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Safety of Nuclear Power Plants: Methods and Results
PRA Level 2 (Source Term) and 3 (Risk Estimates)

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

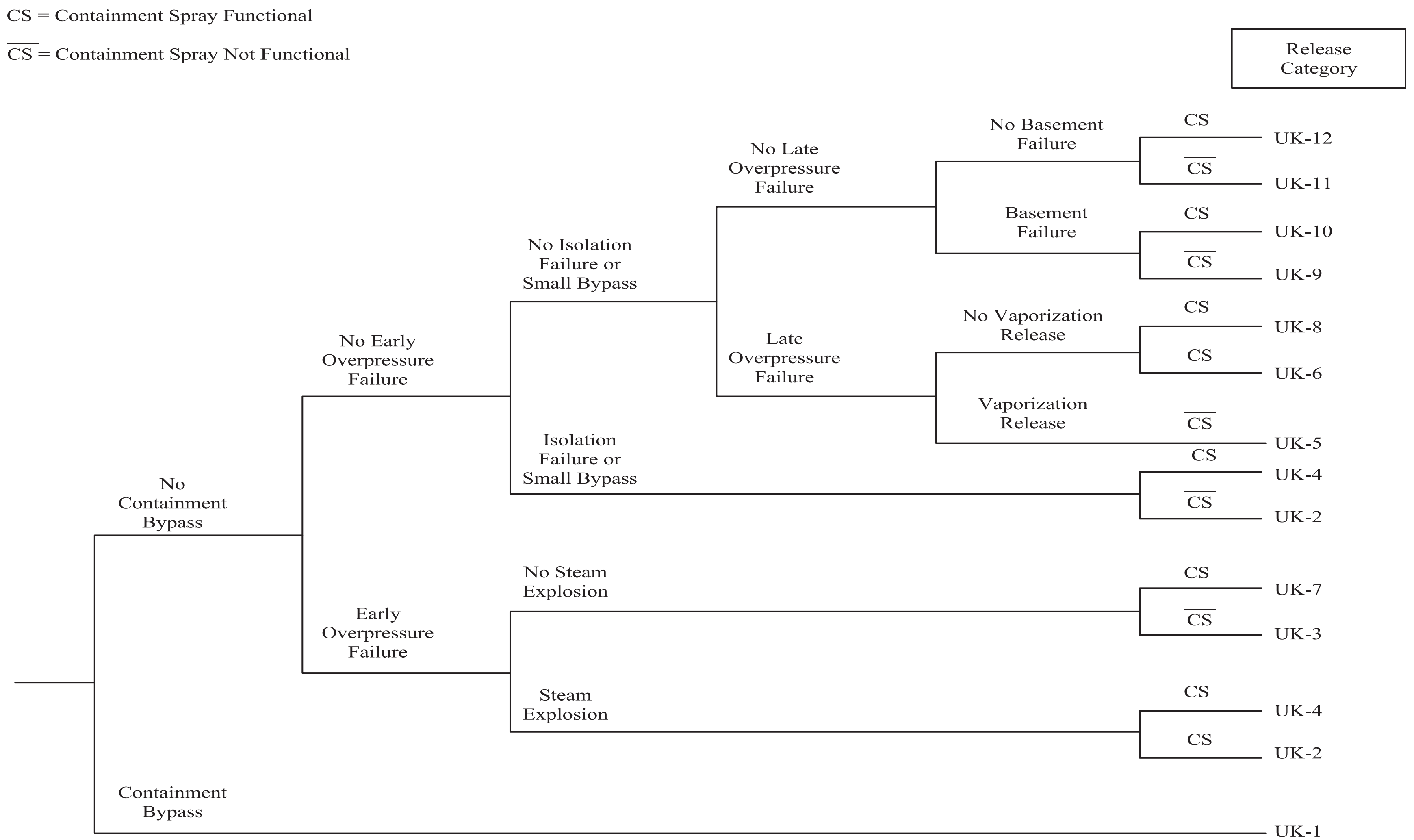
Initiating Events	System damage state	Core damage state
Loss of main feed water	26%	<5%
Loss of main heat sink	20%	<5%
Loss of preferred power	17%	10%
Very small primary leaks	16%	53%
SBLOCA via stuck-open SRV	5%	15%
Steam generator tube rupture	4%	7%
Total expected frequency of system damage state without AM: $8.5x10^{-6}$/year Total expected frequency of core damage state with AM: $2.5x10^{-6}$/year		

--	Expected frequency of system damage state / year	Expected frequency of core damage state / year
Mean	$8.5x10^{-6}$	$2.5x10^{-6}$
5% Fractile	$1.6x10^{-6}$	$4.4x10^{-7}$
50% Fractile (median)	$4.6x10^{-6}$	$1.5x10^{-6}$
95% Fractile	$2.1x10^{-5}$	$7.3x10^{-6}$
„Point Value"*	$5.0x10^{-6}$	$1.7x10^{-6}$

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

Simplified Event Tree for Source Term Characterization



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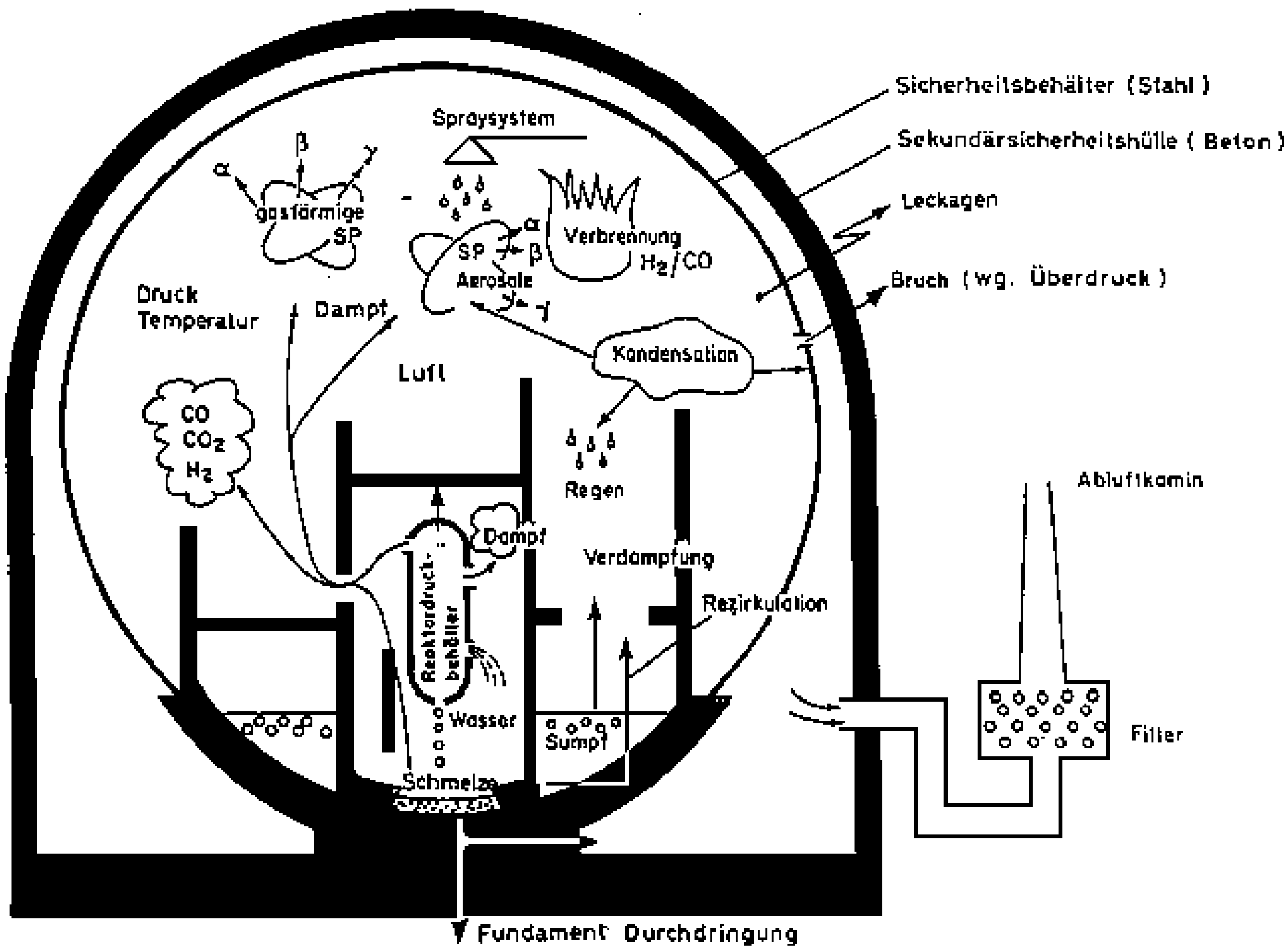
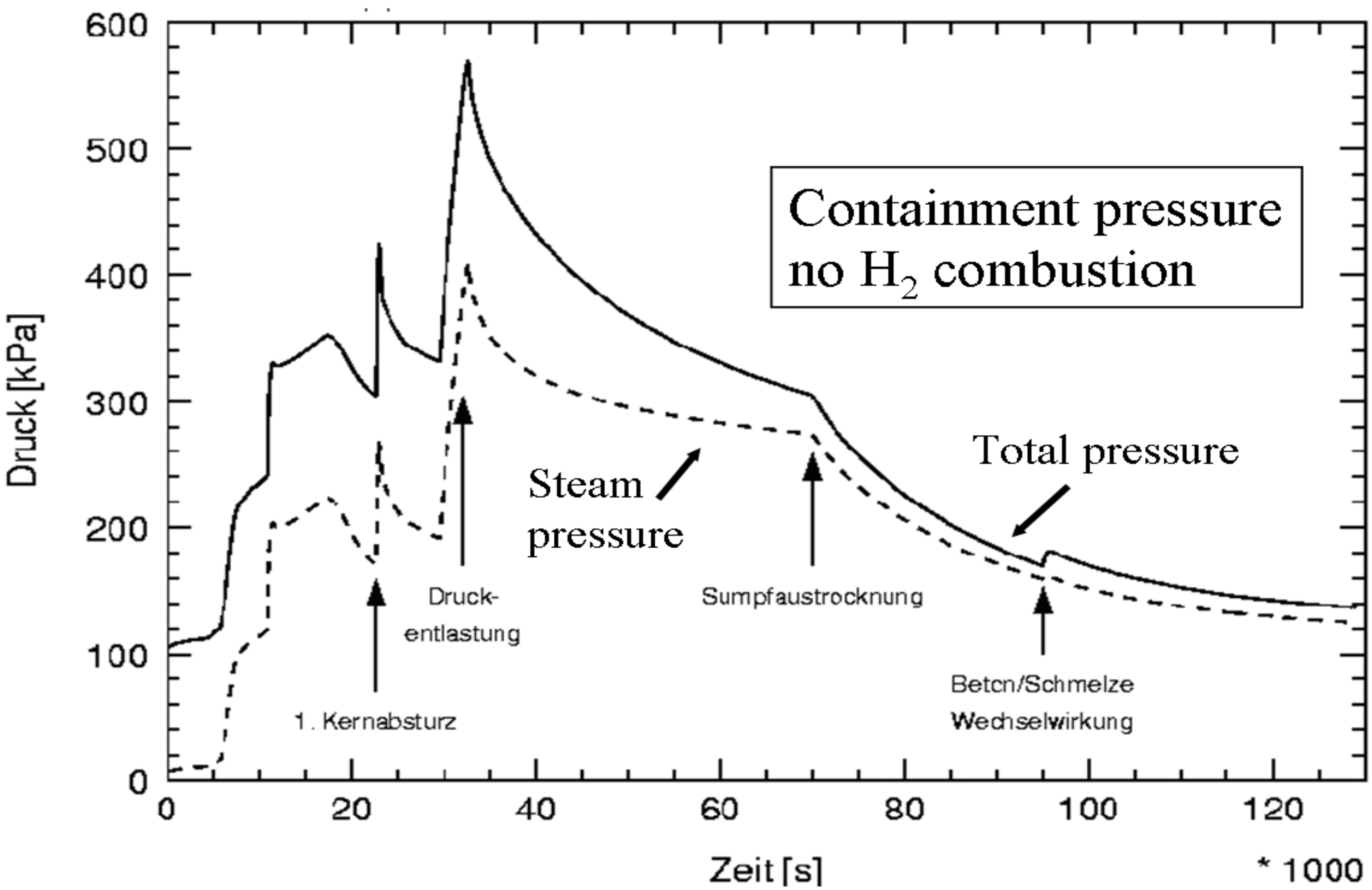
Level 2: Severe Accident Containment Phenomena and Release Paths



Containment Pressure in Case of Core Melt Accident (1/2)



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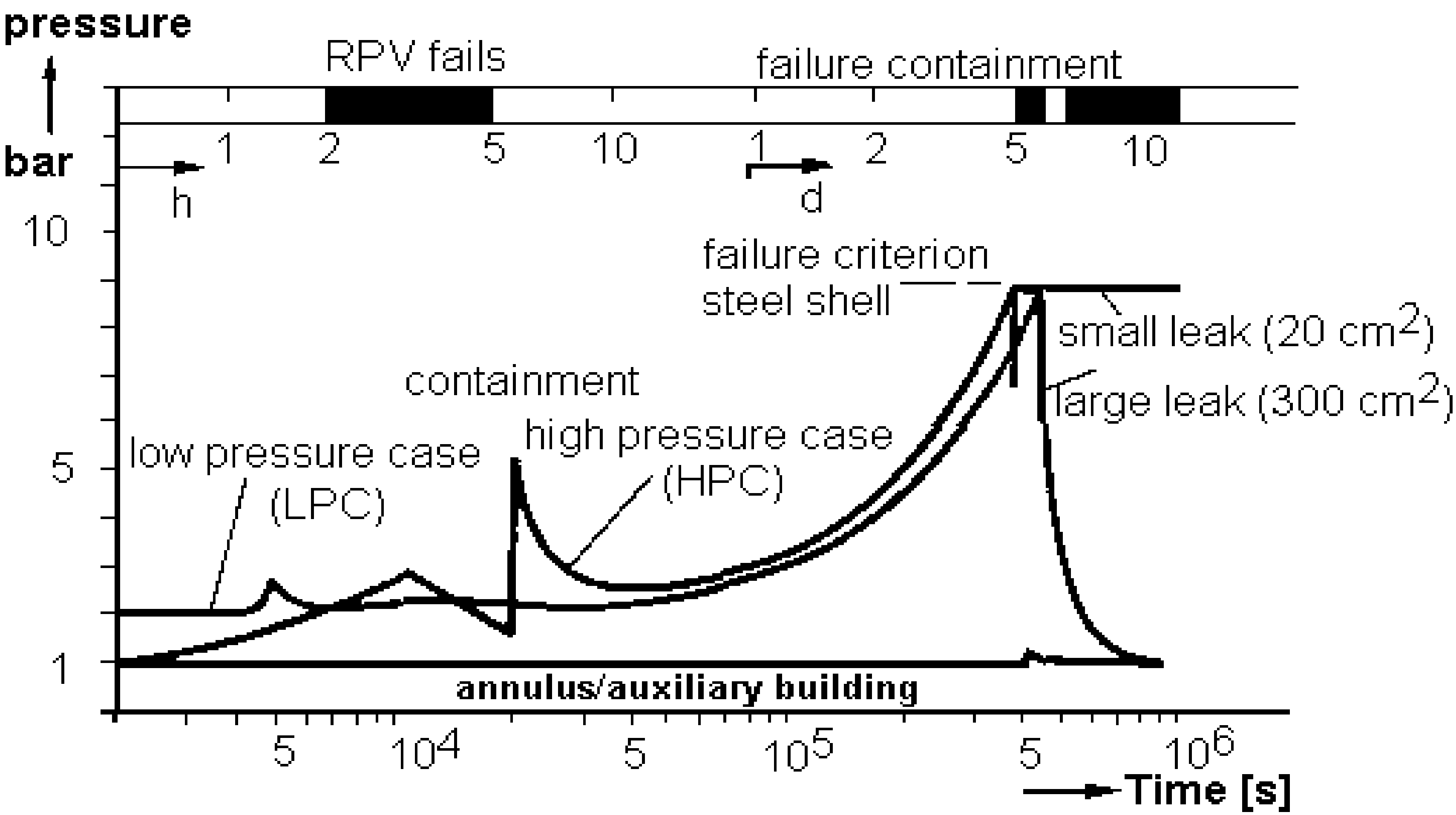
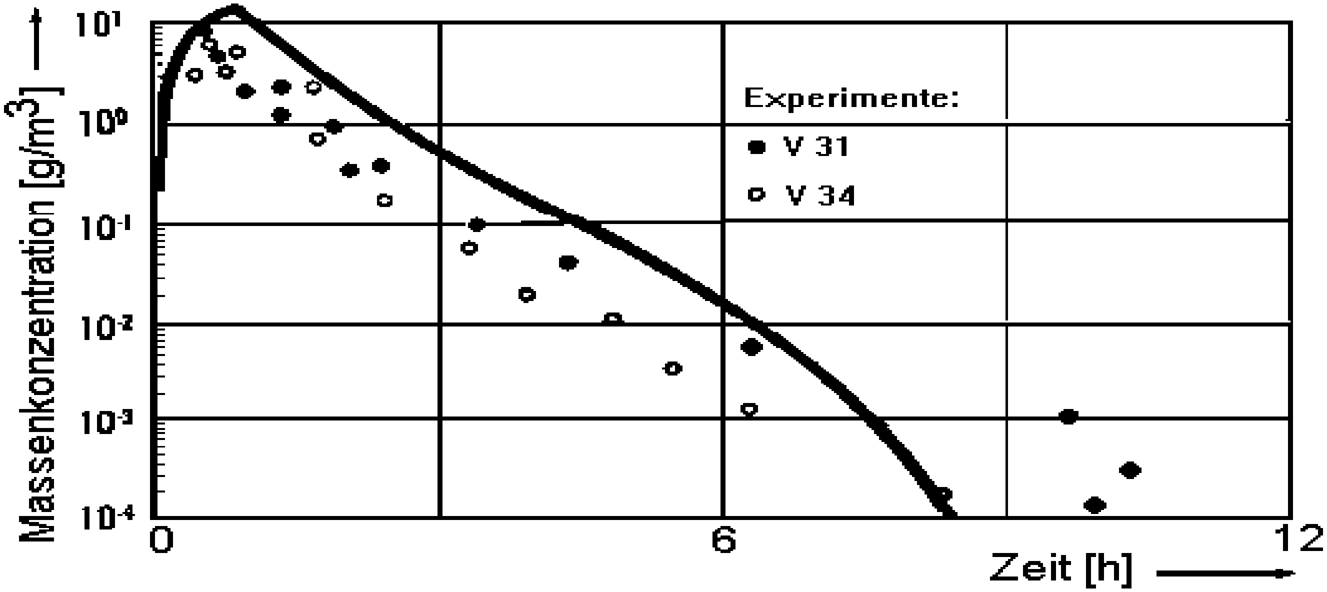
Containment Pressure in Case of Core Melt Accident (2/2)



Aerosol Concentration in the Containment Athmosphere as Function of Time



Comparison of calculated airborne time-dependent aerosol concentration with experimental results

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

GRS PRA Level 2 : GKN-II

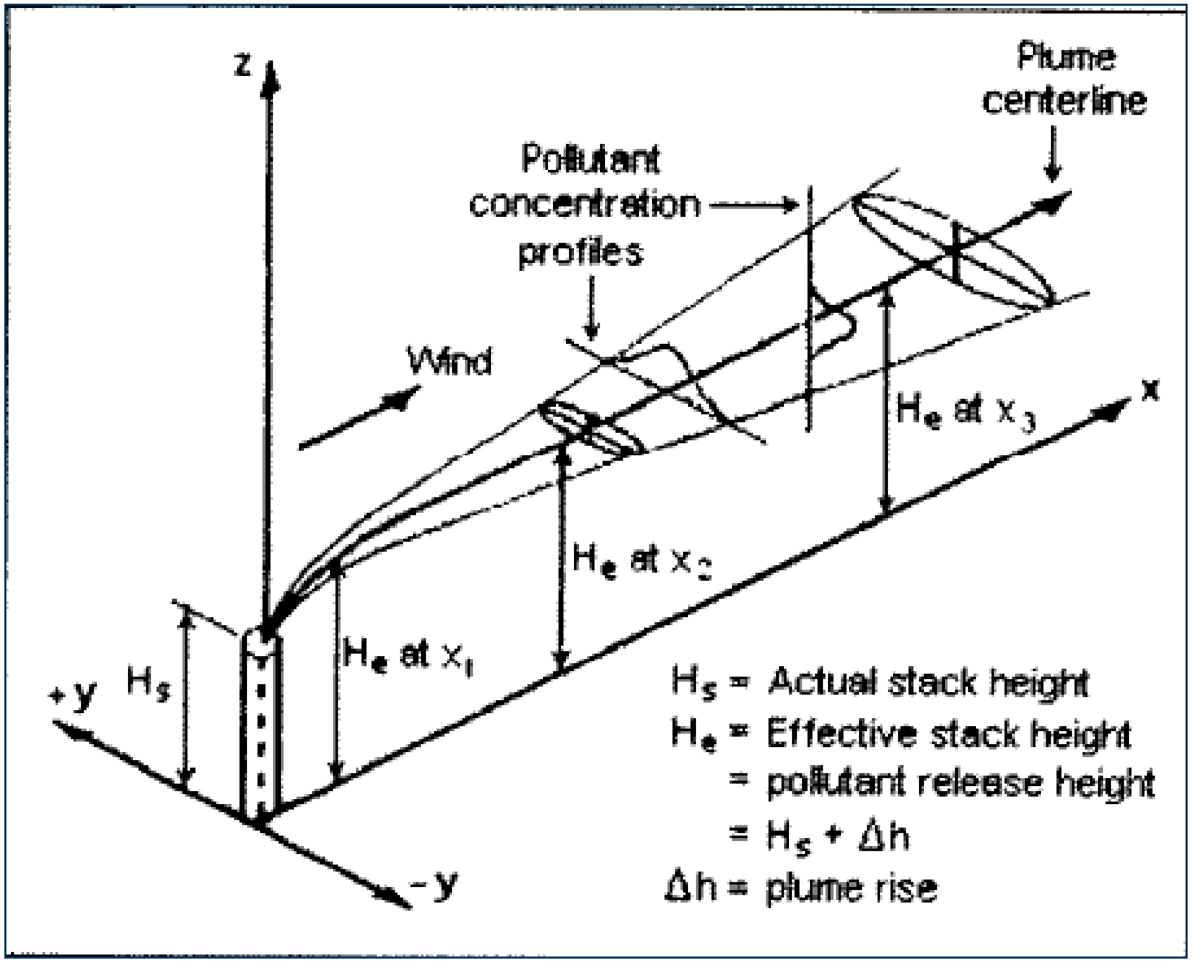
Correlation of initiating events with release categories

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

Level 3: Procedure for the Assessment of Consequences

- Modeling of the distribution and 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 staying in buildings, evacuation, and late relocation;
- 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.

Modelling Atmospheric Transport by Turbulent Diffusion (Gaussian Distribution)

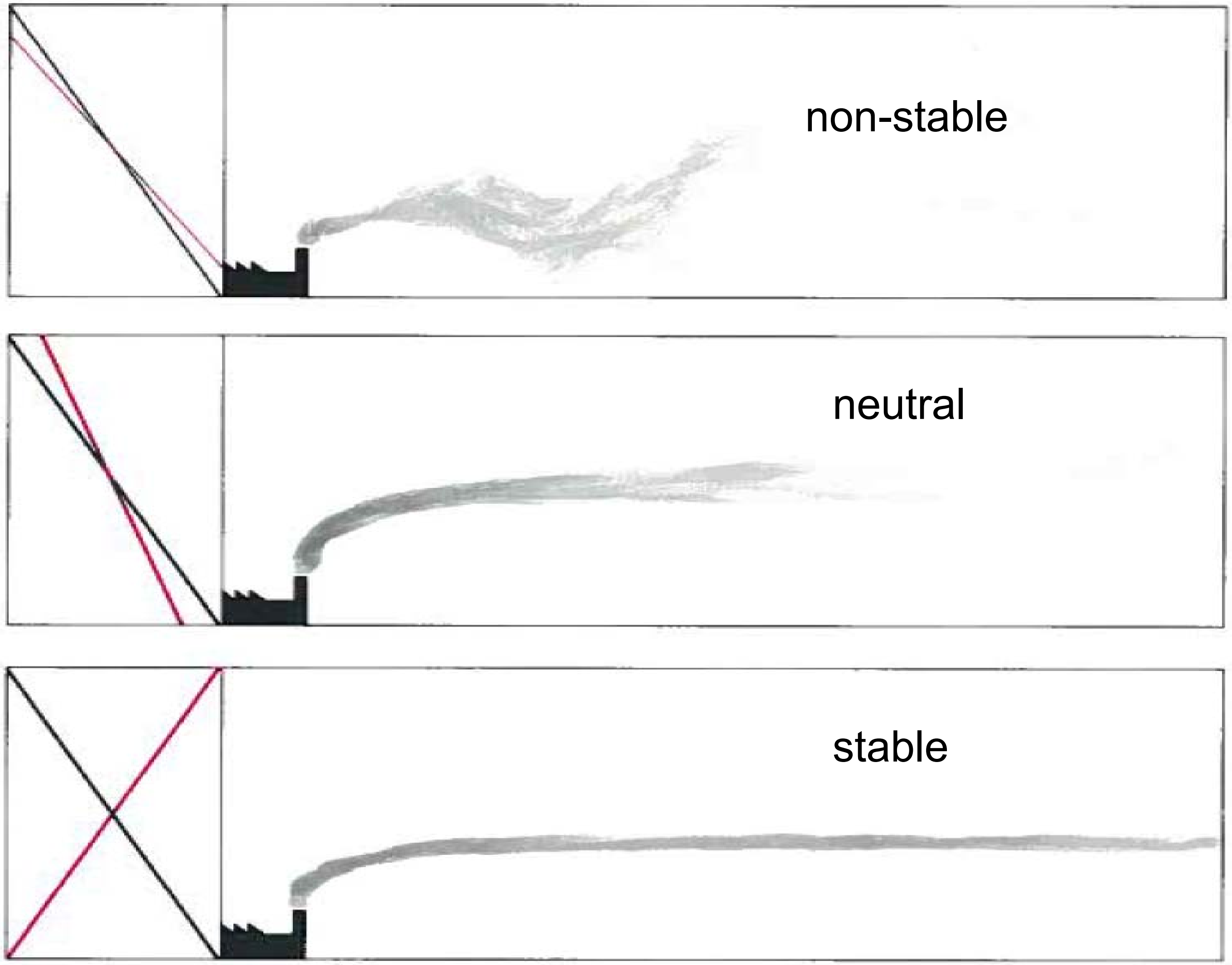


Modelling of Release and Atmospheric Transport

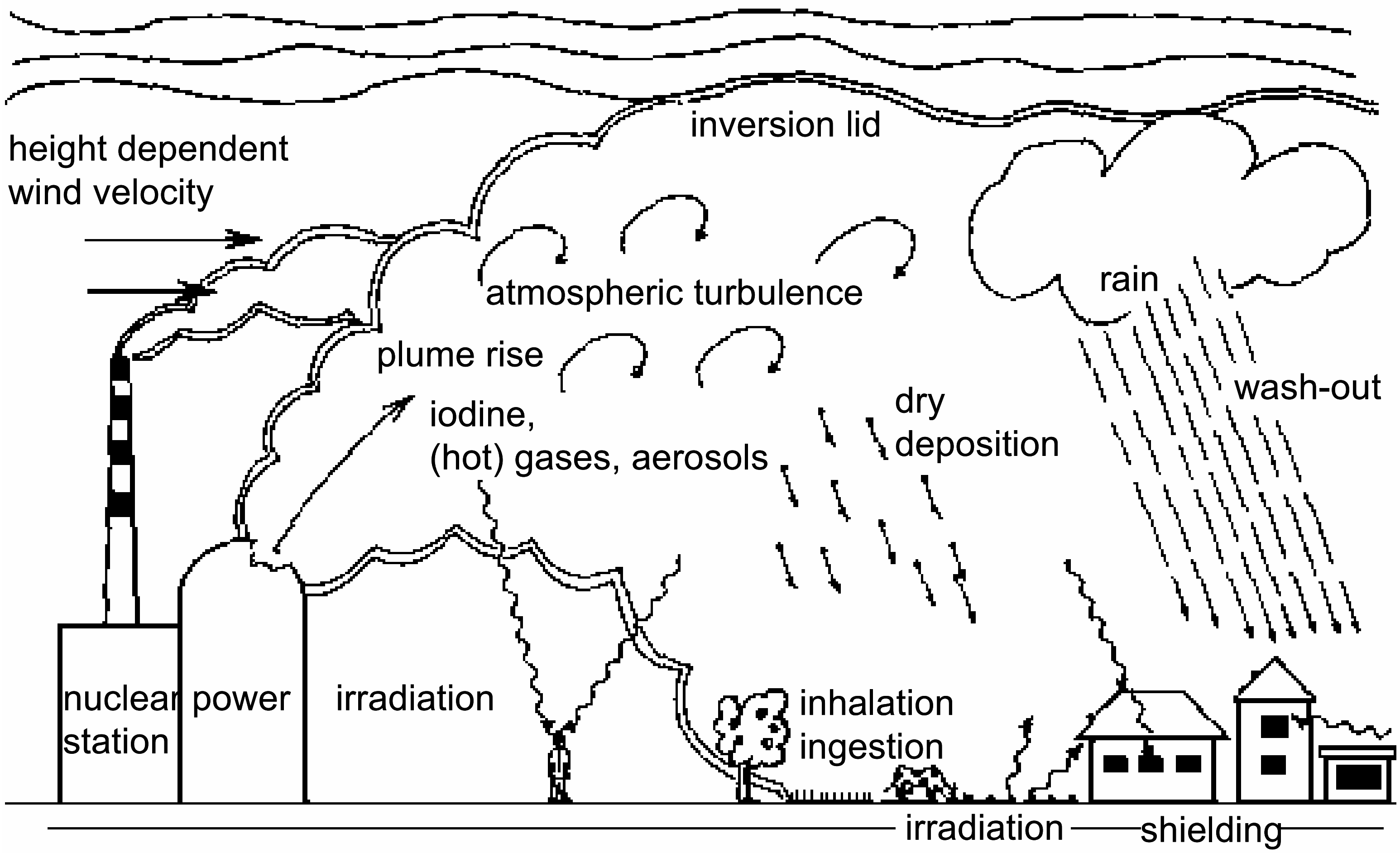
$$C(x,y,z,t) = \frac{Q}{(2\pi)^{\frac{3}{2}} \cdot \sigma_x \sigma_y \sigma_z} \cdot \exp\left(-\frac{(x-ut)^2}{2 \cdot \sigma_x^2}\right) \cdot \exp\left(-\frac{y^2}{2 \cdot \sigma_y^2}\right) \cdot \left\{\exp\left(-\frac{(z-H)^2}{2 \cdot \sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2 \cdot \sigma_z^2}\right)\right\}$$

C: concentration
Q: puff-release term
$\sigma_{x,y,z}$: diffusion parameters
t: transport time

Stability Classes: Shape of Plume and Temperature Profile (black: adiabatic)



Atmospheric Dispersion Phenomena and Exposure Pathways



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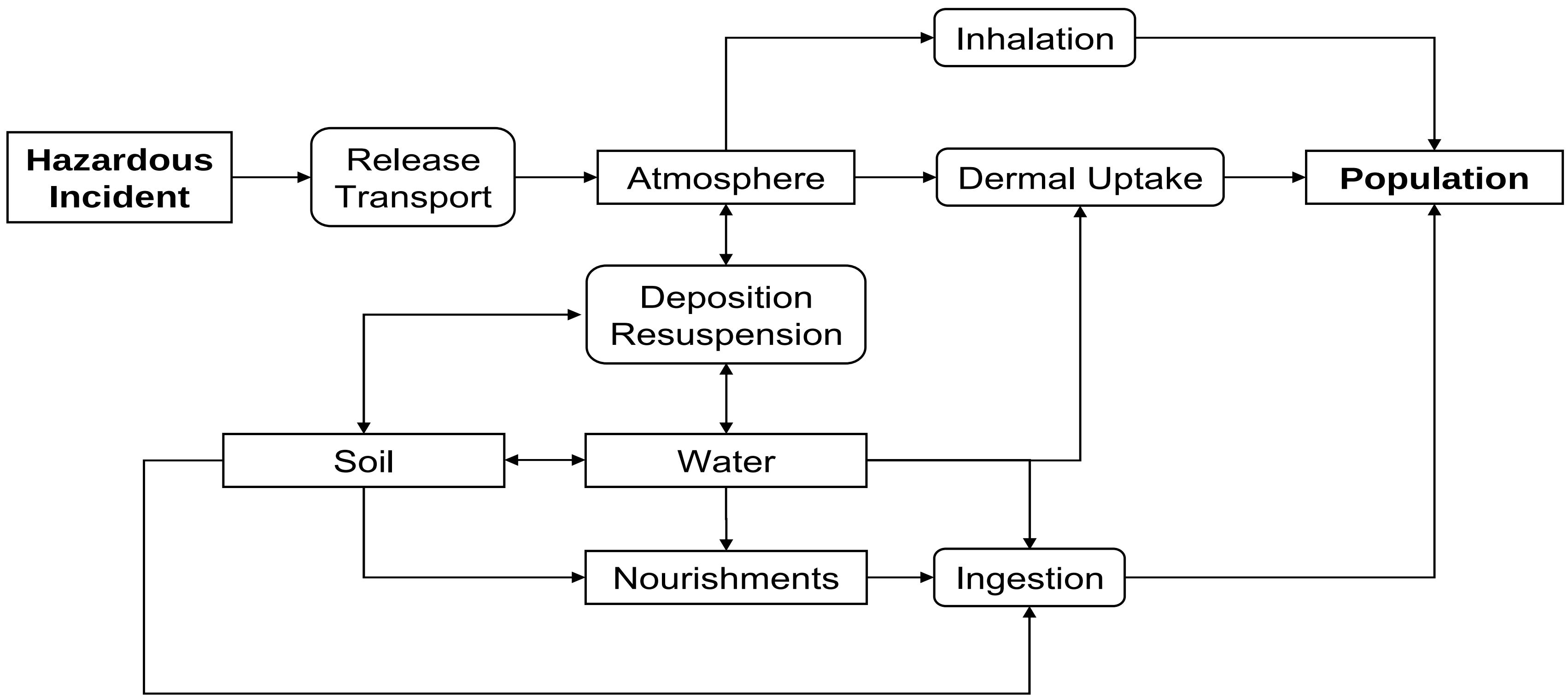
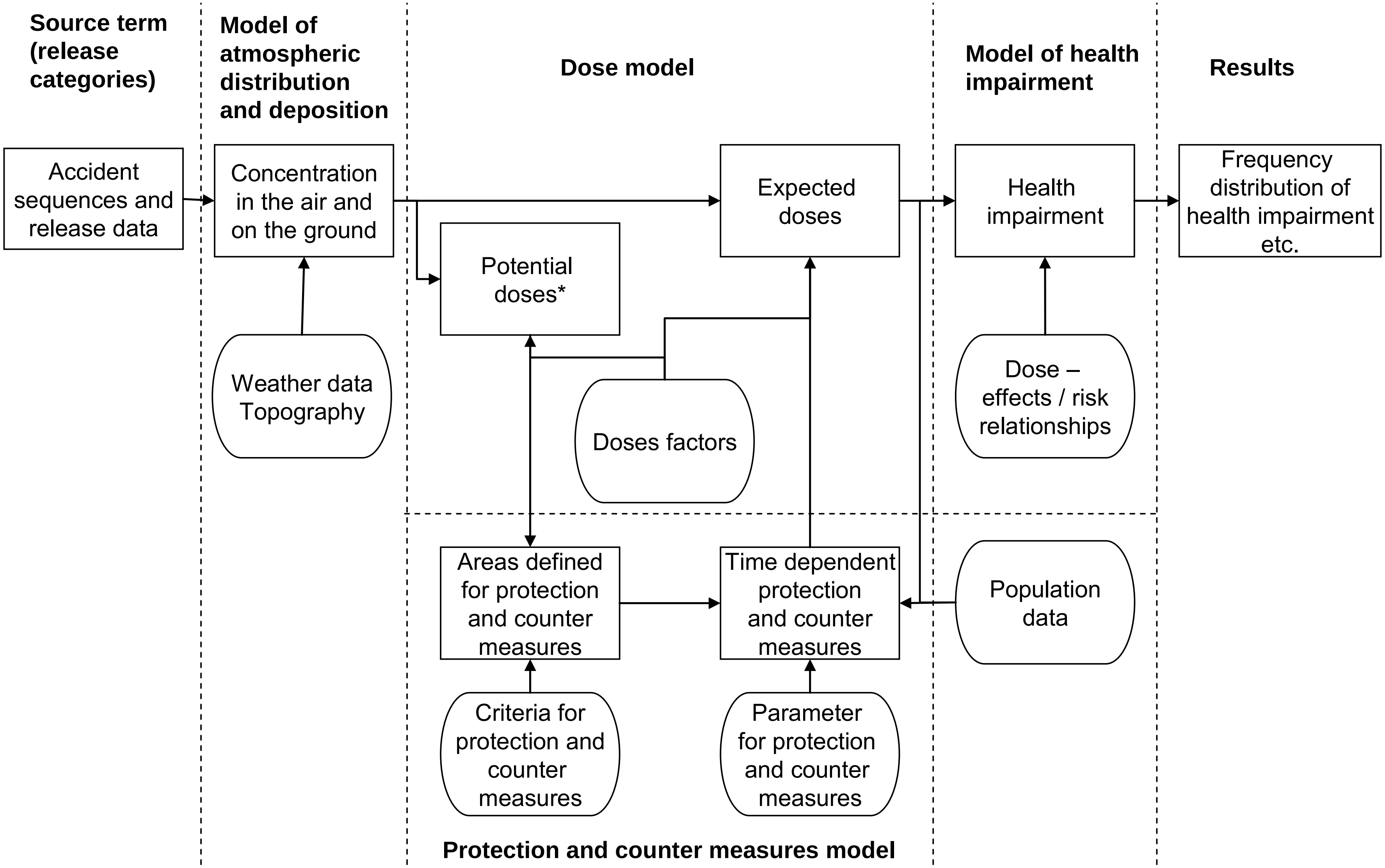
Exposure paths from source to population after atmospheric release of radionuclides





* Permanent stay (exposure) in the open assumed

Exposure to Radioactivity: Basic terms and units

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.

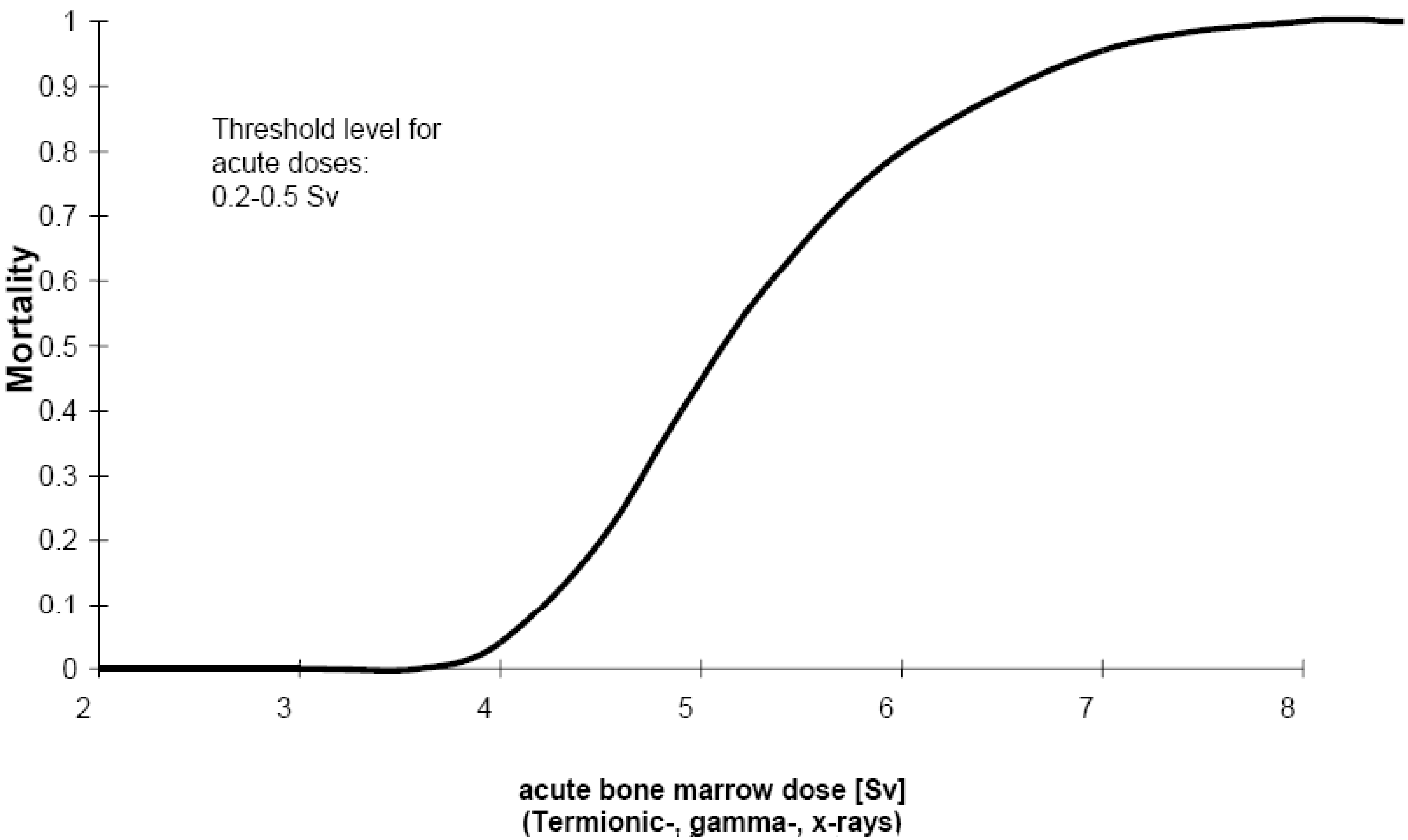
The $\mathbf{LD_{50}}$ lays around **4 to 5 Sv** (400-500 rem).

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

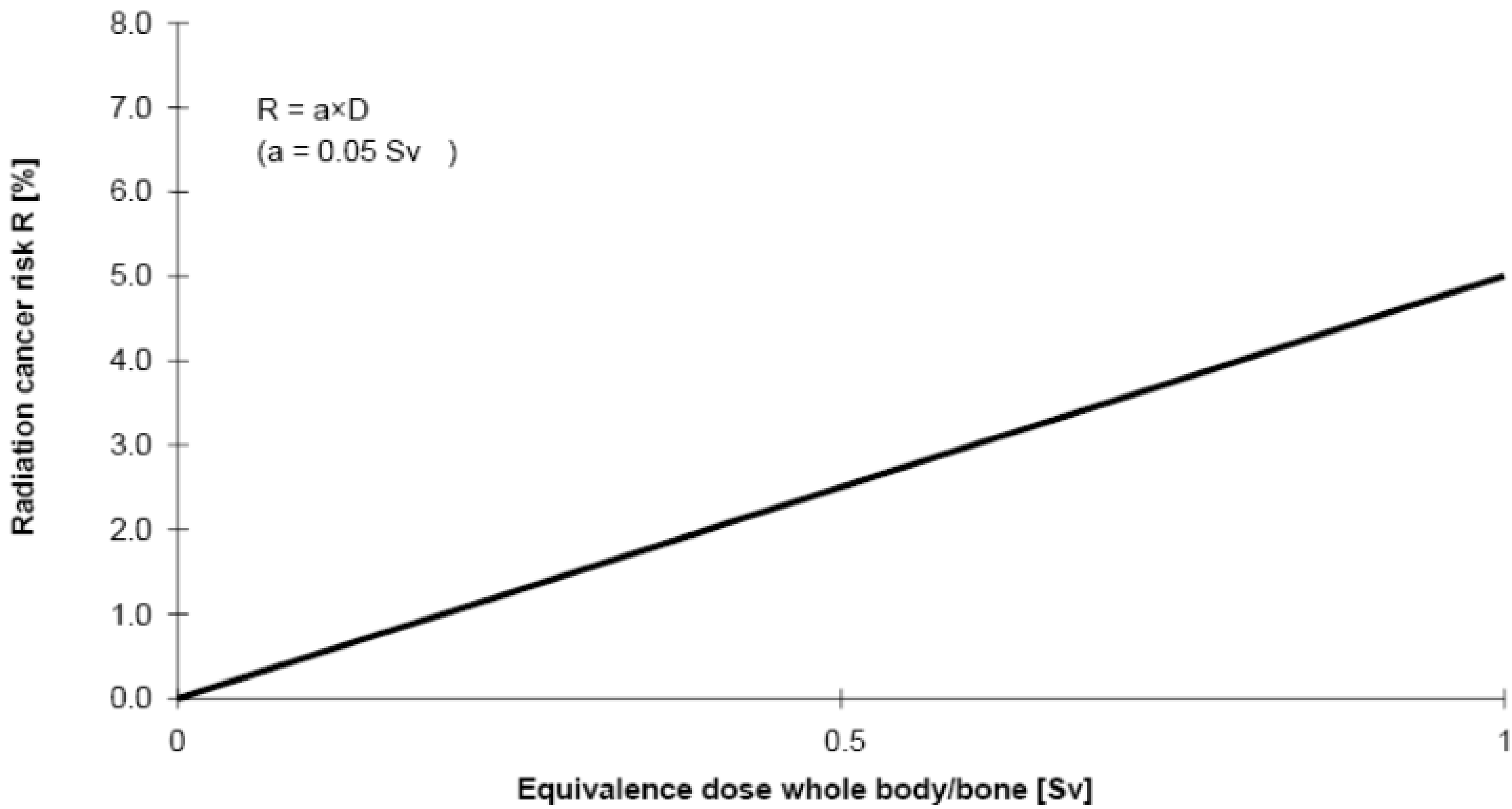
Stochastic radiation damage (Spätschäden):

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



Longterm effects of dose radiation (linear dose-effect relationship)



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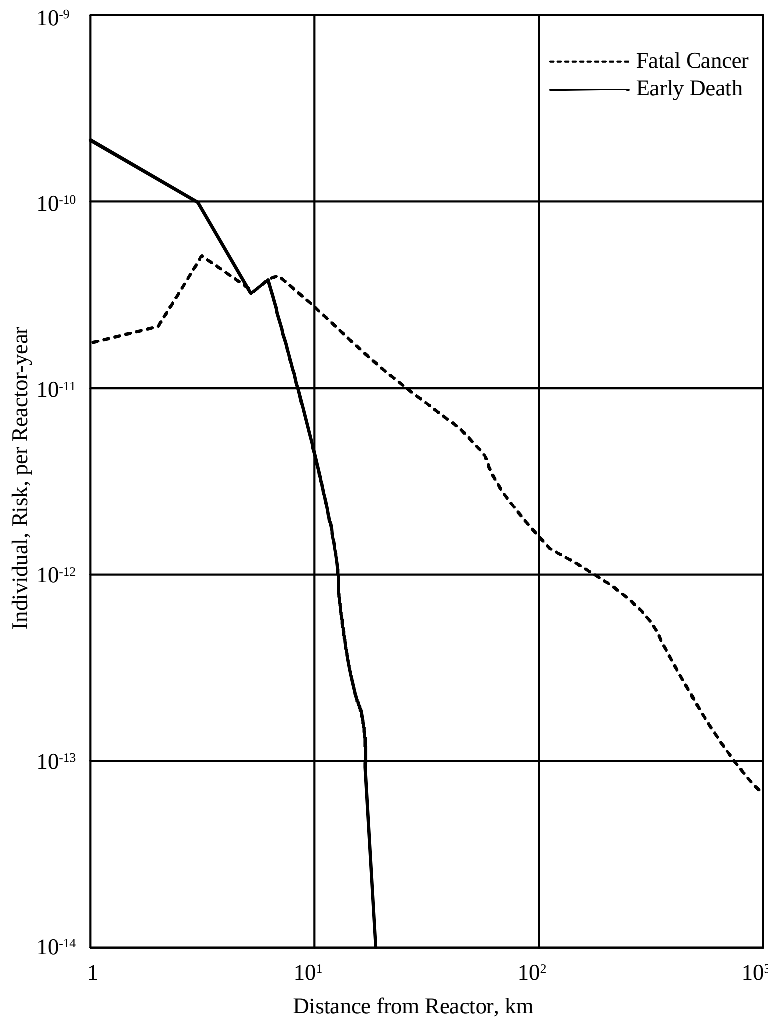
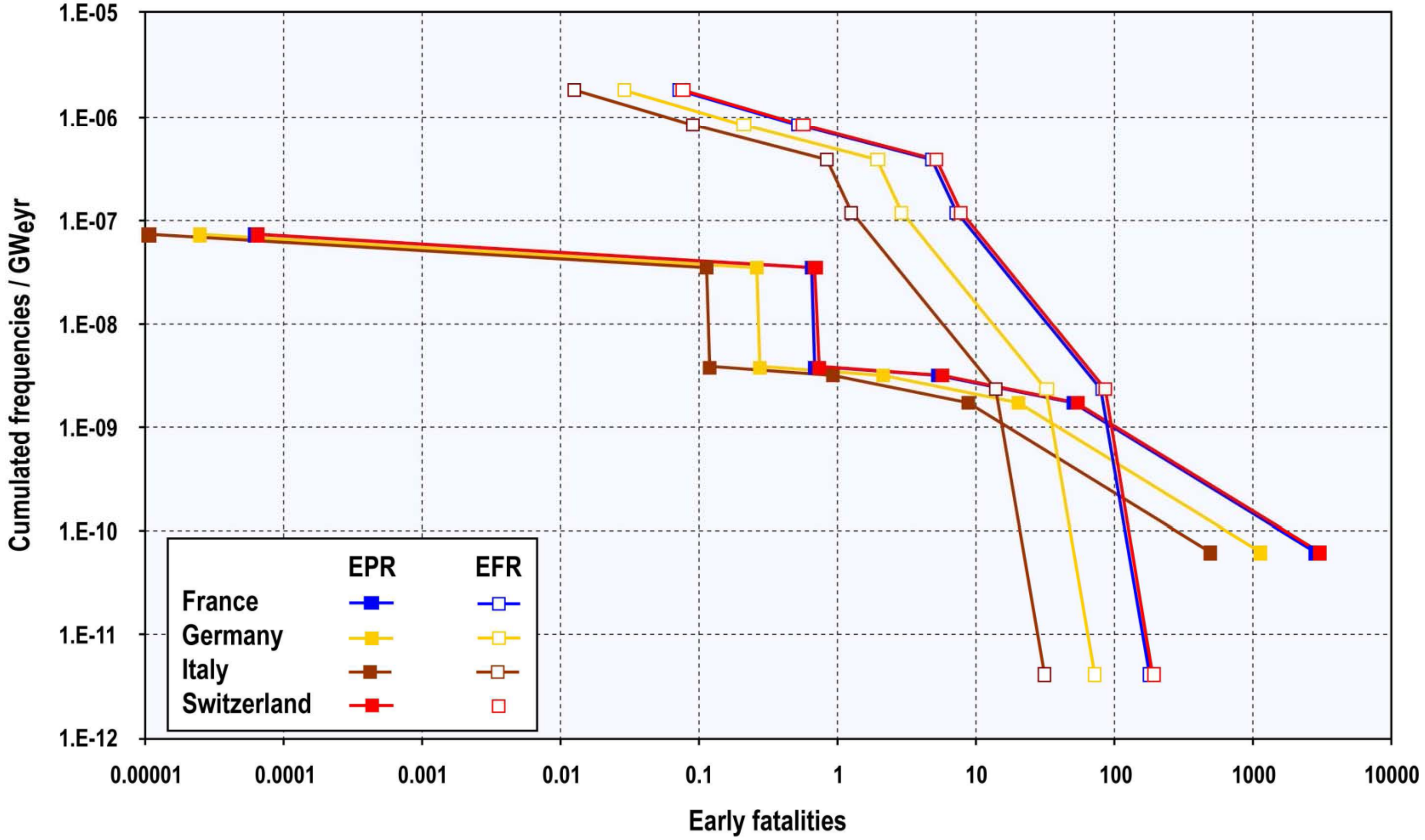
Individual Mortality Risks from Potential Degraded Core Accidents at Sizewell B

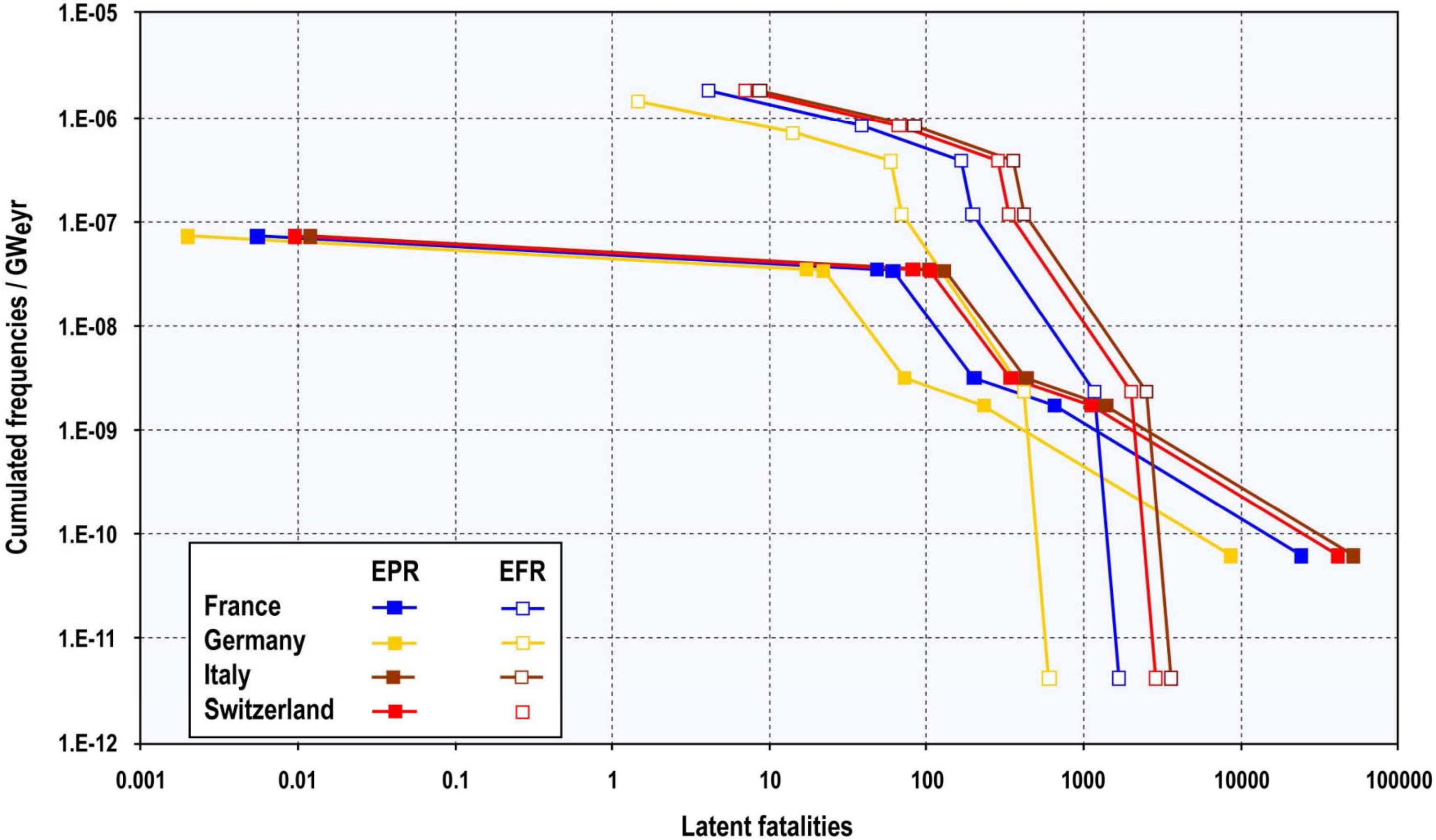


Frequency-Consequence Curve for early Fatalities



EPR and EFR technologies in four countries as defined in the NEEDS technology set; generic source term and 6 release categories; dose-acute effect- relationship with 0.2 – 0.5 threshold value

Frequency-Consequence Curve for Latent Fatalities



EPR and EFR in four countries as defined in the NEEDS technology set; generic source term and 6 release categories; linear dose-stochastic risk- relationship