AN OVERVIEW OF PROBABILISTIC CONSEQUENCE ASSESSMENT

Presentation at the IAEA Postgraduate Educational Course in Radiation Protection and the Safety of Radiation Sources
Aghia Paraskevi , Greece, June 2003

Background

Reactor Safety Study (USNRC, 1975):
The first comprehensive assessment of the consequences and risks to society from potential accidents at Nuclear Power Plants

Development of the CRAC (Calculation of Reactor Accident Consequences) computer code as part of this study

Since 1975 many PCA models have been developed and used around the world not only for NPPs but also for other types of nuclear installations

Most extensive use of two models today:
MACCS: MELCOR Accident Consequence Code System (US), and
COSYMA: Code System MARIA[1] (EU)

Two international groups have been formed to deal with various issues concerning these two codes

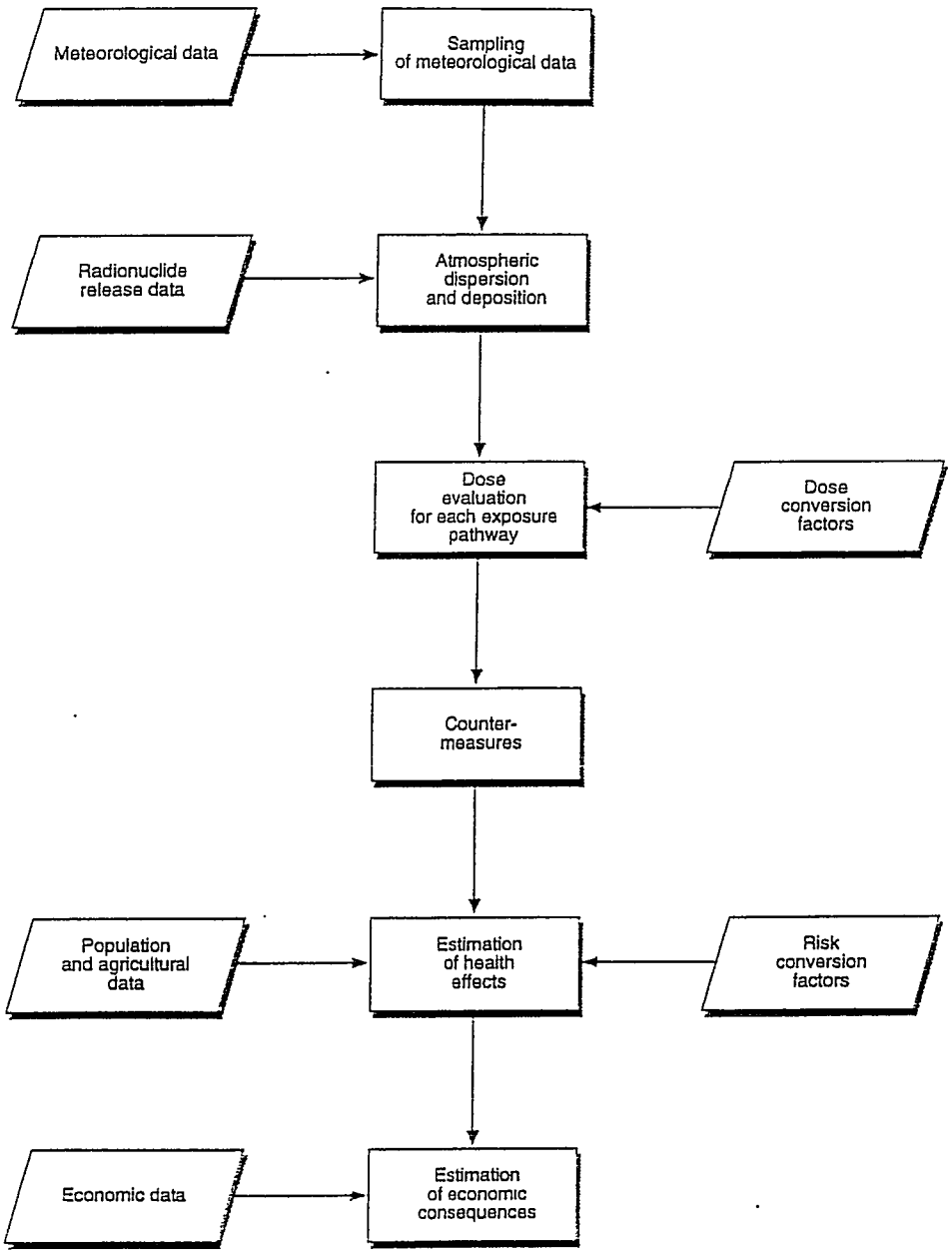
---

(1) MARIA from Methods for Assessing the Radiological Impacts of Accidents

Main Elements of Probabilistic Consequence Assessment:

- Radionuclide Release
- Atmospheric Dispersion and Deposition
- Meteorological Data and Sampling
- Exposure Pathways and Dose Assessment
- Population, Agricultural and Economic Data
- Countermeasures
- Health Effects
- Economic Consequences

Figure 1. Basic elements of probabilistic consequence assessment



Source Terms

Radionuclide Releases to the Atmosphere = *Accident Source Term*, the starting point for a consequence assessment

The source term specifies both the magnitude of the release and the manner of the release for each distinct release associated with an accident

Magnitude: Quantities of each radionuclide released to the atmosphere

Manner: Release parameters, usually:

- Time between reactor shutdown and beginning of the release to the environment
- Duration of the release
- Amount of energy associated with the release
- Height of the release
- Warning time (time available for the initiation of countermeasures before the beginning of the release to the environment)

The physical and chemical form of the released radionuclides is also required

The size spectrum of the released aerosol and the chemical form of its constituents are important

Detailed information seldom available
→ it is generally assumed that radionuclides are released as a 1μm AMAD aerosol with each chemical element in oxide form (except noble gases and part of I released in gaseous forms)

AMAD = activity median aerodynamic diameter

Atmospheric Dispersion

Radionuclide plumes are carried downwind (transport) and through atmospheric turbulence dilute and spread in the crosswind and vertical direction (diffusion)

Dispersion = Transport and Diffusion

Principal question: Concentration profiles
→ Gaussian plume model

Additional factors must be taken into account (e.g. building wake, inversion "lid" in the vertical direction, internal buoyancy of the plume)

Trajectory of the dispersing material - Options:

- Travel in the direction of the wind at the start of the release
- Split the release(s) into a number of phases and assume that the material in each phase travels in the wind direction at the start of that phase
- Wind direction changes every hour throughout the release

Alternative atmospheric dispersion models:

- Puff models
- Long range trajectory models

Dry Deposition

A surface effect whereby material in contact with the ground is removed by processes such as:

- Diffusion to surfaces
- Impaction on surfaces
- Gravitational settling onto surfaces

Wet Deposition

Removal of dispersing material as a result of:

- Interaction with precipitation (rain, snow, etc.) falling through it (washout)
- Incorporation into rain clouds

Meteorology

Gaussian models generally require data on an hourly basis, for at least one year, at one location, usually near the reactor site (source meteorology). Data from other meteorological stations are acceptable if they are representative of the general conditions.

8760 hourly sets of data for a year (MACCS: wind direction, wind speed, stability category, accumulated precipitation). In addition morning/afternoon seasonal mixing layer height

Additional meteorological data (e.g. at regular intervals over the entire region of interest) are required for alternative dispersion models (non-source meteorology)

Hourly Meteorological Database

Each hour can be regarded as the starting time of the release, i.e. the starting point for a sequence of hourly weather data
→ the meteorological record allows for 8760 possible sequences

It is neither practicable nor necessary to analyze all sequences
→ representative sampling is employed

Sampling techniques:
- Random sampling
- Cyclic sampling
- Importance sampling

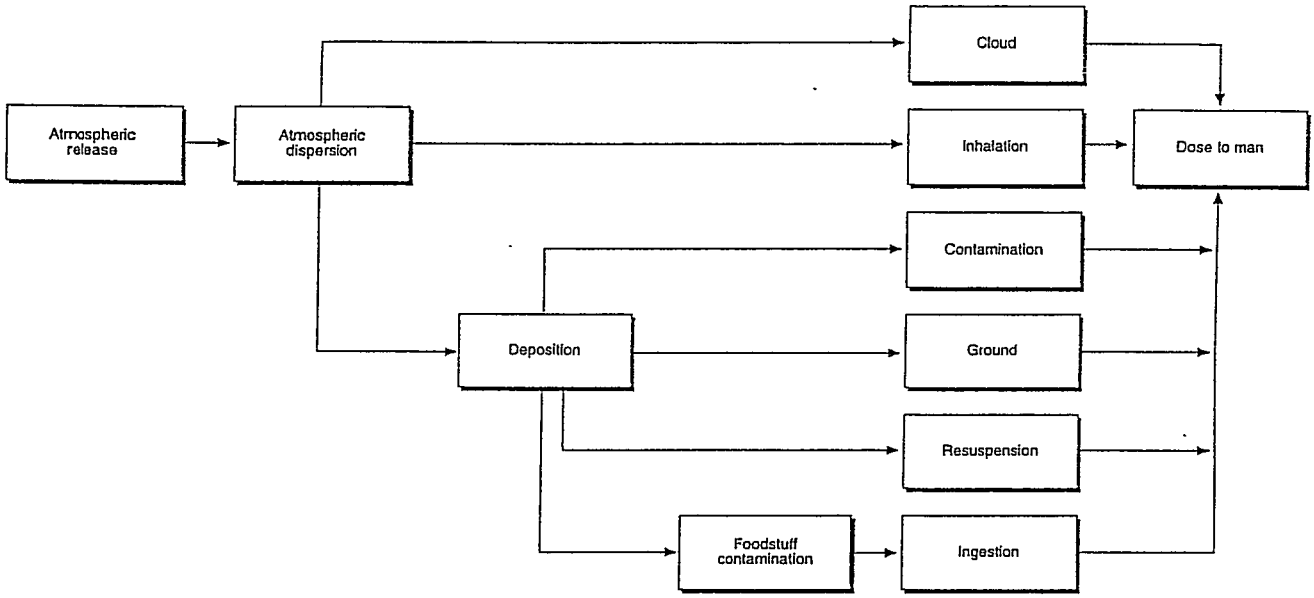
Importance sampling is preferred today since it minimizes the chance of omitting infrequent sequences with significant consequences

Exposure Pathways:

- External irradiation from radioactive material in the passing cloud (cloudshine)
- External irradiation from radioactive material deposited on the ground (groundshine)
- External irradiation from radioactive material deposited on the skin and clothing (contamination)
- Internal irradiation from radioactive material inhaled directly from the passing cloud
- Internal irradiation from radioactive material inhaled following resuspension of the ground deposit
- Internal irradiation from radioactive material ingested following contamination of foodstuffs and drinking water by radioactive material deposited from the cloud

For each pathway a dosimetric model is used to convert the distribution of radioactive material in the environment to distributions of dose to man

Figure 2. **Principle exposure pathways to man following an atmospheric release**



External Dose from the Passing Cloud

Both β and γ emitters contribute to individual exposure

β particles have a short range in air and limited penetration
→ their contribution is small and is often neglected

Calculation of the γ dose involves a 3-D integral over the whole cloud. In practice tabulated results for a semi-infinite cloud are considered an adequate approximation

For people indoors buildings attenuate γ rays providing shielding. A shielding factor is therefore employed (ratio of interior to exterior dose) depending on the type of building

External Dose from Deposited Radioactive Material

Contribution of β particles is generally neglected in this pathway too

The γ dose depends on:

- the exposure time
- the behavior of deposited material (radioactive decay and weathering processes)

Currently the dose is estimated by precalculated factors in a database that give the dose per unit deposit integrated over appropriate time periods

For people indoors a shielding factor is again employed as in the case of cloudshine

External Dose from Radioactive Material Deposited on the Skin and Clothing

Both β (mainly) and γ emitters contribute to individual exposure

The amount of activity deposited on the skin and clothing is often calculated as a fraction of ground deposition

Doses are estimated from the deposited radioactive material on the skin and clothing by the employment of precalculated dose per unit deposit factors

A shielding factor for the effects of clothing on the β dose to the skin is usually introduced

Inhalation Dose from the Passing Cloud

Calculated as the product of the inhalation rate ($2.66 \cdot 10^{-4}$ $m^3 \cdot s^{-1}$ typically for adults), the time integrated air concentration and a precalculated dose per unit activity inhaled (held in a database)

Filtering factors for differences in air concentrations inside and outside buildings are used to modify the inhaled dose

Inhalation Dose from Resuspended Activity

The resuspension process (action of the wind, human activities) produces airborne radionuclides that are available for inhalation. This can occur over long periods of time after the initial event

→ time dependent resuspension factor (ratio of resuspended air concentration to initial surface concentration)

Organ doses calculated as in normal inhalation

Ingestion Dose

Two ways of calculation:

- from the amount of radioactive material deposited, the radionuclide concentration in foods for unit deposition, the food consumption and the dose per unit of radioactive material ingested

- from the amount of radioactive material deposited, a dimensionless food pathway transfer factor (fraction of each radionuclide deposited onto the farmlands that is consumed by man) and the dose per unit of radioactive material ingested

Consumption is treated in two ways:

- local production and consumption (a relatively easy method to apply since data on agricultural production are not required)
- all produce in the contaminated areas is consumed somewhere, not necessarily locally (this method will give a more accurate estimate of the collective dose, but it gives no information on the ranges of individual doses)

Population, Agricultural, Economic Data

The spatial distribution of the population and agricultural production are necessary for evaluating health effects. These distributions together with regional economic data are essential in calculating economic costs

Mapping of available data on an r, θ grid is usually necessary

When agricultural production data are not available they can be approximated by using information on the land area used for farming in conjunction with information on the proportion of the farmland devoted to each agricultural product

Protective actions may be taken to reduce the consequences of an accident on the public. These actions fall into two broad categories:

Short-term Protective Actions or Emergency Response,

having as primary objective to limit the exposure of the population to both internal and external irradiation, with the intention of avoiding early health effects and minimizing high individual risk of late health effects. They include:

- Sheltering - staying indoors, with doors and windows closed and ventilation systems off
- Evacuation - within a fixed area or based on projected dose
- Issue of stable iodine tablets - intended to saturate the thyroid with a non-active isotope
- Decontamination - changing people's clothes, and requiring shower/bath to remove skin contamination

Long-term Protective Actions,
aiming to lower chronic exposure to radiation and ingestion of contaminated food with the intention of reducing the risk of late health effects. They include:

- Relocation - moving people away from contaminated areas (land interdiction) for substantial periods.
- Land decontamination - cleaning, removal or redistribution of activity. Modeled with a decontamination factor defined as the ratio of the contaminant before and after decontamination
- Food disposal - on the basis of intervention levels based on activity levels in food, on predicted individual doses, or on the level of ground contamination

Health effects are distinguished in two general categories:

Early effects or non-stochastic, deterministic effects,
are those effects occurring within a week to about a year after exposure. Resulting from exposure to high doses of radiation. Their severity increases with dose and there is usually a threshold dose for induction.

Late effects or stochastic effects,
are those effects occurring in subsequent years (mainly cancer and hereditary decease). Only their probability depends on the dose

Health effects are also distinguished in somatic effects, those early effects and cancers observed in individuals, and hereditary effects, those affecting descendants of the exposed individuals

Early Effects

Evaluation through a "hazard function"

General form: $r = 1 - \exp(-H)$

where r is the risk of mortality or morbidity, and H the cumulative hazard given by:

$$H = \ln 2 \left(D/D_{50}\right)^{s} \quad \text{for} \quad D > T$$

where: D the dose to the relevant organ,
D_{50} the dose which causes the effect in 50% of the exposed population,
S the shape parameter, which characterizes the slope of the dose-risk function, and
T the threshold dose

The model includes also summation over doses delivered in different time periods, to account for protracted doses which are less harmful than those delivered over a short period

Recently dose-rate dependent models, which account for the fact that doses received at low dose rates are less harmful than those received at high dose rates, are employed for some fatal deterministic effects

The early fatal effects usually calculated with the above model comprise those following the irradiation of the:

- bone marrow (haematopoietic syndrome)
- lung (pulmonary syndrome)
- GI-tract (gastrointestinal syndrome)
- skin (skin burns)

A wide variety of radiation induced injuries is also estimated through this model such as:

- prodromal vomiting
- diarrhoea
- hypothyroidism
- temporary sterility
- microcephaly
- mental retardation
- cataracts

Late Effects

Principal late somatic effects are the increased incidence of cancers, both fatal and non-fatal, spread over several decades following an accident

For each cancer type the risk of cancer incidence r is given by a piecewise linear function:

$R(D) = \alpha \cdot D$ for high exposures, and

$R(D) = \alpha \cdot D / DDREF$ for low exposures

where:

R	the risk of cancer incidence,
D	the absorbed dose to the organ,
α	an effect specific parameter value, and
DDREF	a dose and dose rate reduction factor

DDREF is given a value of two for central estimates of most cancer types (one for breast and thyroid cancers). It is applied when the total dose is less than 0.2 Gy, and for higher doses when the dose rate is less than 0.1 Gy/hr

The model permits the prediction of cancer risk as a function of time. The risk is influenced by the characteristics of the individual such as gender and age at exposure
→ demographic models in conjuction with models predicting risk are necessary.

The two most important demographic factors for the prediction of cancer risks in the population of interest are:
- tha age structure and
- the age specific mortality rates

Assumptions about the variations of the age distribution for calculating long term doses:
- Age specific death rates from natural causes and an assumed birth rate are used to calculate future age distributions (better at short times)
- Age distribution remains constant over time

Hereditary Effects

These effects may occur by:

- changes arising in the base sequence in the DNA of a single gene leading to gene mutation
- rearrangement of collections of genes within and between chromosomes causing chromosomal aberrations

Radiation damage to the male and female germ may increase the incidence of hereditary effects

The evaluation of severe hereditary effects follows the methods for the evaluation of late somatic effects

Economic Impacts

Common framework of the consequences of an accident is their economic cost, providing a measure of the impact

The off site economic impacts of accidents include the costs of countermeasures, i.e.

- evacuation
- relocation
- sheltering
- food restrictions
- decontamination

Some models include also the cost of health effects in the exposed population, a very difficult issue to deal with due to the lack of a generally accepted costing method, especially in respect to the costing of human life

Another difficulty is the lack of adequate national economic statistics necessary for deriving the economics input data

The estimation of the economic impacts of accidents is a still developing area of consequence modeling

Presentation of Results

The consequences of a specific accident vary with the meteorological conditions and wind direction

In present probabilistic consequence codes the consequences are evaluated on an r, θ grid around the release location for each meteorological sequence in turn

At each grid element (usually called a cell) the following quantities can be evaluated:

- radionuclide concentrations
- radiation doses
- numbers of health effects
- areas, persons and amounts of agricultural produce affected by countermeasures
- economic costs

With the exception of concentrations it is customary to sum the consequences at each cell together to give the total consequences observed in the population and the environment

CCDF's

The most common way of presenting consequence magnitudes and their associated probabilities is in the form of Complementary Cumulative Distribution Functions, CCDF's. These are widely used as a measure of public risk

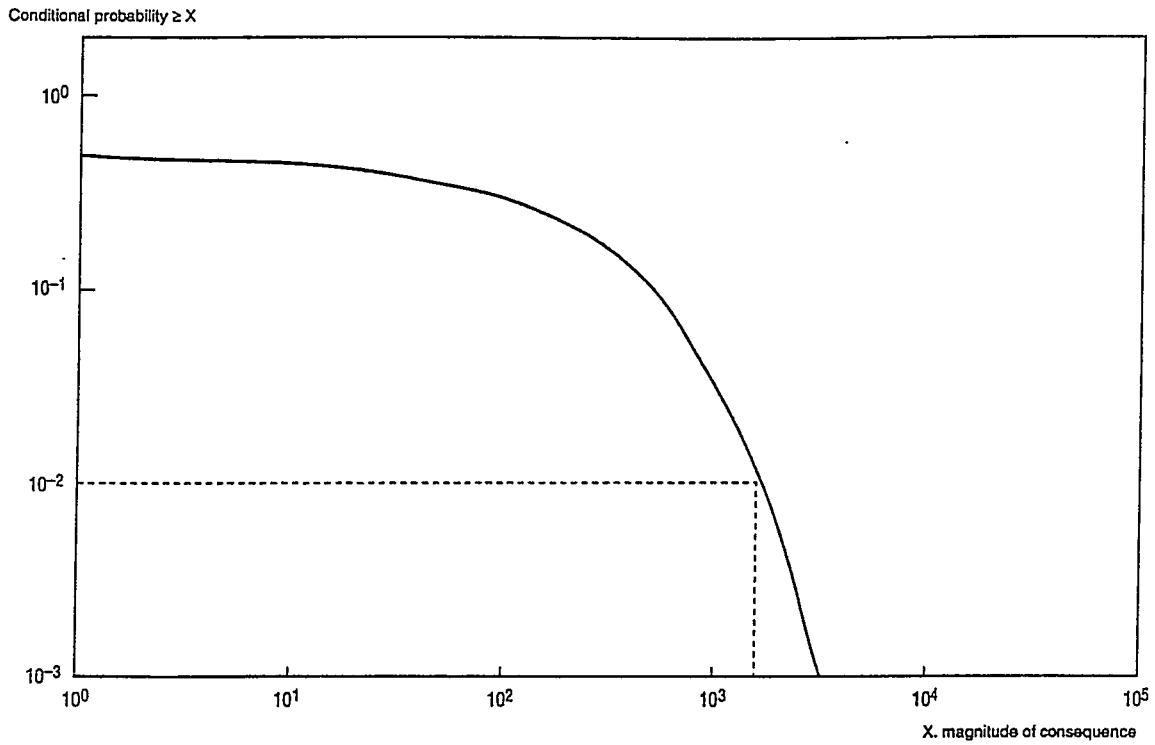
Along with CCDF's the expectation value (a summary measure of risk) and various percentile values are produced for each CCDF. The p-th percentile is that value of consequence C_p for which the following relation holds:

Probability ($C>C_p$) = 1 - p/100

Some other results apart from CCDF's that are produced include:

- the contribution of different exposure pathways to individual and collective doses
- the number of people receiving a particular level of individual dose
- the individual risk of health effects as a function of distance from the release point

Figure .3. **An example of a complementary cumulative distribution function (CCDF)**



1. The distribution of consequences conditional upon a release having occurred is shown.
2. In this example, the consequence magnitude which would be exceeded in one out of one-hundred releases (probability of 10^{-2}) is about 1 500.

Uncertainty

The predictions of accident consequence models will be uncertain. The uncertainties involved are distinguished in:

- modeling uncertainties, due to the lack of knowledge about the most appropriate mathematical formulation to represent the process involved
- completeness uncertainties, resulting from the omission of some contributions to risk
- parameter value uncertainties, due to inadequate knowledge about the most appropriate values to be assigned to the many parameters in the model

A number of studies deal with various aspects of the above uncertainties, with most focusing on parameter value uncertainties, and on individual models or endpoints. More complete studies are currently being performed in a number of institutes