposure pathways would be ingestion of drinking water, crops and animal produce, and external irradiation resulting from domestic use of contaminated water (e.g. for bathing or showering). These latter scenarios are not considered in detail in this report because of low radiological significance.

4.2.6.2. Waste and disposal facility and human activities

If waste ash is not disposed of at the pulp or bio-fuel plant itself, it might be transported to a general municipal waste dump. In the latter case, significant dilution of contaminated ash occurs because of mixing with non-contaminated waste. External exposure and inhalation of the contaminant might occur during transport as well as to non-registered workers at the dumpsite. Appropriate dosimetric scenarios are considered in Section 5.2. Such dumpsites are often used for a limited period of time and other activities causing exposure, such as house construction and transformation of the sites into recreation areas, might eventually take place.

4.3. Development of domestic exposure scenarios

4.3.1. Timber buildings

In some rural areas in, for instance, the Nordic countries as well as the Russian Federation and Belarus, a significant number of houses is constructed partly or entirely from timber. If a house is constructed from wood contaminated with radionuclides, a person residing within it will receive a dose due to prolonged external irradiation from the walls, ceilings and floor of the house.

There are several factors which will affect the radiation dose received. A major factor is the activity concentration of the wood from which the house is built. The activity concentration will depend on the geographical location from which the wood is obtained, the species of tree from which the wood is derived, and the manner in which the timber is prepared for construction. The activity concentrations of radionuclides are generally higher within the bark of the tree than in the wood itself. Normally, however, the bark is removed from timber prior to house construction, though in some cases it may be retained. It is assumed for the purposes of this study that the bark is removed. It is also assumed that, contrary to the manufacture of modern mass-produced furniture (see Section 4.3.4), most timber buildings are built predominantly of sawn woods, with only relatively small masses of reconstituted materials such as chipboard and plywood.

The second major factor controlling radiation dose is the design of the house. Exposure will occur from walls, floor and ceiling, provided each of these is constructed of contaminated wood. Each of these surfaces represents a planar radiation source, the significance of which depends on the mass of wood within each surface. The size of rooms is not the crucial factor here, but rather the thickness of the surfaces, with walls likely to be the thickest. As wall thickness increases, the total activity per unit area of the wall increases. The dose rate at the surface of the wall will also increase with wall thickness, but to a lesser extent than the wall thickness because of self-absorption of gamma radiation by the material in the wall. For the purposes of this study a typical room is considered to be 7 × 7 metres, giving a floor area of about 50 m^2. The height of the ceiling is taken to be 3 metres and the thickness of the walls to be 0.2 metres. It is assumed that an average person spends 4000 hours per year in the house (approximately 11 hours per day). For simplicity, a uniform exposure is assumed, regardless of the person's location in the room.

4.3.1.1. Saunas

Saunas are considered as a special type of building which merit separate discussion. Use of saunas is a significant pastime in many countries and the interiors of saunas are generally constructed almost entirely of sawn wood. From the perspective of calculating radiation doses from contaminated wood within a sauna, the sauna can be considered to be like a small building fitted with wooden furniture. An occupant of a sauna will receive doses from the walls, floor and ceiling (each of which is a planar source) and from furniture (benches) if these are constructed of contaminated wood. Doses from the beta particles from ^{137}Cs and ^{90}Sr should also be considered since there is a direct contact between skin and the wood in a sauna.

In this study, a sauna is considered to be equivalent to a small timber building of approximately 4 × 3 metres (i.e. 12 m^2), with a ceiling height of 2.5 metres. The thickness of the walls is taken to be 0.2 metres. An occupant is assumed to sit on a wooden bench of 0.05 metre thickness. However, the occupation factor would be much lower than that for a house, about 200 hours per year as opposed to 4000 per year in a timber house.

4.3.1.2. Flooring

Wooden floors are considered separately from wooden buildings since in many non-wooden houses, a wooden floor may either be installed at the time the house is built or added later. The same considerations apply to this scenario as apply to the case of a wooden building. However, in the case of a floor constructed of contaminated wood, the occupants of a room are only exposed to a single planar source which is generally much thinner than the walls of a wooden building. The external dose received from radionuclides in a wooden floor is, therefore, likely to be significantly less than that received simultaneously from the walls, floor and ceiling from a house constructed from timber. For this reason this scenario is not considered further being covered by the more conservative scenario described in 4.3.1.

4.3.2. Furniture

External irradiation of a person using furniture contaminated with β and γ emitting radionuclides will occur. Furniture is constructed using various wood-based materials, including sawn wood and manufactured materials such as plywood, medium density fibreboard (MDF) and chipboard. Two main factors will influence the dose received: the activity concentration within the construction material and the proximity of the exposed person to a single piece of furniture or a collection of furniture.

If high quality sawn wood is used to manufacture furniture the original activity concentration of the wood will remain unchanged. However, most mass-produced furniture is not made of sawn wood, but of lower value, reconstructed materials such as chipboard and particle boards such as MDF. Manufacturing processes may result in the activity concentration of the final product being significantly lower than the activity concentration of the original product.

The second factor to be considered in this scenario is the proximity of the exposed person to the furniture. In this study exposure to a single piece of furniture is considered as well as to a collection of furniture within a room.

(a) Exposure from a single piece of furniture is likely to be most significant from an item of furniture such as a bed in which direct contact along the entire length of the body is possible over significant periods of time. In this case, the wood can be considered as a planar source of gamma radiation at a small distance from the body. The thickness of the wood comprising the furniture will determine the total activity within the wood and hence, the dose rate to which the body is exposed. Occupancy of about 3000 hours a year or 8 hours a day is considered as default parameter.

(b) Exposure from a collection of furniture involves less direct contact with the contaminated wood, but will involve a greater mass of wood. However, the contaminated wood will be distributed around the room. The mean density of the wood per unit floor area must then be taken into account. In this study a mass of about 3 to 10 kg of wood per square metre is considered to be a typical value for furniture in an average room. Occupancy is the same as that assumed for a timber house, i.e. 4000 hours per year. For the sake of simplicity, a uniform exposure is assumed, regardless of the person' s position in relation to the furniture.

4.3.3. General construction material

Sawn wood is used as a material in the construction of non-timber buildings, for instance as support material for the roof or as window and door frames. The radiation dose that an occupant of the building is likely to receive from these sources will be much smaller than that received from a house built entirely of contaminated wood. This is simply because the total mass of wood used (and consequently the total radionuclide activity) is much smaller and the wood is not likely to be in such close proximity to the individual as would be the case in a wooden building. For this reason this scenario is not considered any further being covered by the more conservative scenario described in 4.3.1.

4.3.4. Paper and cardboard

During manufacture of paper and cardboard, the activity concentrations of radionuclides in these materials will be significantly reduced compared with that in raw wood. The activity concentration of ^{137}Cs in paper, for instance, is approximately 50 times lower than its original activity concentration in the wood from which the paper is made. This is due to leaching during the pulping process, as described in Section 4.2.4. Additional reduction of activity concentration occurs when contaminated wood pulp is blended with non-contaminated pulp, especially when used paper or cardboard is recycled.

Despite the relatively low activity concentrations likely to be encountered in paper and cardboard, an individual coming into contact with these materials over any significant period will still receive a small external radiation dose. For instance, library or paper/cardboard warehouse staff spend their entire working day in close proximity to large quantities of paper and may receive a dose due to external irradiation. This exposure scenario is basically similar to that described in Section 4.2.1 for storage of large amounts of contaminated wood at sawmills, except that the activity concentration of radionuclides in paper is expected to be lower by a factor of up to 100 relative to that in wood. Hence, the expected dose is estimated to be much lower than that from a stored wood and, therefore, this scenario is not considered further.

4.3.5. Bark chips as a mulch in domestic and public gardens

The use of bark chips as a soil mulch (i.e. a soil surface covering) in both public and domestic gardens has become widespread in recent years. Additionally, bark chips are often used to provide a suitable surface for children's playgrounds to prevent or reduce injuries. Unlike wood ash, bark chips are only spread on the soil surface and not intimately mixed with the underlying soil. They are generally not applied to vegetable gardens, except on footpaths. Thus, the main radiation exposure pathways of relevance to this scenario are direct irradiation by gamma emitters and inhalation of re-suspended particles. One important consideration in calculating dose conversion factors within this scenario is that activity concentrations of radiocaesium tend to be higher in bark than in wood.

4.3.6. Wood as domestic fuel

Wood is often used, especially in rural areas, as a domestic fuel which provides either part or all the energy required for heating buildings and producing hot water. This wood is normally produced locally. Exposure can occur from one or several stoves in the house especially if the ash is allowed to accumulate in the stoves. The exposure pathways are usually external irradiation from wood and ash and inhalation of smoke particles consisting of ash with elevated radionuclide activity concentrations compared with the original wood.

Recently it has become more common to use processed wood pellets for the heating of dwellings since the cost is lower than using oil or electricity. These pellets are produced from waste wood derived from the forest industry. The origin of the wood is never specified and could partly consist of imported wood. The burner is often situated in the basement of the house with automatic supply of new pellets to the fire. In this situation, even if more ash is accumulated than in a conventional hearth the occupational factor is lower in basements than for stoves situated in other rooms.

4.3.7. Ash as a domestic soil conditioner

A common disposal practice for wood ash derived from domestic fuel is to use the ash as a fertilizer or soil conditioner on domestic gardens. This gives rise to three possible exposure routes. First, re-suspension of ash and soil particles contaminated by the ash can give rise to an inhalation hazard. Secondly, vegetables grown on ash-treated soil can become contaminated by root uptake and soil splash and their consumption will lead to internal exposure. Thirdly, if the ash is mixed mainly into the surface soil then direct irradiation of individuals standing on the soil will occur. Ash disposal to domestic soils can take place over many years leading to an accumulation of radionuclides in the soil. In some cases this accumulation might be very significant, especially if disposal takes place in one particular area of the garden.

5. MODEL FORMULATION AND IMPLEMENTATION

5.1. Generic modelling approach

According to the approach outlined in Section 1.4, once a set of conceptual scenarios, as well as the features, events and processes associated with each scenario that could result in exposure due to radionuclides in wood have been identified; it is necessary to define the boundary conditions of the system being considered. The conceptual dosimetric model for each scenario is then expressed in mathematical form as a group of equations. More than one mathematical equation may be appropriate for a given conceptual model. The equations may be empirically and/or physically based, depending on the level of detail required. The equations and their associated parameters form the basis of the mathematical models applied for dose calculations.

In this section, the model parameters are presented and appropriate calculations for each of the conceptual scenarios identified in Section 4 are described. To enable the reader to follow the calculations, a complete list of all the parameters (symbols and units) used is given at the end of the main text. Many of the individual parameter values used in the calculations applied to each of the scenarios are specific to those scenarios and, therefore, presented in appropriate scenario descriptions as tables or single values. Some of the generic parameter values, however, are used in several calculations and these are listed in the Appendix. Finally, at the end of each section in which calculations for each scenario are presented, the dose conversion coefficients (DCC) obtained are tabulated. These dose conversion coefficients are expressed in units of mSv per Bq kg^{-1} and represent the annual dose likely to be incurred within the context of each scenario as a result of exposure to wood with an original activity concentration of 1 Bq kg^{-1} of ^{137}Cs or ^{90}Sr.

It should be noted that, in importing countries, contaminated wood is usually significantly diluted with non-contaminated wood, as described in Section 2.3, and therefore the DCCs presented below should be considered as upper estimates. In practice, blending of wood imported from different countries and/or areas within exporting countries results in significant reductions (one to two orders of magnitude, according to unpublished Swedish data) of the mean radionuclide activity concentrations in wood processed in industry or applied for domestic use compared with activity concentrations in separate portions of imported wood monitored by custom officers.

From the conceptual scenarios developed in Section 4, it was determined that exposure due to radionuclides in wood can occur *via* three exposure pathways, namely external irradiation, inhalation of sawdust or ash aerosols and ingestion of vegetables grown in a garden in which the soil has been conditioned with contaminated wood ash. Thus, in a general case the total annual effective dose E (mSv) is composed of external dose E_{ext} and internal dose $E_{int.}$

$$E = E_{ext} + E_{int} = E_{ext} + E_{inh} + E_{ing} \tag{5.1}$$

where:

annual internal effective committed dose E_{int} (mSv) is composed of doses from inhalation E_{inh} and ingestion E_{ing}, respectively (ie. $E_{int} = E_{inh} + E_{ing}$).

In a general case, the annual effective dose due to external irradiation by gamma radiation E_{ext} (mSv) from a long lived radionuclide can be expressed by the following equation:

$$E_{ext} = D \cdot OF \cdot CC \tag{5.2}$$

where:

D is the dose rate in air at the site of occupational exposure (mGy h^{-1});
OF is the occupational factor, e.g. annual exposure duration (h);
CC is the conversion coefficient from the dose in air to effective dose (Sv Gy^{-1}).

In (5.2) the air dose rate can be expressed as follows:

$$D = C_p \cdot DR_{ext} = C_w \cdot CF_p \cdot DR_{ext} \tag{5.3}$$

where:

C_w is the mean radionuclide activity concentration in wood (Bq kg^{-1});
C_p is the mean radionuclide activity concentration in wood products or by-products (ash, liquor, etc) (Bq kg^{-1});
CF_p is the radionuclide concentration factor from wood to wood products or by-products (ash, liquor, etc) (dimensionless);
DR_{ext} is the external dose rate coefficient to be defined for different geometrical conditions of exposure (mGy h^{-1} Bq^{-1} kg).

A general expression for calculating the dose due to inhalation of air-borne dust containing long lived radionuclides is:

$$E_{inh} = C_d \cdot DL \cdot BR \cdot OF \cdot DH \tag{5.4}$$

where:

E_{inh} is the committed effective dose due to annual inhalation (mSv);
C_d is the mean annual radionuclide activity concentration in dust (Bq kg^{-1});
DL is the mean annual dust load in air (kg m^{-3});
BR is the breathing rate (m^3 h^{-1});
OF is the occupational factor, e.g. annual exposure duration (h);
DH is the internal dose coefficient for inhalation (Sv Bq^{-1}).

In (5.4) the radionuclide activity concentration in dust can be expressed as follows:

$$C_d = C_w \cdot CF_d \tag{5.5}$$

where:

C_w is the mean annual radionuclide activity concentration in wood (Bq kg^{-1});
CF_d is the radionuclide concentration factor from wood to dust (sawdust, ash) (dimensionless).

Inhalation rates for different age classes *BR* were assumed according to ICRP Publication 71 [10] for conditions of light exercise for workers and for outdoor domestic conditions (scenarios of wood ash disposal and occupation in a garden) except for babies and children of 1–2 years. For indoor domestic conditions (scenario: wood as domestic fuel) average inhalation rates were assumed during the entire day. The inhalation rates for different age classes and different human activities are presented in Table A.2 of the Appendix.

The choice of dose coefficients for the inhalation of dust originated from wood, bark or wood ash was made according to their particle size recommended by ICRP for industrial and public exposure and their absorption type in the respiratory tract [10, 11, 14]. Thus, for inhalation of sawdust by adult workers the particles are assumed to be relatively large (AMAD = 5 µm) and, in the case of ^{90}Sr, relatively insoluble (Class S). For domestic scenarios all the particles are assumed to be relatively small (AMAD = 1 µm). In the case of ^{137}Cs in all materials and of both radionuclides in ash, all the particles are considered to be relatively soluble (Class F). For small bark/soil domestic dust default absorption Class M was assumed. Values for age-dependent dose factors are given in Table A.3 of the Appendix [10]. A general expression for calculating the dose due to ingestion of vegetables grown in a garden in which the soil was conditioned with wood ash containing long lived radionuclides is as follows:

$$E_{ing} = C_f \cdot M_v \cdot DG \qquad (5.6)$$

where:

E_{ing} is the committed effective dose due to annual ingestion of contaminated food (mSv);
C_f is the mean annual radionuclide activity concentration in vegetables grown in a garden (Bq kg^{-1});
M_v is the annual consumption of vegetables grown in a garden (kg)
DG is the internal dose coefficient for ingestion [14, 15] (Sv Bq^{-1}).

In (5.6) the radionuclide activity concentration in vegetable products can be expressed as follows:

$$C_f = C_s \cdot TF \qquad (5.7)$$

where:

C_s is the mean annual radionuclide activity concentration in garden soil (Bq kg^{-1});
TF is the radionuclide transfer factor from soil to food grown in a garden (dimensionless).

For each of the scenarios identified in Section 4, the generic equations (5.1)–(5.7) were used to calculate the following doses resulting from ^{137}Cs and ^{90}Sr in wood:

— external dose rates in air and annual effective doses from external exposure'
— dust inhalation doses to (non-radiation) workers and members of the public; and
— food ingestion doses to members of the public.

To estimate appropriate dose conversion coefficients *(DCC)* the annual effective dose, *E*, should be divided by the radionuclide activity concentration in wood C_w, as follows:

$$DCC = (E_{ext} + E_{inh} + E_{ing}) / C_w = DCC_{ext} + DCC_{inh} + DCC_{inh} \qquad (5.8)$$

where:

$DCC_{ext} = CF_p \cdot DR_{ext} \cdot OF \cdot CC$ is the dose conversion coefficient for external exposure (mSv Bq^{-1} kg)
$DCC_{inh} = CF_d \cdot DL \cdot BR \cdot OF \cdot DH$ is the dose conversion coefficient for inhalation (mSv Bq^{-1} kg)
$DCC_{ing} = TF \cdot M_v \cdot DG \cdot C_s / C_w$ is the dose conversion coefficient for ingestion (mSv Bq^{-1} kg).

5.2. Models of industrial exposure

5.2.1. Exposures in the sawmill industry

According to the conceptual scenario for the sawmill industry presented in Section 4.2.1, the external radiation exposure to a worker from timber stockpiled in the sawmill yard, as well as internal radiation exposure from inhaling wood dust, is modelled and assessed below.

5.2.1.1. Exposures to external irradiation from stored wood

In calculating exposure from wood stored at a wood yard it is assumed that 4 m long wooden logs are stacked in parallel rows 1 m wide and are separated from each other by 6 m. The height of the stacks is 4 m and an exposed person is situated at the mid-point between stacks. One can consider a similar geometry as for a person being situated between two half hemispheres. This is a conservative approximation which is valid for large stacks of wood. For this assumption the dose rate in the air D (mGy h^{-1}) resulting from radionuclide concentration in wood C_w (Bq kg^{-1}) is estimated as:

$$D = \frac{C_w \cdot \rho_w \cdot E_\gamma \cdot \eta}{\mu_w} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \left(1 - e^{-\mu_w \cdot R}\right) \cdot \chi \cdot 3600 \cdot 1000 \tag{5.9}$$

where:

ρ_w is the wood density (kg m^{-3});
E_γ is the energy of gamma radiation (eV);
η is yield of photons per decay (dimensionless);
μ_w is the linear attenuation coefficient for wood (m^{-1});
$(\mu_{en}/\rho)_{air}$ is the mass energy absorption coefficient for air (m^2 kg^{-1});
R is here half the length of a stack (m);
χ is conversion factor, joule per electron volt (J eV^{-1});
3600 is number of seconds in an hour (s h^{-1}); and
1000 is used to convert Sv to mSv.

When the dose rate in air is determined from (5.9) the annual effective external dose E_{ext} (mSv) of a worker occupying a wood yard for 2000 hours each year is estimated from (5.2).

Increasing the moisture content in wood results in a proportional reduction of the photon flux and the absorbed dose. For example, a water content of 5% in wood reduces the dose factor by approximately 5%. The calculations were performed for fresh timber (moisture content 70%) and for dry timber and the data are presented below in Table V in the form of DCCs, for a radionuclide concentration in wood of 1 Bq kg^{-1}.

5.2.1.2. Exposures due to inhalation of sawdust in a sawmill

Doses due to inhalation of sawdust particles are calculated as in equation (5.4) assuming a dust load in air of 2 mg m^{-3} (default parameter within the range 0.2–20 [4]) during the entire working day. Other model parameter values are presented in the Appendix. Results are presented in Table III below in the form of dose conversion coefficients.

TABLE III. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg) CALCULATED FOR ANNUAL EXTERNAL EXPOSURES TO ^{137}Cs AND ^{90}Sr IN STORED WOOD AND INHALATION OF SAWDUST IN A SAWMILL

Exposure	Timber condition	^{137}Cs	^{90}Sr
External	Dry	1.5×10^{-4}	0
	Wet	7×10^{-5}	0
Sawdust inhalation	NA	4×10^{-8}	5×10^{-7}
Total	Dry	1.5×10^{-4}	5×10^{-7}
	Wet	7×10^{-5}	5×10^{-7}

5.2.2. Exposures in the construction industry

According to Section 4.2.2, the pathways of worker exposure in the construction industry are similar to those in the sawmill industry, but the levels of both external exposure and radionuclide inhalation are usually lower because wood is only one of several construction materials. In the construction of wooden houses, the radiological conditions could be similar to sawmill conditions. Thus, for the purposes of this report, this scenario is covered by the more conservative scenario for sawmills addressed in the previous section, Table III.

5.2.3. Exposures in the furniture manufacturing industry

According to Section 4.2.3, the pathways of worker exposure at a furniture factory are similar to those in the sawmill industry. However, levels of both external exposure and radionuclide inhalation are usually lower because the amount of stored or processed wood is smaller than in the sawmill yard and also because wood is only one of the materials used in furniture manufacturing. During construction of furniture made entirely of wood, radiological exposure could approach that at a sawmill. Thus, for the purposes of this report, the radiological conditions in the furniture manufacturing industry are covered by the more conservative scenario for sawmills assessed in Section 5.2.1.

5.2.4. Exposures in the wood pulp and paper industries

In accordance with the conceptual scenario presented in Section 4.2.4, the next step is to model and assess external radiation exposure from radionuclides concentrated in the liquor holding tanks to workers. Further exposure to radionuclides in ash depending on the method of utilization and/or disposal is described separately in Section 5.2.6.

As the activity concentration in wood pulp used for production of paper and cardboard is about two orders of magnitude lower than that of wood and, because non-contaminated materials are added to the pulp during the production of paper and cardboard, radiation exposure in the paper industry is not considered to be significant.

In spite of the relatively large amount of paper used in the publishing industry the exposure from radionuclides contained in paper may be considered to be negligible for the same reasons as those which apply in the paper manufacturing industry.

5.2.4.1. Exposure to external irradiation from a liquor holding tank at a pulp mill

Activity concentrations of radionuclides in black liquor can build up to significant levels due to recycling within the pulping process (see Figure 5). The liquor is retained in a holding tank which can represent a significant source of radiation. Exposure to workers will occur from the top of the liquor tank and the dose rate at the top surface of the tank is therefore of importance. To calculate the dose rate from such a storage tank, it is assumed that the tank is cylindrical in shape. Some shielding will be afforded by the metal, usually steel, wall of the tank. Taking this into account, the dose rate in air $\dot{D}$ (mGy h^{-1}) at a height "h" above a cylindrical tank can be calculated in accordance with (5.3) as follows:

$$\dot{D} = C_l \cdot DR_{ext} \tag{5.10}$$

where:

$$DR_{ext} = \frac{\rho_l \cdot E_\gamma \cdot \eta}{2} \left(\frac{\mu_{en}}{\rho} \right)_{air} \cdot \chi \cdot 3600 \cdot 1000 \cdot \int_0^Z \int_{(\mu_s z + \mu_{air} h + \mu_{Fe} a)}^{\left[\sqrt{r^2+(h+z)^2} \cdot \left(\frac{\mu_s z + \mu_{air} h + \mu_{Fe} a}{z+h}\right)\right]} \frac{e^{-\tau}}{\tau} d\tau dz$$

In these equations:

C_l is the radionuclide activity concentration in wood pulp liquor (Bq kg^{-1});
and $C_l = CF_l \cdot C_w$ where:
CF_l is the radionuclide concentration factor from wood to liquor; default value 26 (dimensionless);
C_w is the radionuclide activity concentration in wood (Bq kg^{-1});
ρ_l is the liquor density (kg m^{-3});
E_γ, η , $(\mu_{en}/\rho)_{air}$ and χ are defined above, see (5.9);
μ_s, μ_{air} and μ_{Fe} are linear attenuation coefficients for wood pulp liquor, air and steel (m^{-1});
R is the radius of the tank (m);
Z is the height of the tank (m);
h is the distance above the tank cover (m);
a is the thickness of the steel wall of the tank (m).

The original calculations made by Ravila and Holm [12] for a liquor tank with a radius of 8.6 m and equal height gives $DR'_{ext} = 1.48 \cdot 10^{-17}$ Sv m^3 Bq^{-1} s^{-1}, which was converted in the form of (5.3):

$$\dot{D} = 1.5 \cdot 10^{-6} \cdot C_w.$$

The annual effective external dose E_{ext} (mSv) to a worker who spends 100 hours per year (OF = 100) on a liquor tank at a pulp mill is estimated from (5.2) and (5.10). The results are presented in Table IV in the form of Dose Conversion Coefficients (DCC) for external exposure.

TABLE IV. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg IN WOOD) CALCULATED FOR ANNUAL EXTERNAL EXPOSURES TO ^{137}Cs AND ^{90}Sr IN A WOOD PULP LIQUOR TANK

	^{137}Cs	^{90}Sr
External exposure from liquor tank	1.1×10^{-4}	0

5.2.5. Exposures at bio-fuel plants

According to Section 4.2.5, exposure pathways to workers in the bio-fuel plants are external exposures during handling and incineration of wood and eventual disposal of the ash at a waste dump. Because of blending of wood from different geographical areas, the activity concentrations and associated external exposures are usually significantly lower than at sawmills, see Section 5.2.1 and Table III. Exposures due to ash treatment and disposal are discussed in the next section.

5.2.6. Exposures to wood ash deposits

Wood ash produced at pulp factories and bio-fuel plants is usually deposited in stockpiles prior to final disposal. Eventually, the ash might be placed in industrial/municipal dumpsites, used as fill material at landfills and in roads or applied to forests as a fertilizer. Exposure of workers to external irradiation and to inhalation of ash are the major exposure pathways for workers at an ash deposit.

5.2.6.1. Exposures to external irradiation from stockpiled wood ash and landfill

The dimensions of the industrial ash stockpile considered here are 120m × 30m × 4m. Radiation at a central point on the surface of an ash stockpile of these dimensions can be considered to emanate from a hemispherical volume within the ash. The dose rate in air D (mGy h^{-1}) due to irradiation from such a hemispherical source can be calculated as follows:

$$D = \frac{C_{ash} \cdot \rho_{ash} \cdot E_{\gamma} \cdot \eta \cdot B}{2\mu_{ash}} \left(\frac{\mu_{en}}{\rho} \right)_{air} \cdot \chi \cdot 3600 \cdot 1000 \tag{5.11}$$

In this equation:

C_{ash} is the radionuclide activity concentration in wood ash (Bq kg^{-1});

and $C_{ash} = CF_{ash} \cdot C_w$

where:

CF_{ash} is the radionuclide concentration factor from wood to ash (dimensionless);
C_w is the radionuclide activity concentration in a wood (Bq kg^{-1});
ρ_{ash} is the ash density (kg m^{-3});
B is the build-up factor, equal to 2.5 for an infinite source of ^{137}Cs in water (dimensionless);
E_{γ}, η , $(\mu_{en}/\rho)_{air}$ and χ are defined above, see (5.9).

Usually, the ash contains about 70% water after it is sprinkled with water to reduce re-suspension. The dose rate at a height of 1 m above wet ash has been calculated — this dose rate is by a factor of two lower than one above dry ash with a bulk density (ρ_{ash}) of 800 kg m^{-3}. Having calculated the dose rate in air above infinite hemispherical source of wet wooden ash the effective dose to workers occupying OF=100 hours per year during treatment of stockpiled ash due to external radiation exposure and appropriate DCC values are estimated from (5.8), (5.9) and (5.11), see Table V below.

TABLE V. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg) CALCULATED FOR ANNUAL EXPOSURES TO ^{137}Cs AND ^{90}Sr IN WOOD ASH IN A INDUSTRIAL CONTEXT

Exposure	Ash stockpile		Landfill		Forest fertilisation	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
External	3×10^{-4}	0	2×10^{-4}	0	6×10^{-6}	0
Inhalation of ash	1×10^{-7}	5×10^{-7}	3×10^{-8}	1×10^{-7}	1×10^{-7}	5×10^{-7}
Total	3×10^{-4}	5×10^{-7}	2×10^{-4}	1×10^{-7}	6×10^{-6}	5×10^{-7}

The external dose from ^{90}Sr will not be significant for ash deposits due to the short range of beta particles in air and self-absorption in the stockpiled ash. The bremsstrahlung produced is only a minor fraction of the total energy and consists mainly of low energy photons.

Radiation conditions on the surface of a landfill are similar to those on the surface of an ash stockpile. Here ash becomes wet because of exposure to natural precipitation. As operations at a landfill are not of a permanent nature, the default value for an occupation period can be restricted by 50 hours per year, see Table V.

5.2.6.2. Exposures due to inhalation of ash at ash stockpiles and landfill sites

Committed effective doses due to inhalation of re-suspended ash particles above an industrial ash deposit are calculated using equation (5.4) for a worker occupying OF=100 hours per year during treatment of stockpiled ash. The dust load in air is conservatively assumed to be equal to 2 mg m^{-3} for dry and windy conditions. The inhalation rate for adults is taken from Table A.2 of the Appendix and the effective dose coefficients for soluble compounds of ^{137}Cs and ^{90}Sr with AMAD equal 5 µm are taken from Table A.3 of the Appendix.

On the surface of a landfill one may assume similar air contamination as on the surface of ash stockpiles. As operations at a landfill are not of a permanent nature, the default value for an occupation period can be restricted by 50 hours per year, see Table V below.

5.2.6.3. Exposures due to application of ash as forest fertilizer

Forest workers are affected by radiation from contaminated wood ash via external exposure and dust inhalation both during the period of its application and, subsequently, when attending fertilized forest areas. In the later time period the areas fertilized with contaminated ash can be also visited by members of the general public.

(a) External exposure

The absorbed dose rate of gamma radiation in air D (mGy h^{-1}) can be calculated from the radionuclide concentration in soil C_s (Bq m^{-3}) and an appropriate external dose conversion coefficient derived for exposure to gamma emitters in soil (e.g. [16]) with appropriate corrections. In the case of ash applied as a forest soil fertilizer at a rate of about 0.3–0.4 kg per m^2 [12, 13] the source can be considered to be planar, distributed in the upper layer of the soil with a thickness about 0.5 cm. Later on, due to weathering and generally limited migration in the soil profile, ^{137}Cs tends to become fixed in the upper layer of forest soil with thickness of about 2 cm.

$$D = C_{ash} \cdot M_{ash} \cdot DR_{ext} = C_w \cdot CF_{ash} \cdot M_{ash} \cdot DR_{ext} \tag{5.12}$$

where:

M_{ash} is the ash application rate; default value 0.4 kg m^{-2};
CF_{ash} is the radionuclide concentration factor from wood to ash, (dimensionless);
DR_{ext} is the external dose rate in air coefficient for a planar infinite source in soil (mGy h^{-1} $Bq^{-1}m^{-2}$).

According to reference [16], for a planar infinite source of gamma radiation in soil with the energy E_γ=660 keV, DR_{ext} = $2.1\cdot10^{-9}$ (mGy h^{-1})/(Bq m^{-2}) for a soil thickness of 0.5 cm and $1.8\cdot10^{-9}$ (mGy h^{-1})/(Bq m^{-2}) for a soil thickness of 2 cm.

Based on equations (5.12) and (5.2) and assuming i) that CF_{ash} is equal to 50 for ash and ii) the annual occupancy in a forest area fertilized with ash containing long lived radionuclides is 200 hours for forest workers and 100 hours for members of general public, the annual effective dose from this source can be estimated. The results of this calculation are presented in Table V in the form of DCCs for external exposure.

(b) Inhalation

The use of contaminated ash as a forest soil fertilizer may give rise to internal doses by inhalation of ash dust particles. In the open air, the time averaged concentration of respirable dust particles has been conservatively estimated to be 2 mg m^{-3} including 1 mg m^{-3} of ash dust during its application and only 0.1 mg m^{-3} of ash for later periods because of mixing of ash with the soil. An inhalation rate according to Table A.2 of the Appendix and occupation time in forest as above for persons of all ages have been assumed. The dose to man can be calculated according to equation (5.4) and the results are presented below, see Table V, in the form of DCCs.

The results of annual effective dose calculations for exposures to wood ash in the industrial context are presented in Table V. It should be noted that these dose assessments assume that the industrial enterprise under consideration is entirely supplied by wood imported from radioactively contaminated areas. In practice, the small fraction of wood imported from contaminated areas would be blended with a relatively larger fraction of wood from uncontaminated areas. Thus the Dose Conversion Coefficients (DCCs) presented in Table V are likely to be conservative; probably by as much as one to two orders of magnitude.

5.3. Models of domestic exposure

5.3.1. Exposures from timber buildings

As discussed in Section 4.3.1, the major pathway of exposure of inhabitants of a house constructed from wood contaminated with radionuclides is external exposure from wooden components of the house (walls, floor and ceiling). The external exposure of a person in a sauna deserves separate consideration because of the special exposure conditions which apply in such a 'building'.

5.3.1.1. External irradiation within a room of average dimensions

The absorbed dose rate in air $\dot{D}$ (mGy h^{-1}) from primary radiation emanating from a gamma-emitting radionuclide within a planar wooden source such as a wall with radionuclide concentration C_w at the height r above the source centre can be calculated as follows:

$$D = C_w \cdot DR_{ext} \tag{5.13}$$

where:

$$DR_{ext} = \frac{\rho_w \cdot E_\gamma \cdot \eta \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air}}{4\pi} \cdot \chi \cdot 3600 \cdot 1000 \cdot \int_{-X}^{X}\int_{-Y}^{Y}\int_{0}^{Z} \frac{e^{-(\mu_w \cdot z + \mu_{air} \cdot r)\frac{\sqrt{z^2+y^2+(h+z)^2}}{h+z}}}{x^2+y^2+(h+z)^2}\, dxdydz$$

In these formulas:

ρ_w, E_γ, η, $(\mu_{en}/\rho)_{air}$, μ_w, μ_{air} and χ are defined above (5.9);
h is the distance above the floor (m);
2X, 2Y and Z – are dimensions of the planar source (m).

An absorbed dose rate in air was calculated for ^{137}Cs gamma radiation in the centre of a room within a hypothetical wooden house [17]. The room was assumed to be a simple ‘box’ with external dimensions 7 m × 7 m × 3 m, representing 6 planar sources of radiation. Four walls, floor and roof were assumed to be constructed of wood with thicknesses of 0.2 m, 0.045 m and 0.0225 m, respectively. Calculated dose rate in air coefficients are presented in Table VI.

Having calculated the total absorbed dose rate in air for a room, the annual effective dose due to external radiation exposure within the room during default time of 4000 h is then estimated according to (5.2). The results are presented below in Table VII in the form of DCCs for external exposure.

TABLE VI. DOSE RATE IN AIR COEFFICIENTS (DR_{ext}, mGy h^{-1} Bq^{-1} kg) CALCULATED FOR A ROOM IN A HYPOTHETICAL WOODEN HOUSE

Part of room	Dimensions (m) (length×width×thickness)	External dose rate coefficient (mGy h^{-1} Bq^{-1} kg)
Floor	7 × 7 × 0.045	1.0×10^{-9}
Wall	4 × (7 × 3 × 0.2)	6.0×10^{-9}
Ceiling	7 × 7 × 0.0225	0.5×10^{-9}
Total	–	7.5×10^{-9}

TABLE VII. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg) CALCULATED FOR ANNUAL EXTERNAL EXPOSURES TO ^{137}Cs AND ^{90}Sr IN WOOD USED AS A DOMESTIC BUILDING MATERIAL

External exposure in the:	^{137}Cs	$^{90}Sr/Y$
Average room	2×10^{-5}	0
Sauna	5×10^{-7}	3×10^{-8}

5.3.1.2. *External irradiation within a sauna*

The absorbed dose rate for external exposure within a sauna with a typical size 3m × 4m × 2.5 m will be similar to that in an average room within a timber house. Hence, the same total dose rate coefficient for gamma emitting radionuclides can be used for both an average room and a sauna, although the annual occupancy time assumed for a sauna (100 h) is much lower than for an average room (4000 h).

However, an additional consideration within a sauna is the skin dose likely to be received from beta particles emitted by both ^{137}Cs and $^{90}Sr/Y$. The highest dose rate from beta particles will be at the surface of a wooden bench and, in a sauna, there will be no shielding provided by clothing, which is normally adequate protection from beta radiation. The dose rate D (mGy h^{-1}) on the surface of a wooden bench with radionuclide concentration C_w considered as a semi-infinite source of beta radiation will be as follows:

$$\dot{D} = \frac{C_w \cdot E_\beta \cdot \chi \cdot 3600 \cdot 1000}{2} \tag{5.14}$$

where:

E_β is the mean energy of beta radiation of radionuclide under consideration (keV)

χ is defined above (5.9).

This dose rate can be used as an upper estimate of the dose rate to skin which is the only body tissue irradiated by beta particles at the area of contact with a thick source of beta radiation. In the case of ^{90}Sr the total dose rate will be the sum of dose rates from both ^{90}Sr and its short-lived daughter ^{90}Y. The mean beta energies for ^{90}Sr and ^{90}Y are 196 keV and 934 keV, respectively. In the case of ^{137}Cs the mean beta energy is 188 keV [18]. Thus, the surface dose rate is estimated to be $0.6 \cdot 10^{-7}$ mGy/h for a ^{137}Cs concentration in wood of 1 Bq kg^{-1} and $3.3 \cdot 10^{-7}$ mGy h^{-1} for an equal concentration of $^{90}Sr/Y$. To estimate the contribution of the skin dose obtained in a sauna to the annual effective dose one should additionally account for the fraction of total skin area irradiated. This is estimated to be about 0.1. The tissue weighting factor for skin is 0.01. Thus the corresponding contribution to the effective dose rate is about three orders of magnitude less than that from gamma radiation of ^{137}Cs and can be considered negligible.

5.3.2. *Exposures from flooring*

The dosimetric data necessary for estimation of the external dose from wooden flooring containing radionuclides is given in Table VI as a part of data for the timber house. The annual effective dose calculated according to (5.2) accounting for occupation of 4000 h per year and appropriate conversion coefficient is presented below in Table IX in the form of DCC.

5.3.3. *Exposures from furniture*

According to Section 4.3.3, two geometries should be considered for the external exposure to radionuclides in wooden furniture: a) a person in a wooden bed, and b) a person in a room in which individual items of furniture are uniformly distributed.

5.3.3.1. External exposure of a person in a wooden bed

A bed can be conservatively modeled by a large plane wooden source (slab) about 2 cm thick. In this case the dose rate in the air D (mGy h^{-1}) at the surface of an infinite slab is:

$$D = \frac{C_w \cdot \rho_w \cdot E_\gamma \cdot \eta \cdot \chi \cdot 3600 \cdot 1000}{2 \cdot \mu_w} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot (1 - E_2(\mu_w \cdot b)), \tag{5.15}$$

where:

E_2 is the integral exponential function (dimensionless);
b is the thickness of a slab; default value 0.02 m (m);
C_w, ρ_w, E_γ, η, χ, $(\mu_{en}/\rho)_{air}$ and μ_w are defined above (5.9)

Having calculated the dose rate in air at the surface of a bed according to (5.15) one can estimate according to (5.2) the corresponding annual effective dose to a person spending about 8 h per day or 3000 h per year in this bed. The result is given below in Table IX.

5.3.3.2. External exposure of a person from a suite of wooden furniture

In this case a simple model for calculating external exposure is to assume uniform distribution of furniture and inhabitants of the room in an area of 7 × 7 m, in a layer between the floor and the height of about 2 m. Accounting for about 10 kg of furniture per square meter of the floor (conservative estimate) the density of furniture uniformly distributed in the inhabited 2 m thick layer is estimated to be about 5 kg m^{-3}. Then, the dose rate in the air in the centre of the room 1 m above the floor D (mGy h^{-1}) can be estimated as follows:

$$D = \frac{C_w \cdot \rho'_w \cdot E_\gamma \cdot \eta \cdot \chi \cdot 3600 \cdot 1000}{2 \cdot \mu'_w} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \lambda \cdot (1 - E_2(\mu'_w \cdot \frac{b}{2})), \tag{5.16}$$

where:

ρ'_w is the density of wood in the inhabited layer; default value 5 kg m^{-3};
μ'_w is the linear attenuation coefficient for wood in the inhabited layer (m^{-1});
is geometrical factor accounting for horizontal dimensions of the room (dimensionless);
E_2 is the integral exponential function (dimensionless);
b is the thickness of an inhabited layer; default value 2 m (m);
C_w,, E_γ, η, χ, and $(\mu_{en}/\rho)_{air}$ are defined above (5.9).

Having calculated the dose rate in air in the centre of a room according to (5.16) the corresponding annual effective dose to a person occupying this room for 4000 h per year can be calculated utilizing (5.2). The result is given below in Table IX.

TABLE IX. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg) CALCULATED FOR ANNUAL EXTERNAL EXPOSURES TO AN ADULT RESULTING FROM ^{137}Cs AND ^{90}Sr IN WOOD USED AS A FLOORING OR FURNITURE

External exposure in the:	^{137}Cs	^{90}Sr/Y
Flooring	3×10^{-6}	0
Bed	3×10^{-5}	0
Furniture set	3×10^{-5}	0

5.3.4. *Exposures from general construction*

According to Section 4.3.4, the pathways of human exposure from the wood used for general construction are similar to those from wood in a timber house, but doses are usually lower because the total mass of wood used (and consequently the total radionuclide activity) is much smaller and the wood is not likely to be in such close proximity to the individual as would be the case in a wooden house. Thus, for the purposes of this report, this scenario is covered by the more conservative case for a timber house considered in Section 5.3.1.

5.3.5. *Exposures from paper and cardboard*

As discussed in Section 4.3.5, the activity concentrations of radionuclides in paper and cardboard are significantly lower than those in the raw wood (about 50 times lower than the activity concentration in the wood from which the paper is made). In living rooms, paper and cardboard are usually distributed in connection with items of furniture e.g. in cupboards or on desks. As conditions of the external exposure of inhabitants are similar to conditions of exposure from wooden furniture and, as the activity concentration in paper is lower than in wood by a factor of 50, this scenario can be considered as being covered by the more conservative scenario for furniture addressed in Section 5.3.3, Table IX.

5.3.6. *Exposure from the use of bark chips as a mulch in domestic and public gardens*

As described in Section 4.3.6, the main radiation exposure pathways relevant to the use of bark chips in both domestic and public gardens are i) direct irradiation by gamma emitters and ii) inhalation of re-suspended particles. Ingestion doses due to consumption of garden vegetables grown in soil treated with contaminated bark chips is considered possible, though negligible. One important consideration in calculating dose conversion factors within this scenario is that activity concentrations of radiocaesium tend to be higher in bark than in wood.

5.3.6.1. External dose from use of bark chips as a domestic soil mulch

The external dose rate in air from gamma-emitting radionuclides D (mGy h^{-1}) can be calculated from the radionuclide concentration in bark C_b (Bq m^{-3}) and an appropriate external dose conversion coefficient derived for exposure to gamma emitters in soil [16]. In the case of bark applied as a domestic soil mulch at a rate of about 1 kg m^{-2} (thickness about 2 mm) the source can be considered to be planar, distributed in the upper layer of the soil with a thickness of about 0.5 cm.

$$D = C_b \cdot M_b \cdot DR_{ext} = C_w \cdot CF_b \cdot M_b \cdot DR_{ext} \qquad (5.17)$$

where:

M_b is the bark mulch application rate; default value 1 kg m^{-2};
CF_b is the radionuclide concentration factor from bark to wood (dimensionless)
DR_{ext} is the external dose rate in air coefficient for a planar thin infinite source (mGy h^{-1} Bq^{-1} kg)

According to reference [16], $DR_{ext} = 2.1 \cdot 10^{-9}$ (mGy h^{-1})/(Bq m^{-2}) for a thin infinite planar source of gamma radiation with an energy E_γ=660 keV in a soil layer of 0.5 cm.

Based on equations (5.17) and (5.2) and assuming (i) that CF_b is equal 2 for bark and (ii) the annual occupancy in a garden treated with bark mulch is 300 hours for persons of all ages, the annual effective dose from this source can be estimated. The results are presented in Table X in the form of DCC for external exposure.

TABLE X. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg IN WOOD) CALCULATED FOR EXPOSURES FROM ^{137}Cs AND ^{90}Sr IN BARK USED AS A DOMESTIC SOIL MULCH

Exposure		^{137}Cs			^{90}Sr	
	Baby < 1 y	12–17 y	Adult	Baby < 1 y	12–17 y	Adult
External	8×10^{-7}	8×10^{-7}	8×10^{-7}	–	–	–
Inhalation	1×10^{-9}	4×10^{-9}	5×10^{-9}	5×10^{-9}	2×10^{-8}	2×10^{-8}
Total	8×10^{-7}	8×10^{-7}	8×10^{-7}	5×10^{-9}	2×10^{-8}	2×10^{-8}

5.3.6.2. Inhalation dose from the use of bark chips as a domestic soil mulch

The use of contaminated bark as a soil mulch may give rise to internal doses by inhalation of bark dust particles. In the open air, the time averaged concentration of respirable dust particles has been estimated to be 2 mg m^{-3} including 1 mg m^{-3} of bark dust. An inhalation rate according to Table A.2 of the Appendix and occupation time in garden of 300 h per year for persons of all ages have been assumed. The dose to man can be calculated according to equation (5.4) and the results are presented in Table X in the form of DCCs.

5.3.7. Exposures from the use of wood as a domestic fuel

As discussed in Section 4.3.7, the exposure pathways associated with the use of contaminated wood as a domestic fuel are usually external irradiation from wood and ash in the stove located in living rooms, especially if ash is stored in the stove for significant time periods, and inhalation of smoke particles consisting of ash with an elevated radionuclide activity concentration compared with the wood from which it is derived. Further use of ash as a domestic soil conditioner is modelled in Section 5.3.8. A default occupation time in a dwelling of 4000 h per year is assumed.

5.3.7.1. External doses from the use of wood as fuel

Since the volume of wood is reduced by a significant factor when burned to ash it is common practice for wood ash to be left to accumulate in domestic stoves for several days or even weeks. The accumulating ash within a stove or fireplace can be modelled as a point source of radiation. Exposure of an individual to this source of radiation will primarily be determined by the distance of the individual from the source. For a gamma-emitting radionuclide such as ^{137}Cs, the dose rate emanating from a fireplace or stove can be calculated using the following relationship:

$$\dot{D} = \frac{A \cdot E_\gamma \cdot \eta}{4 \cdot \pi\, R^2 \cdot F_s} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \chi \cdot 3600 \cdot 1000 \qquad (5.18)$$

where:

A is the radionuclide activity in the stove (fireplace) (Bq);
R is the distance from the stove to the centre of the room (m), default value 2 m;
F_s is the shielding factor (stove structure), default value 5 (dimensionless);
E_γ, η , $(\mu_{en}/\rho)_{air}$ and χ are defined above (5.9).

In the case of a fireplace or stove, the activity of the source (A) is calculated as follows:

$$A = C_{ash} \times M_{ash} = C_w \times CF_{ash} \times M_{ash} \qquad (5.19)$$

where:

M_{ash} is mass of ash in the stove (fireplace), default value 2 kg (kg)
CF_{ash} is the radionuclide concentration factor for wood to ash (dimensionless), default value 50.

Having calculated the dose rate in air at typical distance from the stove to the centre of the room according to (5.18) and (5.19), the annual effective dose can now be estimated from (5.2). Results of the dose calculation are presented below in Table XI in the form of DCCs for external exposure.

5.3.7.2. Inhalation doses from the use of timber as domestic fuel

The use of contaminated wood as a fuel for heating and cooking may give rise to internal doses by inhalation of smoke and ash particles. For open fireplaces and non-airtight wood stoves, the time averaged annual concentration of respirable smoke particles in a living room has been estimated to be 0.2 mg m^{-3}. An inhalation rate of 0.9 m^3 h^{-1} for an adult, 0.8 m^3 h^{-1} for a teenager and 0.12 m^3 h^{-1} for a baby (see Table A.2) and an occupation in a house for 4000 h per year have been assumed. The ratio of activity concentrations of both ^{137}Cs and ^{90}Sr in ash to that in wood was assumed to be 50. The dose to man has been calculated according to equation (5.4) with breathing rates as above and dose conversion coefficients from Table A.3. The results are presented in Table XI in the form of DCCs.

5.3.8. Exposure from the use of wood ash as a domestic soil conditioner

As indicated in Section 4.3.8, disposal of wood ash can provide a significant source of radionuclides to garden soils, especially if disposal takes place over many years. It can be assumed that the ash, with a radionuclide concentration denoted by $C_{ash,}$ is mixed into the surface layer of the soil to a depth of about 15 cm. The average soil activity concentration within this layer, denoted by C_{soil}, can be calculated as follows, neglecting radioactive decay.

$$C_s = Y \cdot C_{ash} \cdot M_{ash} / M_s = Y \cdot C_w \cdot CF_{ash} \cdot M_{ash} / M_s \qquad (5.20)$$

where:

Y is the period during which garden soil is conditioned with contaminated ash; the default value is 5 years (years);
M_{ash} is the mass of ash used annually to treat 1 m^2 of the garden soil; the default value is 1 kg m^{-2} y^{-1} (kg m^{-2} y^{-1});
M_s is the mass of arable soil per 1 m^2. For a soil layer 15 cm thick and a soil density of 1500 kg m^{-3} M_{soil} is estimated to be 225 kg m^{-2} (kg m^{-2});
CF_{ash} is the radionuclide concentration factor for wood to ash (dimensionless) the default value is 50.

According to the conceptual scenario adopted here (Section 4.3.8), three exposure pathways will be considered. Firstly, external irradiation of individuals standing on the soil. Secondly, re-suspension of contaminated ash and soil particles resulting in internal exposure via inhalation. Thirdly, consumption of vegetables grown on ash-treated soil leading to internal exposure via ingestion.

TABLE XI. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg in wood) CALCULATED FOR ANNUAL EXPOSURES FROM ^{137}Cs AND ^{90}Sr IN WOOD USED AS A DOMESTIC FUEL

Exposure	^{137}Cs			^{90}Sr		
	Baby < 1 y	12–17 y	Adult	Baby < 1 y	12–17 y	Adult
External	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}	–	–	–
Inhalation	4×10^{-8}	1.4×10^{-7}	1.7×10^{-7}	6×10^{-7}	1.7×10^{-6}	8×10^{-7}
Total	1.1×10^{-6}	1.2×10^{-6}	1.3×10^{-6}	6×10^{-7}	1.7×10^{-6}	8×10^{-7}

5.3.8.1. *External dose from the use of wood ash as a domestic soil conditioner*

The external dose rate in air from gamma-emitting radionuclides in soil is calculated from the soil concentration C_{soil} (Bq kg^{-1}) and an appropriate external dose conversion coefficient DR_{ext} (mGy h^{-1})/(Bq kg^{-1}) derived for exposure to gamma emitters in soils [16]. The annual effective dose E_{ext} (mSv) can then be calculated using equation (5.2) in which the radionuclide soil concentration is given by the formula (5.20).

$$E_{ext} = C_w \cdot CF_{ash} \cdot M_{ash} / M_s \cdot DR_{ext} \cdot OF \cdot CC \tag{5.21}$$

where:

CF_{ash} , M_{ash} , and M_s are defined above (5.20);
OF is the occupational factor, e.g. annual exposure duration (h);
CC is the conversion coefficient from dose in air to effective dose (Sv/Gy).

In the case of a uniform distribution of ^{137}Cs within the surface soil layer to a depth of 15 cm, an appropriate DR_{ext} derived for soils [16] is $1.7 \cdot 10^{-7}$ (mGy h^{-1})/(Bq kg^{-1} in soil). The results of calculation of the effective dose according to (5.21) assuming annual occupation for persons of all ages in a garden OF equal to 300 h are presented below in Table XIII in the form of DCCs for external exposure.

5.3.8.2. *Inhalation dose from the use of wood ash as a domestic soil conditioner*

The calculation of inhalation exposure in this scenario is essentially the same as described by equation (5.4). However, the air concentration of respirable particles and corresponding inhalation dose can be estimated as follows. Assuming soil dust load DL in open air to be $2 \cdot 10^{-6}$ kg m^{-3} and radionuclide soil concentration according to (5.20) the annual effective committed dose E_{inh} due to spending 300 hours per year in a garden, for persons of all ages, is estimated by the following formula.

$$E_{inh} = C_w \cdot CF_{ash} \cdot M_{ash} / M_s \cdot DL \cdot BR \cdot OF \cdot DH \tag{5.22}$$

where:

CF_{ash} , M_{ash} , and M_s are defined above (5.17);
BR is the breathing rate (m^3 h^{-1});
DH is the internal dose coefficient for inhalation (mSv Bq^{-1}).

The default values for BR and DH are taken from the Appendix and the results of calculation according to (5.22) are presented below in Table XIII.

TABLE XII. EXPECTED RANGES OF SOIL-TO-PLANT TRANSFER FACTORS FOR ^{137}Cs AND ^{90}Sr UPTAKE BY PEAS, ROOT CROPS AND GREEN VEGETABLES (DRY WEIGHT BASIS) [19]

Nuclide	Soil-to-plant TF (dimensionless)		
	Lower	Upper	Default
^{137}Cs	1.1×10^{-2}	4.6×10^{-1}	2×10^{-1}
^{90}Sr	2.0×10^{-2}	3.0×10^{0}	2×10^{-1}

TABLE XIII. DOSE CONVERSION COEFFICIENTS (DCC, mSv Bq^{-1} kg IN WOOD) CALCULATED FOR EXPOSURES FROM ^{137}Cs AND ^{90}Sr IN WOOD ASH USED AS A DOMESTIC SOIL CONDITIONER

Exposure	^{137}Cs			^{90}Sr		
	Baby < 1 y	12–17 y	Adult	Baby < 1 y	12–17 y	Adult
External	4×10^{-5}	4×10^{-5}	4×10^{-5}	–	–	–
Ingestion	5×10^{-6}	6×10^{-6}	1×10^{-5}	5×10^{-5}	4×10^{-5}	3×10^{-5}
Inhalation	3×10^{-9}	1×10^{-8}	1×10^{-8}	1×10^{-8}	5×10^{-8}	4×10^{-8}
Total	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}	4×10^{-5}	3×10^{-5}

5.3.8.3. *Ingestion dose from the use of wood ash as a domestic soil conditioner*

Assuming the radionuclide activity concentration in soil is calculated according to (5.20), the corresponding activity concentration in vegetables grown in the garden can be estimated via soil-to-plant transfer factors, TF. Values for soil-plant transfer factors for ^{137}Cs and ^{90}Sr are shown in Table XII. The default values of TFs have been selected close to these for potato and vegetables, which can be produced and consumed by garden owners in significant amounts, see below.

The annual effective committed dose due to ingestion of contaminated vegetables E_{ing} (mSv) grown in soil with radionuclide concentration C_{soil} (Bq kg^{-1}) is then given by the following equation:

$$E_{ing} = C_w \cdot CF_{ash} \cdot M_{ash}/M_s \cdot TF \cdot M_v \cdot WC_{veg}/WC_s \cdot DG \qquad (5.23)$$

where:

M_v is the annual consumption of homegrown fresh vegetables (kg).

The default value for M_v is assumed to be 20 kg for adults, 10 kg for teenagers and 5 kg for a baby.

WC_{veg}/WC_s is the ratio of mean water content in root crops and vegetables to that in soil (dimensionless).

The default value for WC_{veg}/WC_s is assumed to be 0.2 [19].

DG is the internal dose coefficient for ingestion; see Table II-4 (mSv Bq^{-1}).

The results of calculations of the effective dose according to (5.23) are presented in the Table XIII in the form of DCCs for ingestion.

6. GUIDANCE ON THE APPLICATION OF THE DEVELOPED METHODOLOGY

6.1. General application

The objective of Section 5 was to calculate a series of dose conversion coefficients (DCCs) for a number of industrial and domestic scenarios in which exposure of an individual to contaminated wood or wood-derived materials was possible and potentially significant. The probability of an individual being exposed in each of these scenarios will vary greatly, depending primarily on the source of wood being used but also on factors such as differences in industrial working practices from country to country and from factory to factory, as well as the personal habits of individuals at home.

The dose conversion coefficients calculated and presented in Section 5 are intended to be used as screening values for an initial assessment of the relative importance of radiological exposures to contaminated wood. The DCC values calculated were based on values of scenario-specific parameters, which are considered to be moderately conservative for human behavior in both the industrial (non-radiation) and domestic scenarios. These default parameter values are all presented in the Appendix. The full set of DCC's for total dose is presented in the summary Table XIV. However, when the calculated exposures, based on the default DCC values, approach the dose criteria adopted for particular conditions or exceed them, more representative scenario-specific or site specific parameter values should be sought.

It can be seen from Table XIV that, for ^{137}Cs, the critical scenario (corresponding to the highest DCC value) is industrial ash disposal because of significant external exposure from the large volumes of ash containing considerably concentrated radionuclide activities. For ^{90}Sr, the critical scenario is domestic garden soil conditioning with ash because of the relatively high transfer of this radionuclide from soil to vegetation.

TABLE XIV. DOSE CONVERSION COEFFICIENTS FOR MOST EXPOSED POPULATION GROUPS (DCC, mSv per Bq/kg IN WOOD) FOR DIFFERENT SCENARIOS OF TREATMENT OR APPLICATION OF WOOD CONTAMINATED WITH ^{137}Cs OR ^{90}Sr

Category of scenarios	Scenario		DCC, mSv per Bq/kg in wood ^{137}Cs	^{90}Sr
Industrial	Sawmill		1.5×10^{-4}	5×10^{-7}
	Pulp factory		1.1×10^{-4}	0
	Ash disposal:	Stockpile	3×10^{-4}	5×10^{-7}
		Landfill	2×10^{-4}	1×10^{-7}
		Forest fertilization	6×10^{-6}	5×10^{-7}
Domestic	Timber house and sauna		2×10^{-5}	3×10^{-8}
	Flooring		3×10^{-6}	0
	Furniture		3×10^{-5}	0
	Bark chips as a mulch		8×10^{-7}	2×10^{-8}
	Domestic fuel		1.3×10^{-6}	1.7×10^{-6}
	Garden soil conditioning with ash		5×10^{-5}	5×10^{-5}

It should be noted, however, that DCC values applied to both radionuclides are developed based on the very conservative assumption that blending with non-contaminated timber is not accounted for. In practice imported wood will inevitably be blended with non-contaminated wood, resulting in the radionuclide activity concentration being diluted by one to two orders of magnitude (see Sections 2.3 and 7).

The most probable implementation of the developed methodology would be screening level dose assessment based on country-specific monitoring and wood use data. The overall dose assessment procedure consists of several consecutive steps introduced in Section 2.3 and described in detail in the next section.

Another important application of the developed models, associated with the dose assessment considered above, is calculation of the standards, i.e. derived concentrations (DC), for long lived radionuclides in wood and wood-based products subject to international trade or national use. The appropriate general methodology is introduced in Section 2.3 and described in detail in Section 6.3.

6.2. Application of developed models for dose assessment

The procedure of dose assessment using the developed set of generic models and with incorporation of additional site specific data is a multi-stage screening procedure. It consists of several steps, during which the applied radiological models are modified iteratively from the generic ones, developed in Section 5, to specific ones accounting for local conditions. The input data for the dose assessment are the results of determinations of radionuclide concentrations in timber and wood products by way of monitoring, modelling or from official certificates. Depending on the assessment task, average radionuclide concentrations or particular percentiles of a frequency distribution or extreme values are used for dose calculations.

As an initial step in the procedure, the appropriate individual dose criterion (IDC) should be selected. The screening procedure should be terminated and radiological conditions should be considered to comply with radiological criteria when, at a particular step of modelling, the assessed dose to workers and/or members of the public is substantially, by an order of magnitude or more, below the appropriate dose criterion. In case in which doses approach or exceed an established dose criterion, the assessment should be continued.

Depending on the dose assessment outcome, the most appropriate model can be selected to calculate the derived concentration (DC_r) of a particular radionuclide *(r)* in a wood product ensuring that radiation safety requirements are met. Both selected dose criteria and screening procedures applied to national or international conditions may be substantially different. Internationally accepted dose criteria should be used for the purpose of international trade[4]. Within specific countries it may be appropriate to use national dose criteria.

6.2.1. Generic models

The dose assessment screening procedure usually begins (Step 1) with the application of a generic model supplied with moderately conservative default parameters. In this report, a set of models developed and supplied with default parameters as presented in Section 5 and

[4] At the time of writing, international discussions are taking place for the purpose of establishing agreed international criteria for the movement of commodities between countries.

summarized in Section 6.1 should be applied both at the national and international level. The dose should be assessed according to formula (2.1) if contamination with one radionuclide is considered or with (2.2) if more radionuclides are under consideration, for most conservative scenarios of human exposure, i.e. using the largest DCC values from Table XIV.

If the dose to workers and/or members of the public assessed by generic models (2.1) or (2.2), in combination with Table XIV, is substantially below an established dose criterion, this result may be considered as an indicator of safe radiological conditions with regard to wood contamination with radionuclides, and the screening procedure may be terminated. In cases in which doses approach or exceed an established individual dose criterion, more detailed consideration is recommended. This may include different further steps depending on whether national or international dose assessment is performed, see Section 2.3.

6.2.2. Site specific models

When the national dose assessment is performed, the second stage (Step 2) of the screening procedure should be the selection of country-specific or region-specific scenarios to account for national or regional production and social conditions and human habits in those nations or regions, see Section 2.3.

If necessary, the next stage of the national dose assessment (Step 3) should be the specification of model parameters based on local production, social conditions and human habits. In the case of site- or scenario-specific assessments it is important to consider very carefully the most realistic or representative values for each of the scenario-specific parameters described in Section 5 and presented in the Appendix, see also Table XV. Use of scenario-specific parameter values tailored to an individual safety assessment will result in the calculation of new DCC values which are likely to be more relevant for the specific case being considered. Once these scenario-specific DCCs have been obtained, they can be used in equations (2.1) or (2.2) to calculate more precise and realistic human doses.

It should be noted that, by definition, national or regional specification of human exposure scenarios or model parameters is non-applicable to international dose assessment. The wide set of generic scenarios of the industrial wood treatment and domestic applications developed in this publication was selected to be representative for international practice and is intended to cover a wide spectrum of human habits. This is also relevant to the selection of dosimetric model parameters: these are determined as moderately conservative taking into account worldwide practice. Some scenarios originate predominantly from particular countries or areas but in the international context all of them should be considered to be relevant to the total world community.

6.2.3. Mixing of wood with different radionuclide levels

The wood processed and/or utilized in affected countries outside of immediately contaminated areas usually constitutes a mixture of fractions contaminated and non-contaminated with radionuclides. For instance, it is unlikely that domestic firewood will be obtained in large quantities from distant sources. In this case, use of locally produced wood is likely to be more significant. According to expert judgement, based on experience of management of the Kyshtim and Chernobyl accidents in the FSU [20, 21], in the affected countries outside of immediately contaminated areas usually not more than one tenth of the total treated amount of wood originates from contaminated areas and contains elevated levels of long lived radionuclides. This means that on average, radionuclide activity concentrations in mixed wood products is diluted at least by an order of magnitude.

TABLE XV. LIST OF SITE SPECIFIC PARAMETERS FOR EACH SCENARIO CONSIDERED

Scenario	Site specific parameters to be considered
Exposure to stored wood and paper/cardboard	– Linear dimensions of stockpiles of wood / paper – Wood-paper concentration factor
Exposure to sawdust in industrial context	– Air concentration of respirable dust particles – Worker inhalation rates – Worker occupancy times
Exposure to external irradiation from liquor tank	– Linear dimensions of liquor storage tank(s) – Wall thickness of liquor tank – Enrichment factor, wood-black liquor – Density of black liqour – Worker occupancy times
Exposure to ash in industrial context	– Air concentration of respirable ash particles – Linear dimensions of ash deposit – Concentration factor, wood-ash – Bulk density of ash deposit – Amount of ash applied per unit of forest area – Worker inhalation rates – Worker occupancy times
Exposure to wood used as a domestic fuel.	– Air concentration of respirable ash particles – Concentration factor, wood-ash – Occupancy – Mass of wood burned – Distance from stove – Shielding Factor (stove structure) – Inhalation rate – child – Inhalation rate – adult
Exposure to external radiation in timber buildings	– Linear dimensions of room – Wall thickness – Floor thickness – Ceiling thickness – Density of wood (dry) – Occupancy in building
Exposure to bark as domestic soil conditioner	– Air concentration of respirable bark particles – Activity concentration in bark – Concentration factor, bark-wood – Occupancy in garden – Mass of bark applied to garden – Area of garden treated with bark – Inhalation rate – child – Inhalation rate – adult
Exposure to ash as domestic soil conditioner	– Soil/ash concentration in air – Concentration factor, wood-ash – Occupancy in garden – Mass of ash applied to garden – Area of garden treated with soil conditioner – Soil-plant transfer factor – Mass of home-grown vegetables consumed per year – Depth of soil mixed with ash – Inhalation rate – child – Inhalation rate – adult

When wood or wood products are exported from the affected country, an additional dilution of contaminated wood is likely to occur in the importing country after it is mixed with non-contaminated wood, which is either locally produced and/or imported from non-affected countries. Moreover, for economic reasons FSU countries (Belarus, Ukraine, Russia) restrict export of wood and wood products with elevated levels of man-made radionuclides. As a result of these factors, not more than one per cent of the wood imported by other countries originates from areas contaminated with long lived radionuclides. This estimation is based on the FAO statistical data [2], partially presented in Table II. Thus, on average, radionuclide activity concentration in mixed imported wood products is diluted by two or more orders of magnitude.

For conditions of international trade of wood and wood products, as well as of treatment of wood in the affected country outside of areas contaminated with radionuclides, it is recommended that dilution of contaminated wood with non-contaminated wood is accounted for at the last stage: Step 4 of a national and Step 2 of an international dose assessment procedure. For this purpose, appropriate Dilution Factors (DF, dimensionless) are introduced in dose calculation formula (2.3). These dilution factors should be site specific and based on local production statistics. The region-specific or country-specific DF values can be estimated as ratio of the amount of timber and wood products imported per year from areas contaminated with long lived radionuclides to the total amount used annually in the region or country under consideration. The default values of DF, based on Russian and FAO statistical data [2, 20, 21], are given in Section 2.3 of the present report.

Returning to the possibility of the occasional presence of large amounts of contaminated wood in a particular dwelling or farm or in a particular production plant, one should note that among the numerous scenarios of wood treatment considered, the most limiting scenarios appear to be industrial situations in which large amounts of ash are produced and stored. The appropriate source of human external exposure was conservatively modelled assuming a semi-infinite source of gamma radiation without any shielding. However, from the operational experience of the wood industry it is known that large plants usually process wood obtained from different production areas and sources depending on market conditions. This inevitably results in the blending of wood with different radionuclide levels where low levels will naturally dominate.

In the domestic context, where the use of a large quantity of wood obtained from a single source is more likely (e.g. a set of furniture, a wooden house or sauna, etc.), the relevant DCC values (Table XIV) are generally lower by about one order of magnitude compared with industrial scenarios. This ensures a correspondingly lower dose to the general public compared with the dose to workers. Nevertheless, production of large wooden products from wood harvested in highly contaminated areas might be additionally restricted by regulation, and this is actually done in the Chernobyl-affected countries for the areas contaminated above 0.6 MBq m^{-2} of ^{137}Cs in soil [21].

It should be stressed that restriction of particular uses of commodities contaminated with radionuclides, including timber and wood products, is feasible only at the national level in countries with a strict system of radiological control, see Section 2.3. Such a control is unrealistic in terms of the international trade of commodities, in which their unrestricted use should be assumed. Therefore, wood contaminated above levels that result in human exposure above internationally agreed IDC should be excluded from international trade.

6.3. Application of developed models for setting derived standards

In order to protect humans from radiation exposure resulting from 'remote' environmental contamination of forest with long lived radionuclides, in particular with ^{137}Cs and ^{90}Sr, the set of deterministic models developed in this report, together with the default parameter values supplied, in combination with appropriate international dose criteria, could be applied to determine derived concentration (DC) of radionuclides in timber and wood products for use in international trade. The appropriate model, non-dilution or dilution generic model in case of international trade, and formulas for DC calculation (2.4 or 2.5) should be selected depending on the results of two-stage international dose assessment, see section above.

To unify international trade conditions and to account for the fact that it is impossible to regulate movement of particular portions of imported wood in international trade, the application of a single DC for all the countries is expedient. This value, calculated according to formulas (2.4) or (2.5), should be the lowest one from the set available and derived from the largest DCC value. For each radionuclide, a single DC value is suggested for use in practice to ensure compliance of exported/imported wood with the radiological requirements for international trade. Radiological inspectors or customs officers can compare radionuclide activity concentrations in wood or wood-based products, based on official certificates or results of sampling and analysis, with single values of DC based on the results of the present work.

Apart from using the models developed here for the regulation of trade between countries, the models can also be applied to regulate trade within a country, for instance in countries with certain areas contaminated with radionuclides. As presented in the section above, a multi-stage procedure is applicable for national assessment. The model and its parameters to be used for calculation of national standards with formulas (2.4) or (2.5) in the form of resulting DCC values should be selected according to the results of the preceding multi-stage dose assessment. It is recommended to use for this purpose that model version, which provides certain compliance of the monitoring or modelling input data with an appropriate national radiological criterion in the form of annual effective dose.

For particular national situations, e.g. for standardization of radionuclide content in commodities including contaminated wood, specific generic dose levels may be established. Based on these national dose levels and applying the DCC's set developed in the present report or modified as the result of specification of basic model parameters (see above) a set of national permissible concentrations for particular radionuclides in wood can be derived which meets national requirements.

In countries with a well developed radiological infrastructure, especially in countries of the former USSR with some areas severely contaminated with ^{137}Cs and ^{90}Sr due to the Chernobyl and Kyshtim radiation accidents, different permissible levels of wood contamination with radionuclides were established for different uses of wood (dwelling construction, general construction, paper production, etc. — see next section). This approach is applicable if portions of contaminated wood are certified and can thus be traced during their movement and processing within the country under a strict system of radiological control. This would increase opportunities for the use of contaminated wood in conditions in which radiological legislation is observed.

A similar approach is not applicable for wood exported to other countries in which its unrestricted use has to be assumed. For the latter, generic derived radionuclide activity concentrations in wood should be calculated as described above, based on the conservative assumption of unrestricted use in the full range of scenarios considered in Sections 4 and 5 of the present report.

As an example of the practical application of the developed methodology and appropriate DC values for ^{137}Cs in different exported products, the national conditions of the Russian Federation will be considered in the next section and compared with national standards.

7. CASE STUDY: APPLICATION OF THE METHODOLOGY TO THE BRYANSK REGION, RUSSIAN FEDERATION

7.1. Radioecological conditions

The Bryansk region was the most severely contaminated region within the Russian Federation following the Chernobyl accident. Much of the region is forested and use of wood harvested from the area has been partially restricted due to contamination with ^{137}Cs. These restrictions are based on national standards developed since 1986 and updated in 1999 [22]. The Federal Forestry Service of Russia monitors contamination levels in wood from the region and Table XVI shows the average activity concentrations in the wood and other parts of various tree species harvested between 1994 and 1998. These activity concentrations have been decay corrected to 2000 to give an indication of present day contamination levels in wood in the region.

Also indicated in Table XVI is the land area within the Bryansk region, in km^2, which was contaminated at a density of 37–185 kBq m^{-2} (1–5 Ci km^{-2}), 185–555 kBq m^{-2} (5–15 Ci km^{-2}), 555–1440 kBq m^{-2} (15–40 Ci km^{-2}) and more than 1440 kBq m^{-2} (>40 Ci km^{-2}). It can be seen that the total area affected by high contamination (>185 kBq m^{-2} or 5 Ci km^{-2}) is significantly lower than the area receiving < 185 kBq m^{-2} (5 Ci km^{-2}). These less contaminated areas (37–185 kBq m^{-2} or 1–5 Ci km^{-2}) represent 57% of the total contaminated area (11.820 sq.km) or 19 % of the total area of the Bryansk region (34.900 sq.km) and are likely to be more important when considering the harvesting of wood from the area.

7.2. Example dose assessment

According to the methodology developed in this report, the data from Table XVI are used below for an assessment of the dose of the local population, the population of the whole Bryansk region and Russia, as well as the population of foreign countries associated with ^{137}Cs contamination of wood in the Bryansk region. The present methodology has been developed as applied to radionuclide activity concentration in timber, e.g. in barked wood. Therefore, in order to assess the maximum doses that can be obtained by non-radiation workers or the general public due to industrial treatment or domestic use of the Bryansk wood, the range of activity concentrations from Table XVI for barked wood were multiplied by maximum values of DCC from Table XIV, corresponding to the appropriate set of scenarios and their parameters as described below. The results of dose assessment (DA) are presented in Table XVII.

Step 1 of the DA. The total set of generic models with default parameters has been applied not accounting for dilution. Specifically, maximum DCC values from Table XIV were used to obtain human doses (see two upper lines in Table XVII). The limiting industrial scenario is ash disposal to a stock pile and the limiting domestic scenario is garden soil conditioning with ash. In both cases ash treatment or use is crucial because of the high radionuclide concentration. The resulting dose range is from 10 μSv to 1 mSv for industrial applications of wood harvested in areas with different levels of ^{137}Cs soil contamination and an order of magnitude lower for domestic applications.

TABLE XVI. AVERAGE ACTIVITY CONCENTRATIONS OF ^{137}Cs IN WOOD AND OTHER PARTS OF VARIOUS TREE SPECIES (C_w , Bq kg^{-1}) HARVESTED IN THE BRYANSK REGION FROM 1994 TO 1998, DECAY CORRECTED TO 2000 (RUSSIAN FEDERAL FOREST SERVICE, 2000)

Bryansk Region		Area, km^2 6750	2630	2130	310
		^{137}Cs soil deposition range, kBq m^{-2} (Ci km^{-2})			
Wood	Species	37–185 (1–5)	185–555 (5–15)	555–1440 (15–40)	>1440 (>40)
Wood with bark	pine	157	300	1565	2788
	spruce	73	170	1797	1921
	oak				1539
	birch	120	507	1453	3166
	aspen	70	454	2213	7864
Barked wood	pine	44	98	899	884
	spruce	27	53	731	310
	oak		0	0	812
	birch	44	176	581	1301
	aspen	44	181	455	2658
Bark	pine			5966	
	spruce			5722	
	oak				
	birch			3179	
	aspen			1583	
Outer bark	pine	471	1508	3789	8126
	spruce	286		2825	7637
	oak				5488
	birch	1251	1038	2834	8598
	aspen	988	1033	1858	11 223
Bast	pine	500	349	3530	6073
	spruce			5242	
	oak				9206
	birch	266	1237	3474	16 162
	aspen	794	1229	3449	27 574
Small branches	pine	82	519	3217	3620
	spruce		378		4590
	oak				7444
	birch	420	792	5212	12 222
	aspen	400	1197	3589	14 965
Leaves, needles	pine		446	2092	4423
	spruce			7600	
	oak				8818
	birch		1275	3728	15 348
	aspen		2868	3212	19 920

TABLE XVII. ASSESSMENT OF THE DOSE (mSv) ASSOCIATED WITH INDUSTRIAL TREATMENT OR DOMESTIC USE OF THE BRYANSK TIMBER CONTAMINATED WITH ^{137}Cs

Steps of dose assessment	Level of application	Scenario	Parameters	Dilution factor	Treatment/ /use	^{137}Cs soil deposition range, kBq m^{-2} (Ci km^{-2})			
						37–185 (1–5)	185–555 (5–15)	555–1440 (15–40)	>1440 (>40)
1	Local	Generic	Default	1	Industrial	0.01–0.02	0.02–0.07	0.2–0.4	0.3–1.0
					Domestic	0.001–0.002	0.003–0.009	0.02–0.05	0.04–0.1
2	Local	Region-	Default	1	Industrial	0.01–0.02	0.02–0.07	0.2–0.4	0.3–1.0
		specific			Domestic	0.001–0.002	0.003–0.009	0.02–0.05	0.04–0.1
3	Local	Region-	Region-	1	Industrial	≤ 0.01	0.01–0.04	0.1–0.2	0.2–0.5
		specific	specific		Domestic	0.001–0.002	0.003–0.009	0.02–0.05	0.04–0.1
4a	Regional or	Generic	Nation-	0.1	Industrial	0.001–0.002	0.002–0.007	0.02–0.04	0.03–0.1
	national		specific		Domestic	<0.001	≤0.001	0.002–0.005	0.004–0.01
4b	National or	Generic	Default	0.01	Industrial	<0.001	≤0.001	0.002–0.004	0.003–0.01
	international				Domestic	<0.001	<0.001	<0.001	≤ 0.001

Note: Shaded areas indicate that the appropriate dose criteria are approached or exceeded.

Step 2 of the DA. From the overall set of generic models those which are non-applicable to local conditions are forest fertilization with wood ash, landfill with ash and domestic use of bark chips as mulch. These scenarios are not considered in the dose assessment. Default parameters were still applied which do not account for dilution. Because the limiting scenarios in both industrial and domestic situations remain the same, their parameters were not changed and the results of the dose assessment did not change compared with Step 1.

Step 3 of the DA. After removal from consideration of non-applicable scenarios, the set of default parameters should be specified for local conditions. Thus, when ash is dumped in special storage areas or at municipal dumps it is usually mixed with alternating layers of soil. This measure reduces ash re-suspension and decreases the surface dose rate by a factor of 2 to 3. Three limiting industrial scenarios remain, each with DCCs of about 2×10^{-4} $mSv \cdot Bq^{-1} \cdot kg$. Appropriate dose values in Table XVII are applicable to the conditions of the contaminated areas of the Bryansk region as no dilution with non-contaminated wood has been considered. The dose range is from less than 10 μSv to 0.5 mSv for industrial applications and a factor of 5 lower for domestic applications.

Step 4a of the DA. At this step, mixing of wood harvested in the contaminated forest with non-contaminated wood from other areas has been accounted for. According to available data (Russian Federal Forest Service, 2000), the amount of wood contaminated with ^{137}Cs does not exceed 10% of wood used in the whole Bryansk region for industrial and domestic needs. In this case, application of a dilution factor of 0.1 for conditions of the Bryansk region outside of the immediate contaminated area, as well as for adjacent regions of Russia, is justified. The corresponding doses are in the range of 1 to 100 μSv depending on the level of ^{137}Cs soil contamination in the area in which timber was harvested. For domestic use the dose range is between less than 1 μSv and 10 μSv.

Step 4b of the DA. This step is intended mainly for the international trade of wood. As can be derived from FAO statistical data [2] and partially from Table II of this report, the import of wood from Russia by foreign countries amounts to not more than 10% of wood used. The fraction of the Bryansk region in this amount is less than 10% and the share of contaminated areas in total export of the Bryansk timber is definitely less than 10%. Thus, the appropriate dilution factor is much less than 0.001. However, based on a cautious approach (see Section 2.4) a dilution factor not less than 0.01 should be applied for dose assessment. The corresponding conservative estimate of the average dose of the European population from timber produced in contaminated areas of the Bryansk region is presented in Table XVII, i.e. from less than 1 μSv to 10 μSv for industrial treatment or less than 1 μSv for domestic use. For other continents similar assessments should give even lower dose estimates.

The example presented below illustrates the role of blending of wood from different sources in sawmills and pulp and paper mills at the international level which results in a reduction of human exposure. In sawmills and pulp and paper mills it is common practice to process wood from different sources which vary as fluctuating market prices for wood cause one particular source to become cheaper than another. Figure 6 shows the contributions of wood from Russian and Swedish sources to a particular sawmill and pulp plant in Sweden in November 2000 based on statistics supplied by the plant. The relative proportions of wood obtained from different sources are constantly fluctuating, but the information presented in Figure 6 is sufficient to illustrate the effect that blending of wood can exert on the effective radionuclide activity concentration.

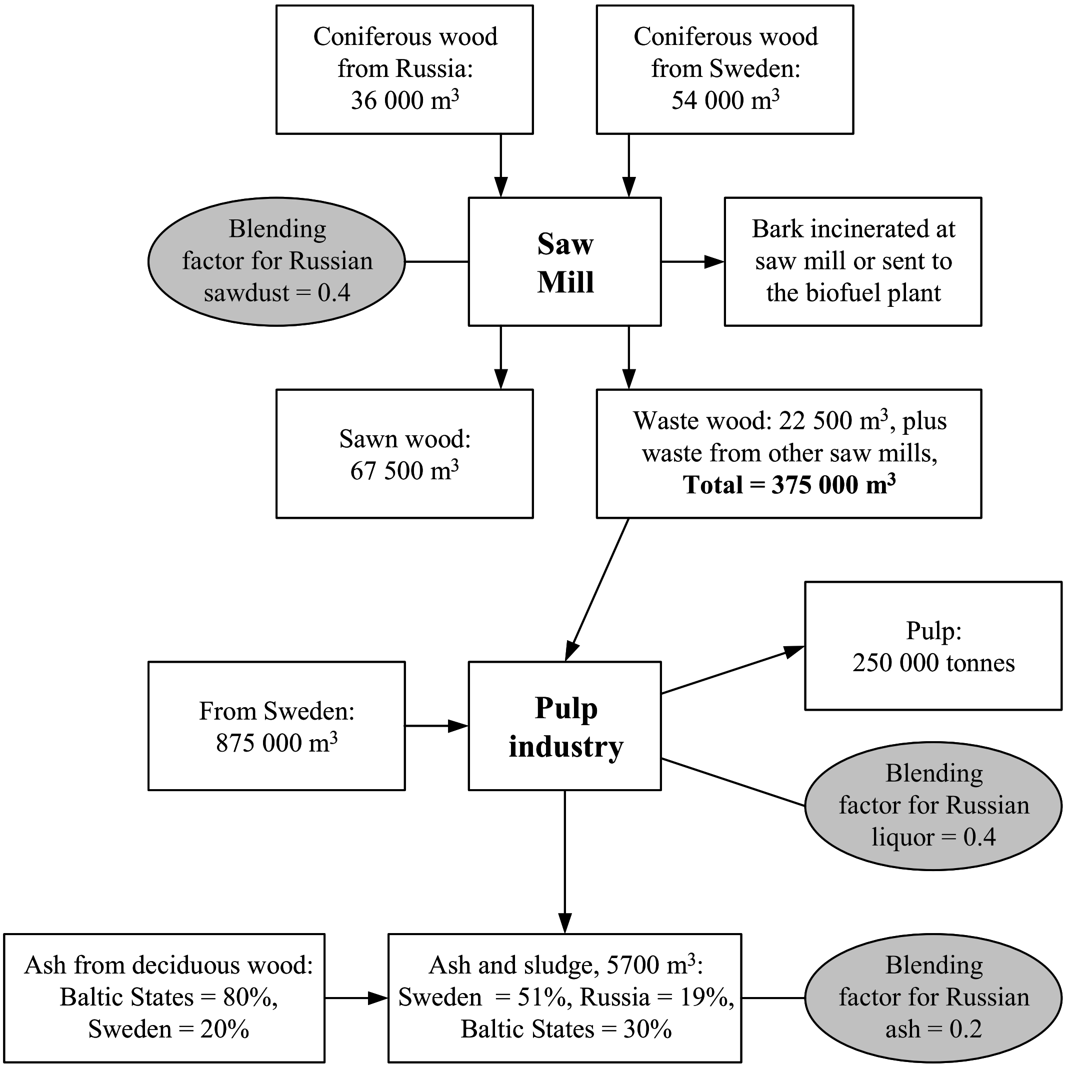

FIG. 6. Flow of coniferous wood imported from Russia in a sawmill and pulp plant in Sweden, November 2000 (data obtained via private communication).

In the manufacture of pulp only coniferous wood is used. A total annual input into this particular sawmill from Russian sources of 36 000 m^3 represents 40% of the total annual throughput of wood. As a result, when considering average exposure via inhalation of sawdust or external irradiation by ash produced in the sawmill a blending factor of 0.4 must be applied when considering the significance of wood from Russian sources. Waste wood from the sawmill is then passed on to a wood pulp plant (which actually receives waste wood from several sawmills) which processes wood from different sources in the same proportion as in the sawmill. Thus, a blending factor of 0.4 is also applicable when considering radiation exposures to liquor in the pulping process.

Finally, when considering the disposal of ash and sludge from the pulp industry an additional stream of ash from deciduous wood must also be considered. In this example, deciduous wood is only obtained from Sweden and the Baltic states, thus resulting in a further proportional reduction of ash contamination obtained from coniferous wood of Russian origin. The blending factor for Russian ash is 0.2, which means that, when considering exposure to radiation from this source, the site specific derived concentration for Russian wood should be multiplied by a factor of 5.

For limiting scenarios of ash disposal, the export/import dilution factors derived from this particular example (0.2 to 0.4) are higher than the default value suggested above for transboundary transportation (0.1). However, accounting for the contribution of the Bryansk wood in Russian exports to Sweden (<0.1) and for the contribution of radioactively contaminated areas in the total wood production of the Bryansk region (<0.1) results in a total DF <0.01 as suggested above for conditions under consideration.

7.3. Establishing radiological criteria

Both steps 1 and 2 of the dose assessment procedure (see Table XVII) have produced public doses of up to 1 mSv, which is high compared with most existing national and international dose criteria. Therefore, further steps in the DA were necessary, and their results are used below to suggest appropriate reference levels.

The results of site specific dose assessment with account taken of local scenarios and model parameters but not accounting for blending of wood with different levels of radionuclide concentration (Step 3), are applicable to conditions of contaminated areas of the Bryansk region. In this case appropriate dose estimations in Table XVII should be compared with a fraction of the action level of 1 mSv (annual effective dose) established by current Russian legislation especially for areas contaminated with long lived radionuclides [23, 24]. The constraint allocated for forest products is not explicitly defined in these documents; it can be assumed to be of the order of 0.1 mSv. Then, from this comparison (Step 3, industrial scenarios) it is evident that timber and wood products from areas with ^{137}Cs soil contamination above 0.6 MBq m^{-2} should not be used locally. In order to establish the derived ^{137}Cs concentration for local application, formula (2.4) should be used:

$$DC_{local} = 0.1\ \text{mSv} / 1.5 \times 10^{-4}\ \text{mSv}\cdot\text{Bq}^{-1}\cdot\text{kg} = 700\ \text{Bq kg}^{-1},$$

where 1.5 $\times 10^{-4}$ mSv Bq^{-1} kg is the maximum DCC from Table XV corrected for local conditions (see Step 3 above).

At the regional and national level the regular national dose criterion should be applied. In Russia a dose criterion of 0.01 mSv per year is applied for the control of forest products [22] which is consistent with the international exemption level [7]. From comparison of this dose criterion with the dose range in line 4a of Table XVI, it is evident that wood produced in areas contaminated above 0.6 MBq m^{-2} of ^{137}Cs in soil should not be used, either at the regional or at the national level. Appropriate regional/national derived ^{137}Cs concentration should be assessed as follows:

$$DC_{reg/nat} = 0.01\ \text{mSv} / (1.5 \times 10^{-4}\ \text{mSv}\cdot\text{Bq}^{-1}\cdot\text{kg} \times 0.1) = 700\ \text{Bq kg}^{-1},$$

where 0.1 is the appropriate dilution factor (see Sections 6.2.3 and 7.2).

In order to meet the internationally accepted exemption dose criterion of 10 μSv [7] and following methodology developed in the present report, the wood produced in areas contaminated above 1.4 MBq m^{-2} of ^{137}Cs in soil should not be used internationally, taking into account appropriate dilution factors (see line 4b of Table XVII). The appropriate model for dose assessment and establishment of a ^{137}Cs reference level is the generic one with the generic set of parameters (see step 4b in Section 7.2):

$$DC_{intern} = 0.01\ \text{mSv} / (3 \times 10^{-4}\ \text{mSv}\cdot\text{Bq}^{-1}\cdot\text{kg} \times 0.01) = 3000\ \text{Bq kg}^{-1}.$$

Taking into account the uncertainty in model predictions, the unified value of ^{137}Cs DC = 1 kBq kg^{-1} in timber and wood products could be recommended as being applicable to all the considered conditions, i.e. local (contaminated areas), regional, national and international.

Based on the dose assessment results above, it can be concluded that the areas of the Bryansk region contaminated at 0.04–0.2 MBq m^{-2} (1–5 Ci km^{-2}) of ^{137}Cs, which are the greatest in areal extent, are most likely to provide harvestable wood which meets appropriate radiological criteria. Wood harvested from these areas and exported for any use is not likely to exceed the derived activity concentration for most of the considered scenarios. However, wood harvested from areas contaminated above 0.6 MBq m^{-2} (15 Ci km^{-2}) of ^{137}Cs should not be used for industrial technologies resulting in production of large amounts of ash which require large-scale storage and disposal.

In the domestic context, firewood (small branches and bark) is likely to exceed the national standard based on the 10 µSv exemption level only if collected from the most contaminated areas (>0.6 MBq m^{-2}). When considering the use of timber for flooring and furniture manufacturing even materials taken from the most contaminated areas with 1.4 MBq m^{-2} (40 Ci km^{-2}) are not likely to exceed the relevant standards for particular scenarios. In any case, since these areas are relatively small this is unlikely to have a large impact on the utilization of wood from the region.

7.4. Existing Russian national standards

In order to keep under radiological control possible human exposure to wood contaminated in areas subjected to radioactive fallout after the Kyshtim accident in 1957 and the Chernobyl accident in 1986, Russian national standards of radionuclide activity concentrations in wood were developed and regularly updated; the recent set of standards was approved in 1999 [22]. As the radiological infrastructure in the country is well developed and control of the movement of contaminated wood is feasible, for economical reasons different standards for ^{137}Cs and ^{90}Sr concentration in different wood categories are in force, see Table XVIII.

The system of national standards presented in Table XVIII is based on the individual exemption annual dose equal 0.01 mSv and a set of national industrial and domestic scenarios. It can be seen in Table XVIII that higher standards are applied for industrial uses of wood. For domestic uses lower standards are applied. The lowest activity concentration in fresh needles is suggested for preparation of animal fodder, which is a common practice in Russia and not used in most other countries.

However, this set of scenarios does not include some uses of wood which are typical for Western European and North American countries. In particular, operations with wood ash, which were found to be critical for international trade, are not considered as national scenarios. For this reason, some of the Russian national standards are significantly above (up to an order of magnitude) the standards for ^{137}Cs in timber and wood products suggested in the previous section. This clearly demonstrates the necessity to harmonise national and international standards to promote international trade of commodities and, in particular, of wood and wood products.

TABLE XVIII. RUSSIAN NATIONAL PERMISSIBLE LEVELS OF ^{137}Cs AND ^{90}Sr CONCENTRATION IN WOOD PRODUCTS [22]

Wood products	NPL, kBq kg^{-1}	
	^{137}Cs	^{90}Sr
Alive stand for industrial use		
Wood with bark	11.1	5.2
Barked wood	3.1	2.3
Alive stand for domestic use		
Instruments for outdoor use	3.1	2.3
Products for indoor and personal use (furniture, parquet, musical instruments, etc.)	2.2	0.5
Fuel	1.4	0.4
Civil construction	0.4	5.2
Secondary forest resources	2.2–3.1	0.5–2.3
Fresh needles for making green fodder	0.6	0.1

Appendix

VALUES OF PARAMETERS USED FOR DOSE CALCULATION

TABLE A.1. GENERIC PARAMETERS

Symbol	Description	Values (where appropriate) ^{137}Cs	^{90}Sr	Unit
ρ_W	density of wood	430		kg m^{-3}
ρ_l	density of wood pulp liquor	1200		kg m^{-3}
ρ_A	bulk density of wood ash	800		kg m^{-3}
ρ_S	bulk density of soil	1500		kg m^{-3}
CF_{ash}	concentration factor for radionuclide from wood to pulp liquor	26		–
CF_{ash}	concentration factor for radionuclide from wood to ash	50		–
E_β	mean energy of a beta particle	–	196, 934	keV
E_γ	gamma energy of primary photons	661660	–	eV
η	is the number of gamma rays per decay	0.8521	–	–
μ_{air}	linear attenuation coefficient for air	9.7×10^{-3}	–	m^{-1}
μ_{water}	linear attenuation coefficient for water	8.590	–	m^{-1}
μ_w	linear attenuation coefficient for wood	3.694	–	m^{-1}
μ_{ash}	linear attenuation coefficient for wood ash	6.443	–	m^{-1}
μ_{Fe}	linear attenuation coefficient for iron	58.15	–	m^{-1}
$(\mu_{en}/\rho)_{air}$	mass energy absorption coefficient for air	0.00293	–	$m^2 kg^{-1}$
$(\mu_{en}/\rho)_{water}$	mass energy absorption coefficient for water	0.00327	–	$m^2 kg^{-1}$
χ	conversion factor, joule per electron volt	1.6×10^{-19}		J eV^{-1}
CC	conversion coefficient from the dose in air to effective dose	0.7		Sv Gy^{-1}
DL_w	default air concentration of dust particles, outdoor working conditions	2×10^{-6}		kg m^{-3}
DL_d	default air concentration of dust particles, indoor domestic conditions	2×10^{-7}		kg m^{-3}

TABLE A.2. BREATHING RATES (BR) FOR DIFFERENT AGE CLASSES AND DIFFERENT HUMAN ACTIVITIES [10]

Scenarios	Inhalation rate (m^3 h^{-1}) for age groups: <1 y	1–2 y	2–7 y	7–12 y	12–17 y	>17 y
Industrial	NA	NA	NA	NA	NA	1.5
Domestic outdoor	0.12	0.22	0.57	1.1	1.4	1.5
Domestic indoor	0.12	0.22	0.36	0.6	0.8	0.9

TABLE A.3. EFFECTIVE DOSE COEFFICIENTS (DH, 10^{-6} mSv Bq^{-1}) FOR INHALATION OF ^{137}Cs AND ^{90}Sr IN THE FORM OF ASH, SAWDUST AND BARK DUST [10, 11, 14]

Radionuclide form	Exposure	AMAD, μm	Solubility type	Age group, years	^{137}Cs	^{90}Sr	Reference
Ash	Domestic	1	F	<1	8.8	130	ICRP-71, 72
				1–2	5.4	52	
				2–7	3.6	31	
				7–12	3.7	41	
				12–17	4.4	53	
				>17	4.6	24	
	Occupational	5	F	>17	6.7	30	ICRP-68
Sawdust			F		6.7	–	
			S		No data	77	
Bark dust	Domestic	1	M	<1	36	150	ICRP-71, 72
				1–2	29	110	
				2–7	18	65	
				7–12	13	51	
				12–17	11	50	
				>17	9.7	36	

TABLE A.4. COMMITTED EFFECTIVE DOSE PER UNIT INTAKE *VIA* INGESTION (DG, mSv/Bq) OF ^{137}Cs AND ^{90}Sr FOR DIFFERENT AGE GROUPS [7, 15]

Nuclide	Age group					
	<1 y	1–2 y	2–7 y	7–12 y	12–17 y	>17 y
^{137}Cs	2.1×10^{-5}	1.2×10^{-5}	9.6×10^{-6}	1×10^{-5}	1.3×10^{-5}	1.3×10^{-5}
^{90}Sr	2.3×10^{-4}	7.3×10^{-5}	4.7×10^{-5}	6×10^{-5}	8×10^{-5}	2.8×10^{-5}

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LIST OF SYMBOLS AND UNITS USED IN THIS PUBLICATION

A	activity of a radionuclide in a source	Bq
AMAD	activity median aerodynamic diameter	µm
B	buildup factor of the dose of gamma radiation	–
BR	breathing rate	$m^3\ h^{-1}$
C_{ash}	activity concentration of a radionuclide in ash	$Bq\ m^{-3}$
C_b	activity concentration of a radionuclide in bark	$Bq\ kg^{-1}$
C_s	activity concentration of a radionuclide in soil	$Bq\ kg^{-1}$
C_w	activity concentration of a radionuclide in wood	$Bq\ kg^{-1}$
C_d	activity concentration in dust	($Bq\ kg^{-1}$)
C_p	activity concentration in wood products or by-products (ash, liquor, etc)	($Bq\ kg^{-1}$)
CF_p	concentration factor from wood to wood products or by-products	(dimensionless)
CF_d	concentration factor from wood to dust (sawdust, ash)	(dimensionless)
CC	conversion coefficient from the dose in air to effective dose	$Sv\ Gy^{-1}$
CF_{ash}	concentration factor for a radionuclide from wood to ash	(dimensionless)
$\dot{D}$	absorbed dose rate in air	$Gy\ h^{-1}$
DCC	annual dose conversion coefficient	$Sv\ Bq^{-1}\ kg$
DR_{ext}	dose rate coefficient for external exposure	$Gy\ h^{-1}$ per $Bq\ kg^{-1}$
DH	effective dose coefficient for inhalation of a radionuclide	$Sv\ Bq^{-1}$
DG	effective dose coefficient for ingestion of a radionuclide	$Sv\ Bq^{-1}$
DL	air concentration of contaminated dust particles (dust load)	$kg\ m^{-3}$
E	annual effective dose	Sv
E_β	mean energy of beta radiation	eV
E_γ	energy of gamma radiation	eV
F_s	shielding factor	(dimensionless)
h	height above source	m
M_{ash}	mass of ash applied to 1 m^2 of a garden soil	$kg\ m^{-2}$
M_v	mass of home-grown vegetables consumed annually	kg
OF	occupational factor, e.g. annual exposure duration	h
r	distance to source from point of measurement	m
TF	soil–plant concentration ratio for a radionuclide	–
x	source length	m

y	source width	m
z	source depth/height	m
η	yield of gamma rays per decay	–
μ_{air}	linear attenuation coefficient for air	m^{-1}
μ_{ash}	linear attenuation coefficient for ash	m^{-1}
μ_{Fe}	linear attenuation coefficient for iron	m^{-1}
μ_l	linear attenuation coefficient for wood pulp liquor	m^{-1}
μ_w	linear attenuation coefficient for wood	m^{-1}
$(\mu_{en}/\rho)_{air}$	mass energy absorption coefficient for air	$m^2\ kg^{-1}$
χ	conversion factor, joule per electron volt	$J\ eV^{-1}$
ρ_{ash}	bulk density of wood ash	$kg\ m^{-3}$
ρ_l	density of wood pulp liquor	$kg\ m^{-3}$
ρ_S	bulk density of soil	$kg\ m^{-3}$
ρ_w	density of wood	$kg\ m^{-3}$

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