Sundhedsstyrelsen

Statens Institut for Strålebeskyttelse

Radiation doses from the transport of radioactive waste to a future repository in Denmark - A model study

2011

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URL: http://www.sis.dk

Subject: Transport study, radioactive waste, accident probability, dose assessment, Danish repository

Language: English

Category: Udredning

Version: 1.0

Version date: (04.05.2011)

File format: pdf

Published by the National Board of Health, (May 2011).

Electronic issue ISBN: 978-87-7104-197-2

Printed issue ISBN: 978-87-7104-198-9

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Executive summary

Radiation doses from the transport of radioactive waste to a future repository in Denmark – A model study

This study examines the risk associated with transport of the national inventory of radioactive waste stored at Risoe, to a future final repository in Denmark. The study demonstrates that the risk from the transport of the waste should not limit the selection of a location of a final repository. This conclusion is based on calculations of potential doses performed in RADTRAN; a computerized algorithm used worldwide for this type of transport study.

Transport mode and regulations
Transport of the national inventory of radioactive waste must comply with national regulation based on international guidelines from the International Atomic Energy Agency (IAEA). The modelling thus presumes that the transport occurs by the use of appropriate packages conforming to the IAEA requirements on: Content limits for packages and conveyances, performance and maintenance standards for package designs.

In principle, transport of the radioactive waste can take place by road, sea, rail or air - or a combination of these. However, based on an initial assessment of the safety, practicability and cost of each transport mode; transport by rail and air has been rejected. Both modes would require road transport at the initial and final stages of the transport, leading to a relatively high number of handling operations. This significantly increases the potential doses. Rail transport implies intersection of city centres adding to the potential consequences of an accident scenario that comprise relatively large amounts of transported waste. Also, for air transport the predictable costs of a large number of flights disfavour the possibility. The study thus focuses on modelling of the road and sea transport modes.

Modelling
The road and sea transport modes are developed into two conceptual models which are fed into RADTRAN. RADTRAN is originally developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC), which is the nuclear regulatory authority in the U.S. RADTRAN has been further developed and is now widely used by e.g. the U.S. Department of Energy (DOE) and the IAEA.

The modelling accounts for radiation doses for incident free transports as well as for accidents. It also allots the probabilities of accidents to occur at various severities. To do this, the model make use of a comprehensive set of input parameters including: waste type, chemical and physical properties of the waste, activity and dose rate, package type, vehicle type and dimension, route characteristics, as well as crew members, bystanders and the population density along the route. It further handles accident scenarios with different types of packages.

The overall probability of an accident to occur is obtained from Danish statistical analysis of the traffic, while the characteristics of the accident in relation to the radioactive material are obtained from countries having developed detailed models of such accidents. The characteristic accidents are divided into 6 severity categories, and the probability and release fraction values originate from the U.S. The release fractions are specified for different types of packages and can vary more than a factor of 10, as their ability to retain the content under accident conditions vary in accordance with the IAEA requirements. Finally, the dispersion of radioactive material in an accident situation is assumed to occur with the wind, contaminating a standardised distribution area. RADTRAN uses a standard (Gaussian) atmospheric dispersion model to simulate the dispersion and standard dispersion parameters have been used for this study.

In summary, the calculations are to a large extent based on the least favourable boundaries of the model, giving rise to the highest potential doses a scenario can reasonably incur. For instance, the transport distance is modelled as the longest possible from the present storage site. Likewise, the accident scenarios include the most critical waste type loaded on one vehicle. However, other weather situations might give rise to a different distribution of accident doses. Still, to retain realistic scenarios it is found appropriate to use accurate input parameters for average speed, traffic density and population density based on the latest Danish observations. Overall the model is thus not a description of reality; it is a reasonably conservative estimate that provides a good basis for an evaluation of a feasible transportation method, which may be optimised if pursued in reality.

Results

For road transport all the radioactive waste can be transported by 250 individual transports by a truck with a trailer. The total collective dose for all incident free road transports is in the order of 40 person-mSv. The crew members receive approximately half, whereas bystanders along the route and persons sharing the route receive the other half. The total collective dose for a total of 10 incident free sea transports of all the radioactive waste including the handling and subsequent transport by road from the harbour to the repository is in the order of 20 person-mSv. The crew members receive approximately three quarters, whereas bystanders and persons sharing the route receive the last quarter.

In both cases the members of the public constitute a large group. This means that for each transport the dose pr. individual is low; within an order of magnitude of 0,0001 mSv. Therefore, although the modelling is performed conservatively, the calculated doses suggest that both transport methods can be carried out well within the national dose limits, which are 20 mSv per year for workers and 1 mSv per year for members of the public.

For an accident situation the accident that causes the highest calculated collective dose has a probability of 1:20.000.000 to occur for road transport and 1:33.000.000 for sea transport. The calculated 50 year collective dose from these accidents is 9.500 person-mSv for road transport and 24.000 person-mSv for sea transport. In these scenarios, the number of affected persons is conservatively modelled to be 1,4 million, using the largest possible population density in the area affected by the standard dispersion model. This collective dose amounts to less than 1 per thousand of the dose (ca. 1 million person-mSv) the same group of persons receives from the background radiation over the same period of time (excluding internal doses from natural radon).

The highest individual doses calculated for accident situations are on the order of 1 mSv for road transport and 10 mSv for sea transport, assuming that the given indi-

Used concepts

Individual dose:

Radiation dose to a person expressed in mSv.

mSv (millisievert):

Unit for radiation dose (effective dose)

Collective dose:

The sum of the individual doses to all persons in a defined group expressed in person-mSv.

person-mSv:

Unit for collective dose

Probability of 1:20.000.000:

One out of 20 million (e.g. one very severe accident out of 20 million performed transports).

vidual stay for 24 hours within the closest 30 meters of the damaged cargo. The modelled accident doses are 1 to 10 times the average dose received from background radiation per year in Denmark (excluding radon).

The risks associated with the modelled accident scenarios are therefore judged to be low and thus; acceptable. In this context, it is important to note that the calculated accident doses cannot be multiplied proportionally with time, as various immediate and gradually applied countermeasures, such as evacuation or relocation, in reality could be applied in the nearest surroundings after an accident.

Conclusions

The radiation doses calculated for transport of radioactive waste to a future repository in Denmark, demonstrates that the risk associated with road and sea transport should not limit the future selection of a location of the repository. From a safety perspective both road and sea transport seem to be feasible modes of transport.

The direct transport costs based on the relevant service providers are estimated to be 2 million DKK for road transport and 5 million DKK for sea transport. These cost estimates do not include eventual costs for acquiring and preparing suitable waste packages conforming to the transport regulations.

Resumé

Stråledoser fra transport af radioaktivt affald til et fremtidigt slutdepot i Danmark - Et modelstudie

Forstudiet om transport af radioaktivt affald analyserer den risiko, der er forbundet med transport af det danske radioaktive affald, der opbevares på Risø, til et fremtidigt slutdepot i Danmark. Studiet viser, at risikoen ikke begrænser valget af et slutdepots placering i Danmark. Denne konklusion er baseret på modelberegninger af potentielle stråledoser udført i RADTRAN, et computerprogram der bruges internationalt til denne type undersøgelser af transport af radioaktive stoffer.

Transportform og regler

Transport af det danske radioaktive affald skal ske i overensstemmelse med danske bestemmelser og internationale retningslinjer, der begge er baseret på retningslinjer fra det Internationale Atomenergiagentur (IAEA). Modelleringen forudsætter således, at der anvendes egnede kolli (beholder med radioaktivt indhold), der opfylder IAEA's retningslinjer vedr. begrænsning af mængden af radioaktive materialer i kolli og på køretøjer samt standarder for kollienes ydeevne og deres vedligeholdelse.

I princippet kan transporten af det radioaktive affald gennemføres som en vej-, sø-, jernbane- eller lufttransport - eller som en kombination af disse. Baseret på en indledende vurdering af sikkerheden, praktiske forhold og økonomiske omkostninger for hver transportform er jernbane- og lufttransport blevet forkastet. Begge disse transportformer forudsætter vejtransport i både de indledende og afsluttende faser af transporten, hvilket øger omfanget af håndteringer og dermed de potentielle doser. Jernbanetransport indebærer endvidere gennemkørsel af bycentre, hvilket øger de potentielle konsekvenser af en ulykke, hvori der indgår store mængder transporteret affald. Endelig gælder det for lufttransport, at de forventede økonomiske omkostninger gør, at lufttransport må afvises. Studiet fokuserer derfor på modellering af vej- og søtransport.

Modellering

Der er opstillet konceptuelle modeller for vej- og søtransport, og disse er indarbejdet i modelværktøjet RADTRAN. RADTRAN er oprindeligt udviklet af Sandia National Laboratories for den amerikanske strålebeskyttelsesmyndighed, Nuclear Regulatory Commission (NRC). RADTRAN er efterfølgende blevet videreudviklet og anvendes nu i vid udstrækning af f.eks. det amerikanske Department of Energy (DOE) og IAEA.

Modellerne anvendes til at vurdere stråledoserne i forbindelse med transporter, hvor der ikke sker et uheld, samt for ulykkessituationer. Forskellige ulykkessituationer tildeles sandsynligheder hørende til deres alvorlighedsgrad. For at kunne gøre dette anvender modellen et omfattende sæt af inputparametre, herunder affaldstype, kemiske og fysiske egenskaber af affaldet, aktivitet og dosishastighed, type af kolli, type og dimensioner af køretøj, karakteristik af ruten, samt antal af chauffører, besætningsmedlemmer, andre personer på og langs ruten. Desuden ses på ulykkesscenarier med forskellige kollityper.

For den overordnede sandsynlighed for en transportulykke er der benyttet statistiske analyser af trafikken i Danmark, mens en ulykkes særlige kendetegn i forhold til det radioaktive materiale stammer fra lande, der har udviklet detaljerede modeller for sådanne ulykker. I modellerne opdeles ulykkerne i 6 alvorlighedsgrader, der baseret på amerikanske undersøgelser er tildelt tilhørende sandsynligheder og fraktioner af frigjort radioaktivt materiale ved ulykken. Fraktionen af frigjort materiale, der er tildelt de forskellige kollityper, kan variere mere end en faktor 10 fra én kollitype til en anden, da kollienes evne til at tilbageholde indholdet i en ulykkesituation varierer i overensstemmelse med IAEA's retningslinjer. Endelig antages det, at det frigjorte radioaktive materiale i en ulykkessituation spredes med vinden, og at dette forårsager en forurening af et område langs vindretningen. RADTRAN anvender en standard (Gaussisk) atmosfærisk spredningsmodel til at simulere spredningen, og tilhørende standard spredningssparametre har været anvendt i dette studie.

Beregninger er i vid udstrækning gennemført med modellernes mindst gunstige randbetingelser. Resultaterne angiver således de højeste potentielle stråledoser et scenarie med rimelighed kan frembringe. Eksempelvis er transportafstanden modelleret som den størst mulige fra den nuværende opbevaringslokalitet. Ligeledes forudsættes det i ulykkescenarierne, at den mest kritiske affaldstype læsses i størst mulig mængde på ét køretøj. Ulykkesscenarierne benytter dog inputparametre for en gennemsnitlig vejrsituation selvom andre vejrsituationer end de benyttede kan medføre en anden fordeling af doserne i en ulykkessituation. For at opnå realistiske scenarier er det ligeledes valgt at bruge inputparametre for gennemsnitlig hastighed, trafiktæthed og befolkningstæthed, baseret på de seneste danske observationer. Alt taget i betragtning er modellerne altså ikke en egentlig beskrivelse af virkeligheden, men et forholdsvist forsigtigt skøn, der giver et godt grundlag for en vurdering af en mulig transportform, der kan optimeres, såfremt den gennemføres.

Resultater
For vejtransport gælder, at alt det radioaktive affald kan transporteres i 250 individuelle transporter hver med en lastbil med anhænger. Den samlede kollektive stråledosis fra alle transporterne, såfremt der ikke sker et uheld, er i størrelsesordenen 40 person-mSv. Chaufførerne modtager ca. halvdelen, mens personer på og langs ruten modtager den anden halvdel. Den samlede kollektive dosis fra de i alt 10 søtransporter af alt det radioaktive affald, herunder håndtering og efterfølgende transport ad vej fra havnen til slutdepotet, er i størrelsesordenen 20 person-mSv. Besætningen modtager cirka tre fjerdedele heraf, mens personer på og langs ruten modtager den sidste fjerdedel.

I begge tilfælde udgør de berørte personer på og langs ruten en større gruppe. Det betyder, at for hver enkelt transport er stråledosis til den enkelte person lille, omkring en størrelsesorden på 0,0001 mSv. Selvom modelleringen er udført konservativt, viser de beregnede stråledoser, at begge transportformer kan gennemføres godt indenfor de danske dosisgrænser, der er 20 mSv pr. år for arbejdstagere og 1 mSv pr. år for enkeltpersoner i befolkningen.

Den ulykkesituation, som beregnes til at medføre den højeste kollektive stråledosis, har en sandsynlighed på 1:20.000.000 for at forekomme for vejtransport og 1:33.000.000 for søtransport. Den beregnede kollektive stråledosis over 50 år fra disse ulykker er 9.500 person-mSv for vejtransport og 24.000 person-mSv for søtransport. I disse scenarier er antallet af berørte personer konservativt beregnet af standard spredningsmodellen til at udgøre 1,4 millioner, da der er anvendt en for-

Anvendte begreber

Individuel dosis:

Stråledosis til en person udtrykt i mSv.

mSv (millisievert):

Enhed for stråledosis (effektiv dosis).

Kollektiv dosis:

Summen af de individuelle doser til alle personer i en defineret gruppe udtrykt i person-mSv.

person-mSv:

Enhed for kollektiv dosis

Sandsynlighed på 1:20.000.000:

Én ud af 20 millioner (fx én alvorlig ulykke ud af 20 millioner gennemførte transporter).

stads-befolkningstæthed i hele det berørte område. Den kollektive stråledosis er mindre end 1 promille af den kollektive dosis (ca. 1 millioner person-mSv) den samme gruppe af personer modtager fra baggrundsstrålingen over den samme tidsperiode (De interne stråledoser fra naturligt forekommende radon ikke medregnet).

De højeste individuelle doser, der er beregnet for en ulykkessituation, er i størrelsesordenen 1 mSv for vejtransport og 10 mSv for søtransport, forudsat at de pågældende personer opholder sig i 24 timer inden for de nærmeste 30 meter fra ulykkestedet. Disse stråledoser er 1 til 10 gange den gennemsnitlige dosis, en person modtager årligt fra baggrundsstrålingen i Danmark (radon ikke medregnet).

Risiciene forbundet med de modellerede ulykkesscenarier er derfor vurderet til at være små, og dermed acceptable. I denne sammenhæng er det vigtigt at bemærke, at de beregnede stråledoser fra en ulykke ikke kan ganges proportionalt med tiden, da forskellige såvel umiddelbare som gradvist indførte beskyttelsesforanstaltninger, fx evakuering eller flytning af personer fra nærmeste område, kunne blive iværksat såfremt en ulykke indtræffer.

Konklusioner
De stråledoser, der er beregnet for transport af det danske radioaktive affald fra Risø til et fremtidigt slutdepot i Danmark, viser at risikoen forbundet med vej- og søtransport ikke begrænser den kommende udvælgelse af en placering af depotet i Danmark. Fra et sikkerhedsmæssigt perspektiv synes både vej- og søtransport at være mulige transportformer.

De direkte transportomkostninger er estimeret at være 2 millioner kroner for vejtransport og 5 millioner kroner for søtransport. Disse estimater omfatter ikke eventuelle omkostninger til anskaffelse og klargøring af egnede affaldsbeholdere, der opfylder transportbestemmelserne.

1 Introduction

This study examines the risk associated with transport of the national inventory of radioactive waste, to a future final repository in Denmark, and clarifies whether the risk associated with the transport might be limiting for the future selection of a location.

The waste is presently stored by the responsible operator of the waste; Danish Decommissioning (DD) at the Risoe peninsula in Roskilde fjord. It partly originates from the nuclear research and the decommissioning of the nuclear research facilities at the Risoe site and partly from industrial and medical usage. Waste has been stored at the Risoe site since the Risoe National Laboratory was established in the 1950's.

The parliamentary resolution B48, approved March 13, 2003 of the Danish Parliament to decommission the nuclear research facilities at the Risoe site includes a decision to initiate work that leads to the construction of a final repository for the radioactive waste. A working group with participation of the relevant ministries and institutions, defined the process forward in the so-called "Basis for Decision", which was presented to the Danish Parliament in January 2009.

In agreement with the Basis for Decision, the National Board of Health was assigned the task to assess the risk associated with transport of the waste from its present location at Risoe to the future repository. This study therefore considers the potential radiation doses associated with transport of the waste, as well as the probability of an accident and the potential radiation doses an accident could cause.

The study is generic as the future location is unknown, and it does not appoint a specific route or a particular transport mode. It does not include the loading and unloading that takes place at Risoe and at the future repository, since it is assumed to be performed regardless of the chosen method. The results are given as both collective and individual radiation doses (effective), based primarily on conservative but feasible assumptions concerning a range of numeric variables, e.g. the transport distance or the shipped amount of activity, combined with actual values for traffic density, population density, accident rates, etc. in Denmark.

The study does not include a specific analysis of the risk to the environment. In accordance with the 2007 recommendations of the International Commission on Radiological Protection (ICRP) [1], the standards of environmental control needed to protect the general public, are considered to ensure that the environment, is not put at risk.

It is essential that the dose assessments are conservative in the sense that the resulting doses are calculated in much cases on basis of the least favourable boundaries of the model. When an input parameter is selected from an interval of possible values, the value which gives rise to the highest possible dose is used. In other words, the modelled doses are the highest possible the scenario can reasonably incur. The model is thus not a description of reality. It is an estimate that provides a good basis for an evaluation of a feasible transportation method, which may be optimised if pursued in reality.

The road and sea transport modes are developed into two detailed conceptual models which are fed into RADTRAN. RADTRAN is originally developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (NRC), and is now widely used by e.g. the U.S. Department of Energy (DOE) and the IAEA.

Lastly, the study presents a rough estimation of the costs of the two transport methods and, as an appendix, an extensive overview of the modelling input parameters.

2 Transport regulations

The transport of low and medium level waste from the storage facilities at Danish Decommissioning (DD) at the Risoe site to a future repository shall be performed in accordance with all applicably Danish regulations, especially the regulations for the transport of radioactive materials.

The general provisions for transport of radioactive substances in Denmark are given in order no. 993 of 5 December 2001 on the transport of radioactive substances issued by the National Board of Health. This order is issued in pursuance of Law no. 94 of 31 March 1953 on the use etc. of radioactive substances. In addition to the general provisions mode dependent transport regulations are given for transport by road (ADR), sea (IMDG-code), rail (RID) and air (ICAO).

These Danish regulations as well as the international mode dependent regulations for the transport of radioactive materials are all based on and refers to the safety standard on the safe transport of radioactive material established by the International Atomic Energy Agency (IAEA) [2].

2.1 IAEA transport regulations

The objective of the IAEA transport regulations is to establish requirements that must be satisfied to ensure safety and to protect persons, property and environment from the effects of radiation in the transport of radioactive material. This protection is achieved by requiring:

- Containment of the radioactive contents.
- Control of the external radiation levels.
- Prevention of criticality.
- Prevention of damage caused by heat.

These requirements are primarily fulfilled by a graded approach to content limits for packages and conveyances and to performance standards applied to package designs, depending upon the hazard of the radioactive contents. Secondly, they are satisfied by imposing requirements on the design and operation of packages and on the maintenance of packaging, including considerations of the nature of the radioactive contents. Finally, they are satisfied by requiring administrative controls, including, where appropriate, approval by competent authorities.

It is the responsibility of the consignor to ensure that the required safety is obtained throughout the entire transport and to ensure that all relevant requirements including all required documentation to the package are fulfilled. Transport comprises all operations and conditions associated with, and involved in, the movement of radioactive material; these include design, manufacture, maintenance and repair of packaging, and the preparation, consigning, loading, carriage including in-transit storage, unloading and receipt at the final destination of loads of radioactive material and packages.

Classification of packages

The IAEA transport regulations uses five main types of packages (packaging + contents). These are:

- Excepted package
- Industrial package
- Type A package
- Type B package
- Type C package (only air transport)

In accordance with the graded approach a set of requirements regarding performance and contents of radioactivity is applied to each package type. The graded approach is applied in specifying the performance standards in the regulations which are characterized in terms of three general severity levels:

- Routine conditions of transport. The package must withstand impacts in an incident free transport.
- Normal conditions of transport. The package must withstand impacts in a transport where minor mishaps occur.
- Accident conditions of transport. The package must withstand the impacts in an accident situation.

A description of the three types of packages, which could be foreseen for the transport of the low and medium level waste, is presented below:

Industrial Package
Radioactive materials with low specific activity or objects which have become surface contaminated can be transported in industrial packages. The total activity of an industrial package can be quite high, although the specific activity is low provided that the package contains large amounts of material. The radioactive material in an industrial package is metals and low level waste and is often contained in boxes and steel drums. For the purpose of this study an industrial package will be designated: Type I package.

Type A Package
The allowed activity in a Type A package is limited so that the potential consequences of a presumed standard accident where the packaging is damaged will not lead to radiation doses to rescue workers or others above a level corresponding to internationally accepted dose levels. Before a package is defined as a Type A package, the mentioned requirements must be documented. There are no requirements to the type of construction materials that Type A packages may be constructed of. Therefore, Type A packages are made of wood, metal, plastic, cardboard covered glass, drums lined with concrete etc.

Type B Package
Materials containing radioactivity greater than allowed for Type A packages, must be transported in Type B packages. Type B packages must be constructed to with-

stand impacts that can occur during normal transport as well as impacts occurring in an accident situation. To demonstrate that a package type fulfils the requirements it must undergo series of drop tests, impact tests and fire test which simulate the conditions in an accident situation. Additionally, the package construction must be approved by the regulatory authorities in the country of origin and in some cases, if the package is to be transported internationally, in the transit countries as well.

The radioactive waste at DD is at present stored in waste storage facilities in different types of packagings and containers. Whether these packagings and containers with their respective contents comply with the requirements of the transport regulations are at present not fully documented. It might therefore later be necessary to ensure this is the case or to use overpacks which comply with the transport regulations. For the calculations in this study it is assumed that the waste is transported in packages, which comply with the transport regulations.

3 Methods of transport

Should the future repository site be different than the Risoe site, a transport of the waste will be necessary. The transport can in theory take place by road, sea, rail or air - or a combination of these. The selection of the most favourable method of transport is based on an assessment of its practicability, costs and most importantly; safety.

The safety assessment is based on three fundamental properties: The potential radiation doses associated with the waste transport itself, the probability of an accident, and the potential doses an accident could cause. The potential doses associated with the transport alone are yet again primarily a function of the number of handling operations associated with the transport, the transport distance, and the number of persons along the route.

The practicability is primarily a function of the number of handling operations. As any additional handling increase the probability of a handling accident, as well as the doses of the transport, it will increase the overall risk.

A given transport method may be considered unjustified from an economical viewpoint. This situation may arise if an alternative and less costly method can be shown to lead to similar or lower potential doses. Even, an alternative method with initially higher potential doses may be preferred on economical grounds, if it can be shown that the alternative method can be optimised and thereby yield potential doses in the same range or lower.

Based on an initial assessment of the various advantages and disadvantages of the different modes of transport in the above context, this study focuses on transport by road and sea, whereas transport by rail and air is rejected as explained below.

3.1 Road transport

The concept of transporting the waste packages by road is to load the packages onto trucks at the Risoe site and drive these to the repository where the packages are unloaded. The route will typically include primary and secondary roads, and avoid towns to the widest reasonable extend.

Transport of radioactive materials by road is a well-known method. The primary advantage of this method is that it is simple: By using trucks the handling of the waste packages and the number of operations is kept at a minimum relative to all other transport methods. This minimises the probability of a handling accident as well as the doses related to the handling and thus the overall risk. An additional advantage is that the infrastructure needed, is already in place

The disadvantages of this method are:

1) Due to the amount of waste, a large number of transports is required, increasing the probability of an accident
2) Persons other than the crew will get exposed to radiation along the route

3) The drivers will be placed relatively close to the waste packages during transport.

3.2 Sea transport

The concept of transporting the waste packages by sea is to load the packages onto barges at the Risoe site, sail to a harbour in the vicinity of the repository, transfer the packages to trucks and drive these to the repository where the packages are unloaded. The route on land will follow secondary roads and avoid town centres to the widest reasonable extend.

The primary advantage of this method is that a barge can carry large quantities which results in few voyages, leading to a reduced probability of an accident. In terms of exposure to radiation; persons, other than the crew, will not get exposed to radiation along the route, and the crew may be placed relatively far from the waste packages depending on the configuration of tug and barge. Finally, the infrastructure is already in place, as the Risoe site has its own harbour at the Roskilde fjord.

The disadvantages of this method are:

1) A similar number of truck transports as for the road solution is expected, as trucks are likely to be required for the land based last part of the voyage.
2) Relative to the road solution the number of handling operations increases, as the waste packages must be transferred from the barge onto trucks.
3) The consequences of an accident may be relatively large due to the large amounts of waste pr. voyage.

3.3 Rail transport

The concept of transporting the waste packages by rail is to load the packages onto trucks at the Risoe site, transport them by road to a suitable train station and unload them at an in-transit area with a capacity similar to the capacity of the train. The packages are then loaded onto the train, transported to a station in the vicinity of the repository, where they are transferred to trucks, transported to the repository and unloaded.

The advantage of using a train is that large amounts of goods can be transported in each voyage, minimising the overall risk and the doses related to the transport. In terms of radiation exposure it is an additional advantage that the driver will be placed relatively far from the waste packages.

The disadvantages of this method are:

1) The number of handling operations is extensive. The waste packages must be transported by trucks both to and from the train leading to a large number of on- and off-loading operations
2) This method also requires an in-transit area at the train station, which is likely to be situated in the vicinity of a comparatively densely populated area. An in-transit area would have to be access-controlled leading to further doses of guards.

3) The consequences of an accident may be relatively large due to the large amounts of waste pr. voyage.
4) The railroads in Denmark typically intersect the centre of the cities, thereby increasing the potential consequences of an accident.

3.4 Air transport

The concept of transporting the waste packages by air is to load the waste packages onto trucks at the Risoe site, transport them by road to the nearest suitable airport and load them directly into a cargo airplane. The packages area then flown to an airport in the vicinity of the repository, where they are transferred to trucks, transported to the repository and unloaded.

Other than moving part of the transport into the air and thus eliminating radiation exposure to bystanders, there are no major advantages of this transport method.

The disadvantages of this method are:

1) The relatively large number of handling operations.
2) The relative complexity of the handling operations.
3) The relatively low cargo capacity pr. flight.
4) The limited distance between the pilots and the waste packages.
5) The relative high costs.

3.5 Implications of the initial assessment

The initial assessment of the possible methods of transport concludes that shipment of the waste by train or air should be rejected, whereas shipment by road or by sea should be studied further.

This conclusion is based primarily on the number and the relative complexity of the handling operations that are inferred for shipment by train or by air. These are limiting factors, as both the number and complexity of handling operations have direct implications for the potential doses, especially to the crew. Moreover, the consequences of potential accidents such as a severe plane crash of a train collision in a central city location are judged to be relatively severe, either because of the impact speed (plane) or the amount of waste that may be involved in an accident close to densely populated areas (train).

4 Conceptual models

As pointed out previously, this study must clarify whether the risk associated with the transport might be limiting for the future selection of a location for a Danish repository.

To model the transport and the radiation doses that potentially arise from it, two overall scenarios are possible, i.e. with or without an accident. In the so-called incident free scenario the transport is performed as planned and no incidents occur, while in the accident scenario focus is kept on the accident alone and its consequences. It is thus necessary to establish a model that quantifies the radiation doses associated with the transport, as well as the probability of an accident and the potential radiation doses an accident could cause.

In the previous chapter two methods of transport; road and sea, were selected on the basis of an initial assessment of the relative advantages and disadvantages associated with each possible method. Both methods have been developed into two conceptual models for input to the algorithm.

The fundamental decisive factors for the algorithm and the conceptual models are given below followed by a description of both the incident free and the accident affected transports.

4.1 Criteria and constraints

The overall concept of the road transport is to load the waste packages onto trucks at the Risoe site and drive these to the repository where the packages are unloaded. Although it is assumed that each truck has a trailer and that both truck and trailer carry packages, a large number of transports can be expected as there, according to [3] and [4], in total are approximately 6300 packages that must be transported.

Considering the sea transport, the concept is to load the packages onto a barge or barges in the harbour at the Risoe site, sail to a harbour in the vicinity of the repository and load the packages onto trucks and transport them to the repository. As barges come in very different shapes and sizes and as this is a model study, assumptions have to be made regarding the barges. An advantage of the barges is that their size allows shipments of large quantities pr. voyage and therefore fewer voyages are required than transportation by trucks.

The algorithm must handle a set of basic criteria that applies to both conceptual models:

- It must account for the radiation doses in case of an incident free transport.
- It must take into account the radiation doses if an accident occurs, as well as the probabilities of accidents to occur at various severities.
- It must take into account various detailed parameters such as for instance: the waste type, the chemical and physical properties of the waste, the activ-

ity and dose rate, the packaging, the transport vehicle, the route, the members of the crew as well as bystanders and the population density along the route.

- It must be able to handle accident scenarios involving different types of packages.

4.1.1 Optimisation

It is essential that the assessment is conservative in the sense that the resulting doses in most cases are calculated on basis of the least favourable boundaries of the model. When an input parameter is selected from an interval of possible values, the value which gives rise to the highest possible dose is used. In other words, the modelled doses are therefore the highest possible the scenario can reasonably incur.

Optimisation, which can be stated as a process or method used to make a system of protection as effective as possible within the given criteria and constraints, can be planned for to a large extend. It is however uncertain what kind of optimization will be relevant when the actual transport takes place and this uncertainty will influence the results of the model.

For instance, even though it is common practice to shield waste packages with relatively high dose rates with waste packages with lower dose rates, this practice is not applied in the model. Optimisation was, on the other hand, applied on an overall scale in the selection of the road and sea transport methods over the rail and air. This, however, does not influence the actual modelling.

A model is thus not a description of reality. It is an estimate that provides a good basis for an evaluation of a feasible transportation method, which may be optimised if pursued in reality.

4.1.2 Excluded and included handling

The loading and unloading, i.e. handling that takes place at the Risoe site and at the future repository site are not considered in this study. This is because the handling is considered a part of the day to day operations at the Risoe site and at the future repository. It is also assumed to be performed regardless of the chosen method.

The unloading and loading of packages from barges to trucks is an operation that must be considered when estimating doses of the transport on barges as the workers involved can be considered to be exposed to radiation. Hence, when estimating the method of road transport only the actual transport is considered, while when estimating the method of sea transport, not only the actual transport by sea must be considered, but also the handling and the subsequent transport by road must be included.

4.2 Incident free transport

Incident free transport is defined as transport under routine conditions during which the packages withstands impacts in an incident free transport, cf. section 2.1. In other words the transport is performed as planned and no accidents occur. Thus the conceptual model includes the planned actual transport of the packages where the vehicle is moving, as well as planned stops and planned handling operations in e.g. relation to loading and unloading. The risk is thus related to persons in the vicinity of the packages, whom as a consequence hereof are exposed to radiation. However, as the transport might actually be planned, the doses to such persons can be planned to be kept as low as reasonably achievable.

The persons that come close to a package being transported are:

- Workers, i.e. crew members and handlers.
- Persons sharing the route of transport, i.e. in vehicles on the transport route.
- Persons along the route of transport, e.g. residents and pedestrians.

With respect to incident free sea transport the conceptual model includes only exposure to the crew on the tug/barge. This is because the distance to persons sharing the route or persons along the route is assumed to be large. It is consequently assumed that it is only the crew that is exposed to radiation until the waste packages are transferred to road transport for the last leg of the route.

4.3 Accident situation

An accident situation is defined as a situation in which the waste packages undergo accident conditions of transport, cf. section 2.1. When modelling such a situation, the focus is on the accident itself, its probability and the potential doses it may lead to. Doses during the routine part of the transport are not added. An accident only has radiological consequences if release of a fraction of the radioactive material occurs and release only occurs if the package with the radioactive material is damaged beyond a certain degree: That is, if the accident is sufficiently severe.

4.3.1 Accident probability

To structure this in the algorithm, an overall probability of accidents to occur is used. But as accidents occur at various severities, where most accidents would not cause a damage of the package, the accidents must be categorised into severities. Thus, each severity is assigned a fraction of the overall probability of an accident to occur which in fact assigns a probability to each severity as shown in table A.11 in appendix 1. The most likely accident, i.e. the accident with the highest probability does not expose the radioactive materials and there is no release of those. With increasing severity of an accident, the probability reduces; hence the least probable accident is the most severe, where radioactive materials are dispersed. Such an accident can for instance be a massive impact with another vehicle combined with severe fire exposing and dispersing radioactive materials.

4.3.2 Dispersion

Should an accident occur where a fraction of the radioactive materials are released it is assumed that they are dispersed with the wind as a cloud of radioactive materials where the ground under the cloud becomes contaminated because of deposition from the cloud. The radioactive materials are deposited on the ground with the highest concentration closest to the source and with decreasing concentration as the distance increases. As a standard in both conceptual models the dispersion and deposition are calculated to a distance of 120 km.

The amount of dispersed radioactive material is dependent on the fraction of radioactive material released from the packages, which is dependent on the severity of the accident and of the chemical and physical properties of the radioactive material.

Should an accident occur where the radioactive material is dispersed, the conceptual models assume that there is no relocation of persons and no cleanup of the dispersed radioactive material. This is however a conservative assumption as in realty a survey would be conducted and a temporary relocation of persons could be enforced in the nearest surroundings until the termination of a possible cleanup. This would in total result in lower collective doses than the results of the method used in the models.

4.3.3 Dose calculation

The doses in an accident situation are, besides being dependent on the dispersion also dependent on the composition of the radioactive material, i.e. which radioisotopes, their activity and the chemical and physical composition of the material in which they are incorporated. The doses are modelled by listing the radioisotopes and their activity for each package as shown in appendix 1, then the dispersion of the isotopes is modelled and the doses are calculated for different exposure pathways.

The exposure pathways in an accident are as follows:

- Inhalation – internal radiation doses from direct inhalation of airborne substances.
- Cloudshine – external doses from airborne substances.
- Groundshine – external doses from deposited substances.
- Resuspension – internal doses from inhalation of deposited substances that have been re-suspended.
- Ingestion – internal doses from consumption of contaminated agricultural products.

Should an accident occur where cultivated land would get contaminated a restriction on the use of agricultural products from the affected region would be enforced. The ingestion doses would thereby be eliminated. Ingestion doses are therefore not treated any further in this study.

The external doses are dependent on the release of the radioactive materials from a package, while the internal doses, besides being dependent on the release also are dependent on the intake via inhalation.

4.3.4 Accidents causing the highest collective doses

It is important when considering the transport of the radioactive waste to know what could happen should the accident causing the highest collective doses occur. In the conceptual model the accident causing the highest doses is modelled by assuming that the waste type that would cause the highest doses in an accident are transported in the largest possible quantities in the same voyage, although this may not be the case in an actual transport. By doing so the largest possible quantities of the radioactive substance are dispersed, that again causes the highest doses. Therefore, when modelling the road transport, a truck is modelled as being filled with this waste type and considering sea transport all of the packages with this waste type are modelled as being on a single voyage.

As a barge is normally at sea with no persons close by an accident would normally not cause radiation exposure to others than the crew. However, in this study the accident causing the highest doses is modelled as occurring where persons are close by; in the same manner as the accident causing the highest doses in road transport.

5 The modelling tool

5.1 RADTRAN

The computer algorithm RADTRAN 5.6 with the input file generator RADCAT 2.3 has been used to estimate the effective doses from transport of all the radioactive waste from the storage facilities at the Risoe site to a future repository site and to assess the probabilities of accidents and the potential doses accidents could lead to.

RADTRAN is a modelling tool originally developed by Sandia National Laboratories for the Nuclear Regulatory Commission (NRC), which is a nuclear regulatory authority in the U.S. Later, RADTRAN has been further developed and is now widely used by, e.g. U.S. Department of Energy (DOE) and the International Atomic Energy Agency (IAEA) as shown in [5], [6] and [7].

RADTRAN is developed to be used when estimating doses and related probabilities associated with transport of radioactive materials, both when considering incident free scenarios, i.e. the normal transport which is performed as planned and no incidents occur and of potential accidents.

5.2 RADTRAN input parameters

The mathematical modelling of the doses and probabilities associated with the transport of the waste from the Risoe site to a future repository site, requires a comprehensive set of input parameters. A detailed presentation of the input parameters is given in appendix 1. The below section however discusses the use of input parameters with relevance to waste, waste packages, vehicles, routes and accident severities.

5.2.1 Waste and waste package

The amounts, composition and activity of the waste used in this study is a simplified description of the actual waste presently stored at the Risoe site as described in [3] and [4]. The waste is categorised in [3] and [4] into 23 types, while in this study, for simplicity some of the similar categories are combined, resulting in a total of 13 waste types (Table 5.1). A more detailed description of each waste type is given in appendix 1. The data presented for the 13 types, has been used in the mathematical modelling of the two conceptual transport models.

The table shows the types of waste as well as the number and type of the associated containers within which it is presently stored. Conservative estimates of the dose rates at a distance of 1 m from the surface of the packages are also shown. Preliminary estimates of the package types required for transport according to the transport regulations, are given, as discussed in section 2.1.

Table 5.1. *Waste type-, container- and dose rate parameters. The package types necessary for transport are estimated.*

Waste type	# of containers	*Container type	Package dose rate at 1 m [μSv/h]	Package type for transport
Graphite	7	ISO	25	A or I
Aluminium	10	ISO	25	A or I
Steel, SS and lead	103	ISO	25	A or I
Concrete	236	ISO	25	A or I
Low Level Waste	5620	Drums	25	A or I
DR3	15	ISO	25	A or I
Hot Cells	90	ISO	25	A or I
Radiation sources	3	SC	100	B
Alpha sources**	3	SC	25	B
Irradiated Uranium**	28	SC	100	B
Non-irradiated Uranium	2	ISO	25	A or I
Tailings	150	ISO	1	A or I
Top shield plug and -ring	2	Specially designed	2000	A

* ISO: A 10' ISO container of half height.
SC: Steel container for storing radioactive waste.
Drums: 210 l drum with concrete lining.

** Alpha sources and Irradiated Uranium includes 233 kg of special waste, including samples of spent nuclear fuel.

The table shows that most of the waste is or will be packed in 10' ISO containers, steel containers or drums. For modelling purposes it is assumed that only 10' and 20' ISO containers are used in the transport, besides the specially designed container for top shield plug and –ring. Therefore, it is assumed in the following that there can be either 3 steel containers or 18 drums in one 20' ISO container.

When modelling the normal transport, i.e. the incident free transport it is assumed that the radioactive material is not dispersed and therefore information of the waste is not required except for the dose rates of the packages and vehicles. However, in an accident scenario where dispersion of radioactive materials will occur, the composition of the waste is important as the potential doses of the accident depend on the composition of the waste.

The dose rate of the packages is used in RADTRAN only when calculating doses in relation to handling, i.e. when loading and unloading, e.g. trucks. In all other cases it is the overall dose rate of the truck that is used by RADTRAN when dose rate is needed for calculations. It is the dose rate of the packages that define the overall dose rate of the truck, but in RADTRAN the two parameters are treated separately.

5.2.2 Vehicle and route

The truck to be used to transport the waste packages is assumed to be of the type that can carry one 20' ISO container and also to have one container on a trailer. Hence it is assumed that in each voyage either two 20' ISO containers or eight 10' ISO containers of half height are transported. Having assumed that and knowing from [4] the total amounts of the waste it follows that the number of voyages by road will be approximately 250.

Table 5.2. *Road transport scenario. Parameters used for modelling transport by primary and secondary roads.*

	Primary road - Highway	Secondary road	Origin of the values used.
Length [km]	400	50	Preliminary study performed by GEUS. The values are the longest possible and therefore conservative.
Speed [km/h]	86	50	Generic values from traffic observations in Denmark. [8]
Population density [pers/km^2]	100	1000	Population densities are generic values based on population densities in Denmark. [9]
Vehicle density [veh/h]	830	314	Generic values from traffic counts in 2009. [8]
Persons per vehicle sharing the route	2	2	RADTRAN default value
Accident Rate [accidents/veh-km]	$2{,}07 \cdot 10^{-7}$	$5{,}95 \cdot 10^{-6}$	Estimated values based on data sets involving total kilometres driven by trucks and number of accidents where trucks are involved. [8]

The location of the future repository has not been decided and therefore assumptions have to be made regarding the route to it. According to a study, performed by GEUS on potential areas in Denmark for the repository, the longest route possible to an area under consideration is approximately 400 km on a highway and 50 km on a secondary road. By using these values a conservative estimate is made of the radiation doses and risk of accidents as these factors are directly correlated to the time driven.

Statistical values from The Danish Road Directorate, [8] and Statistics Denmark, [9] are used for road type related parameters such as the overall accident rate, vehicle density and average speed. Additionally, it is assumed that the crew is only one person and when modelling the crew radiation exposure it is assumed that this person is not shielded from the radiation.

The sea transport of the waste is assumed to be to a harbour in the vicinity of the future repository; then the waste packages are loaded onto trucks which transport them by secondary roads to the repository. Hence sea transport requires additional handling and transport by roads as well. The distance needed to travel by sea is not known and therefore it is conservatively assumed that it is 650 km, which is approximately the longest distance from the Risoe site to a harbour in Denmark. Likewise it is assumed that the maximum transport distance by secondary roads from the harbour to the repository is 25 km.

Table 5.3. Sea *transport scenario. Parameters used for modelling transport by minor and larger waters.*

	Minor waters such as Roskilde fjord	Larger waters	Origin of the values used
Length [km]	50	600	The distance to the future repository is not known and therefore the longest possible distances are chosen.
Speed [km/h]	8	10	Values are conservatively selected by modeller.
Population density [pers/km2]	1000	100	Population densities are generic values based on population densities in Denmark. [9]
Accident Rate [accidents/veh-km]	10^{-6}	10^{-6}	Deduced from [10]

It is assumed that the sea transport is done in 10 shipments. Hence, each shipment contains one-tenth of all the waste. It is also assumed that the crew of the ship/barge is 4 persons and when in harbour an average time for unloading the ship/barge and loading the trucks is 5 minutes pr. container. The subsequent road transport is modelled identical to the part of the road transport occurring on secondary roads where the waste is considered being transported all the way from the Risoe site, except for the distance which is 25 km instead of 50.

5.2.3 Accident related parameters

RADTRAN calculates the probability of a transport accident as well as the potential radiation doses should the accident occur. To be able to do so a number of risk and accident related parameters must be provided.

The overall probability of an accident to occur is obtained from statistical analysis of the traffic, shown in [8] and [10], while the characteristics of the accident in relation to the radioactive material must be obtained from other countries as the experience of such accidents is non-existing in Denmark. The accidents are divided into 6 severity categories in RADTRAN, as shown in table 5.4. The values originate from the DOE, [5].

Table 5.4. Severity *categories of accidents and their probabilities should an accident occur [5].*

	Type A or I package		Type B package	
Accident severity category	Probability fraction	Release fraction	Probability fraction	Release fraction
1	0,81	0	0,99993	0
2	0,14	$1,2*10^{-5}$	$6,2*10^{-5}$	$2,6*10^{-5}$
3	0,028	$9,2*10^{-4}$	$5,6*10^{-6}$	$2,4*10^{-5}$
4	$1,9*10^{-4}$	$5,0*10^{-4}$	$5,2*10^{-7}$	$2,6*10^{-5}$
5	$1,9*10^{-2}$	$7,9*10^{-3}$	$7,0*10^{-8}$	$6,2*10^{-5}$
6	$1,2*10^{-4}$	0,38	$2,2*10^{-10}$	$6,7*10^{-5}$

The table shows that the probability of a specific category of an accident generally decreases with increasing severity and that the fraction of the released radioactive materials increases with increased severity. This is because a number of measures are taken to ensure safe transport of radioactive materials where especially the requirements to the packages are of importance.

The table shows that for a Type A or I package the release fractions and the probabilities of release are magnitudes higher than for a Type B package. This is because the Type B package is designed to withstand much greater impacts than a type A or I package.

The dispersion of a radioactive material, assuming that an accident of such severity that release of radioactive materials has occurred, i.e. the containment of the radioactive material has been damaged, is dependent on the physical and chemical properties of the material. Thus for modelling the dispersion, in RADTRAN the waste must be divided into groups dependent on the physical and chemical properties as shown in table A.4 in appendix 1 and assigned appropriate values for the various dispersion parameters in RADTRAN. The values for these parameters are not known specifically for the waste to be transported and therefore, values from the literature have been used. The U.S. government and others have performed experiments, gathered experience and documented these in, e.g. [5] from which the values in this study are used.

The dispersion of radioactive material in an accident situation is assumed to occur with the wind. A Gaussian atmospheric dispersion model that can simulate the dispersion is incorporated in RADTRAN. The values used in this study for the various distribution parameters are the RADTRAN default values which are based on the U.S. national average meteorology and wind speed. Therefore, in the RADTRAN dispersion simulation, the areal distribution is standard, but the activity concentration is dependent on the source. As this study is generic and not made for a specific location in Denmark, this is considered to be appropriate.

Dispersed radioactive materials are, in RADTRAN calculated to decay with the isotope specific half-lifes as reported in ICRP 38, [11]. Likewise, the different doses, mentioned in section 4.3.3 to members of the public, are calculated in RADTRAN on basis of dose conversion factors reported in FGR 12, [12] and ICRP 72, [13].

6 Modelling results

6.1 Doses and probabilities

The results of the modelling done with RADTRAN are presented in this section. The results show the modelled doses in the incident free scenario, and also the accident situation where the probabilities of the occurrence of accidents are presented as well as the doses, an accident could lead to.

6.1.1 Incident free transports

Road transport – incident free
The results of the incident free modelling of road transport, i.e. the modelling of a normal road transport where no accidents occur are shown in table 6.1.

Table 6.1. *Modelled collective doses in person-mSv from incident free road transport.*

Road transport	Collective dose from the single transport with the highest doses person-mSv	Collective dose from all transports person-mSv
Received by crew*	1,1	20
Received by persons beside the route	0,80	6,4
Received by persons sharing the route	1,5	12
Total rounded collective dose	3	40

* The crew is modelled as being one person pr. voyage, but not necessarily the same person performing all the voyages.

The table shows that the total collective dose of transporting all the waste packages from the Risoe site to a future repository in approximately 250 voyages by road results in a collective dose of approximately 40 person-mSv. The crew of the truck is modelled to receive approximately half of the total dose while persons sharing the route and persons beside the route collective receive the other half.

The collective dose of 20 person- mSv received by the crew from transporting all the waste packages is modelled by assuming that the crew is one person pr. voyage. The national dose limit for workers is 20 mSv pr. year pr. individual and the dose to a single crew member could therefore potentially exceed the limit. However, the modelling of the transports has not been optimised with regards to radiation protection by, e.g. placing packages with lower dose rates closer to the crew than packages with higher dose rates. The dose to individual members of the crew should therefore be expected to be lower than the modelled.

The single transport by road that causes the highest doses is modelled to be the transport of the waste package with the highest dose rate, i.e. the Top Shield Plug. This transport is modelled to cause a collective dose of 3 person-mSv, where the crew receives approximately one third of that.

The highest individual dose to a bystander, i.e. to a person beside the road when the truck passes, is modelled to be within an order of a magnitude of 0,0001 mSv. The doses received by persons either beside or sharing the route are collective doses shared by a large number of persons. Thus, although some receive more than others, the dose pr. individual is low, as is evident from the modelled maximum dose of 0,0001 mSv (0,1 µSv) received by a bystander. Even if the same bystander received a dose from all the transports, the total dose to that bystander would by far less than the national dose limit for individual members of the public which is 1 mSv pr. year.

In conclusion, with respect to bystanders the modelled doses associated with incident free road transport are small and well below the dose limits. As regards the crew the modelled doses could potentially exceed the national dose limit. It is therefore pertinent to deploy optimisation with respect to radiation protection and dose monitoring if the modelled scenario is realised.

Sea transport – incident free
The results of modelling of the incident free sea transport, including the loading of the packages onto trucks and transporting by road to the repository is shown in tables 6.2 and 6.3.

Table 6.2. *Modelled collective doses in person-mSv from all incident free sea transports.*

Sea transport	Collected dose from all voyages, person-mSv			
	Sea	Handling	Road	Total
Received by crew	0,13	12	1,8	14
Received by persons beside the route	0	0	2,2	2,2
Received by persons sharing the route	0	0	1,7	1,7
Total rounded collective dose	0,1	12	6	20

Table 6.2 shows that the collective dose received from transporting all the waste by sea and subsequently by road, including the handling is modelled to be approximately 20 person-mSv. This collective dose is primarily received by the crew and

in particular the crew handling the packages who receives about two-third of the total collective dose.

Although the crew driving the truck and handling the waste packages is modelled as being one person pr. voyage, the doses received by the crew from transporting all the waste is a collective dose, as it can be assumed that the work is divided between more than one person.

Table 6.3. *Modelled collective doses in person-mSv from the incident free sea transport that causes the highest doses.*

Sea transport	Collective dose from the single transport with the highest doses, person-mSv		
	Sea	Handling	Road
Received by crew members	0,003	0,14	0,077
Received by persons beside the route	0	0	0,28
Received by persons sharing the route	0	0	0,21
Total rounded collective dose	0,003	0,1	0,6

The modelling shows that the single transport causing the highest collective dose is the transport of the Top Shield Plug. This single transport causes a collective dose of 0,003 person-mSv, when on the sea, while the handling causes an individual dose of 0,14 mSv to the handler. When on the truck the waste package causes a collective dose of 0,57 person-mSv in total where the persons along and sharing the route receive the majority of that.

The transport from the harbour to the repository is modelled as being identical to the part of the road (truck only) transport from the Risoe site to the repository that occurs on secondary roads only, except for the distance. The individual dose received by a bystander thus becomes identical, i.e. approximately 0,0001 mSv.

In conclusion, with respect to bystanders the modelled doses associated with incident free sea transport are small and well below the national dose limit for individual members of the public. As regards the crew the modelled doses could potentially approach the dose limit for workers although still unlikely to exceed it. It is therefore pertinent to deploy optimisation with respect to radiation protection and dose monitoring if the modelled scenario is realised.

6.1.2 Accident situation

When considering potential accidents in relation to the transport of the waste packages it is important to focus on both the probability of an accident to occur and the doses an accident could lead to.

Accident probabilities
The modelled overall probabilities pr. voyage of an accident to occur when considering the transport of the waste packages is shown in table 6.4. The table also shows the probabilities of an accident that could lead to a breach of the containment and release of the radioactive materials.

Table 6.4. *Probabilities pr. voyage of accidents and of accidents resulting in release when transporting the waste packages from the Risoe site to a future repository site. Based on [4], [5] and [6].*

		Overall probability of an accident	Type A or I package Probability of release	Type B package Probability of release
Road transport	From Risoe to repository	$3,8*10^{-4}$	$7,1*10^{-5}$	$2,6*10^{-8}$
Sea transport	Sea transport	$6,5*10^{-4}$	$1,2*10^{-4}$	$4,4*10^{-8}$
	Road transport from harbour to repository	$1,5*10^{-4}$	$2,8*10^{-5}$	$1,0*10^{-8}$

The values in table 6.4 show the probabilities of accidents pr. voyage. For instance; the overall probability of an accident when performing a single road transport from the Risoe site to a future repository is $3,8*10^{-4}$, which is approximately 1 out of 2600. That is one accident, regardless of its severity could be expected to occur for every 2600 voyages or in other words the probability of an accident to occur is approximately 0,04% pr. voyage.

The table shows that the probability of an accident to occur of such severity that could lead to a release of radioactive materials from a Type A or a Type I package is 0,0071% pr. voyage by road and 0,012% pr. voyage by sea.

The table also shows that the probability of release from a Type B package is magnitudes lower than from a Type A or I package. The reason is that a Type B package is designed to transport larger amounts of radioactive materials and therefore designed to withstand greater impacts than a Type A or I package.

The probability of accidents does generally decrease as the severity increases and the fraction of the radioactive materials released in an accident increases with increasing severity. Therefore, an estimate of the probabilities and doses, of the most severe accident, i.e. with reference to table 5.4 a severity category 6 accident, of both Type A or I packages and of Type B packages containing the waste type that would cause the highest doses have been made.

Category 6 accident – Type A or Type I packages

The modelling shows that a category 6 accident with Type A or I package containing the waste type aluminium, results in the highest overall doses. Therefore, when considering a category 6 accident by road, all the packages on the vehicle are assumed to be loaded with the type aluminium. Similarly, for the category 6 accident when transporting the waste packages by sea, all the packages with aluminium are assumed to be transported in one shipment plus the normal one-tenth of the total amounts of waste, as described in chapter 4 and 5.

The severity of an accident is independent of where it occurs. However, the doses it leads to are not, as the population density determines the number of persons who would receive doses from the released radioactive materials. The category 6 accident causing the highest doses, occurs when transporting the waste packages in areas with high population density. In this study it would thus occur when transporting on a secondary road or when sailing close to land.

The modelled doses of a category 6 accident and its probability are presented in table 6.5.

Table 6.5. *Modelled collective doses in person-mSv as a result of a category 6 accident with a Type A or I package and its probability to occur.*

	Road transport	Sea transport	
	Accident by road	Accident by sea	Accident by truck from harbour to repository
Overall probability of a category 6 accident	$5{,}0*10^{-8}$	$5{,}0*10^{-9}$	$2{,}5*10^{-8}$
50 year collective inhalation and external dose, person-mSv	9.500	24.000	9.500

The category 6 accident by road is modelled to lead to a collective dose of approximately 9.500 person-mSv. Likewise, a category 6 accident when transporting the waste by sea results in a collective dose of 24.000 person-mSv. The collective doses are calculated as being cumulative for a period of 50 years after the accident. Additionally, the collective doses are calculated as a summation of the doses received by every individual affected by the accident which are modelled to be approximately 1,4 million persons. The number, 1,4 million affected persons is modelled on the basis of the dispersion of the radioactive materials and of the population density. The vast majority of those persons are only exposed marginally and the individual doses to those persons are entirely insignificant.

Although a collective dose of 24.000 person-mSv may intuitively seem high, this dose is less than 2% of the yearly collective dose from natural sources in Denmark to the modelled group of persons. Hence, such a collective dose does not have any detectable effects on the public health.

The probability of the accident is modelled to be approximately $5*10^{-8}$, i.e. one category 6 accident out of 20 million road transports. The probability of the category 6 accident, when transporting by sea is modelled to be approximately $5*10^{-9}$, i.e. one accident out of 200 million shipments.

The collective dose that occurs in the category 6 accident when transporting by sea is modelled as being approximately twice the collective dose that occurs when transporting by road. This is primarily because the amounts of waste transported pr. voyage by sea are larger than by road and the amounts of radioactive material involved in an accident are therefore larger by sea than by road. The probability of an accident is however an order of magnitude lower, when transporting by sea. This is primarily because the overall probability of a category 6 accident at sea is lower than on road, as shown in table 6.5.

The collective doses modelled for a category 6 accident, that occurs when transporting the waste packages by road from a harbour in the vicinity of the future repository to the repository, are identical, to the doses calculated should the packages transported by road the whole way from the Risoe site. This is because the transports are identical when on a secondary road except for the distance. The probability of a category 6 accident when transporting by road from the harbour to the repository is, as shown in table 6.5 half of what it is when transporting the waste by road from the Risoe site. This is because the distance to be transported on secondary roads is assumed to be half.

The radioactive materials that are dispersed from an accident are deposited on the ground with the highest concentration closest to its source, i.e. the transport vehicle and therefore the persons closest to the accident will receive the highest doses. Hence, should an individual stay for 24 hours within the closest 30 meters of the category 6 accident that causes the highest doses from the road transport, this individual would receive a dose of approximately 1 mSv. Individuals further away would receive lower doses and at a distance of approximately 250 meters the individual dose becomes approximately 0,1 mSv within the first 24 hours. Likewise, the category 6 accident causing the highest doses when transporting by sea causes a dose to an individual that is within the closest 30 meters of approximately 10 mSv within the first 24 hours and at 250 meters the individual dose becomes approximately 1 mSv.

The modelled accident doses to an individual are in the same order of magnitude as a medical CT-scan and 1 to 10 times the average dose received from background radiation per year in Denmark. It is important to note that these modelled doses cannot be multiplied proportionally with time, as various immediate and gradually applied countermeasures, such as evacuation or relocation, could be applied in the nearest surroundings after an accident.

The overall probability of a category 6 accident to occur for sea transport, i.e. both the transport by sea and by road is found by adding the probabilities. This adds up to $3*10^{-8}$ or 3 category 6 accidents out of 100 million category 6 transports. The probability is thus in the same order of magnitude as the probability of a category 6 accident for road transport, i.e. when driving the packages all the way from the Risoe site.

Category 2-6 accident – Type B packages
Although the category 6 accident with Type A or I packages is the accident resulting in the highest doses, it is of interest to know the collective doses in an accident with release from Type B packages. The model shows that the largest doses occur when the waste packages containing irradiated uranium encounter a category 6 accident. Thus analogue to the category 6 accident with Type A or I package, the accident is modelled where a truck is filled with this waste type and where all the waste packages of this type are on a ship/barge plus one-tenth of the total amounts of waste.

However, although the release fractions from a Type B package for severity categories 2-6 all are within the same order of magnitude, as shown in table 5.4, the probabilities of an accident to occur decreases with increasing severity category. Therefore, although a category 6 accident results in the highest collective doses, the category 2 accident results in doses that are within the same order of magnitude, but with a probability that is magnitudes higher.

The results of the modelling of an accident with a Type B package can be seen in table 6.6.

Table 6.6. *Modelled collective doses in person-mSv as a result of a category 6 accident with a Type B package and its probability to occur.*

	Road transport	Sea transport	
	Accident by road	Accident by sea	Accident by truck from harbour to repository
Overall probability of an accident with release (category 2-6)	$9{,}0*10^{-8}$	$3{,}0*10^{-9}$	$4{,}5*10^{-8}$
Overall probability of a category 6 accident	$3{,}0*10^{-13}$	$1{,}0*10^{-14}$	$1{,}5*10^{-13}$
50 year collective inhalation and external dose, person-mSv	800	3.600	800

A sea transport is performed with many packages pr. shipment, where many of these will be of Type A or I, with poorer containment compared to type B packages. Therefore, in an accident where the containment of the Type B packages is breached, the containment of the Type A or I packages will be breached as well. In that situation, the radioactive materials in the Type A or I packages will contribute to the overall radiation exposure. However, in table 6.6 only the collective dose from the radioactive materials released from the Type B packages are shown.

The table shows that the 50 year collective dose from a category 6 accident for a Type B-package is lower than for a Type A or I package and that the probabilities of the category 6 accident are by far lower. This is because Type B packages are designed to withstand far greater impacts than a Type A or I package. However, the categories 2-6 all have similar release fractions (Table. 5.4), and result in doses that are within the same order of magnitude. The overall probability of such an accident is therefore calculated by summing categories 2-6. The resulting probability is found to be within the same order of magnitude as a category 6 accident for a Type A or I package.

Concluding remarks of the modelling results
The conclusions of the modelling results are:

Incident free:

- The total collective dose of road transport of all the radioactive waste is modelled to be 40 person-mSv.
- The total collective dose of sea transport of all the radioactive waste including handling and subsequent transport by road from the harbour to the repository is modelled to be 20 person-mSv.
- Although the modelling of the incident free transports is performed conservatively, the modelled doses suggest that both transport methods can be carried out well within the national dose limits.

Accident situation:

- The modelled accident that causes the highest collective dose has a probability of $5*10^{-8}$ to occur for road transport and $3*10^{-8}$ for sea transport.
- The modelled 50 year collective dose from these accidents are 9.500 person-mSv for road transport and 24.000 person-mSv for sea transport.
- The modelled collective dose of 24.000 person-mSv is less than 2% of the yearly collective dose from natural sources in Denmark to the modelled group of persons. Hence, such a collective dose does not have any detectable effects on the public health.
- The probability of release of radioactive materials in an accident situation is magnitudes lower for Type B packages than for Type A or I packages.
- An accident with a Type B package causes lower collective doses than the corresponding accident with Type A or I package.

6.2 Sensitivity analysis

As the values of some of the model input parameters are uncertain and in some cases not known, estimated values have been used. The results do naturally reflect this uncertainty. The following is an assessment of the effect of changes in the most important input parameters on the results of the modelling.

Distance travelled
The distance to be travelled with the radioactive materials is not known and therefore the conservative assumption of using the largest possible distance from the Risoe site to a future repository has been made. Should the actual distance be different than the assumed, it will therefore always be smaller. The effects of this on the doses of an incident free transport is proportional, i.e. if the distance travelled is reduced, the dose to crew, and the collective dose to others will be reduced proportionally.

Changes in the distance travelled do not have any effect on the doses of an accident. However, the probability of an accident is reduced proportionally to the distance travelled.

Velocity
The data used for the velocity when modelling the transport on trucks are statistical values from [4]. On the other hand, the modelled velocity by sea is dependent on the type of ship/barge used and is therefore not known and conservative values have been chosen. The velocity, together with the distance travelled determines the time the radioactive materials are in transport and therefore inflict upon the results of the incident free modelling. Thus changes in the velocity result in equally large, but inverse proportional changes in the doses, except for persons in vehicles using the same route where the doses change inverse proportionally but twice the velocity change. The velocity has no influence on the results of the modelled accidents.

Population density
The route to a future repository is not known, leaving the population density along the route unknown also. General, but conservative values are therefore used for the population density, i.e. 1.000 persons for suburban areas and 100 for rural areas.

The population density is used in RADTRAN to model how many persons are expected to be affected by the transport and by a potential accident. Hence, the doses to residents along the road in an incident free transport and the collective dose to the population in the accident scenario change proportionally to the changes in the population density.

Dose rate for packages and vehicles
Dose rate for packages is only used in the model in relation to handling while the dose rate for vehicles is used for every other calculation where dose rate is needed for the model calculations. A change of the dose rate of packages results in a proportionally large change in the doses to handlers. Likewise, a change of the dose rate of vehicles, when modelling incident free transports causes a proportionally large change in the modelled doses to crew, persons using the road and residents along the road. Dose rate for packages and vehicles is not used in RADTRAN when modelling accidents.

Number of packages pr. transport
The number of packages pr. transport is modelled on the basis of assumed vehicle and package dimensions. In case of fewer packages pr. transport, the doses pr. incident free transport would be the same, which would lead to larger collective doses as the number of transports would increase. The probability of an accident would increase as the number of transports increase, but in case of an accident the potential severity of it would be reduced as there is less radioactive matter on each transport.

Shielding of crew
Shielding of the crew has not been applied in the current modelling. This is of course conservative, as shielding will be applied should this be necessary. The shielding of the crew does only apply to the crew, but as the crew receives a large part of the total collective dose in the incident free transport, shielding may become relevant. The shielding of crew is not relevant when modelling accidents in RADTRAN.

Accident related parameters
The accident related parameters discussed below are important in the modelling of accidents, but have no influence on the incident free transports.

The overall probabilities of accidents to occur are obtained from ref [4] and [8] and these determine the modelled accident rate in RADTRAN. However, the overall probabilities have no influence on the potential radiation doses of accidents.

The severity fractions, i.e. the fractions of accidents having a certain severity, that are used in this study, are based on experiments and experience in the U.S. as presented in [6] and table 5.4. The severity fractions have direct influence on the probability of an accident of a certain severity to occur and, as the table shows, on the release of radioactive materials and thus on the potential radiation doses of an accident.

Given that the containment of a package has failed in an accident situation, the radioactive materials may be dispersed with the wind. The simulation of the wind in the current study is based on the U.S. national average meteorology and wind speed, which is considered appropriate for the purpose of this model study.

Except from the wind, the model parameters that define the distribution of the radioactive matter are; release fraction, fraction of the released that becomes aerosols and the fraction of which becomes respirable. Changes in the release fraction and the fraction that becomes aerosols cause an equally large change in the results, as these parameters in the model control how much radioactive matter is released and dispersed. Changing the values for the fraction of aerosols that is respirable causes an equally large change in the inhalation dose, but does not affect external doses as this parameter governs the quantity of the radioactive matter that can be inhaled.

7 Estimate of the cost of transporting the waste

Estimates of the cost of transporting all the radioactive waste at the Risoe site to a future repository, at for now an unknown location in Denmark are presented in this chapter. The estimates are based on dialogs with relevant stakeholders within the transport business in Denmark. As there are several uncertainties regarding the transport, such as the distance, assumptions have been made which influence the results of this cost estimates. Precise knowledge of the cost of the transports cannot be obtained until these uncertainties have been eliminated and a more thorough cost calculation can be made. The estimates presented in this chapter are therefore to be considered as approximate.

The loading of vehicles at the Risoe site and unloading at the repository has not been included in this study and is therefore not included in the cost estimates. Additionally, any preparing of the waste packages, including possible acquiring of suitable transport casks and documentation needed to comply with the transport regulations, that might be needed for transport is not included in the cost estimates.

The cost estimates do not include value added tax (VAT).

7.1 Road transport

The cost of transporting the waste on trucks is dependent on the distance to be driven and whether a toll road is to be used, but as the distance is not known, it is assumed to be 450 km, which as described previously is the largest possible distance. In that case the cost would be approximately 7.000 DKK pr. voyage, where it is taken into account that transport of dangerous goods, including radioactive waste is more expensive than transport of ordinary goods. The overall cost, with the approximately 250 voyages would therefore be approximately 2 million DKK.

7.2 Sea transport

The sea transport scenario is as previously described to ship it from the harbour at the Risoe site to a harbour in the vicinity of the repository, load it onto trucks and drive it to the repository. As the distances are not known the conservative assumption is made that the shipment by sea is 650 km and the subsequent transport by road is 25 km.

The cost of renting a barge including a tug is approximately 50.000 DKK pr. day and as a round trip including loading and unloading, can be expected to take eight days, the cost of renting a barge becomes 400.000 DKK pr. shipment. As there are assumed to be 10 shipments the cost becomes 4 million DKK for the barge and tug alone. The harbour fee including the harbour pilot is expected to cost additional 200.000 DKK in total for the 10 shipments.

When at the harbour, the packages must be unloaded from the barge and loaded onto trucks. The cost of that is approximately 500.000 DKK in total, where it is assumed that the packages can be loaded directly from the barge onto the trucks.

The transport on trucks from the harbour to the repository costs approximately 1.000 DKK pr. transport which with 250 transports becomes approximately 250.000 DKK for transporting all the packages.

Hence the overall cost of transporting all the waste on barges including handling and transport on trucks from the harbour to the repository becomes approximately 5 million DKK.

8 Conclusions

The radiation doses modelled for transport of radioactive waste to a future repository in Denmark, demonstrates that the risk associated with road and sea transport should not limit the future selection of a location of the repository. From a safety perspective both road and sea transport seem to be feasible modes of transport. Although the modelling in most cases is performed conservatively, the modelled doses suggest that both transport methods can be carried out well within the national dose limits. Additionally, the dose levels associated with the modelled accident scenarios are low and the scenarios are thus found to be acceptable taken the related probabilities into account

Based on an initial assessment of the safety, practicability and cost of each transport mode, road and sea transport are judged to be feasible modes of transport, whereas transport by rail or air are not. The latter modes would require road transport at the initial and final stages of the transport, leading to a relatively high number of handling operations. This increases the potential doses, relative to the other transport modes.

For road transport all the radioactive waste can be transported by 250 individual transports by truck with a trailer. The total collective dose for all incident free road transports is in the order of 40 person-mSv. The crew members receive approximately half, whereas bystanders along the route and persons sharing the route receive the other half.

The total collective dose for a total of 10 incident free sea transports of all the radioactive waste including the handling and subsequent transport by road from the harbour to the repository is in the order of 20 person-mSv. The crew members receive approximately three quarters, whereas bystanders and persons sharing the route receive the last quarter.

In both cases the members of the public constitute a large group. This means that for each transport the dose pr. individual is low; within an order of magnitude of 0,0001 mSv. Therefore, although the modelling is performed conservatively, the modelled doses suggest that both transport methods can be carried out well within the national dose limits, which are 20 mSv per year for workers and 1 mSv per year for members of the public.

For an accident situation the modelled accident that causes the highest collective dose has a probability of 1:20.000.000 ($5*10^{-8}$) to occur for road transport and 1:33.000.000 ($3*10^{-8}$) for sea transport. The modelled 50 year collective dose from these accidents is 9.500 person-mSv for road transport and 24.000 person-mSv for sea transport. In these scenarios, the number of affected persons is conservatively modelled to be 1,4 million, using the largest possible population density in the area affected by the standard dispersion model. This collective dose amounts to less than 0,1 % of the dose (ca. 1 million person-mSv) the same group of persons receives from the background radiation over the same period of time (excluding internal doses from natural radon).

The highest individual doses modelled for accident situations are on the order of 1 mSv for road transport and 10 mSv for sea transport during the first 24 hours, which is 1 to 10 times the average dose received from background radiation per year in Denmark (excluding radon). The risk associated with the modelled accident scenarios is therefore judged to be low and thus; acceptable.

The direct transport costs based on the relevant service providers are estimated to be 2 million DKK for road transport and 5 million DKK for sea transport. These cost estimates do not include costs for acquiring and preparing suitable waste packages conforming to the transport regulations.

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Appendix 1: Input values to RADTRAN

This appendix shows the input values used in RADTRAN and their origin.

Table A.1. Waste types an waste packages.

Parameter	Description and values	Reference to the origin of the values
Name	Name used for the different package types used in the model. Each package type represents a waste type. The following waste types are used: 1. Graphite 2. Aluminium 3. Steel, Stainless steel and lead 4. Heavy concrete and concrete 5. Low level waste of various kind 6. Waste from DR3 7. Waste from Hot Cell 8. Radiation sources 9. Special waste. 20 larger alpha sources 10. Irradiated uranium 11. Non irradiated uranium 12. Tailings and tailings contaminated concrete 13. Top shield plug and top shield ring from DR3	The packages/waste types are deduced from [3] and [4].
Long Dim(m)	Longest dimension of the packages: • ISO = 3.00 • SC = 2.12 • Drum = 0.88 • TSP_TSR = 3.0	Same container types as used to store waste in at Risø. The size of the TSR_TSP package is assumed on basis of dialogs with Danish Decommissioning. The precise size is not known as these waste items have not yet been created.
Dose Rate	Dose rate in 1 m from the package surfaces. The values used are shown in table A.2.	Information of the waste packages from Danish Decommissioning.
Gamma fraction	It is assumed on the basis of [2] that the neutron radiation can be ignored. The value is thus set to 1.	Deduced from [3].
Neutron fraction	The neutron radiation can be ignored and the value is set to 0.	Deduced from [3]

Table A.2. Number of waste containers, their type and doserate and the preliminary estimate of package types.

	Graphite	Aluminium	Steel, Stainless steel and lead	Concrete	Low Level Waste	DR3	Hot Cells	Radiation sources	Alpha sources	Irradiated U	Non-irradiated U	Tailings	Top shield plug and ring
# of con-tainers	7	10	103	236	5620	15	90	3	3	28	2	150	2
Container type	ISO	ISO	ISO	ISO	Drums	ISO	ISO	SC	SC	SC	ISO	ISO	Specially designed
Package dose rate [μSv/h]	25	25	25	25	25	25	25	100	25	100	25	1	2000
Package type	A or I	A or I	A or I	A or I	A or I	A or I	A or I	B	B	B	A or I	A or I	A

The number of containers and their type is found in [4].

Table A.3. Contents of relevant nuclides in each waste type and their activity in GBq/package. The activity is calculated on the basis of [3] and [4].

	Graphite	Aluminium	Steel, Stainless steel and lead	Concrete	Low Level Waste	DR3	Hot Cells	Radiation sources	Alpha sources	Irradiated U	Non-irradiated U	Tailings	Top shield plug and ring
H-3	400		349	$364*10^{-3}$				$1.53*10^{3}$					185
Co-60	1.71	$1.98*10^{3}$	259	$46.6*10^{-3}$	$125*10^{-3}$	358	236	$60.9*10^{3}$					$1.27*10^{3}$
Se-75		7.40						577					
Sr-90		10.2	6.47		$476*10^{-3}$	$733*10^{-3}$	52.8	281		$10.6*10^{3}$			
Ba-133			19.4	1.59				$333*10^{-3}$					$117*10^{-3}$
Cs-137		10.2	6.47		$654*10^{-3}$	1.07	72.2	$58.7*10^{3}$		$15.2*10^{3}$			
Sm-151					$7.12*10^{-3}$		1.10			216			
Eu-152	149	40.8	6.47	$386*10^{-3}$	$5.34*10^{-3}$			3.33					5.70
Eu-154	20.6			$25.4*10^{-3}$	$26.0*10^{-3}$		4.77			$1.00*10^{3}$			$342*10^{-3}$
Ir-192								$1.07*10^{3}$					
C-14	17.1							140					1.11
Ca-41				$80.5*10^{-3}$									$289*10^{-6}$
Ni-63			173	161		$1.20*10^{3}$		13.0					785
Tc-99					$534*10^{-6}$		$44.4*10^{-3}$			7.04			
Ag-108m			1.75										$526*10^{-3}$
Ra-226								95.0	137			$73.8*10^{-3}$	
Th-230												$73.8*10^{-3}$	
Th-232												$72.5*10^{-3}$	
U-234								4.00			10.5	$60.0*10^{-3}$	
U-238								9.33			12.5	$62.5*10^{-3}$	
Pu-238				$148*10^{-3}$	$29.2*10^{-3}$		4.48	1.00		408			
Pu-239			$9.71*10^{-3}$	$157*10^{-3}$	$3.91*10^{-3}$		$578*10^{-3}$		61.7	47.0			$61.4*10^{-6}$
Pu.240				$8.47*10^{-3}$	$6.05*10^{-3}$		$867*10^{-3}$			70.5			
Am-241				$148*10^{-3}$	$33.6*10^{-3}$		6.79	985	135	530			
Cm-244					$8.90*10^{-3}$		1.73			120			

Table A.4. Grouping of waste types and isotopes on basis of physical and chemical properties, which are relevant for accident modelling.

	Graphite	Aluminium	Steel, Stainless steel and lead	Concrete	Low Level Waste	DR3	Hot Cells	Radiation sources	Alpha sources	Irradiated U	Non-irradiated U	Tailings	Top shield plug and ring
H-3	Dek_NVol		Dek_NVol	Dek_Nvol				Rad_NVol					TSP_TSR
Co-60	Dekom	Dekom	Dekom	Dekom	LLW	DR3	Hot_Clls	Rad					TSP_TSR
Se-75		Dekom						Rad					
Sr-90		Dekom	Dekom		LLW	DR3	Hot_Clls	Rad		U			
Ba-133			Dekom	Dekom				Rad					TSP_TSR
Cs-137		Dek_NVol	Dek_NVol		LLW	DR3_HVol	Hot_NVol	Rad_NVol		U_NVol			
Sm-151					LLW		Hot_Clls			U			
Eu-152	Dekom	Dekom	Dekom	Dekom	LLW			Rad					TSP_TSR
Eu-154	Dekom			Dekom	LLW		Hot_Clls			U			TSP_TSR
Ir-192								Rad					
C-14	Dek_HVol							Rad_HVol					TSP_TSR
Ca-41				Dek_HVol									TSP_TSR
Ni-63			Dekom	Dekom		DR3		Rad					TSP_TSR
Tc-99					LLW		Hot_Clls			U			
Ag-108m			Dekom										TSP_TSR
Ra-226								Rad	A_Src			Tailings	
Th-230												Tailings	
Th-232												Tailings	
U-234								Rad			U	Tailings	
U-238								Rad			U	Tailings	
Pu-238				Dekom	LLW		Hot_Clls	Rad		U			
Pu-239			Dekom	Dekom	LLW		Hot_Clls		A_Src	U			TSP_TSR
Pu.240				Dekom	LLW		Hot_Clls			U			
Am-241				Dekom	LLW		Hot_Clls	Rad	A_Src	U			
Cm-244					LLW		Hot_Clls			U			

Table A.5. Values used for modelling the shipments performed on trucks.

Vehicle Name	
Number of packages	It is assumed that there will be 6 10' ISO containers or 2 20' ISO containers pr. shipment. Shipment of TSP and TSR is assumed to be done separately and as special arrangement and therefore with a single package pr. transport. It is assumed that either 3 SC containers or 18 drums are placed in one 20' ISO container.
Number of shipments	Is set to 1 as the dose from 1 shipment is of interest. To achieve the collective dose from all the shipments, the results of the modelling are multiplied with the number of shipments, which is calculated as the number of packages in total divided by the number of packages pr. shipment.
Vehicle size	It is assumed that the length (size) of the truck corresponds to a truck carrying a 20' ISO including a trailer which also has a 20' ISO. Hence the length becomes 12 m. However, it is assumed that the transport of the Top Shield Plug and Ring will be done in two separate special arrangements because of weight and the radiation, it is therefore assumed that the size of the vehicle in this case is 6 m.
Vehicle Dose Rate	Is set the same as package dose rates.
Gamma fraction	Same value as for the packages, i.e. 1.
Neutron fraction	Same value as for the packages, i.e. 0.
Crew size	One man crew is assumed
Crew distance [m]	Distance of 2 m is assumed
Crew shielding factor	Is set to 1, i.e. no shielding, which is very conservative.
Crew view [m]	The view of the crew is the diagonal dimension of the packages seen from the crew, i.e. ISO: 3,57 SC: 2,37 Drum: 1,98 TSP_TSR: 3,6

Table A.6. Values used for modelling the shipments performed by sea.

Vehicle Name	
Number of packages	As it is assumed that the waste can be transported in 10 shipments when transporting by sea, it is thus assumed that each shipment carries one tenth of the waste, i.e. one tenth of the total amounts of all the waste types. However, in order to create a worst case scenario it is assumed that all the waste packages of the type that causes the highest doses in an accident situation are transported in one shipment.
Number of shipments	Is set to 1 as the dose from 1 shipment is of interest. To achieve the collective dose from all the shipments, the results of the modelling are multiplied with the number of shipments.
Vehicle Dose Rate	Is set to 25 µSv/h as packages with higher dose rate can be expected to be placed on the barge so that these are shielded by packages having lower dose rate.
Gamma fraction	Same value as for the packages, i.e. 1.
Neutron fraction	Same value as for the packages, i.e. 0.
Crew size	Is assumed to be 4
Crew distance	Distance of 10 m is assumed. Depending on the barge, the distance can be much larger.
Crew shielding factor	Is set to 1, i.e. no shielding, which is very conservative.
Crew view	Is assumed to be 10.

Table A.7. Values used for modelling the transports performed on trucks.

	Primary road - Highway	**Secondary road**	**Origin of the values used.**
Length [km]	400	50	Preliminary study performed by GEUS. The values are the longest possible and therefore very conservative.
Speed [km/h]	86	50	Generic values from traffic observations in Denmark. Data is from [8].
Population density [pers/km^2]	100	1000	Population densities are generic values based on population densities in Denmark presented in [9].
Vehicle density [veh/h]	830	314	Generic values from traffic counts in 2009and presented in [8].
Persons per vehicle	2	2	RADTRAN default value
Accident Rate [accidents/veh-km]	$2{,}07 \cdot 10^{-7}$	$5{,}95 \cdot 10^{-6}$	Estimated values based on data sets involving total kilometres driven by trucks and number of accidents where trucks are involved. [9]
Zone	Rural	Suburban	Selected by modeller.
Type	Primary highway	Secondary road	Selected by modeller.

Table A.8. Values used for modelling the shipments performed on barges.

	Minor waters such as Roskilde fjord	**Larger waters**	**Origin of the values used**
Length [km]	50	600	The distance to the future repository is not known and therefore the longest possible distances are chosen.
Speed [km/h]	8	10	Values are conservatively selected by modeller.
Population density [pers/km^2]	1000	100	Population densities are generic values based on population densities in Denmark presented in [9].
Accident Rate [accidents/veh-km]	10^{-6}	10^{-6}	Deduced from [10].

The transport by road from the harbour in the vicinity of the repository to the repository is modelled with the values shown for secondary road in table A7, except the distance which is assumed to be 25 km.

Table A.9. Values used for modelling radiation exposure when moving the packages from the barges to the trucks.

Number of handlers	It is assumed that there is only 1 handler.
Distance [m]	It is assumed that the distance is 2 meters.
Time [h]	It is assumed that handling of each package takes 5 minutes.

Table A.10. Atmospheric dispersion parameters in RADTRAN.

Isopleth P	RADTRAN default population densities are selected. Hence it is assumed that the population density defined by the user is uniformly distributed.
Weather	RADTRAN default average weather is selected. Hence the radioactive matter is dispersed based on U.S. average meteorology and wind speed.

Table A.11. Probability fractions and release fractions. [5].

	Type A or I package		Type B package	
Accident severity category	**Probability fraction**	**Release fraction**	**Probability fraction**	**Release fraction**
1	0,81	0	0,99993	0
2	0,14	$1,2*10^{-5}$	$6,2*10^{-5}$	$2,6*10^{-5}$
3	0,028	$9,2*10^{-4}$	$5,6*10^{-6}$	$2,4*10^{-5}$
4	$1,9*10^{-4}$	$5,0*10^{-4}$	$5,2*10^{-7}$	$2,6*10^{-5}$
5	$1,9*10^{-2}$	$7,9*10^{-3}$	$7,0*10^{-8}$	$6,2*10^{-5}$
6	$1,2*10^{-4}$	0,38	$2,2*10^{-10}$	$6,7*10^{-5}$

Table A.12. Deposition velocity and respirable fraction.

Deposition velocity [m/s]	0,02
Respirable fraction	0,05

Table A.13. Aerosol fractions.

	Dek_NVol	Dekom	Dek_HVol	LLW	DR3	DR3_NVol	Hot_NVol	Hot_Clls	Rad_NVol	Rad	Rad_Hvol	A_Src	U_NVol	U	Tailings	TSP_TSR
Aerosol fraction	0,01	0,01	0,01	0,01	0,05	0,05	0,05	0,05	0,05	10^{-6}	10^{-6}	0,01	1	1	0,05	0,01

Table A.14. Various parameters in RADTRAN where the default values were used.

Parameter	**Value**
Shielding factor for rural residents	1.00
Shielding factor for suburban residents	0.87
Ratio of pedestrians/km^2 to residential population/km^2	6.00
Minimum small package dimension for handling [m]	0.05
Distance from shipment to maximum exposure [m]	30.0
Vehicle speed for maximum exposure [km/h]	24.0
Average breathing rate [m^3/sec]	$3.30*10^{-4}$
Distance of freeway vehicle carrying radioactive cargo to pedestrians [m]	30.0
Distance of freeway vehicle carrying radioactive cargo to right-of-way edge [m]	30.0
Distance of freeway vehicle carrying radioactive cargo to maximum exposure distance [m]	800
Distance of non-freeway vehicle carrying radioactive cargo to pedestrians [m]	27.0
Distance of non-freeway vehicle carrying radioactive cargo to right-of-way edge [m]	30.0
Distance of non-freeway vehicle carrying radioactive cargo to maximum exposure distance [m]	800
Perpendicular distance to freeway vehicle going in opposite direction [m]	15.0
Perpendicular distance to non-freeway vehicle going in opposite direction [m]	3.00
Perpendicular distance to all vehicles going in same direction [m]	4.00

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