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# Assessing the risk of the transport of radioactive material

## Keywords

transport, transport modes, probabilistic safety assessment, risk-informed decision making, transport computer code, spent fuel, radioactive waste

## Abstract

Transport of dangerous goods are always under critical observation of the public, in particular in case of transport of spent fuel or radioactive waste. In both cases transports are often crossing borders of countries, e.g., waste resulting from reprocessing of spent fuel. The transports could take place by ships, trucks, rails and airplanes and these options and the resulting risks are compared. Transport risk includes health and safety risks that arise from the exposures to workers and members of the public to radiation from shipments Moreover, it is shown that the more modern approach of risk-informed decision making elaborated for application to nuclear installations can also be applied to assess the risk of the transport of radioactive material.

## 1. Introduction

The objective of the transport regulations [17] issued by the International Atomic Energy Agency (IAEA) 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 all types radioactive material (including spent fuel and packages with radioactive waste).

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).

A description of the different types of packages is provided in [17].

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 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.

Since transport occurs in the public domain and frequently involves intermodal transfers, it is a potentially vulnerable phase of domestic and international commerce. This requires – in addition to safety aspects – a uniform and consistent approach to security which is provided in [17].

From a security point of view, a threshold is defined for determining which packages or types of radioactive material need to be protected beyond prudent management practice. Minimizing the likelihood of theft or sabotage of radioactive material during transport is accomplished by a combination of measures to deter, detect, delay and respond to such acts.

These measures are complemented by other measures to recover stolen material and mitigate possible consequences, to further reduce the risks.

There are interfaces between safety and security. Most of them are complementary such as classification of the material and packaging. However, some interfaces must be carefully managed, e.g. information security vs. external communication [33].

In the following the risk of transport of radioactive material is focused on the safety assessment.

The safety assessment regarding the transport of radioactive material is based on three fundamental properties:

- Potential radiation doses associated with the waste transport itself,
- Probability of an accident, and
- 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 potential transport mode may be considered unjustified from an economical viewpoint.

This situation may arise if an alternative and less costly transport mode 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 even lower.

Such broader approach can make use of the integrated risk-informed decision making process originally elaborated for application to nuclear installations as described in section 5.

Based on a preliminary assessment of the various advantages and disadvantages of the different transport modes in the above context, decisions can be taken which type of transport is the appropriate one for the type of radioactive material transported and the local situation of the starting point of the transport and the final destination. This will be illustrated in the examples.

## 2. Transport options

The first step for a preliminary safety assessment is to identify the most appropriate option(s) which fulfil the national and international requirements (e.g., [15], [17] and [22]).

### 2.1. Road transport

The concept of transporting the radioactive material by road is to load the packages onto trucks at the site where the packages are stored and to drive these to the final destination where the packages have to be unloaded. The route will typically include primary and secondary roads and avoid towns as far as possible.

Transport of radioactive material by road is a well-known method. The primary advantage of this type of transport is that it is simple: By using trucks the handling of the 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. Moreover, the infrastructure needed is already in place.

The disadvantages of this type of transport are:

- Due to the amount of radioactive material, a large number of transports is required, increasing the probability of an accident,
- Persons other than the crew will get exposed to radiation along the route,
- The drivers will be placed relatively close to the radioactive material during transport.

### 2.2. Sea transport

The concept of transporting the radioactive material by sea is to load the packages onto barges at the site and sail to a harbour at the final destination where the packages are unloaded.

However, it depends on the site characteristics both of the starting point and the final destination if the loading activities require a transfer of the packages to trucks on the sites or if the trucks had to run on roads to the next harbour outside the sites.

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 radioactive material depending on the configuration of tug and barge. The disadvantages of this type of transport are:

- In case transports have to be performed to reach the harbour, a similar number of truck transports as for the road solution is expected, as trucks are likely to be required for the land based starting or last part of the voyage in case the ships cannot pick up and/or deliver the packages to a harbour of the final destination.
- The consequences of an accident may be relatively large due to the large amounts of waste per voyage.

## 2.3. Rail transport

The concept of transporting the waste packages by rail strongly depends on the fact if the starting point of the transport and the final destination has a direct connection to the railway. Otherwise the packages have to be loaded onto trucks, transported by road to a suitable train station and unloaded 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 final destination, where they are again transferred to trucks, transported to the final destination 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 type of transport in case that there is no direct connection to the railway are:

- The number of handling operations is extensive. The packages must be transported by trucks both to and from the train leading to a large number of on- and off-loading operations.
- This option 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.
- The consequences of an accident may be relatively large due to the large amounts of packages per voyage.
- The railroads typically intersect the centre of the cities, thereby increasing the potential consequences of an accident.

## 2.4. Air transport

The concept of transporting the radioactive material by air is to load the packages onto trucks at the starting point, 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 final destination, where they are transferred to trucks, transported to the final destination and unloaded.

Other than moving part of the transport into the air and, thus, eliminating radiation exposure to bystanders, there are in general no major advantages of this transport method. However, according to the geographical situation or the urgency for the transport, air transport could be the only practical and acceptable solution (e.g., in case of radioactive pharmaceuticals).

The disadvantages of this method are:

- The relatively large number of handling operations.
- The relatively low cargo capacity per flight.
- The limited distance between the pilots and the packages.
- The relative high costs.

## 3. Implications of the initial assessment

The initial assessment of the possible types of transport and the final proposals strongly depend on the infrastructure at the starting point of the transport and the final destination.

Moreover, if the starting point and the final destination are separated by the sea, e.g. in case of transports from UK to Germany or France to Japan resp. Korea, only the sea option and theoretically the air option remain even in case that these transport options require additional handling steps and are cost intensive.

Another aspect which has to be taken into account during the initial assessment is that calculations for an appropriate design of the packages are performed for a certain storage time and the following transport. Important aspects have to be taken into account if the assumed storage time will be exceeded. Long term degradation effects have to be analysed such as corrosion, basket properties and absorber efficiency. Therefore, enhancing technical and regulatory boundary conditions are currently discussed regarding the storage. But it has also to be ensured that the package still fulfils all transport requirements enhanced [8] and the transport risks have to be calculated.

### 3.1. Example Denmark

In this example, the risk of a transport of radioactive material from the Risø site as the current intermediate storage site for waste packages to a potential repository site has been in investigated in more detail [28].

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.

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).

The total collective dose for all incident free road transports has been estimated to be in the order of 40 person-mSv according to [28]. 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 has been estimated to be in the order of 20 person-mSv according to [28]. 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 per 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 ($5 \cdot 10^{-8}$) to occur for road transport and 1:33.000.000 ($3 \cdot 10^{-8}$) 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.

### 3.2. Example Germany

The vitrified high level waste arising from the reprocessing of spent nuclear fuel at Sellafield in the United Kingdom has to be returned to Germany. The shipment of the specific flasks will include transport via the Irish Sea, the English Channel and the North Sea with ships of the Pacific Nuclear Transport Limited (PNTL) classified to the INF 3 standard [22]. INF 3 ships are certified to carry irradiated nuclear fuel or high-level radioactive wastes and ships which are certified to carry plutonium with no restriction of the maximum aggregate activity of the materials.

Therefore, a safety assessment has been performed to analyse the severity and the frequency of mechanical impacts, fires and explosions with the potential to affect the packages.

The assessment approach was to apply information on accident severities and frequencies derived from general maritime accident data and to adapt this information to the much increased safety features of a specific INF 3 ship.

One important aspect is to identify and explain the differences between ships carrying hazardous cargoes and those of INF 3 standard which are used for the transport of high level vitrified waste. Nine specific areas of the ships design and operation have been identified as adding overall safety “value” to the transport of this type of material:

- **Ship structure:** double hull; 400 tonnes additional steel; watertight longitudinal and transverse bulkheads; designed against collision with a vessel of 24,000 tonnes and 15 knots.
- **Propulsion systems:** duplicate diesel engines, gearboxes, propellers and a bow thrusters’ drive system at the front of the ship.
- **Power plant for electrical systems:** two independent generating systems at the front and rear of the ship; additional separate emergency generator and battery system; redundancy of power cabling along both sides of the ship.
- **Fire safety:** very low fire load densities within the cargo holds and the passageways; water filled bulkhead between living

accommodation/engine room and the cargo holds; watertight and fire resistant bulkhead doors along the passageways; a full multi-zone and multi-sensor fire detection system signalling to bridge and engine room; extinguishing systems with supply for cargo holds, engine room, fore and aft generator rooms; fire hose reels and portable extinguishing systems within accommodation areas and machinery spaces; back up redundant sprinkler systems within each of the holds, fed from both sides of the ship's fire ring main, requires manual connection; 4 main plus 1 emergency fire pump.

- **Cargoes:** the cargo of the ship consists exclusively of very heavy (50 to 100 tonne range) flasks of type B standard similar to those used for spent fuel which are mounted rigidly.
- **Crew:** 26 men; higher certificates of competence for navigating and engineer officers; multi-skilling; training programmes.
- **Communications:** multiple alternate systems such as satellite communication, telex over radio, radio telephone; automatic voyage monitoring system which transmits position, speed and heading reports to the control centre every two hours.
- **Radar and anti-collision systems:** two independent, type approved radar systems, anti-collision system (ARPA = Auto Radar Plotting Aid).
- **Emergency preparedness:** special home based emergency team; home based tracking system; provision for emergency personnel, procedures and equipment.

The ships of the PNTL fleet have been operated during the last 20 years without any significant accident. In this period

- an experience of about 90 ship years has been accumulated,
- about 150 shipments have been performed,
- about 4.5 million nautical miles travelled,
- about 8000 tonnes of nuclear fuel transported,
- about 4000 flasks (max. 5 tonnes fuel/flask) transported.

By employing statistical methods to statistical data without any event, an occurrence frequency (expected value) of an accident of $1.1\cdot10^{-7}$/nautical miles can be derived from this experience.

However the PNTL fleet specific database is not sufficient to estimate realistic probabilities of extreme accident scenarios. An alternative method to provide a more realistic estimation of the accident probability of an INF 3 ship is to consider the accident statistics for conventional cargo ships. For this reason there are several attempts in the literature to apply the world wide experience of the large conventional transport fleet to nuclear cargo transporting ships.

Existing databases differ concerning the number of ships, type of ships included in the data base, definition of accidents, number of recorded incidents, time period. The interpretation of these databases within the different studies therefore gives a wide range of probabilistic information [25].

In the frame of the overall assessment, internal fires, collisions, fire induced by collisions and foundering has been investigated. As an example, the assessment of the internal fires is described in the following in more detail.

To quantify the probability of ship internal fires which could affect the cargo the particular safety features of the INF 3 ship have been taken into account. The procedure of the fire risk analysis for the PNTL ship is adopted from the fire safety analysis for nuclear power plants (see, e.g., [2] and [5]). From the potential fire scenarios on board a PNTL ship, the locations with the highest frequencies for initiating fires were identified following expert evaluation and take into account their severity with respect to cargo.

Though the accidental examples for general ships are not directly applicable to create the scenario of the severe fire accident of the INF ship, these data were basically investigated to study the fire accidents of ships. Based on the fire loads present, considerations of event frequencies and the possibilities of fire spread to the cargo holds, as the severest scenario discussed in [1], main engine room fires during voyage carrying the packages dominate the fire risk to the cargo and were, therefore, selected.

The results of the detailed analysis are summarised in the form of an event tree in Figure 1 in line with the recent IEC standard [21]. It should be noted that the available accident statistics of the insurance companies include only so-called damage fires, i.e. fires which have developed from an initiating fire to a severity with relevance to the insurers. The event tree therefore starts at the top with such a damage fire inside the main engine room, for which, as a conservative estimate, an occurrence frequency of $2\cdot10^{-7}$/nautical miles has been derived from the accident statistics for cargo ships in general. This reveals an occurrence frequency for a fully developed main engine room fire of $2\cdot10^{-4}$ per voyage.

This assumption of a fully developed fire - excluded an initial fire without damage - is reflected in the first level of the event tree where only a 20% probability for successful manual fire fighting is assumed. The consecutive level of the event tree refers to the success or failure of the halon system to extinguish the fire in the engine room at this stage. If unsuccessful, the next line of defence with respect to the cargo is a water-filled steel bulkhead which separates the main engine room from the cargo area.

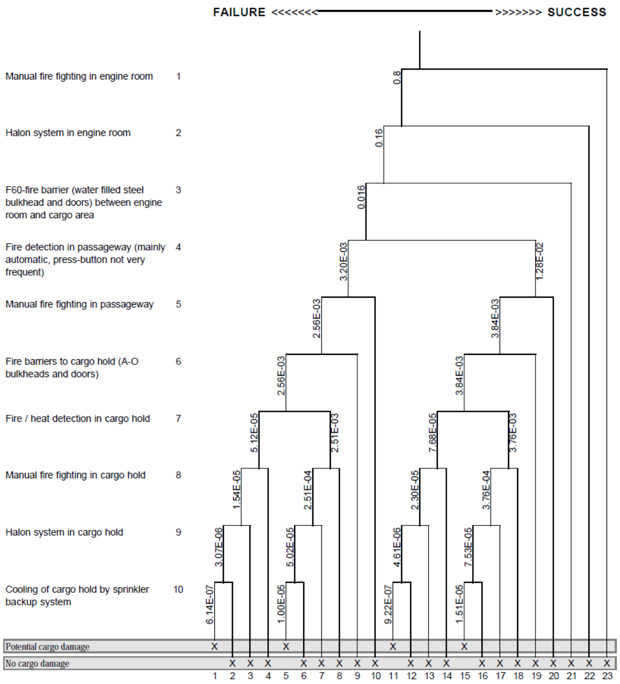

*Figure 1*. Event tree for a main engine room fire

Concerning all conceivable combustible fire loads in the main engine room this barrier is sufficient to prevent a fire spread to one of the passageways on both sides of the ship running along the bulkheads of the cargo holds.

Only in the case that one of the fire doors leading from the main engine room to a passageway is inadvertently open - contrary to specified procedures and including surveillance from the navigation bridge - there is a possibility for fire propagating to the passageway. For this conditional probability a conservative value of $10^{-1}$ was chosen from [11] respective [12].

All further decision levels and the associated conditional failure probabilities are evident from Figure 1. Finally, four event sequences of the tree can result in a fire propagation to the interior of a cargo hold and have the end point "potential cargo damage" with associated conditional probabilities lower than $1.5\cdot10^{-5}$ for each event sequence, equivalent to of $3.0\cdot10^{-9}$ per voyage taking into account the initial probability of $2\cdot10^{-4}$ per voyage for a fully developed main engine room fire. This leads for all the four branches of the event tree with the potential to affect the cargo to a probability of $5.3\cdot10^{-9}$ per voyage.

The fire risk analysis assesses the probabilities and severities of possible fires in a cargo hold. In any case the available fire loads are small enough that the thermal threat to a large flask is negligible.

The overall results have shown that there is a high safety margin due to the special safety features of the INF 3 ships compared to conventional ships. The remaining accident probability for a transport of vitrified high level waste from UK to Germany is very low. No realistic severe accident scenarios that could seriously affect the flasks and could lead to a radioactivity release have been identified.

In fact, there has been still no accident during the shipment from the United Kingdom to Germany, neither a fire nor a collision nor a foundering.

## 3.3. Example Korea

According to the long term management strategy for spent fuels in Korea, they will be transported from the spent fuel pools in each nuclear power plant to the central interim storage facility. Also, transport activities will take place between the central interim storage facility and the final repository which will start its operation by the year 2065. Therefore, the safe and economical logistics for the transport of these spent fuels have to be determined by considering their transport risks and costs.

Four maritime transport scenarios have been investigated [24] by considering the type of transport casks and transport means in order to suggest a safe and economical transport logistics system for the spent fuels in Korea.

For four transport scenarios (a collision, a fire, and a foundering and sinking accident), the transport risks resulting from accidents during a transport from a nuclear power plant site to a centralized interim storage facility are estimated and compared by using the RADTRAN5 code which is explained below.

In addition, road transport scenarios have been considered for different transport casks for spent fuels between the central interim storage facility and the final repository. The accidents for the road transport cover an impact and a fire.

The expected values for the population risk in person-Sv for the maritime transport are in the range of $1.74\cdot10^{-8}$ and $2.20\cdot10^{-8}$ for a collision accident, $1.85\cdot10^{-9}$ and $2.35\cdot10^{-9}$ for a fire accident, $1.34\cdot0^{-8}$ and $1.70\cdot10^{-8}$ for a foundering and sinking accident [24].

The calculated values for the population risk in person-Sv for both a maritime and road transport show low radiological risks with manageable safety and health consequences.

According to the results for both the maritime and road transport, the number of journeys per year was found to be a very important factor if one transports the same number of transport casks for the spent fuels.

Although the amount of transport casks per year is the same for the four scenarios, the population risk for the case of using the INF-2 ship shows a higher value than that for the case of using the INF-3 ship. This may be attributed to the fact that the INF-3 ship can carry more transport casks per journey than the INF-2 ship because of their certification as explained in example 2.

Among the accidents considered during the maritime and road transports, the population risks for the fire accident shows a minimum value of the population risk because the occurrence probability of the fire accident is the lowest and the same value for the release fraction is used.

## 4. Estimation of transport risks

Transport risk includes health and safety risks that arise from the exposures to workers and members of the public to radiation from shipments of radioactive material [29]. The health effect risks arise from exposures to people who travel, work, or live near transport routes and transport workers themselves to radiation from the packages [9, 10].

For estimating transport risks computer codes have to be used. The most used transport risk assessment computer code is the RADTRAN code [30, 31] supported by RADCAT [34] which have been developed by the Sandia National Laboratories and are regularly be updated. The current version is RADTRAN5.6.

It is a computer code especially for an analysis of the consequences and risks of a radioactive material transport. It can be used for the estimation of doses and related probabilities associated both when estimating an incident-free transport of a radioactive material and with accidents that might occur during transport.

In that context incident-free (or normal) transport is a transport during which no accident, packaging, or handling abnormality or malevolent attack occurs. All the accidents that might occur during transport have to be considered in the transport risk assessment.

All major modes of commercial transport may be analyzed with RADTRAN5: highway, rail, barge, ship, cargo air, and passenger air. The RADTRAN5 component models and their interrelationships are shown in *Figure 2*.

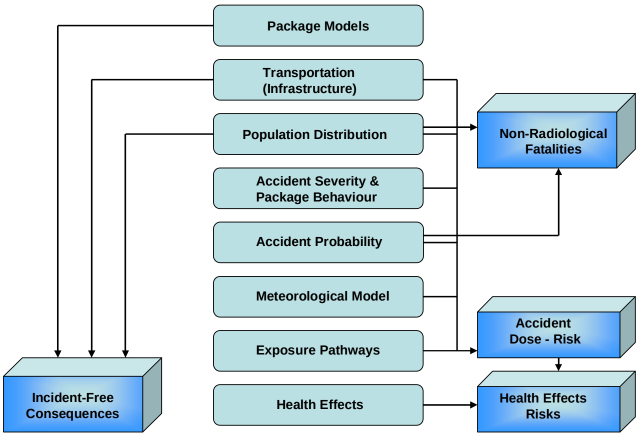

*Figure 2*. RADTRAN – component models and their interrelationship

However, one of the main problems as often in calculations is to set up the safety assessment on a sound database. Data can be derived in a general manner from international experience. Occurrence probabilities, e. g., for maritime transport can be derived from [33] providing, for example., collision frequencies for 21 ocean regions.

## 5. Integrated risk-informed decision making approach

While making a decision of any issue dealing with nuclear safety, results of deterministic safety considerations [4] and probabilistic assessments are not the only determinants in the decision making process (see, e.g., [18]).

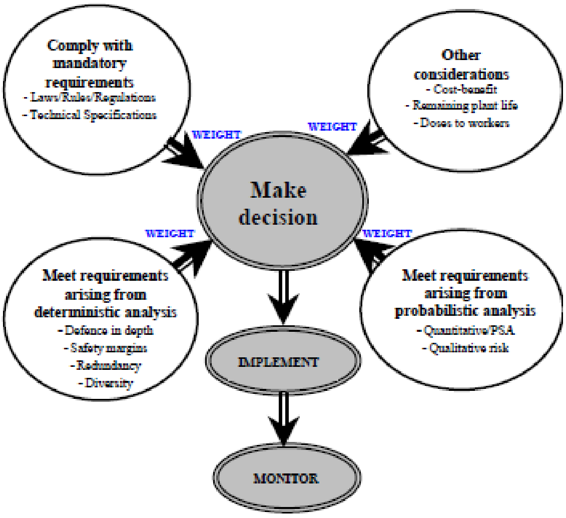

*Figure 3*. Risk-informed decision making process according to [16]

The concept of risk informed decision making as shown in *Figure 3* was initially described in [16] which outlined a process that could be used by utilities and regulatory bodies to make decision on safety or regulatory issues and is addressed in [32] for the aspects of transport.

Further discussion of the integrated risk informed decision making process was given in [19] which presented some framework for the decision making process.

The integrated risk informed decision making approach examines possible different options taking into account in a systematic manner factors that are important to the safety, security or regulatory issue [6]. In particular, there is explicit consideration of both the likelihood of events and their potential consequences together with such factors as good engineering practice, sound managerial arrangements as well as a knowledge that has been derived from experience and engineering good practices [26].

The IAEA is currently working on a TECDOC [20] which is intended to provide guidance on its implementation including some example of already conducted applications. After the technical meeting in March 2011 a further expert meeting is scheduled for the late summer 2012 to enable a publication of the TECDOC in 2013. Moreover, this document may be the basis for developing a safety guide on this topic in the future.

However, this risk informed decision making process is up to now only applied for nuclear power plants. *Figure 4* adopted this approach for issues related to the decision on the best option for the respective transport mode of radioactive material.

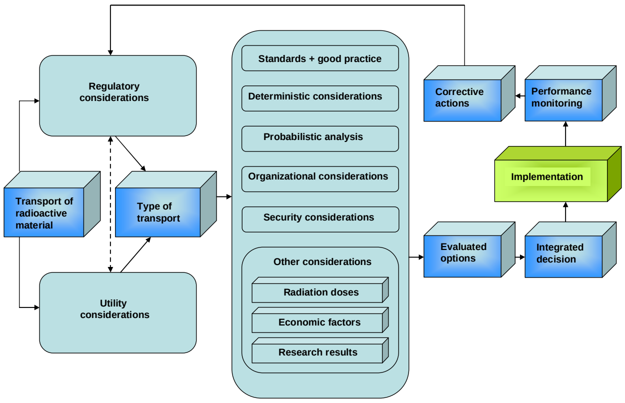

*Figure 4*. General structure of an integrated risk-informed decision making process adopted to transport of radioactive material

As can be seen from *Figure 4*, the further developed integrated risk-informed decision making process includes deterministic and probabilistic analyses as central parts of the risk assessment process. However, this integrated approach takes into account also other aspects such as security considerations, and radiation doses and economic factors.

- **Standards and good practices** – The respective regulations have to be fulfilled, good practices with regard to experiences in transport of radioactive material in other countries could be helpful.
- **Deterministic considerations and probabilistic analysis** – The safety assessments must demonstrate that for the material transported (in particular, in case of spent fuel) will remain in a subcritical state during routine, normal and credible accident conditions of storage and transport.
- **Organizational considerations** – Management for a wide range safety covers of aspects including safety culture, leadership, control and competence of people involved in transport.
- **Security considerations** – The security plan takes into account design basis threats and risk derived from a national threat analysis. Security measures need to be in conformity to IAEA guidelines. Prior to any shipment the security arrangements have to be assessed and approved by the regulator.
- **Radiation doses** – Arrangements are in place for health physics coverage and monitoring of radiation doses of the personnel during shipment.
- **Emergency management** – This has to include notification of local emergency agencies, communication channels, actions taken in a breakdown or accident situation and reference to the state emergency plan.
- **Research results** – Appropriate engineering research will be applied for transporting long-term stored radioactive material and compromised fuels, e.g. development and use of special package types.

## 6. Concluding remarks

Some attempts are already made to develop an integrated method for risk management in transport [23] using the typical steps of a risk management tool [3].

A method of risk and safety assessment during the ship salvage using the hazard, release and consequence analysis is provided in [13] and based on the proposal for a performance-oriented risk-based method for assessment of safety of ships in damaged conditions [14] also addressing accidents with larger impact on the environment using the concept of the ALARP risk evaluation criteria.

In general, such approaches could also be applied for the transport of radioactive material as far as the risk assessment provides quantitative results. The primary goal of the risk assessment for the transport of radioactive material is the quantification and evaluation of the radiological consequences associated with accident-free transport and potential transport and handling accidents of shipments of radioactive material (e.g., vitrified waste, spent fuel, radioactive waste).

The probabilistic assessment method which should be applied for this kind of transport involves typically a five-step analysis approach:

- Description of the type, quantity and mode of transport,
- Analysis of transport accidents and the associated mechanical and/or thermal impact load conditions and the expected frequency of occurrence for the mode of transport being considered,
- Assessment of the system response of the packaging and the material inside to specific accidental load conditions, e. g, mechanical impaction, fire and the subsequent environmental release,
- Estimation of the environmental release and frequency of occurrence considering the range of shipping patterns and accident severity's,
- Assessment of the environmental radiological consequences for different meteorological conditions.

The transport risk assessment method requires a complex modelling effort and is specifically designed to describe the broad range of shipping arrangements and credible transport and handling accidents including low-probability accidents with high consequences and higher-probability accidents having - if at all - low radiological consequences, Accident frequencies for the study have been derived from historical records of transport accidents or have been adopted from the general literature.

The current system of standards and regulations governing the transport of spent fuel and other radioactive materials appears to have functioned well, and the safety record for past shipments of these types of materials is excellent. However, past performance does not guarantee that future transport operations will match the record to date, particularly as the logistics involved expand to accommodate a much larger number of shipments.

In addition, the current set of transport-related regulations requires updating to reflect changes in fuelling practices and transportation after extended storage [27].

Past experiences in the United States and abroad, and extensive comments to the Commission, indicate that many people fear the transportation of radioactive materials. Thus, greater transport demands are likely to raise new public concerns. This is addressed in a recent study [7] reflecting consequences from the Fukushima accident in March 2011.

Therefore, a comprehensive transport risk assessment is necessary to ensure that all safety relevant aspects are taken into account.

The type of transport means depends on the potential and most appropriate transport options taking into account the results of the risk assessment.

In the past the decisions on the most appropriate type of transport has mainly been based on deterministic safety assessments and partially probabilistic safety considerations. This is in the meantime improved by applying the five-step analysis approach addressed above.

However, future transport risk assessments should take into account current developments in other nuclear areas.

Recently, the integrated risk-informed decision making process as a systematic framework for including a broad spectrum of aspects has been developed which is already implemented in some countries like Canada, United Kingdom and the USA for application in nuclear power plants and other facilities. It is shown that this new approach can also be applied for issues related to the decision on the best option for the respective transport mode of radioactive material.

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