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**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

**Accident Analysis of Railway
Transportation of Low-Level
Radioactive and Hazardous
Chemical Wastes**

**Application of the
"Maximum Credible Accident"
Concept**

E. Ricci
R. B. McLean

OPERATED BY
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ABSTRACT

The maximum credible accident (MCA) approach to accident analysis places an upper bound on the potential adverse effects of a proposed action by using conservative but simplifying assumptions. It is often used when data are lacking to support a more realistic scenario or when MCA calculations result in acceptable consequences. The MCA approach can also be combined with realistic scenarios to assess potential adverse effects.

This report presents a guide for the preparation of transportation accident analyses based on the use of the MCA concept. Rail transportation of contaminated wastes is used as an example.

The example is the analysis of the environmental impact of the potential derailment of a train transporting a large shipment of wastes. The shipment is assumed to be contaminated with polychlorinated biphenyls and low-level radioactivities of uranium and technetium. The train is assumed to plunge into a river used as a source of drinking water.

The conclusions from the example accident analysis are based on the calculation of the number of foreseeable premature cancer deaths that might result as a consequence of this accident. These calculations are presented, and the reference material forming the basis for all assumptions and calculations is also provided.

ABBREVIATIONS AND ACRONYMS

Bq	becquerel
CAG	Carcinogen Assessment Group (EPA)
cfs	cubic feet per second
d	day
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
ft	foot
g	gram
gal	gallon
ICRP	International Commission on Radiological Protection
in.	inch
kg	kilogram
km	kilometer
L	liter
lb	pound
m	meter
m ³	cubic meter
MCA	maximum credible accident
mCi	millicurie
mg	milligram
μCi	microcurie
μg	microgram
NEPA	National Environmental Policy Act
ORGDP	Oak Ridge Gaseous Diffusion Plant
PCB	polychlorinated biphenyl

Abbreviations and Acronyms (continued)

pCi	picocurie
PGDP	Portsmouth Gaseous Diffusion Plant
ppm	parts per million
s	second
Sv	sievert
Tc	technetium
TSCA	Toxic Substances Control Act
U	uranium
USGS	U.S. Geological Survey

THE MAXIMUM CREDIBLE ACCIDENT CONCEPT

The assessment of environmental effects of potential accidents that might result from proposed actions is usually a part of the environmental impact analysis process established by the National Environmental Policy Act (NEPA 1969). The identification and analysis of potential accidents help determine the upper bounds of any adverse impacts associated with the accidents.

An accident analysis should describe the probability of occurrence and the seriousness of each of the various credible accidents the action might cause. Generally, the accident analysis draws conclusions about the acceptability of the operation under study in terms of numbers of potential deaths (i.e., foreseeable premature deaths) that may occur because of the proposed action.

The maximum credible accident (MCA) is defined as the most serious accident that might conceivably (reasonably but not likely) occur during performance of the action. Parameters of an MCA are derived very conservatively in most cases. Thus, if the MCA results in insignificant (or manageable) consequences, then no further analysis is needed, with considerable savings of time and resources. However, if the consequences of the MCA are significant, additional analysis may be required to identify ways to reduce accident probability, or mitigate consequences, or both.

THIS GUIDE

This guide to accident analysis presents the logic, calculations, and references used in the formulation and analysis of an MCA assumed to occur during rail transportation of low-level radioactive and hazardous wastes.

Specifics about this guide's purpose, scope and format, including types of wastes and contaminants covered, are discussed in the following sections.

PURPOSE AND SCOPE

The purpose of this guide is to help the reader use the MCA concept to prepare an accident analysis of transportation of low-level radioactive and hazardous chemical wastes.

Contaminants and concentrations specifically used as examples in this guide are polychlorinated biphenyls (PCBs), on the order of 5-10 ppm, uranium (about 50 ppm), and technetium (about 10 Bq/g). However, the methods and guidelines described can be used for a variety of other hazardous contaminants and concentration ranges. For example, the methodology used in the analysis of PCBs can be applied to carcinogens listed among the hazardous substances of Table 302.4 of the *U.S. Environmental Protection Agency Regulations* (40 CFR Pt. 302). The evaluation method used for uranium may be applied to thorium, transuranic elements, and residues of uranium and thorium

processing. The method used for technetium may be applied to other water-soluble radioactive substances.

It is essential, however, that the analyst exercise careful judgment when using this guide, to ensure that the suggested guidelines, tables, parameters, calculations, assumptions, and evaluations properly apply to the wastes, contaminants, and concentrations being analyzed.

This guide can be used for accident analyses involving either individual contaminants or mixtures. The mixtures may include only hazardous chemicals, only low-level radioactive materials, or combinations of both. In particular, the guide can be useful in transportation accident analysis for wastes defined as "mixed wastes." (By definition, the radioactive component of mixed wastes should have the characteristics of "low-level radioactive waste" under the Low-Level Radioactive Waste Policy Act. The nonradioactive component should have the characteristics of "hazardous waste" under the Resource Conservation and Recovery Act).

FORMAT

To make this guide clear and realistic, an example is used based on an actual accident analysis (Ricci and McLean 1987). The example concerns railway transportation of dirt contaminated with small amounts of PCBs and low-level uranium and technetium radioactivities.

The structure of this guide parallels that of a transportation accident analysis, and each section is illustrated by the example. Calculations, comparisons, and evaluations are shown in detail. To facilitate reading, the text of the example is given in *italic type*.

ACCIDENT ANALYSIS GUIDELINES AND EXAMPLE

1. INTRODUCTION

1.1 PROPOSED ACTION

The starting and ending points of the trip and the type of transportation are described. A brief mention is made of the nature and amount of waste and the purpose of the trip.

Example:

This analysis evaluates the potential consequences of an accident that might occur while carrying out the proposed action: the transportation by rail of 7.692 million lb (3489 metric tons) of contaminated dirt from the Portsmouth Gaseous Diffusion Plant (PGDP), Ohio, to the Oak Ridge Gaseous Diffusion Plant (ORGDP), Tennessee, for incineration in the new Toxic Substances Control Act (TSCA) Incinerator. The dirt to be shipped is from a PGDP ditch where liquids containing small amounts of enriched uranium and polychlorinated biphenyls (PCBs) have contaminated the dirt over the years.

1.2 CHARACTERISTICS OF THE LOAD

This section describes in detail the total amount of waste to be shipped, the characteristics and number of waste containers needed, the distribution of the containers in the train, and the number of trips that will be necessary to complete the action. The characteristics and concentrations of each contaminant are discussed, including chemical or radiochemical analyses or both, and any other relevant waste information.

Example:

The dirt would be shipped in a total of 4698 containers, of which 327 are 83-gal (314-L) drums and 4371 are 110-gal (416-L) drums. The former can hold an average of 1067 lb (484 kg) of dirt, while the latter can hold an average 1680 lb (762 kg). These drums meet U.S. Department of Transportation (DOT) specifications and are similar in shape and construction to regular 55-gal (208 L) drums.

Each railroad car can carry 56 drums of mixed sizes. Five to ten cars in each train would be loaded with drums, the exact number varying from train to train. If all trains contained ten cars loaded with drums, then 8.4 trips ($4698 \div 560$) would be required to complete the proposed action.

At PGDP, 135 samples of dirt were analyzed for PCBs (R. E. Blake, Portsmouth Gaseous Diffusion Plant, Ohio, personal communications to E. Ricci, Oak Ridge National Laboratory, Tenn., October 14-15, 1987). The average (mean) concentration of PCB in these samples is 9.5 ppm; the standard deviation is 57.1 ppm. This large standard deviation occurs because of a skewed distribution of data. Forty-one determinations have concentrations below 1 ppm, of which four fall below the detection limit. In contrast, only 13 determinations are above 10 ppm, of which 12 are below 56 ppm, and one (an obvious outlier) is 660 ppm. Therefore, the median PCB concentration of 2.0 ppm (i.e., the concentration that is smaller than half of the data points and larger than the other half) is used in this analysis. Any new observation would have equal probabilities (50%) of being either larger or smaller than 2.0 ppm.

Uranium and technetium (Tc-99) concentrations were also determined at PGDP in 50 samples of the dirt to be shipped. The average enrichment of the uranium is 4.5% U-235. Technetium is a common contaminant of uranium enrichment fractions from reprocessed reactor returns. The average concentration of elemental uranium in the dirt is 18.0 ppm, with a standard deviation of 16.5 ppm; and the average radioactivity of Tc-99 is 5.3 Bq/g, with a standard deviation of 8.2 Bq/g. Because of these large standard deviations, and to use the same treatment for these data and the PCB values, median concentrations (13.0 ppm and 3.17 Bq/g respectively) were also used for uranium and technetium.

Small amounts of other contaminants in the dirt were also identified by PGDP but were found to be "nonhazardous waste" in terms of U.S. Environmental Protection Agency (EPA) regulations (personal communications, above).

1.3 TRAIN ROUTE

Knowing the expected railroad route for the shipment is essential to establish an MCA scenario. This route is usually determined by the originator (or shipper), and the analyst can obtain preliminary routing information (through the waste originating organization) from the railroad organization. This information is completed by using detailed railroad route maps.

Railroad maps for each of the states are compiled in the *Handy Railroad Atlas* (Rand McNally 1985), a very useful publication that is updated approximately every four years. The atlas also includes vicinity maps for large cities and other relevant information.

Detailed railroad maps are presented in a compilation of zone maps (DOT 1974). This publication includes two maps for each of the 490 U.S. transportation zones--one map for transportation infrastructure and another

for tonnage and signals. These are large-scale maps that, depending on the zone, may cover an area from 400 to 32,000 square miles.

Once established, it is necessary to examine the route in fine detail to identify points where effects of an accident (e.g., derailment or collision) would be most serious, e.g., a bridge over a river used as a source of drinking water. This detail can be found in maps of scale 1:250,000 (USGS 1980). These maps are multicolored, measure approximately 22 x 34 in., and span one degree latitude by two degrees longitude (i.e., one inch represents four miles). The U.S. Geological Survey has published over 500 of these maps covering the United States and can provide both an index (free) and the maps (\$1.00 to \$3.00 each).

The total mileage of the route can be determined by using the computer model INTERLINE (Peterson 1985). It is recommended that this model be used also to verify the route previously obtained from the maps. The model produces a listing of the towns on the route, the mileages between these towns, the route's total mileage and, for each leg, the railroad responsible, the track class (quality), the usual speed, and whether the leg is a main or a branch line.

Based on this information, this section of the analysis should include a detailed description of the rail route illustrated with one or more maps. Points where accidents might have serious consequences should be marked on large-scale maps and discussed in some detail in the text.

Example

The planned rail route for transporting the load of drums from PGDP is shown in Fig. 1. The trip would originate with North Western Railroad at the Tays Spur Junction, near PGDP, and proceed in Ohio through Sardinia and Red Bank to Cincinnati. From there, the load would be carried by Southern Railroad through Ludlow, Georgetown, Lexington, Danville, Junction City, Somerset, and Pine Knot in Kentucky, and continue in Tennessee through Oneida, Helenwood, New River, Oakdale, Harriman, De Armond, and Blair to ORGDP. The rail companies may introduce small last-minute modifications to this route, based on daily traffic conditions. This 414-mile (666-km) route includes main and branch lines of various track classes.

The rail route crosses more than 40 creeks and small rivers, and also two important rivers: the Ohio River on the Ohio-Kentucky border and the Cumberland River (Lake) in Kentucky. The rail crossings over these large rivers, estimated from a 1:250,000-scale map (USGS 1980), are 1300 ft (400 m) and 2100 ft (640 m) long respectively. The 75-year average discharge for the Cumberland River at the crossing location (Bettendorf et al. 1985) is 3181 cfs (90.1 m³/s). The flow of the Ohio River is orders of magnitude greater.

Fig. 1. Rail route to be used for transportation of the contaminated dirt (heavy solid line).

1.4 ANALYSIS APPROACH

This section describes the advantages of the use of the MCA concept as the basis for an accident analysis and provides a justification for its use in the present analysis. Credits and acknowledgements may either be included in this section or be mentioned in a separate section at the end of the report.

Example:

Preliminary analysis of the data discussed in the preceeding sections suggests that an accident during rail shipment of the contaminated dirt might not result in very serious consequences for the population. Therefore, a very unlikely (but not impossible) maximum credible accident (MCA) is considered and is analyzed in a very conservative manner. The advantage of this approach is that, if the consequences of this MCA are found to be insignificant, then no further evaluation is necessary, resulting in considerable savings of money and time.

J. J. Beauchamp (Engineering Physics and Mathematics, ORNL), P. E. Johnson (Computing and Telecommunications, ORNL), T. D. Jones, D. C. Kocher, and J. P. Witherspoon (Health and Safety Research Division, ORNL), were consulted during this analysis.

2. ACCIDENT ANALYSIS

This section is the core of the document. It contains a description of the accident scenario and analysis assumptions, as well as detailed calculations of essential parameters (e.g., source term) and accident results.

2.1 ACCIDENT SCENARIO

It is essential that a conservative scenario be selected for an MCA so that the MCA's credibility cannot be challenged. The MCA should be the worst possible, yet reasonably believable, event that could occur. Consideration of a scenario implies simultaneous consideration of its attendant source term (see Sect. 2.3).

The MCA scenario is described in detail in this section (including the amount of waste involved in the accident), with a map illustrating the location of the accident.

Example:

Most conservative assumptions have been made to establish the MCA scenario. This scenario is the derailment of a complete train, fully loaded with contaminated dirt, as it crosses the bridge over the Cumberland River. This crossing is shown in Fig. 2. The flow of the Cumberland River is the lower of the two major rivers that the train crosses (Sect. 1.3).

The train, which is assumed to fall and sink into the river, carries ten cars, each loaded with 56 large drums. Each 110-gal (416-L) drum contains 1680 lb (762 kg) of contaminated dirt (Sect. 1.2). Therefore, $10 \times 56 \times 1680 \text{ lb} = 940,800 \text{ lb}$ (426,700 kg) of contaminated dirt would fall into the Cumberland River as a result of this derailment.

Moreover, all drums are assumed to break completely open, so all the dirt in them is washed away. The PCB, technetium, and even the uranium (which is present mostly in the form of insoluble oxides) are assumed to be completely and homogeneously dissolved and carried away by the waters as a contaminated water "slug."

2.2 ACCIDENT PROBABILITY

By definition, an MCA is conceived as a very unlikely, worst-type event and does not generally require a numerical probability calculation. However, probabilities for railroad accidents are usually easy to calculate because of data available from the Federal Railroad Administration (DOT 1986). Consequently, because MCA probability constitutes complementary information, it should be included in the accident analysis when available.

Fig. 2. Location of the postulated MCA at the Cumberland River crossing (scale = 1:250,000).

Example:

The most recent railroad accident rate provided by the Federal Railroad Administration is $6.01\text{E-}6$ accidents per train per mile (DOT 1986). This rate includes data from collisions, derailments, or other events involving the operation of on-track equipment and resulting in damages exceeding \$4900.

From Sect. 1.3, the length of the crossing over the Cumberland River is 2100 ft [0.40 mile (640 m)]. Therefore, the probability for one train transporting contaminated dirt to have an accident at the Cumberland River bridge is

$$(6.01\text{E-}6 \text{ accident/train per mile}) \times (0.40 \text{ mile}) = 2.40\text{E-}6 \text{ accident/trip.}$$

Multiplying this probability by the number of trips (i.e., 8.4 trains, Sect. 1.2) gives the probability of such an accident to occur during performance of the entire task as $2.02\text{E-}5$.

2.3 SOURCE TERM

The source term is the amount of radioactive or hazardous material (or a combination of both) that is released during the accident. The time, circumstances, precise location and rate of the release in the accident scenario are also required to establish the contaminated medium (water, air, etc.) and the contaminants' initial concentrations. Consequently, both the accident scenario and the source term of an MCA must be developed simultaneously.

This section generally consists of various subsections in accordance with the number of contaminants released by the accident and the number of media affected. The accident illustrated by the example results in contamination of drinking water by one hazardous and two radioactive substances. However, analogous calculations could be made, for example, for a fire that would release contaminants into the atmosphere, thus creating a concentration of noxious materials in respirable air.

Example:

As discussed in Sect. 2.1, the MCA would result in the dispersion of 426,700 kg of contaminated dirt in the Cumberland River. To ensure a most conservative analysis, the median concentrations of PCB, uranium, and technetium found in this dirt (Sect. 1.2) are tripled. Thus, for the purpose of this analysis, these concentrations are assumed to be: PCB, 6.0 ppm; uranium, 39.0 ppm; and technetium, 9.5 Bq/g. On the basis of the load

*Simplified exponential notation is used in this analysis (e.g., $6.01\text{E-}6 = 6.01 \times 10^{-6}$).

characteristics, (Sect. 1.2), the uranium is assumed to consist of 95.5% U-238 and 4.5% U-235. Because U-234 is enriched along with U-235, the U-234 abundance is assumed to have increased from its natural value (0.0057%) in the same proportion as that of U-235:

$$\text{U-234 assumed abundance} = (4.50/0.71) \times (0.0057) = 0.04\%.$$

2.3.1 PCB in the River

The total amount of PCB dissolved in the river is

$$[6.0 \text{ mg/kg (or ppm)}] \times (426,700 \text{ kg}) = 2.56\text{E}+6 \text{ mg} = 2.56 \text{ kg}.$$

The solubility of the PCB Aroclor-1254 is $57 \mu\text{g/L}$ (Verschuieren 1983) and is used here as typical of PCBs. The volume of river water needed for total dissolution is, then

$$(2.56 \text{ kg}) / (5.7\text{E}-8 \text{ kg/L}) = 4.49\text{E}+7 \text{ L} = 44,900 \text{ m}^3.$$

Considering the flow of the Cumberland River [$90.1 \text{ m}^3/\text{s}$ (Sect. 1.3)], the time required for the total amount of PCB to dissolve is

$$(44,900 \text{ m}^3) / (90.1 \text{ m}^3/\text{s}) = 498 \text{ s} = 8.3 \text{ min}.$$

In other words, all the PCB is assumed to form a homogeneous, $57\text{-}\mu\text{g/L}$ solution in a $44,900 \text{ m}^3$ water slug; this slug passes by an object fixed at the river bank in 8.3 min. (Naturally, the volume of this slug will increase as it travels downstream, while contaminants' concentrations in it will decrease, as discussed in Sect. 2.4.)

2.3.2 Radionuclides in the River

Uranium and technetium are assumed to dissolve completely and homogeneously also in 8.3 min and thus travel with the PCB in the slug.

Uranium. The specific activities of pure uranium isotopes are: U-238, $0.334 \mu\text{Ci/g}$; U-235, $2.14 \mu\text{Ci/g}$; and U-234, $6195 \mu\text{Ci/g}$. From the isotopic percentages given in Sect. 2.3, the combined specific activity is

$$(0.955 \times 0.334 \mu\text{Ci/g}) + (0.0450 \times 2.14 \mu\text{Ci/g}) + (0.0004 \times 6195 \mu\text{Ci/g}) \\ = 2.89 \mu\text{Ci/g}.$$

Thus, the total amount of element uranium exposed to the river waters and its radioactivity are:

$$[39 \text{ mg/kg (or ppm)}] \times (426,700 \text{ kg}) = 1.66\text{E}+7 \text{ mg} = 16.6 \text{ kg U; and}$$

$$(16.6 \text{ kg}) \times [2.89 \text{ mCi/kg (or } \mu\text{Ci/g)}] = 48.0 \text{ mCi}.$$

We have assumed that this radioactivity is dissolved in a $44,900\text{-m}^3$ water slug (Sects. 2.1 and 2.3.1). Thus, its concentration in the slug is

$$(48.0 \text{ mCi}) / (44,900 \text{ m}^3) = 0.00107 \text{ mCi/m}^3 = 1070 \text{ pCi/L}.$$

Technetium. In an analogous manner (Sect. 2.3), the total Tc radioactivity in the spilled dirt and its concentration in the water slug are

$$(9.5 \times 1000 \text{ Bq/kg}) \times (426,700 \text{ kg}) / (3.7\text{E}+10 \text{ Bq/Ci}) = 0.110 \text{ Ci}; \text{ and}$$

$$(0.110 \text{ Ci}) / (44,900 \text{ m}^3) = 2.44\text{E}-6 \text{ Ci/m}^3 = 2440 \text{ pCi/L}.$$

2.4 ANALYSIS RESULTS

Unlike the mild, protracted, and acceptable exposures of the public to pollutants resulting from operations in environmental compliance, the exposure caused by an MCA would be expected to be acute and short lived. Therefore, the analysis of an MCA is generally based on an assessment of the risk of premature death to an individual exposed to the short, acute injury.

The risk calculation is based on the "reference man" defined in ICRP-23 (1975). The reference man weighs 70 kg, drinks 2 L of water per day, and breathes air at the rate of 20 L/min (28.8 m³/d). The evaluation of risk assumes that a 10⁻⁵ risk of premature death (or lifetime risk) is acceptable, in accordance with Anderson (1983), p. 287, and Jones, Owen, and Wells (1987), pp. 33-41.

The example accident analysis calculates risks caused by contamination of drinking water. However, analogous calculations can be made for risks caused by inhalation of contaminated air, on the basis of the breathing rate (20 L/min) of the reference man. If necessary, the air dispersion of the accident-caused plume, from the source to the exposed individual, can be calculated by using computer models. The ISC model (EPA 1986) is commonly used for industrial pollutants. The dispersion of radioactive contaminants is calculated with the AIRDOS-EPA model (Moore et al. 1979). These models estimate meteorological dispersion factors (Chi/Q ratios in s/m³) for each contaminant.

This section can be divided, as in Sect. 2.3, into several subsections, according to the various radioactive and non-radioactive hazardous contaminants released during the MCA, and according to the various media affected. It is recommended that risks from hazardous chemicals and radiological risks be studied separately. This approach is useful because the analyses of these categories differ. Section 2.4 starts with a short description of the risk categories studied and the assumptions used in the analysis.

Example:

In the MCA scenario, as the contaminated water slug proceeds down the Cumberland River, it may expose persons who drink water (including water from treatment plants on this river) to PCB and radioactive doses. As the slug moves, its contaminants are diluted by mixing and downstream inflows.

However, the slug volume increases, and its residence time at a given location generally increases.

To add conservatism to this analysis, it is assumed that the contaminants are not diluted in the slug but, despite this, its residence time (population exposure time) does increase from 8.3 min (Sect. 2.3.1) to one full day. The reference man (ICRP-23 1975) is assumed to drink 2 L of water per day.

2.4.1 Risks from Hazardous Chemicals

In accordance with the Carcinogen Assessment Group (CAG) of EPA, risk is calculated by the equation $R = S \times D$, where R is the personal lifetime risk (dimensionless) of an individual exposed (for 70 years) to dose D of a toxic substance. It is common to express D in milligrams per kilogram per day (mg/kg/d). The S parameter is a constant defined as risk coefficient. In CAG publications, S is also called "animal slope" or simply "slope" (Jones, Owen, and Wells 1987) because it usually includes a factor to scale from animals to man. It is given in (mg/kg/d)⁻¹.

For calculations of risks resulting from nonradioactive carcinogens, S can be obtained from the Report EPA/600/8-83/025F, Table 27, p. 165 (EPA 1985). Doses D are calculated for the reference man discussed above.

Example:

PCB Risk. The risk coefficient, or slope, for PCB (EPA 1985, Table 27) is $S = 4.34 \text{ (mg/kg/day)}^{-1}$. The dose to the reference man weighing 70 kg, from drinking 2 L of water contaminated with 57 µg/L of PCB, is

$$D = (0.057 \text{ mg/L}) \times (2 \text{ L/d}) / (70 \text{ kg}) = 1.63\text{E-}3 \text{ mg/kg/d} .$$

Because exposure to this dose is for one day, using the above risk equation the lifetime personal risk is

$$R = 4.34 \text{ (mg/kg/d)}^{-1} \times 1.63\text{E-}3 \text{ mg/kg/d} \times [1 \text{ d} / (365 \times 70 \text{ d})]$$

$$R = 2.77\text{E-}7 .$$

Because a 10⁻⁵ risk of premature death per lifetime is considered acceptable (Jones, Owen, and Wells 1987, pp. 33-41; Anderson 1983, p. 287), the PCB risk from the MCA is insignificant.

2.4.2 Radiological Risk

Two approaches to evaluate the radiological risk are useful. One is based on calculation of risks of premature cancer deaths and will be used

first. The second approach is based on methods recommended by the International Commission on Radiological Protection (ICRP) and will be used to verify results from the first approach (see Sect. 2.4.3). Use of both approaches adds credibility to the accident analysis and is recommended.

Risks of premature cancer deaths were tabulated by Sullivan et al. (1981) for 150 radionuclides, for a cohort of 100,000 persons ("reference adults"), and for each of four exposure pathways: inhalation, ingestion, immersion in contaminated air, and irradiation from a contaminated ground surface (Tables 6-9, pp. 38-52 of the reference). Part of this information was used by Jones, Owen, and Wells (1987), Table 11, p. 38, to calculate radionuclide concentrations (picocuries per liter) in drinking water capable of causing 10^{-4} , 10^{-5} , and 10^{-6} chances of premature death.

Example:

Uranium. Table 11 in Jones, Owen, and Wells (1987), p. 38, lists 100 pCi/L as the lowest soluble uranium concentration in drinking water capable of causing an individual a 10^{-5} risk of premature death after lifetime (70-year) ingestion. That is, there is one chance in 100,000 that a person would develop cancer and die as a result of drinking this water. Because a linear response to dose is assumed, in this table the risk is directly proportional to the concentration of uranium in drinking water.

In Sect. 2.3.2, the uranium concentration, caused by the MCA, to which an individual would be exposed for one day was calculated to be 1070 pCi/L. The risk associated with the MCA is then

$$[(1070 \text{ pCi/L}) / (100 \text{ pCi/L})] \times [(1 \text{ d}) / (70 \times 365 \text{ d})] \times 1.0\text{E-}5 = 4.19\text{E-}9 .$$

Technetium. In an analogous manner, the Tc-99 drinking water concentration capable of causing a 10^{-5} risk of premature death to an individual chronically exposed is 710 pCi/L (Jones, Owen, and Wells 1987, Table 11).

The Tc-99 concentration in drinking water, resulting from the MCA, to which an individual would be exposed for one day is 2440 pCi/L (Sect. 2.3.2). Thus, the risk associated with the MCA is

$$[(2440 \text{ pCi/L}) / (710 \text{ pCi/L})] \times [(1 \text{ d}) / (70 \times 365 \text{ d})] \times 1.0\text{E-}5 = 1.35\text{E-}9$$

The total radiological risk is then

$$4.19\text{E-}9 + 1.35\text{E-}9 = 5.46\text{E-}9 .$$

Because a 10^{-5} risk of premature death is considered acceptable (Sect. 2.4.1), the radiological risk posed by the MCA is insignificant.

It should be noted that a 10^{-5} risk of premature death per year is usually considered acceptable for total radionuclides (i.e., lifetime risk = 70 years $\times$ 1.0 E-5/year = 7.0 E-4), whereas a risk of 10^{-5} per lifetime is

acceptable for hazardous individual chemicals. However, this difference is inconsequential to the example accident analysis because the total exposure of the population as a result of the MCA was assumed to last only one day (Sect. 2.4).

2.4.3 Verification of Radiological Risk

The radiological risk can also be calculated on the basis of methods recommended by ICRP. The lifetime risk of premature death due to ingestion of radioactivity is

$$\text{Lifetime risk} = \text{radioactivity ingested} \times \text{risk factor} \times \\ \times \text{effective dose equivalent} .$$

The "effective dose equivalent" is defined and discussed in detail in ICRP-42 (1984), p. 3. It represents an overall dose (in rem/microcurie) to the whole body resulting from the summation of appropriately weighted doses to the individual organs. Tabulations of effective dose equivalents can be found in Dunning (1983). A previous report (Dunning et al. 1981) may also be useful because of its longer narrative and list of references. The "mortality risk factor" for radiation-induced cancers in individuals is established by ICRP as 0.01/Sv (10^{-4} /rem) (ICRP-26 1977, p. 12). Somewhat more conservative risk factors are used by some health physicists, ranging from $(1.25 \times 10^{-4})/\text{rem}$ to $(2.0 \times 10^{-4})/\text{rem}$.

Example:

If an individual (reference man) drinks 2 L of water per day, the total radioactivities of uranium and technetium ingested in one day would be 2140 pCi (0.0021 μCi) and 4880 pCi (0.0049 μCi) respectively (Sect. 2.3.2). The risk factor is assumed to be $1.25\text{E-}4/\text{rem}$.

The effective dose equivalent for ingestion of uranium (U-238, U-235, or U-234) is 0.022 rem/ μCi , for a 50-year commitment (Dunning 1983, pp. 35-41). The corresponding effective dose equivalent for Tc-99 is 0.0014 rem/ μCi . Thus, based on the risk equation, the lifetime risk of a premature death would be

$$\text{Uranium risk} = (0.0021 \mu\text{Ci}) \times (1.25\text{E-}4 \text{ rem}^{-1}) \times (0.022 \text{ rem}/\mu\text{Ci}) = 5.78\text{E-}9 ,$$

$$\text{Technetium risk} = (0.0049 \mu\text{Ci}) \times (1.25\text{E-}4 \text{ rem}^{-1}) \times (0.0014 \text{ rem}/\mu\text{Ci}) \\ = 8.58\text{E-}10 , \text{ and}$$

$$\text{Total radiological risk} = 5.78\text{E-}9 + 0.86\text{E-}9 = 6.64\text{E-}9 .$$

This risk compares well with $5.46\text{E-}9$, the value obtained in Sect. 2.4.2, and is insignificant compared with the acceptable risk of $10^{-5}/\text{year}$.

3. SUMMARY AND CONCLUSIONS

This section should include a brief description of the MCA scenario, source term and results, and should also stress the high degree of conservatism that normally characterizes an MCA.

Use of the MCA concept in an accident analysis is meaningful only if results indicate that the total risk associated with the MCA is not significant. That is, the analysis concludes that the total risk of premature death to individuals exposed to the MCA is less than 10^{-5} (Anderson 1983, p. 287; Jones, Owen, and Wells 1987, pp. 33-41). Therefore, this conclusion is expressed in this section.

Example:

This analysis evaluates the potential consequences of a maximum credible accident associated with the rail transportation, from PGDP to ORGDP, of drums filled with dirt contaminated with PCB, uranium, and technetium. A very conservative scenario is assumed for this accident analysis. It is assumed that a complete train, fully loaded with 560 large drums containing 426,700 kg of contaminated dirt, derails and sinks into the Cumberland River. Moreover, the drums completely break open, and the dirt is washed away with complete dissolution of the PCB, uranium, and technetium. These contaminants then proceed to contaminate drinking water downstream. Further conservative assumptions are also made throughout the calculations.

The lifetime personal risk due to drinking water contaminated with PCB for one day is calculated to be $2.77E-7$, while the sum of the lifetime risks for uranium and technetium is $5.46E-9$. Verification of this combined radiological risk by a different method results in a value of $6.64E-9$, which is only slightly higher.

Because a lifetime 10^{-5} risk of premature death is considered acceptable, it is concluded that the risk associated with this transportation task is insignificant.

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