ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Safety of Nuclear Power Plants

Methods and Results PRA Level 1 (Dependent Failures), Level 2 (Source Term), Methods and Results PRA Level 3

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Structure and "Levels" of a PRA for Nuclear Power Plants

Plant response to initiating events → **Level 1** → Frequency of core damage (CDF)

- includes accident management measures

Physical effects, containment response → **Level 2** → Frequency and amount of radionuclides released (source term, PDF)

Athmospheric dispersion, potential and expected doses, dose-effect/risk relation → **Level 3** → Frequency and quantities of environmental and health effects

Present model assumptions for FTA

- All failures of a system are due to independent failures at components ('elements') level
- The failure of an element has no functional influence on other system elements
- The physical effects of an element failure on other elements are marginal
- By adding (redundant) elements the systems failure probability can be reduced to a minimum

These assumptions contradict common experience!

German Nuclear Power Plants

- Failure of starting all four emergency diesels leads to dependent failures; the batteries for starting the diesels have been insufficiently maintained (NPP Würgassen).
- A polluted screening system in the river water inlet (single failure) lead to a lack of cooling water for the main and auxiliary cooling water pumps (dependent failures of the redundant cooling water supply; Lingen BWR).
- A lighting strike (external event as common cause) lead via the bearing oil supply to the shut down of two main cooling water pumps (NPP Stade).
- Crack in a connecting welding seam in the seal water supply system of the main cooling pumps (cascading failure). The causal single failure was the sudden opening of a valve due to a broken spindle nut (NPP Stade).

Definitions

Dependent failure (DF)

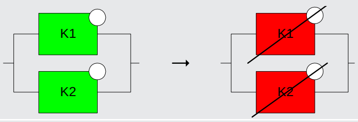
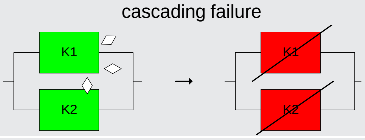
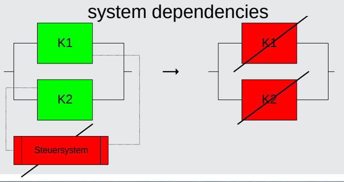
Event, of which the occurrence probability cannot be modelled as a product of single occurrence probabilities (mathematical), or

Event, which is caused by any interdependent structures (multiple failure, technical)

- **CCF (com**mon cause failure)
  Description of a type of a dependent failure, at which a common single cause triggers several failures occurring (almost) simultaneously
- CMF (common mode failure)
  Description for a specific CCF, in which several (system-)units fail in the same way
- CF (causal or cascade failures)
  Description for spreading or interdependent failures
- Common **cause initiating events**
  Description for initiating events which can cause several events or event scenarios, e.g. area event such as earthquakes or flooding
- DF are only important in redundant (parallel) systems.

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Causes of DF

Type	Description
common cause 	*m* of *n* system made of *n* identical units. Under certain conditions they all fail at the same time.
cascading failure 	Adjacent units of a redundant group fail due to the influence of the first failure.
system dependencies 	System interconnections lead to dependencies

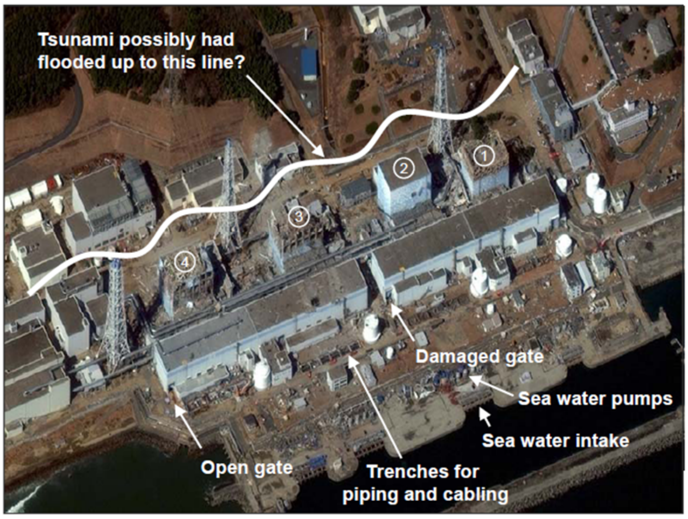
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik: Department of Mechanical & Process Engineering:

Fukushima-Daiichi After Tsunami

VGB POWERTECH



Sources: Janti, Digital Globe, 2011

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik: Department of Mechanical & Process Engineering:

Transition to the Modeling of DF

without consideration of existing DF

- uncompleted description of technical systems;
- to optimistic results of safety analysis for highly redundant systems

problems:

- lack of data for highly reliable systems, usually from limited operational experiences (normal operation state, functional testing)
- it is difficult to classify observed events into dependent and independent ones.

required steps to consider DF

1. Indentification of DF in a technical system.
2. qualitative and quantitative consideration of DF within a reasoned framework (model building).
3. possibility to prevent/reduce the consequences of DF.

Modeling approaches: methods to consider DF

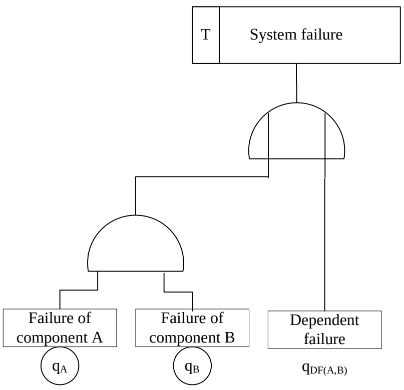
Explicit Methods

- **Event specific models**
  Consideration special consequences from e.g. earthquakes, fire, floods, broken pipes or leakage in the primary loop.
- **Event tree and fault tree analysis**
  Consideration of functional interdependencies (units).
- **Models for the quantification of human actions**
  Consideration of interdependencies between single human actions.
- Examples are interconnecting models in THERP (Technique for Human Rate Error Prediction).

Explicit methods comprise structural and functional interdependencies, they are system-specific but they don't cover DF within systems completely.

Modeling

A. Explicit method



Modeling (implicit method)

Marshall-Olkin-Model (fundamental modeling)

- **1. System modelling excluding DF**

Example: '2 out of 3-system' with units A, B and C

- System failure, when two units fail: {A, B}, {A, C}, {B, C}
- Probability of system failure: $Q_s = q_a \cdot q_b + q_a \cdot q_c + q_b \cdot q_c - 2\, q_a \cdot q_b\, q_c$

Simplification and notation

- All units failure probabilities are identical: $q_a = q_b = q_c = Q_{k=1}$
  k (k = 1, 2, …, n): Number of involved units in the failure
- Simplification: $\Pr(a \cup b) \approx \Pr(a) + \Pr(b)$

System failure probability of a '2 out of 3-system' excluding DF

$$Q_s = q_a \cdot q_b + q_a \cdot q_c + q_b \cdot q_c = 3 \cdot Q_1^2$$

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

2. Inclusion of DF

Probabilities of failure combinations

- q_{AB}, q_{BC}, q_{AC}
- q_{ABC}

Assumption: equality of all units:

- $q_{AB} = q_{BC} = q_{AC} = \ldots = Q_{k=2}$
- $q_{ABC} = Q_{k=3}$

'2 out of 3-system'

- Probability of a DF including two units: $3 \cdot Q_2$
- Combination of three (all) failures: $q_{ABC} = Q_3$.

3. System failure probability

System failure probability Q_s including DF:

$Q_s = \Sigma\Pr(\text{independent failures}) + \Sigma\Pr(\text{dependent failures})$

'2 out of 3-system'

$$Q_s = 3 \cdot Q_1^2 + 3 \cdot Q_2 + Q_3.$$

Failure probability of the units

Q_t is the total failure probability of an element in a group of redundant elements, inclusive of all dependencies. The interrelationship between Q_t and Q_k is asked for:

$$Q_t = \sum_{k=1}^{n} \binom{n-1}{k-1} \cdot Q_k$$

with binominal coefficient

$$\binom{n-1}{k-1} \equiv \frac{(n-1)!}{(n-k)! \cdot (k-1)!}$$

Number of failure combinations of an element with (k-1) different elements in a group of (n-1) identical elements.

Group of 3 redundant elements

$$Q_t = \binom{3-1}{1-1} \cdot Q_1 + \binom{3-1}{2-1} \cdot Q_2 + \binom{3-1}{3-1} \cdot Q_3 = Q_1 + 2 \cdot Q_2 + Q_3$$

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Calculation of Q_k by using relative frequencies

$$Q_k = \frac{n_k}{\binom{n}{k}}$$

n_k: Number of failures with k involved elements and the binominal coefficient for the calculation of the combinations with k of n elements.

Annotation

Ideally the different Q_k can be drawn directly from of observation data. Some models simplify the consideration of DF by making additional assumptions.

One of these models is the ***β*-factor-model**.

β-factor-model

Simplifying assumptions

Failures in a group of redundant elements are either independent or all of the *n* elements fail.

- With $k = 1$, $Q_{k=1}$ is the failure probability of independent failures
- With $k = n$, $Q_{k=n}$ is the failure probability for (totally) dependent failures
- All other failure combination are excluded by definition, so
  $Q_k = 0$ for $n > k > 1$ (for other failure combinations)

For 'm out of n-system' it is generally

$$Q_t = Q_1 + Q_n.$$

Definition of the β -factor

$$\beta = \frac{Number\ of\ DF}{Number\ of\ all\ failures} \qquad \beta = \frac{Q_n}{Q_1 + Q_n} = \frac{Q_n}{Q_t}$$

From this it follows directly

- $\beta \cdot Q_t = Q_{k=n}$
- $\beta \cdot (Q_1 + Q_n) = Q_{k=n}$

With $Q_n = Q_t - Q_1$ follows

- $Q_{k=1} = Q_t (1 - \beta)$

Finally

$$Q_k = \begin{cases} (1-\beta) \cdot Q_t & k = 1 \\ 0 & m > k > 1 \\ \beta \cdot Q_t & k = n \end{cases}$$

'2 out of 3-system'

System failure probability $Q_S = 3\cdot\ + 3\cdot Q_2 + Q_3$

Changes in the β-factor-model to $Q_s = 3 \cdot (1-\beta)^2 \cdot Q_t^2 + \beta \cdot Q_t$

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich | Laboratory for Safety Analysis | DMAVT Departement Maschinenbau & Verfahrenstechnik: Department of Mechanical & Process Engineering

Multiple-Greek-Letter-Model (MGL-Model)

Assumptions identical to the β-factor-model, but combinations of failures are possible

Parameter, Definitions	Example: Group of 3 Redundant Elements
Q_t: total failure probability of a unit	$Q_t = Q_1 + 2Q_2 + Q_3$
$\alpha = 1$	$\alpha = 1$
β: all *dependent* failure probabilities relating to Q_t	$\beta = \frac{2Q_2 + Q_3}{Q_t} = \frac{2Q_2 + Q_3}{Q_1 + 2Q_2 + Q_3}$
γ: *fraction* of DF probability of a unit, with at least 2 units failing	$\gamma = \frac{Q_3}{2Q_2 + Q_3}$

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich | Laboratory for Safety Analysis | DMAVT Departement Maschinenbau & Verfahrenstechnik: Department of Mechanical & Process Engineering

To consider the MGL-factors the equation for Q_t will be solved for Q_k (k = 1, 2, 3). The resulting terms will be replaced by the parameters β, γ, etc.

Example: Group of 3 Redundant Elements	given: $Q_t = Q_1 + 2Q_2 + Q_3$
$Q_1 = \frac{Q_t - (2Q_2 + Q_3)}{1} = Q_t - (\beta Q_t) = Q_t(1-\beta)$	$\beta = \frac{2Q_2 + Q_3}{Q_t} = \frac{2Q_2 + Q_3}{Q_1 + 2Q_2 + Q_3}$
$Q_2 = \frac{Q_t - (Q_1 + Q_3)}{2} = \frac{Q_t - [Q_t(1-\beta) + \gamma(2Q_2 + Q_3)]}{2} = \frac{Q_t - [Q_t(1-\beta) + \gamma(\beta Q_t)]}{2} = \ldots = \frac{Q_t - \beta(1-\gamma)}{2}$	$\gamma = \frac{Q_3}{2Q_2 + Q_3}$
Q_3 ...	etc.

The results for a redundant group can be generalised by using the notation $\Phi_1 = 1, \Phi_2 = \beta, \Phi_3 = \gamma, \dots, \Phi_{m+1} = 0$

$$Q_k = \frac{1}{\binom{n-1}{k-1}} \cdot \left(\prod_{i=1}^{k} \Phi_i \right) \cdot (1 - \Phi_{k+1}) \cdot Q_t$$

Example: Redundant Group with 3 Elements

$Q_{k=1}$	$Q_{k=2}$	$Q_{k=3}$
$= \frac{1}{\binom{3-1}{1-1}} \cdot (\Phi_1) \cdot (1-\Phi_2) \cdot Q_t$	$= \frac{1}{\binom{3-1}{2-1}} \cdot (\Phi_1 \cdot \Phi_2) \cdot (1-\Phi_3) \cdot Q_t$	$= \frac{1}{\binom{3-1}{3-1}} \cdot (\Phi_1 \cdot \Phi_2 \cdot \Phi_3) \cdot (1-\Phi_4) \cdot Q_t$
$= 1 \cdot (1-\beta) \cdot Q_t$	$= \frac{1}{2} \cdot 1 \cdot \beta \cdot (1-\gamma) \cdot Q_t$	$= 1 \cdot \beta \cdot \gamma \cdot (1-0) \cdot Q_t$

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT
Departement Maschinenbau & Verfahrenstechnik:
Department of Mechanical & Process Engineering

Example: Substituting Q_k in the equation "System Failure Probability of a 2 out of 3 System Q_s with DF portion", $Q_s = 3 \cdot \; + 3 \cdot Q_2 + Q_3$, equals

$$Q_s = 3(1-\beta)^2 Q_t^2 + \frac{3}{2}\beta(1-\gamma)Q_t + \beta\gamma Q_t$$

Supposing the MGL-factors are unknown, they can be determined via the respective Q_k (see above: parameters, definitions). The probabilites can be determined via

$$Q_k = \frac{n_k}{\binom{n}{k}}$$

Equating $\gamma = 1$ leads to the result of the β-factor-model. In general, the *b*-factor-model is a special case of the MGL-Model

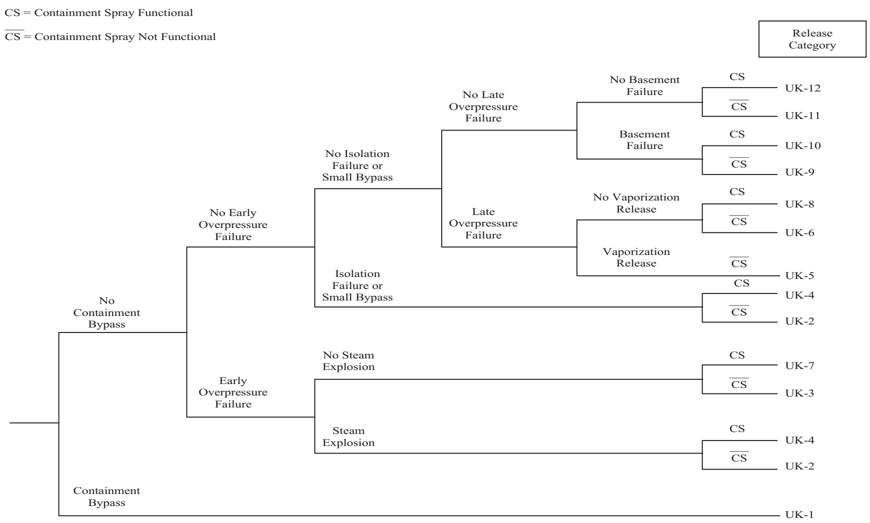
GRS-Results Level 1 PRA, German NPP GKN-II, Full Power

Initiating Events	System damage state	Core damage state
Loss of main feed water	26%	<5%
Loss of main heat sink	20%	<5%
Loss of preferred power	17%	10%
Very small primary leaks	16%	53%
SBLOCA via stuck-open SRV	5%	15%
Steam generator tube rupture	4%	7%

Total expected frequency of system damage state without AM: 8.5×10^{-6}/year
Total expected frequency of core damage state with AM: 2.5×10^{-6}/year

--	Expected frequency of system damage state / year	Expected frequency of core damage state / year
Mean	8.5×10^{-6}	2.5×10^{-6}
5% Fractile	1.6×10^{-6}	4.4×10^{-7}
50% Fractile (median)	4.6×10^{-6}	1.5×10^{-6}
95% Fractile	2.1×10^{-5}	7.3×10^{-6}
„Point Value“*	5.0×10^{-6}	1.7×10^{-6}

Simplified Event Tree for Source Term Characterisation



Selected Release Categories and Source Term Values

Release Category, Description and Frequency	Release Characteristics					Release Fractions of Core Inventory			
	Release starts [hrs]	Duration [hrs]	Warning time [hrs]	Energy [MBTu/hr]	Height [m]	Xe-Kr	I	Cs-Rb	Ba-Sr
UK-1 Containment bypass **2.4 (-9)**	1	3	0	0.3	10	9(-1)	7(-1)	5(-1)	6(-2)
UK-2 Early containment failure Steam explosion **4.0 (-10)**	1	0.5	0	20	10	9(-1)	7(-1)	4(-1)	5(-2)
UK-5 Late containment failure Vaporisation release **8.0 (-9)**	8	0.5	4	20	10	1 (0)	6(-2)	3(-1)	4(-2)
UK-6 Late containment failure No vaporisation release **4.2 (-9)**	12	0.5	8	20	10	9(-1)	9(-3)	2(-1)	2(-2)

Note: 1 Btu/hr = 0.29 watts; 2.4(-9) means 2.4 x 10-9 per reactor year

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

GRS Level 2 PRA: GKN-II

Correlation of initiating events with release categories

Final state of the containment Note: in all cases except the last one, the melt penetrates the concrete foundation and reaches the underground	Fractions of the core damage states (CDS) Initiating events and fractions						Mean over all CDS 1.0
	L<25 .56	L>25 0.05	LPR 0.15	LSG 0.09	TLP 0.11	TWP 0.04	
Damage due to high pressure failure of reactor pressure vessel	0.005	-	-	0.014	0.009	0.002	0.030
Failure to isolate containment ventilation	<<	<<	<<	<<	<<	<<	<<
Failure due to overpressure at reactor pressure vessel failure (DCH)	0.003	<<	<<	0.001	-	<<	0.004
Meltthrough of sump suction line	0.024	0.001	0.005	0.004	0.004	<<	0.038
Leak due to overpressure after failure to depressurize	0.021	0.001	0.005	0.003	0.004	<<	0.034
Intact with depressurization	0.434	0.020	0.095	0.050	0.078	0.002	0.679
Intact without depressurization (no reactor pressure vessel failure)	0.073	0.028	0.045	0.032	0.014	0.036	0.228

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik:
Department of Mechanical & Process Engineering:

Level-3: Procedure for the assessment of consequences

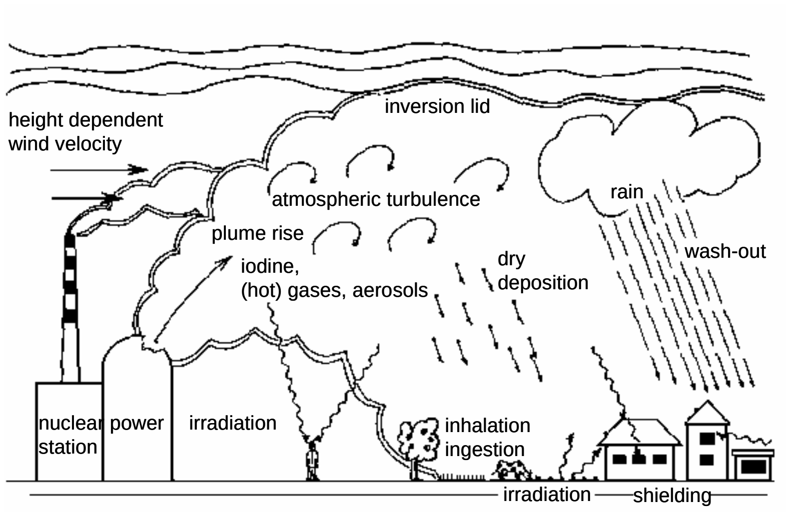
- Modeling the distribution and the duration the isotopes stay in the atmosphere;
- Identification of the potential radiation dose due to external radiation, then identification of the realistic radiation dose considering protection measures like protection through buildings, evacuation and alarm;
- Identification of the radiation dose due to internal radiation considering the prohibition of food and preventive measures (protection of the thyroid through iodine pills);
- Deriving the **individual** fatal risk;
- Identification of the exposition of the population and of the collective dose under consideration of population density, deriving the **collective** fatal risk.

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT
Departement Maschinenbau & Verfahrenstechnik:
Department of Mechanical & Process Engineering:

Atmospheric Dispersion Phenomena

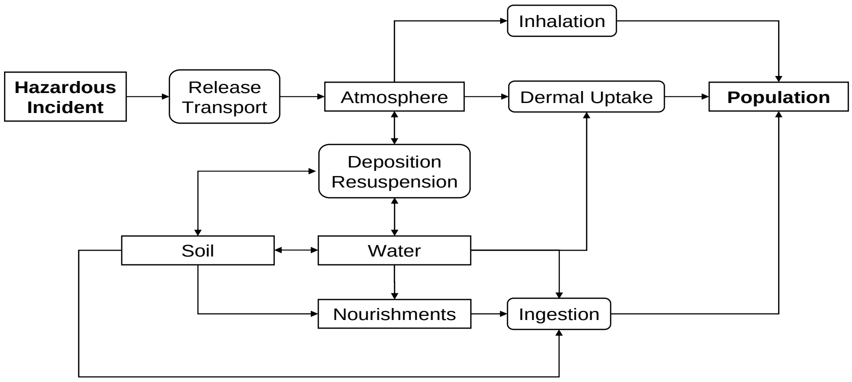


ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis — INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT Departement Maschinenbau & Verfahrenstechnik; Department of Mechanical & Process Engineering

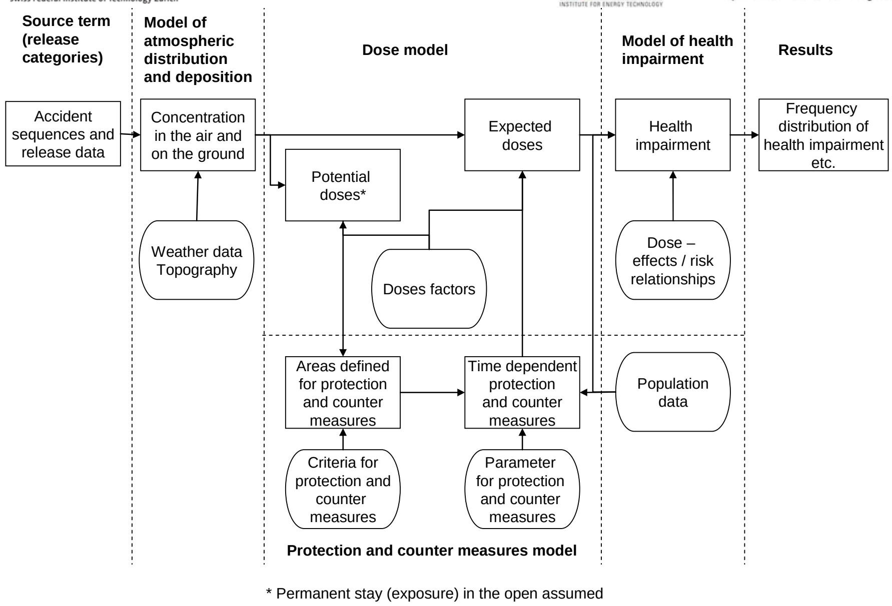
Exposure paths from the source to the population after an atmospheric release



ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Laboratory for Safety Analysis — INSTITUTE FOR ENERGY TECHNOLOGY

DMAVT Departement Maschinenbau & Verfahrenstechnik; Department of Mechanical & Process Engineering



* Permanent stay (exposure) in the open assumed

Exposure to radioactivity

Units

Activity Number of radioactive nuclear transformations per time unit
SI-Unit: 1 Becquerel (Bq) = 1 s^{-1}
Historical: Curie (Ci) 1 Ci = 3.7×10^{10} Bq

Absorbed dose absorbed radiation per mass unit
SI-Unit: 1 Gray (Gy) = 1 J kg^{-1} = 100 rad
Historical: rad = radiation dose
1 rad = 100 erg g^{-1}
1 erg = 1 g × 1 $cm^2 s^{-2}$ = 10^{-7} J

Equivalence dose The biological effects of an absorbed dose depends on the type of radiation. The equivalence dose is represented with a factor (relative biological effectiveness, RBE) which represents the weighted dose.

SI-Unit: 1 Sievert (Sv) = 1 Gy × RBE
Historical: rem = radiation equivalent man
1 rem = 1 rad × RBE = 0.01 Sv

Radiation	RBE
Termionic-, gamma-, x-rays	1
Alpha particle	20
Neutrons < 10 keV	5
10-100 keV	10
100-2000 keV	20

Types of damage

Deterministic radiation damages (Frühschäden)

The cardiotoxic dose is the threshold dose of the cell killing rate and the body's cell building rate. The degree of damage of a dose depends on whether a part or the whole body is radiated.

Typical non stochastic radiation damages are burnt skin and radiation illness.

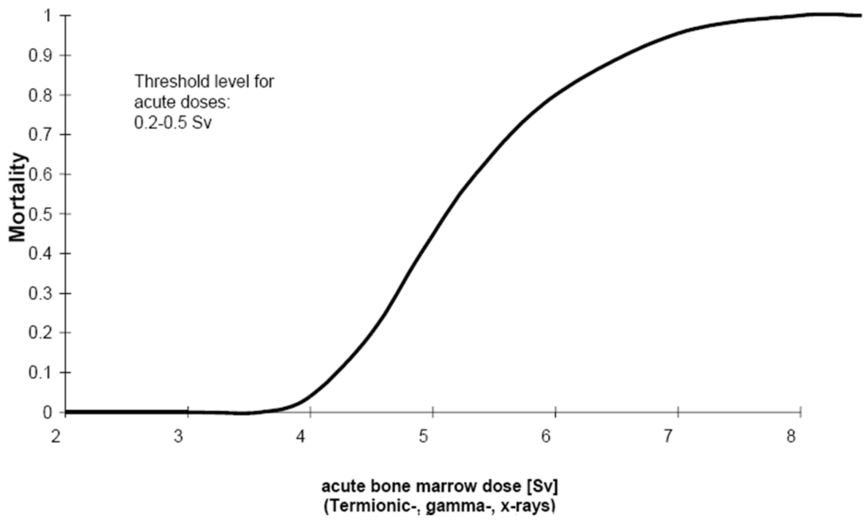
The $\mathbf{LD_{50}}$ lays around **4 to 5 Sv** (400-500 rem).

The threshold level lies between **0.2 and 0.5 Sv** (20-50 rem)

Stochastic radiation damage (Spätschäden):

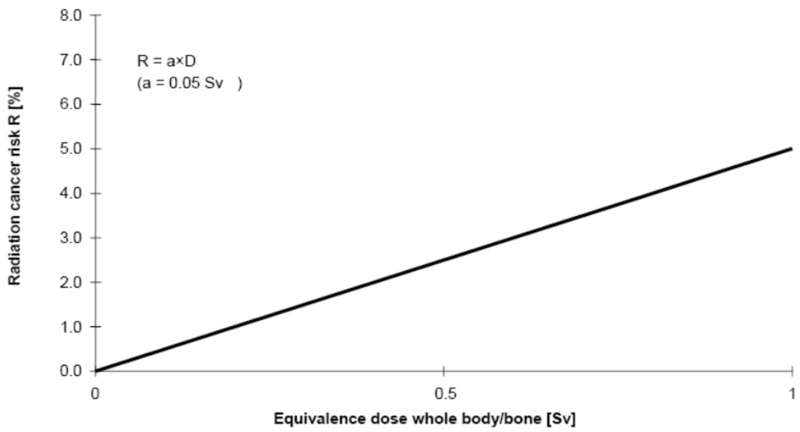
Typical stochastic radiation damages are latent diseases like leukaemia, tumours and damaged genes. Radiation cancer can't be distinguished from normal cancer.

Lethality of acute dose of radiation



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Laboratory for Safety Analysis
INSTITUTE FOR ENERGY TECHNOLOGY
DMAVT
Departement Maschinenbau & Verfahrenstechnik
Department of Mechanical & Process Engineering

Longterm effects of dose of radiation



Representing results of a risk analysis

- **Risk** is represented by the parameters **frequency** and **consequence** of an undesired event
  - The **frequency** of an event is estimated by the use of accident statistics, assessments and models (FMEA, Event- / Fault Trees)
  - The **consequences** for the public are estimated by the use of dispersion and dose-effect models.
- The **results** of the risk analysis are often represented in frequency-consequence diagrams. The cumulative frequency and the frequency are plotted against each other. For a given extent of an event the frequency can be read out of the diagram.

Result Representation