METHODOLOGIES FOR ASSESSING THE RADIOLOGICAL IMPACT ARISING FROM THE TRANSPORT OF RADIOACTIVE MATERIALS

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Abstract

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The paper seeks to provide advice on the suitability of existing radiological consequence models for specific transport situations. The review was commissioned by the Health and Safety Executive of the United Kingdom as part of its programme of research to provide a firm basis for its requirements in relation to transport operations. Many mathematical models were identified as having been applied to transport issues. Four important models were selected for closer scrutiny: CRAC 2, RADTRAN II, INTERTRAN and MARC. Large deterministic codes, for example CRAC 2 and MARC, are useful when applied to situations that warrant detailed probabilistic assessments of radiological consequences. This may be the case for large notional releases from Type B packages, which may be shown to be of particular significance from the results of a less detailed consequence model, for example, in a risk analysis code, such as RADTRAN II or INTERTRAN. It is noted that all attempts to quantify the risk from the transport of radioactive materials suffer from a lack of good input data concerning the probabilities of occurrence for defined accident severity categories and the associated values for release and aerosolization factors.

1. Introduction

Methodologies for assessing the radiological impact arising from the transport of radioactive materials (RAM) can be used in retrospective studies. To date the need for such studies has been limited because transport accidents involving RAM have been rare and very few have resulted in a loss of material to the environment, hence the impact has been small. Assessments of radiological impacts also have roles to play in the development of statutory requirements, optimisation exercises, design criteria, emergency planning procedures, risk analyses, reviews of radiation exposure and in contributing to the public debate concerning transport issues.

This review of methodologies[1] was commissioned by the Health and Safety Executive of the United Kingdom as part of its programme of research to provide a firm basis for its requirements and recommendations in relation to transport operations. The objectives of this paper are to provide advice on the suitability of existing models for specific transport situations with respect to radiation protection.

At least two types of situations have to be addressed by transport accident models. Firstly, loss of shielding incidents which give rise to enhanced external radiation levels but which do not necessarily involve a release of RAM. Secondly, accidents which cause a loss of containment leading to a release of a respirable aerosol. A recent review of accidents and incidents during the transport of RAM in the UK [2,3] has shown that loss of shielding events have been the main contributors to radiation exposure.

Mathematical models are the most practicable method of analysing postulated incidents involving radioactive materials. Application of these models to transport operations is particularly difficult because the location of an incident can be almost anywhere and there is a very wide diversity of materials, package types and modes of transport to consider. In the absence of an ideal model, the use of mathematical models alone will not provide complete solutions to the problems to which they are applied. The choice of model, either from the range available or to be developed, will be determined by the project objectives and the effort and systems available.

A comprehensive assessment of radiological consequences will cover the following aspects: atmospheric dispersion, meteorology, population distribution, dosimetry, health effects and in some cases countermeasures, agricultural production and economic impacts. The model should address all potentially significant pathways of exposure:

(i) Direct exposure from penetrating radiation from a consignment with impaired shielding;
(ii) Penetrating gamma radiation emerging directly from a plume of released activity;
(iii) Exposure of the skin to beta radiation emerging directly from the plume;
(iv) Direct inhalation of material that has become respirable;
(v) Inhalation of material which has been deposited and later resuspended;
(vi) External irradiation from skin contaminated by radioactive material;

(vii) External irradiation from ground contaminated by the deposition of airborne activity;

and for some releases:

(viii) Exposure from the consumption of contaminated foodstuffs.

For many circumstances relating to transport operations it will be unwarranted to model all pathways of exposure. Some models cover a larger number of aspects and exposure pathways than others but all share some common ground.

2. A summary of existing radiological consequence models

A literature search was conducted to identify published radiological consequence models which have been applied to the transport of RAM. Several of the models identified are related to one another. Many are adapted from reactor accident codes.

CRAC (Calculation of Reactor Accident Consequences)[4] was developed at Sandia National Laboratories in 1975 and revised in 1981 to become CRAC 2[5]. It is a consequence model that has been applied to postulated releases during transport operations.

RADTRAN[6] is a risk assessment methodology written in 1977 and updated in 1980 to become RADTRAN II[7]. Work on RADTRAN III is currently being undertaken at Sandia.

INTERTRAN[8] is an international code for risk assessment coordinated by the IAEA in 1979 and assisted by the Swedish Nuclear Power Inspectorate. RADTRAN II is the basis for the INTERTRAN code.

MARC (Methodology for Assessing Radiological Consequences)[9] was developed by the NRPB in 1982. Like CRAC it is a tool for use in risk assessments that has been applied to transport operations.

NECTAR[10] was written by and for the CEGB of the UK in 1982 and is used in the design and safety studies for future plant. It is essentially a deterministic code that has been applied to transport studies.

TREC II[11] was initiated at Pacific Northwest Laboratory in 1979 and was transferred to Sandia in 1980. It was developed for the US Department of Energy as a risk analysis tool for evaluating high level waste management systems.

TIRION[12] was developed by the Safety and Reliability Directorate (SRD) of the UK Atomic Energy Authority (UKAEA). Version 4 was completed in 1978.

TRIP[13] estimates the risks to the public arising from the overland transport of hazardous cargoes. It was written by SRD in 1980.

3. A comparison of selected models

For detailed comparison CRAC 2, RADTRAN II, INTERTRAN and MARC were selected as being the models most often applied to transport studies.

3.1 Atmospheric dispersion

CRAC 2 and MARC employ a similar level of complexity based on implementations of the Guassian plume model. Plume rise and both wet and dry deposition are modelled. Both codes were developed primarily for accident consequence assessments of a nuclear plant. Source terms for transport accidents are generally smaller and it is important for the interval lengths at which concentrations are calculated to be correspondingly finer to compensate for large potential variations in concentrations over short downwind distances. RADTRAN II and INTERTRAN share a simplified approach to atmospheric dispersion using a tabulation of time-integrated dilution factors. Plume rise and wet deposition mechanisms are not modelled.

3.2 Meteorology and meteorological sampling

Accident consequence models can be used to predict the impact of a release of radioactive material in a particular set of meteorological conditions. However their most frequent prospective application is to estimate the statistical distributions of consequences which arise because a notional release will be subject to a range of meteorological conditions with associated probabilities of occurrence. CRAC 2 and MARC have similar meteorological sampling routines which ensure that the entire range of consequence for a given release are adequately covered to probabilities of occurrence as low as 10^{-3}. These models are able to take account of changes in atmospheric conditions during the time that the plume is travelling.

In INTERTRAN and RADTRAN II, meteorological conditions are characterised by the Pasquill stability categories A to F. The effects of rainfall are ignored and wind direction is unimportant because uniform population distributions are

TABLE I. SUMMARY OF PATHWAYS OF EXPOSURE CONSIDERED BY THE MODELS FOR ATMOSPHERIC RELEASES OF RADIOACTIVITY

Pathway of exposure	CRAC 2	RADTRAN II	INTERTRAN	MARC
Cloud-γ irradiation	Yes	No	No	Yes
Cloud-β irradiation	No	No	No	Yes
Inhalation of the plume	Yes	Yes	Yes	Yes
Resuspension	Yes	Yes	Yes	Optional
External γ-irradiation from deposit	Yes	Yes	Yes	Yes
Ingestion	Yes	No	No	Yes

employed. Although a range of windspeed is possible in each Pasquill category a single representative speed is assigned to each category. Constant meteorological conditions are assumed to persist for the duration of the plumes travel. This approach is very sparing of computational resources, but will not give the full range of consequences reflecting the spectrum of meteorological conditions.

3.3 Population distribution

The population distribution is defined in terms of the number of people living with each of a number of angular sectors and distance bands in CRAC 2 and MARC. Users may choose to use uniform population densities: concentric distributions or actual population densities using census data. RADTRAN II and INTERTRAN use up to three evenly distributed population zones corresponding to urban, suburban and rural districts.

3.4 Pathways of exposure for atmospheric release of radioactivity

A summary of the pathways of exposure considered by each of the models is presented in Table I. CRAC 2 and MARC model all major pathways of exposure while RADTRAN and INTERTRAN include only the most significant pathways for most releases.

TABLE II. SUMMARY OF HEALTH EFFECTS CONSIDERED FOR ATMOSPHERIC RELEASES OF RADIOACTIVY

	CRAC 2	RADTRAN II	INTERTRAN	MARC
Early effects				
Mortality				
bone marrow irradiation	✓	✓		✓
lung irradiation	✓	✓	✓	✓
G.I. Tract irradiation	✓			✓
Morbidity				
lung fibrosis	✓	✓	✓	✓
prodromal vomitting	✓	✓	✓	✓
stem cell loss		✓	✓	
temporary sterility (males)		✓	✓	
early thyroid effects		✓	✓	
Latent effects				
Fatal cancer				
bone	✓	✓	✓	✓
leukaemia	✓	✓	✓	✓
lung	✓	✓	✓	✓
breast	✓	✓		✓
liver				✓
thyroid		✓	✓	✓
lower large intestine	✓	✓	✓	✓
skin				✓
stomach		✓		
pancreas		✓		
others	✓			✓
Non-fatal cancer				
thyroid				✓
skin				✓
breast				✓
Hereditary effects		✓	✓	✓

3.5 Health effects modelling for atmospheric releases of radioactivity

The health effects modelled by each of the codes are identified in Table II . There are significant differences in the methods used by the codes to estimate the incidence of the same health effect. Constraints of space do not allow these differences to be covered in this paper. Some of the most important aspects are listed in Section 5.

4. The application of radiological consequence models to the near field

The near field is taken to correspond to an area extending to a radius of about 100 m from the incident. It is an area which is not covered in detail by the models reviewed in this paper. Clearly it is an area of prime importance and the exposure of persons in the vicinity, including the crew of the conveyance and the emergency teams who may be expected to undertake duties in this area, should be taken into account.

Generic assessments of near field radiological consequences are difficult. Exposures incurred will be highly dependent on incident specific details including: the precise location of the release, local topographical features, involvement of injury to personnel, time of day, the geometrical configuration of the RAM with respect to the packaging and conveyance and the numbers of persons present. It is acknowledged that similar uncertainties prevail in all consequence modelling but exposures in the near field are particularly sensitive to these factors.

In the event of an accident occurring in the UK, contingency plans and emergency arrangements are established to make it likely that operations in the near field will be conducted under health physics supervision within about 2 hours of the rescue services attending the scene. Subsequent radiation exposures in the near field would be planned as far as possible. Emergency services include dealing with radioactive materials as part of their training.

5. Recommendations

The choice of model to apply to a given problem will be determined by the objectives of the project and the effort available. The quality and sophistication of the model output will be related to the resources required to provide commensurate input data.

Codes such as CRAC 2, MARC and NECTAR address a comprehensive range of pathways of exposure, health effects and meteorological conditions and use relatively complex methods to model atmospheric dispersion. Considerable effort will be required by a user to become familiar with the large amount of input data. These large demands, particularly on computer resources, make it unlikely that such models will be applied to comprehensive risk analyses of transport operations. Such work requires radiological consequence models to be run for ranges of release fractions, package types, package contents and release locations. Large deterministic codes are useful when applied to transport events that warrant detailed probabilistic assessments of radiological consequences. This may be the case of large notional releases from some Type B packages in urban areas, identified perhaps, as being of particular significance using a less detailed consequence model in a risk analysis.

RADTRAN II and INTERTRAN are designed to be simple methods for the assessment of risk from transport operations involving RAM. Probabilities of occurrence are assigned to each of eight severity categories as functions of mode of transport, degree of degradation of package integrity and release fractions of package contents. To achieve the objective of risk assessment, the radiological consequence model must be run for each release considered. Therefore the model has to be relatively sparing of computer resources to execute in a reasonable timescale. Comments on the default input data of these codes regarding the eight severity categories lies outside the scope of this paper. With respect to the radiological consequence models, the following points are important when considering the output:

(i) The atmospheric dispersion model is simplistic and considers only constant meteorology;
(ii) Only dry weather conditions are modelled;
(iii) Uniform population distributions are assumed;
(iv) Direct exposure from radiation emerging directly from the plume is not modelled;
(v) The incidence of early mortality is based solely on irradiation of the lung;
(vi) The incidence of early morbidity is computed using a 50-year committed dose equivalent;
(vii) The incidence of fatal cancer is calculated using risk factors which are applicable to a population which will live long enough for the total risk to be expressed;
(viii) It is assumed that the population will be evacuated after an exposure time of 24 hours for a period of ten days and only returned if doses are less than a specified clean-up level.

In 1985 the IAEA convened a Technical Committee[14] which was charged to assess the radiological impact from the transport of RAM. One of the working groups specifically examined the problems encountered by users of INTERTRAN in order to identify these problems in an organised manner, to develop potential solutions where possible, and to recommend ways in which the usefulness of INTERTRAN could be improved. The report of that working group considered the accident section of INTERTRAN, although suffering from a number of important deficiencies, to be a useful framework for accident assessment, in particular to facilitate the exchange of information between countries. The report also stated that users should supplement their risk analysis with a consequence analysis or safety assessment.

Loss of shielding events may give rise to enhanced external radiation levels while the conveyance is moving or stationary. These events can be assessed using models designed to estimate the collective and individual doses from external gamma radiation during normal transport operations. The degree of sophistication required to model such exposures is far less than that needed to model releases of RAM to the environment. Such models are included in RADTRAN II, INTERTRAN and an NRPB model called TRANSDOS[15] which is able to use the population data based on the 1 km^2 grid for Great Britain.

All attempts to quantify the risk from the transport of RAM suffer from a lack of good input data concerning the assignment of probabilities of occurrence to defined accident severity categories, values of release fractions and aerosolisation factors. It is in these areas that the most important advances can be made.

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