A Literature Survey and Review of Transport Risk Assessments

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INTRODUCTION

The use of probabilistic risk assessment (PRA) techniques to derive risk estimates for a wide range of industries is well accepted. One application of such techniques is to transport operations. This paper presents a review of the available literature concerning transport risk assessments of radioactive material (RAM) and other dangerous goods.

REVIEW APPROACH

The intention of the review was to cover as wide a range of relevant subject matter as possible. A list of relevant papers was compiled from two computer databases: Compendex, containing 2.1 million international engineering and technology related abstracts dating from 1970 onwards; and INIS, containing technical papers relating to the peaceful use of nuclear science and technology since 1976. That list of potentially relevant papers was then reduced by eliminating those judged not to be relevant following consideration of titles and abstracts. Finally eighteen papers were selected for detailed review (see References for a full list of these papers).

The scope of the review was limited to PRAs published in the open literature and reports available within AEA Technology. Therefore, commercially or politically sensitive papers would not be identified. In addition, some papers in languages other than English were excluded, owing to the cost of translation.

AIMS OF THE REVIEW

The following four areas of the risk assessment reports were considered in the review:

- Methodology used,

- Quantified risk estimates,
- Conclusions on the level of risk, and
- Other comments and points of interest.

In addition to reviewing the papers the study assessed the comparability of their results. The aim was to compare the risks associated with RAM transport and the transport of other dangerous goods, and to compare the risks associated with different modes of transport.

METHODOLOGIES

The evaluations of risks in the papers reviewed used a variety of different computer models and methods of arriving at frequency values. Each assessment used input data in a form specific to its own method or to the transport operation considered. However, in all cases the base vehicle accident frequencies were derived from historical data.

In general, the risk assessment methodologies followed the pattern originally developed by Battelle Laboratories in the early 1970s [Cashwell and Neuhauser 1989], consisting of the following five steps.

- *Transport System Description* - basic information on the transport system. For example: facility locations and routes; packages and vehicles; physical and chemical material properties; population distributions and meteorological characteristics along the route.
- *Event Sequence Identification* - scope of analysis, hazard identification, failure scenarios, failure modes.
- *Event Sequence Evaluation* - estimation of event sequence probabilities using fault tree or event tree analysis. This requires details of route-specific data on hazard frequencies, normal and transport accident thermal and mechanical stresses, and the response of transport system components to these stresses.
- *Consequence Calculations* - the consequences of any accident, which are dependent on its severity, location, and prevailing environmental conditions. A range of effects is considered and these effects form the input data to computer models which determine the consequences. Consequences are generally measured in terms of radiation doses, fatalities, or injuries but some also include financial and environmental effects.
- *Risk Calculations* - event frequencies and consequences, combined to obtain the level of risk. The at-risk group or individual is defined at the start of each study; it may be workers directly involved in the transport operation, members of specific population groups or regions, or an individual representative of one of these groups.

The following risk definitions may be used:

- *Societal Risk* - the frequency of a given number of fatalities occurring as a result of an incident during a particular transport operation.
- *Expectation Value of Risk* - the expected number of fatalities (or injuries) arising from the operation.
- *Individual Risk* - the frequency at which a given individual will be expected to suffer injury or death as a result of a particular transport operation.

QUANTIFIED RISK ESTIMATES

Direct comparisons between the papers were difficult, owing to differences in materials transported, mode of transport, route and units of risk measurement. However, some useful comparisons can be made and these are discussed below.

Risk Expressed as Expected Number of Fatalities

In trying to gauge the level of risk associated with different transport operations it is clear that some common measure is required. For example, it would probably be misleading to compare the expected number of fatalities associated with an operation using one short route directly against the expected number of fatalities associated with a large operation involving numerous routes and covering long distances. One common measure suitable for comparing many transport risks is risk per vehicle-kilometre or package-kilometre.

It is possible to derive such a comparison from data in five papers in the review (Rhoads and Andrews 1980, Cashwell et al. 1986, Tunaboylu et al. 1986, Saccomanno and Shortreed 1990 and Appleton et al. 1993). This analysis is summarized in Table 1.

Note that this comparison may not be considered appropriate for dissimilar materials such as radioactive waste and chlorine; risk levels that are tolerated from one source may not be tolerated from another. When making comparisons it is necessary to consider the different types of risk (e.g., nuclear and non-nuclear), the different perceived benefits to be gained from the operations, and other differences in the nature of the risks involved.

The comparison is also limited by the uncertainties in the input data, basic assumptions, approximations and levels of conservatism which may introduce large margins of error in the results. Note also that the level of risk to society associated with a transport operation cannot always be satisfactorily expressed as a single number of expected fatalities, as this gives no understanding of the range of possible consequences, and particularly the balance between low-consequence/high-frequency events and high-consequence/low-frequency events.

Nevertheless, some useful conclusions can be drawn from the data presented in Table 1:

- The estimated radiological risks due to radioactive materials (RAM) transport accidents are in the range of 10^{-10} to 10^{-13} fatalities per vehicle-km. The estimates for the United States are lower than for the United Kingdom and France; this may be due to differences in population and traffic density, or the degrees of conservatism in the assessments.

- The estimated radiological risks due to incident-free RAM transport in the United Kingdom and the United States are in the range of 10^{-8} to 10^{-9} fatalities per vehicle-km.
- The estimated risks due to chlorine transport accidents in the United States and Canada are in the region of 10^{-7} fatalities per vehicle-km.

In the papers reviewed, base accident frequencies are similar within a given mode of transport. There are essentially two reasons for differences in risk estimates between operations:

- Differences in the resistance of packages and transport vehicles to various accident stresses will result in differences in the frequencies with which package containment is lost.
- Differences in the quantity and, perhaps more importantly, the nature of the goods carried will result in differences in the consequences if a loss of containment occurs. For example, in the case of exposure to radiation the risk measured is of latent cancer fatalities, rather than of early death for many other types of hazardous materials.

- Several different criteria for comparison of risk are expressed. Four examples are:

- Risk per GW-hr (for fuels) (Rhoads and Andrews 1980) - this gives a measure of the relative benefits of the operation rather than purely fatalities per year.
- Comparing the number of fatalities (for both accident and incident-free transport) with the number of national fatalities associated with general truck and rail accidents and deaths due to cancer from background radiation (Cashwell et al. 1986).
- Expressing radiological fatalities as a percentage of deaths in the same exposed population due to normal background radiation (Weiner et al. 1991).
- Comparing the doses received by the target population with the national dose guidelines (Lange et al. 1991).

Societal Risk Expressed as Fn Curves

Risk is a function of both event frequency and consequence. The results of a PRA are therefore often expressed as the expected frequency of N or more fatalities; this can then be plotted as a frequency (F) versus the number of fatalities (n) for the operation; the so-called Fn curve. Four papers (Rhoads and Johnson 1978, Purdy 1993, Considine et al 1989 and UK Health and Safety Commission 1991) express risk results in terms of Fn data or plots. It is not consistent, however, to attempt to plot each of these Fn curves on one graph because it takes no account of the size or type of operation, the benefits to be gained from the operation, or the approximations and assumptions made.

The general conclusions of these reports are that non-nuclear hazardous materials transport operations (typically LPG, motor fuel, chlorine and ammonia) represent a relatively high level of risk which should be examined with a view to making them as low as reasonably practicable (ALARP). Rhoads and Johnson find the risks from radioactive material transport shipments to be two or three orders of magnitude below those for chlorine shipments and four or five orders of magnitude below those for total 'man-caused events'.

In some circumstances Fn curves may be used to make comparisons against certain accepted guidelines. The UK Health and Safety Executive (HSE) study (UK HSC 1991) compares the risk Fn curves for a number of non-nuclear hazardous materials with lines of tolerability overlaid on the graph. Two lines are presented: a 'just tolerable' line above which the risks are considered unjustifiable in any circumstances; and a 'negligible' line below which the risks are considered negligible. Between the two lines the HSE recommended that the risks should be examined and reduced so far as is reasonably practicable. The values of the tolerable and negligible risk lines were developed from the findings of the Canvey Island risk study in the United Kingdom (UK HSE 1978 and 1981) which referred to a petrochemical complex.

The assessment of transport to the Konrad repository in Germany (Lange et al. 1991) presents the results of the study in terms of frequency of receiving a given dose against dose rate. Superimposed on these plots are contours representing an equivalent dose for different distances away from the accident release location. These results are difficult to compare with any others presented in this study, but the report concluded that there would be no unacceptable transport release accidents within the 40-year lifetime of the repository.

GENERAL COMMENTS EXPRESSED ON THE LEVELS OF RISK

Each of the papers on RAM transport operations concludes that the associated levels of risk are either very low or at least acceptable. Most of the radiological risk associated with RAM transport is due to incident-free transport doses (Cashwell and Neuhauser 1989, Appleton et al. 1993).

Some authors express their concern at the current level of risk associated with non-radioactive material transport operations (Saccomanno and Shortreed 1990, and UK HSC 1991). Saccomanno and Shortreed comment that the societal risk associated with chlorine transport on a specific route in Canada suggests "that safety could be enhanced, if appropriate policies were directed at reducing truck accident rates, or re-routing rail chlorine shipments so as to avoid major population concentrations."

There is no general view that road is safer than rail or vice versa for any hazardous materials transport system (Tunaboylu et al. 1986, and Purdy 1993). However, the Konrad repository study (Lange et al. 1991) states that because of a lower accident risk of rail transport compared to road, the envisaged high fraction of rail transport for that operation has a beneficial effect.

DISCUSSION

There is little indication in most of these reports of the sources or conservatism of the input data. However, a number of the reports do emphasize the importance of considering the accuracy and/or validity of the results from most PRAs, given the nature of the data used to derive the levels of risk. This is of particular relevance when making comparisons. One other technique mentioned is the use of sensitivity analysis as part of the assessment, to show what effect variations in certain less accurately defined parameters would have on the outcome. In the transport operations covered by the papers in this review it is common that one or two major factors tend to dominate the level of risk.

The public perception of risk or public attitudes to risk was included in the review (MacGregor et al. 1994). One finding was that distance from a RAM transport route does not affect the public's perception of its risk. The report also states that information and publicity are important factors in reducing public concern, and that the actual level of risk is irrelevant in the minds of the public.

In general RAM transport risk levels fall well below the risks associated with the transport of other hazardous materials, both in the United Kingdom and in the United States, when measured per vehicle-kilometre. However, deciding whether a risk is tolerable to society involves balancing the risks against the benefit and considering the nature of the risks. Absolute risk is only one of the factors to be considered, and PRAs are therefore only one input to the decision.

The risk assessments provided no evidence that any particular mode of transport is inherently safer in all cases. Specific features of the operations considered were of greater importance in influencing overall risks.

CONCLUSIONS

- A broadly similar methodology is used in transport PRAs for a variety of hazardous materials.
- The absolute risks associated with RAM transport are generally lower than for other hazardous materials.
- The results of any PRA should always be considered with the applicability and conservatism of the input data in mind.
- Two papers express risk in terms of fatalities per GW-hour and dose per GW-year, as a way of achieving comparability between industries and operations. Other benefit measures could include financial wealth, lives saved or food produced: these would apply equally to materials not involved in energy production.

- Deciding whether a risk is tolerable depends on balancing the risk against the benefits, so absolute risk is not the whole story.
- Public perception of RAM transport risk is dominated more strongly by publicity and information than by the absolute risk associated with an operation.

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Table 1. Summary of Risks expressed as Expected Fatalities per Vehicle-km

Reference	Country of Origin	Risk Considered	Operation		Expected Fatalities/yr	Vehicle-km/yr	Fatalities/ vehicle-km
Rhoads and Andrews 1980	United States	Radiological accidents	US Nuclear wastes (road & rail)		3×10^{-6}	1.25×10^{7}	2.4×10^{-13}
			US Nuclear fuel cycle (road and rail)		1×10^{-4}	2×10^{7}	5×10^{-12}
		Accidents	US Chlorine transport (rail)		9	2.25×10^{7}	4×10^{-7}
Cashwell et al. 1986	United States	Radiological *	Road transport of HLW to Hanford repository		0.08	1.4×10^{6}	5.8×10^{-8}
			Rail transport of HLW to Hanford repository		2.8×10^{-3}	3.3×10^{5}	8.6×10^{-9}
Tunaboylu et al. 1986	Switzerland	Radiological accidents**	Plutonium oxide transport	United States	n/a	n/a	1×10^{-11}
				France	n/a	n/a	1×10^{-10}
			Plutonium nitrate transport	United States	n/a	n/a	3×10^{-10}
				United Kingdom	n/a	n/a	2×10^{-10}
Saccomanno and Shortreed 1990	Canada	Accidents	Chlorine transport by road (route-specific)		2.1	6.7×10^{6}	3.1×10^{-7}
			Chlorine transport by rail (route-specific)		0.5	2×10^{6}	2.5×10^{-7}
Appleton et al. 1993	United Kingdom	Radiological incident-free	Transport of radioactive wastes by road and rail and by many routes to a repository at Sellafield		0.01	9.3×10^{5}	1.1×10^{-8}
		Radiological accidents			1.5×10^{-5}	9.3×10^{5}	1.6×10^{-11}

* It is not clear from the report whether this includes both accidents and incident-free transport. The numbers indicate that both are considered.

** Accident data derived from the total fatalities per transport and the length of transport route.

n/a Not available.