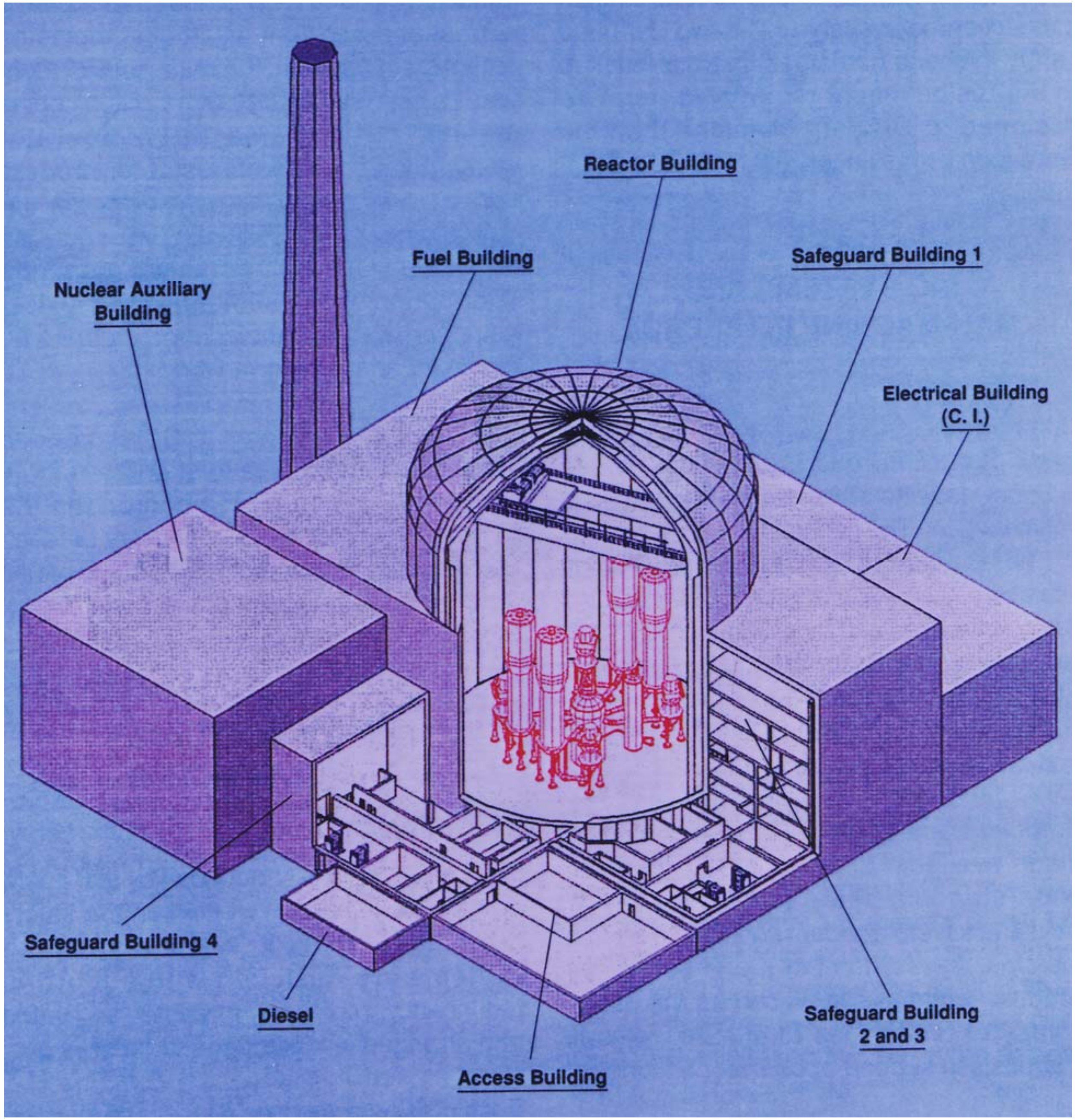
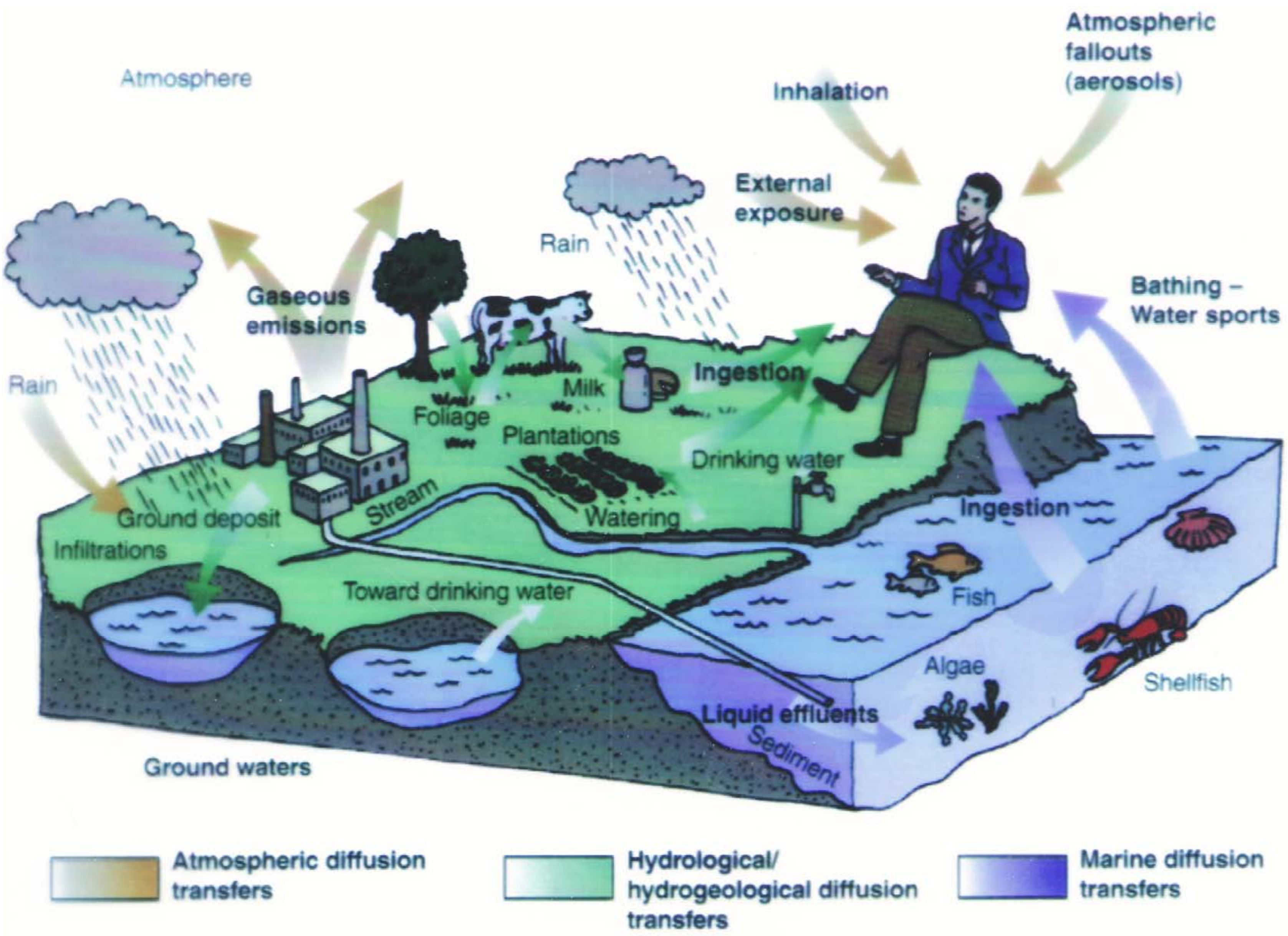
Nuclear Reactor Safety (LWRs) in the 21st Century

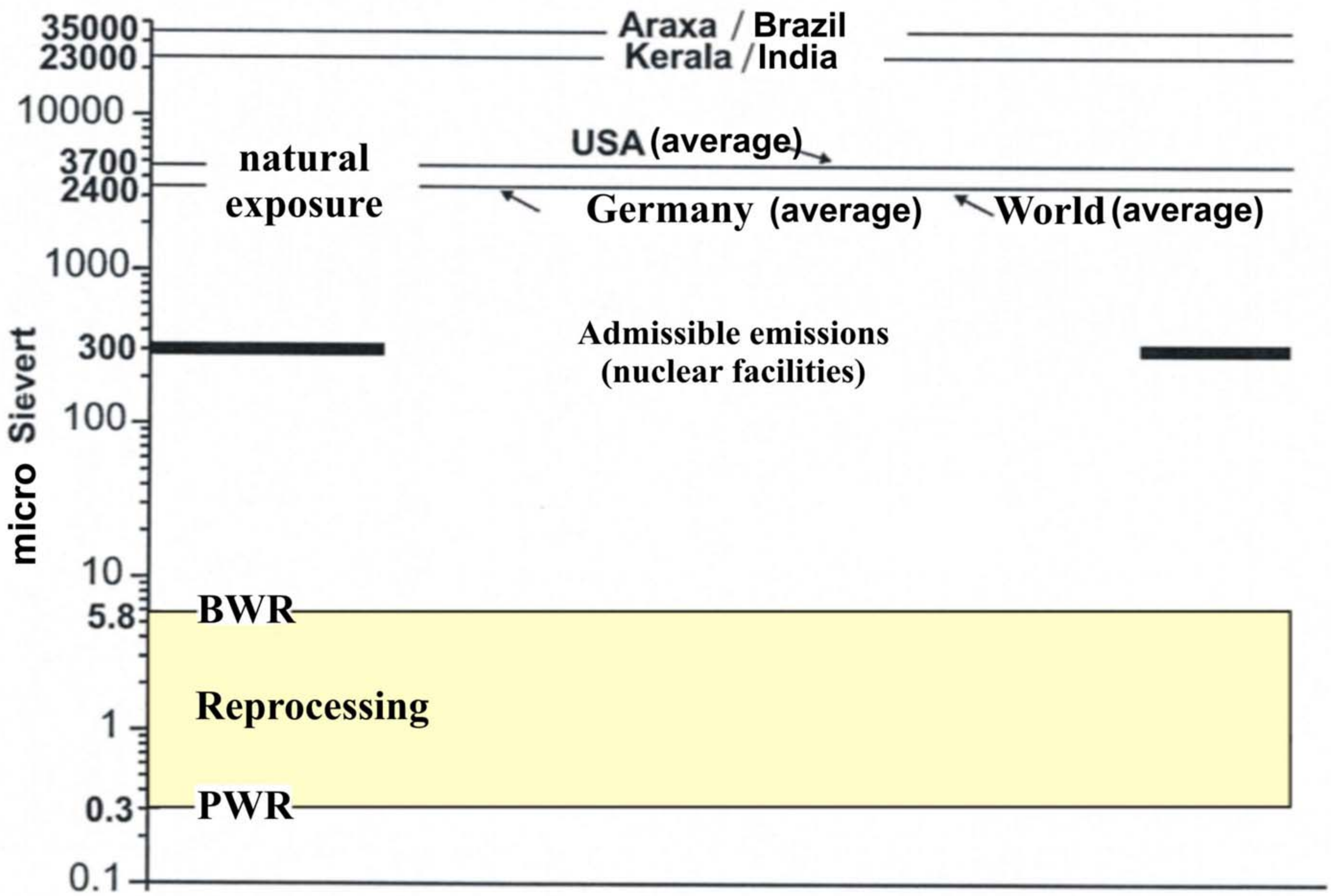
G. Kessler


Reactor Building
Fuel Building
Safeguard Building 1
Nuclear Auxiliary Building
Electrical Building (C. I.)
Safeguard Building 4
Diesel
Access Building
Safeguard Building 2 and 3

- Radioactivity release at normal operation

- Accidental Risk

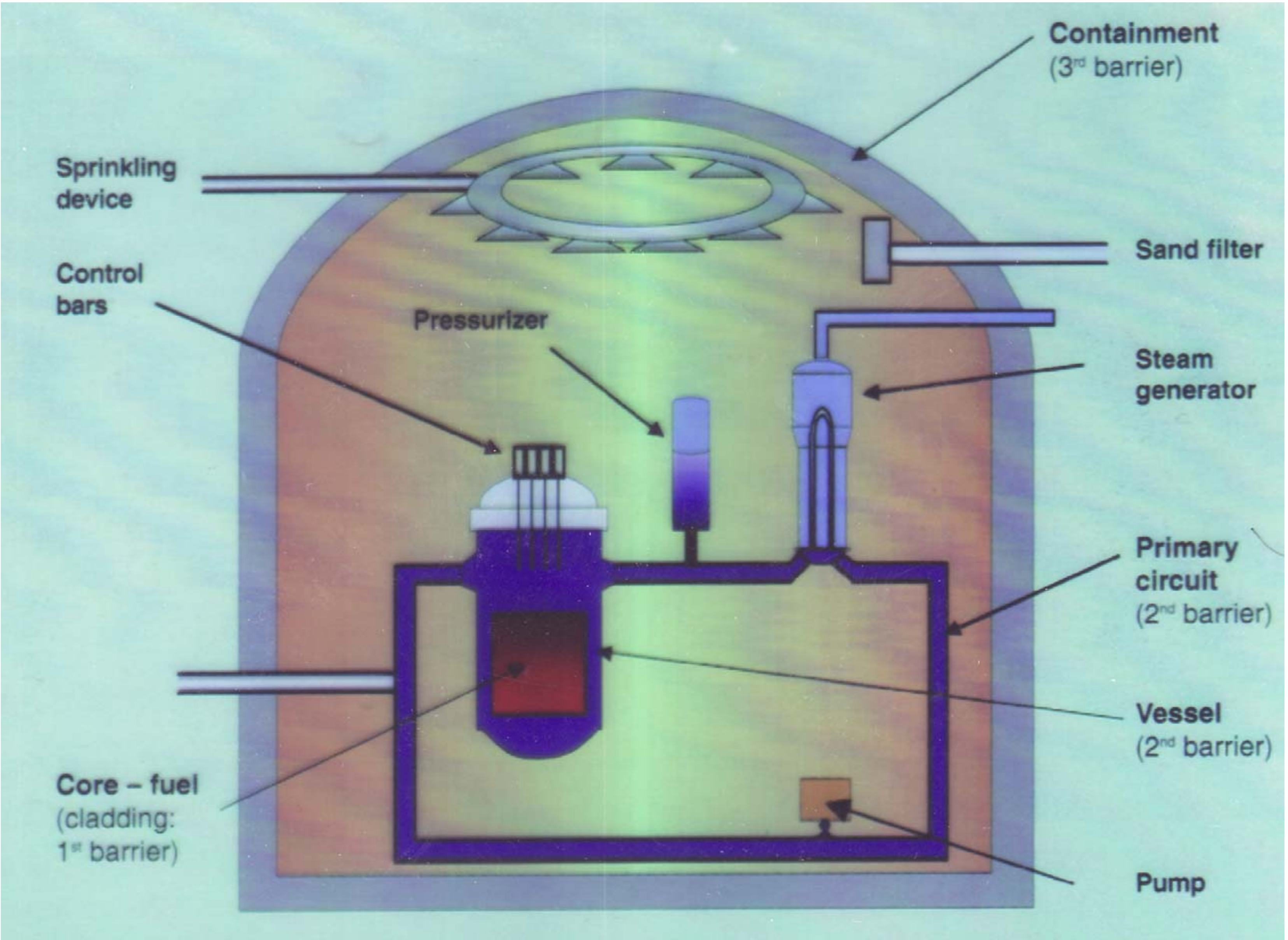

Atmosphere
Atmospheric fallouts (aerosols)
Inhalation
External exposure
Rain
Gaseous emissions
Bathing – Water sports
Ingestion
Milk
Foliage
Plantations
Drinking water
Rain
Stream
Watering
Ground deposit
Infiltrations
Ingestion
Fish
Toward drinking water
Algae
Shellfish
Liquid effluents
Sediment
Ground waters
Atmospheric diffusion transfers
Hydrological/ hydrogeological diffusion transfers
Marine diffusion transfers


Araxa / Brazil
Kerala / India
USA (average)
natural exposure
Germany (average)
World (average)
Admissible emissions (nuclear facilities)
BWR
Reprocessing
PWR
micro Sievert
35000
23000
10000
3700
2400
1000
300
100
10
5.8
1
0.3
0.1

Total : $\approx 10^{10}$ Ci oder $\approx 3 \cdot 10^{20}$ Bq

Isotope	$T_{1/2}$	Ci	Bq
H-3	12,4 a	$4 \cdot 10^{4}$	$1 \cdot 10^{15}$
Kr-85	10,7 a	$6 \cdot 10^{5}$	$2 \cdot 10^{16}$
I-129	$1{,}6 \cdot 10^{7}$ a	3	$1 \cdot 10^{11}$
I-131	8 d	$8 \cdot 10^{7}$	$3 \cdot 10^{18}$
I-133	21 h	$2 \cdot 10^{8}$	$6 \cdot 10^{18}$
Cs-134	2,1 a	$1 \cdot 10^{7}$	$4 \cdot 10^{17}$
Cs-137	30 a	$1 \cdot 10^{7}$	$3 \cdot 10^{17}$

Radioactivity-inventory at reactor core
(1300 MWe, 40,000 MWd/t)

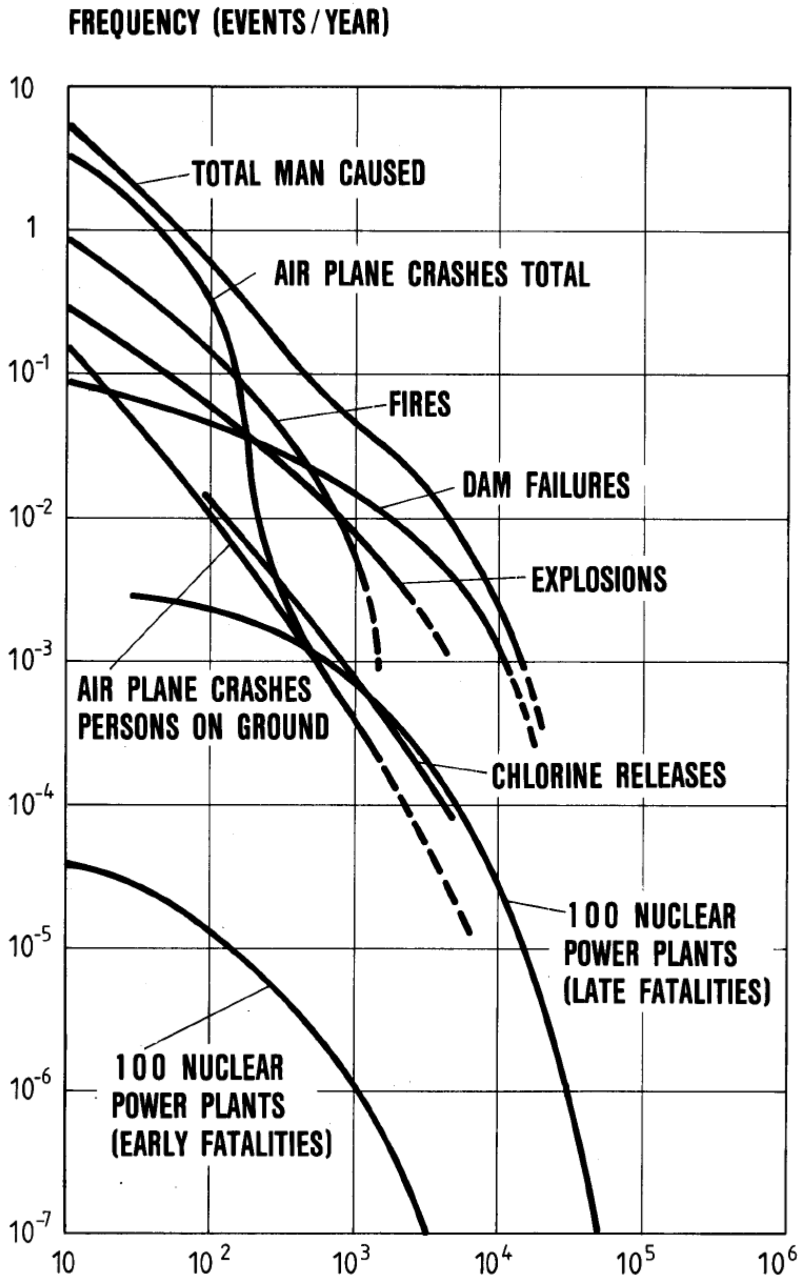

Containment
(3rd barrier)
Sprinkling
device
Sand filter
Control
bars
Pressurizer
Steam
generator
Primary
circuit
(2nd barrier)
Vessel
(2nd barrier)
Core – fuel
(cladding:
1st barrier)
Pump

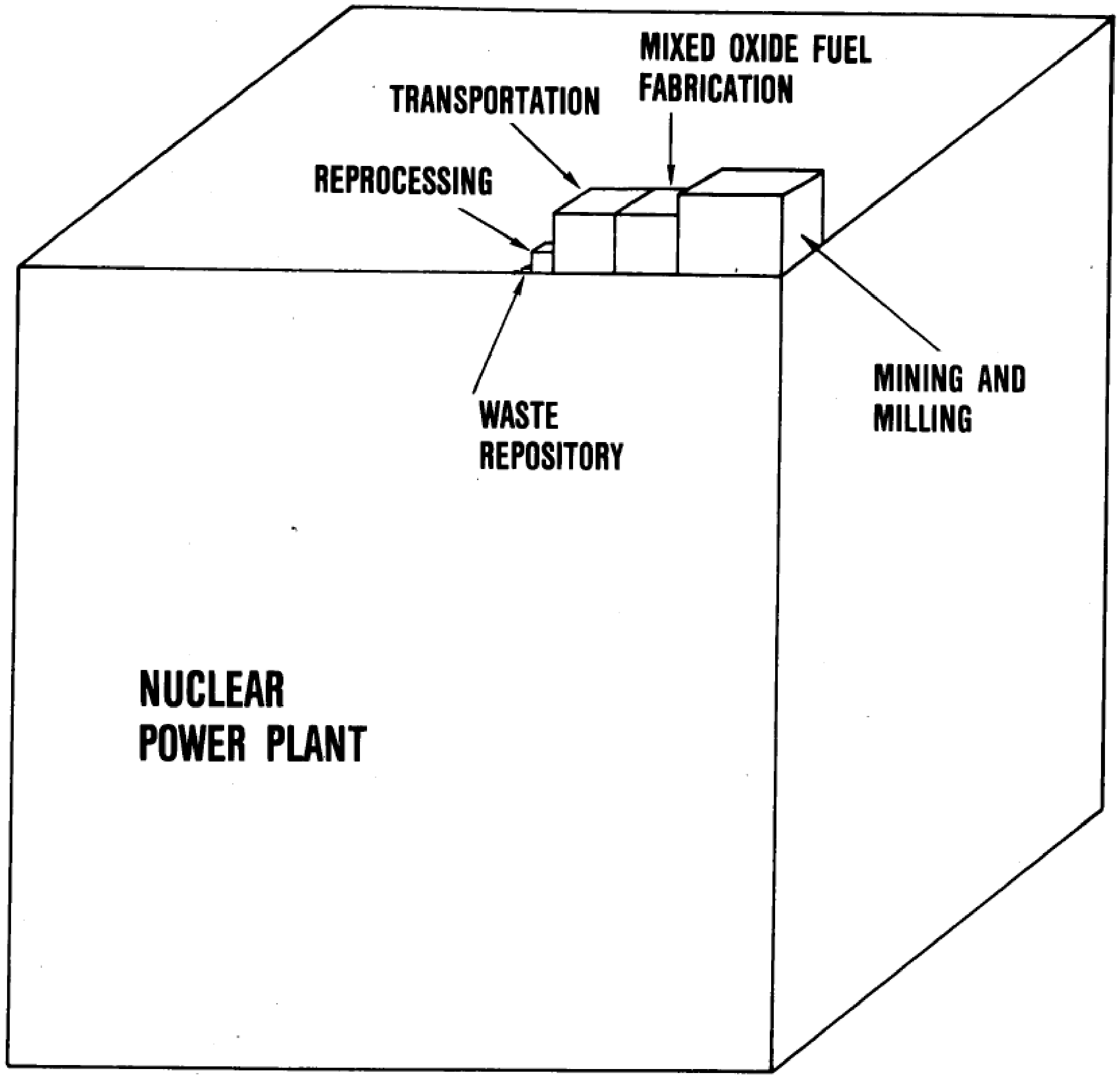
Safety Design Principles (LWRs)

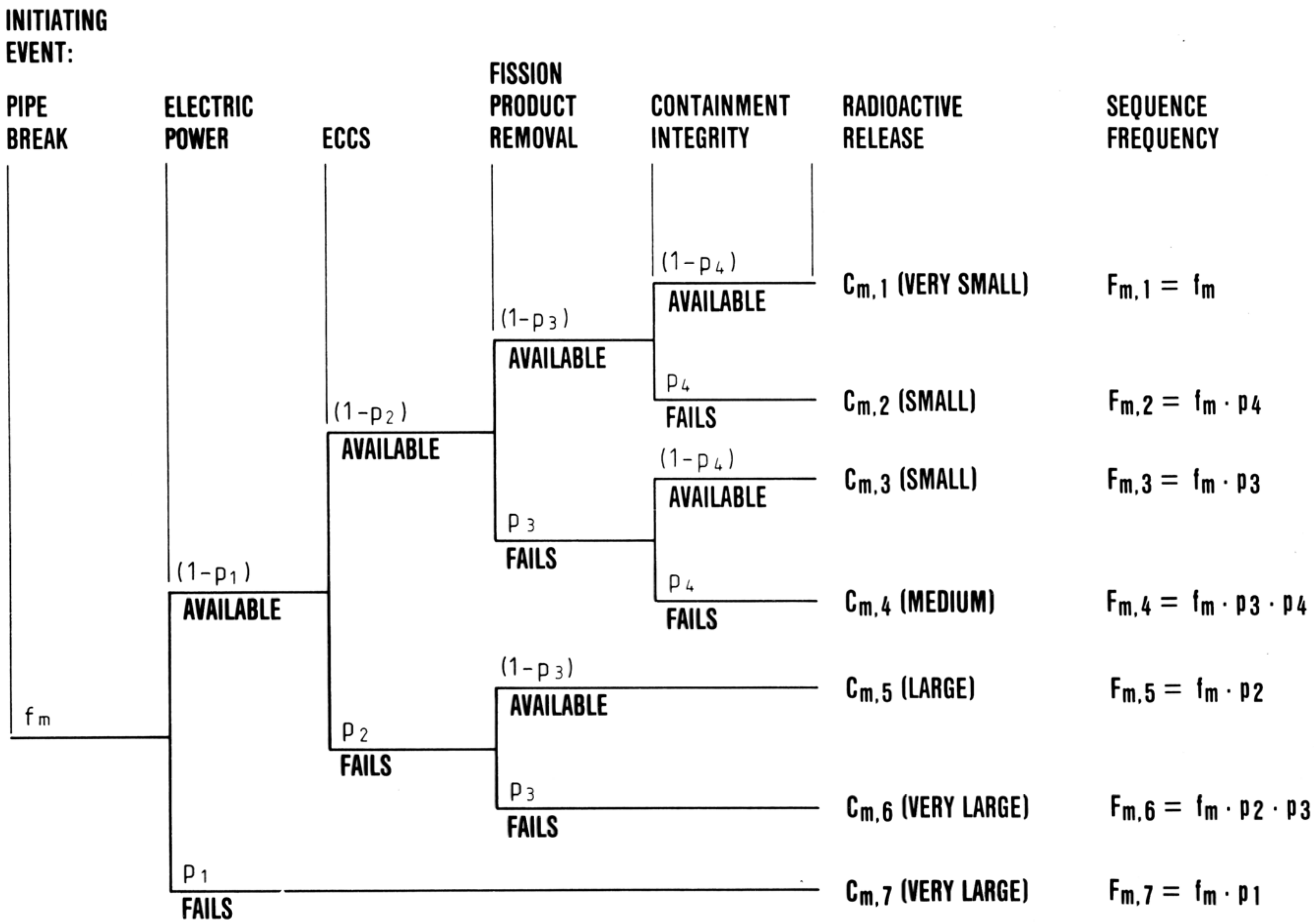
- negative doppler coeffcient
- negative coolant void coefficient
- safe control and shut down by neutron poison rods or borated water
- leak before rupture criterion
- safety valves
- emergency power supply (diesel generators, gas turbines batteries)
- emergency cooling systems
- emergency feedwater systems
- principles of redundancy and diversity
- aerosol filters
- barrier system against radioactivity release
- outer containment barrier

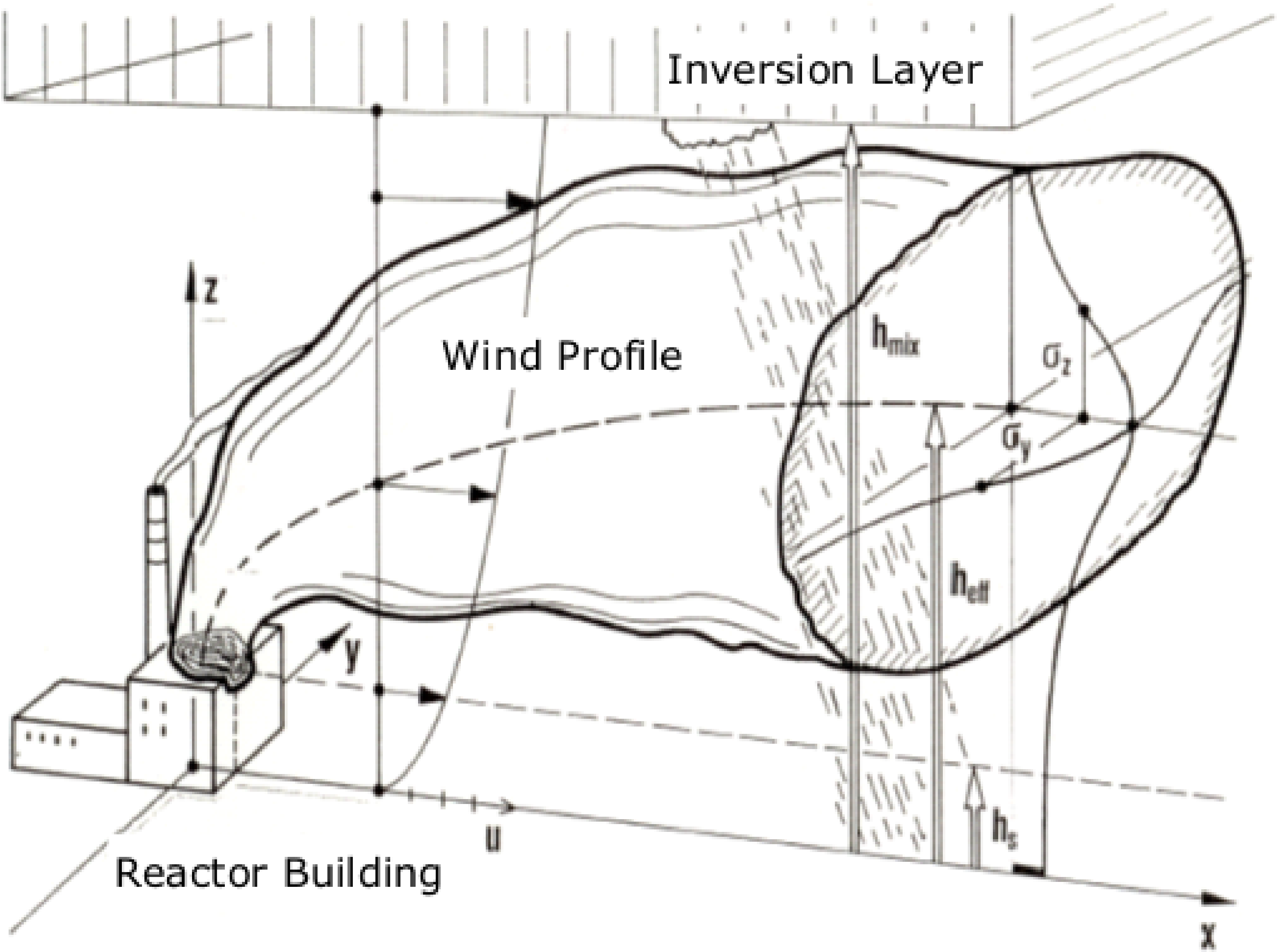
Probabilistic Risk Analysis

WASH-1400 (1982)

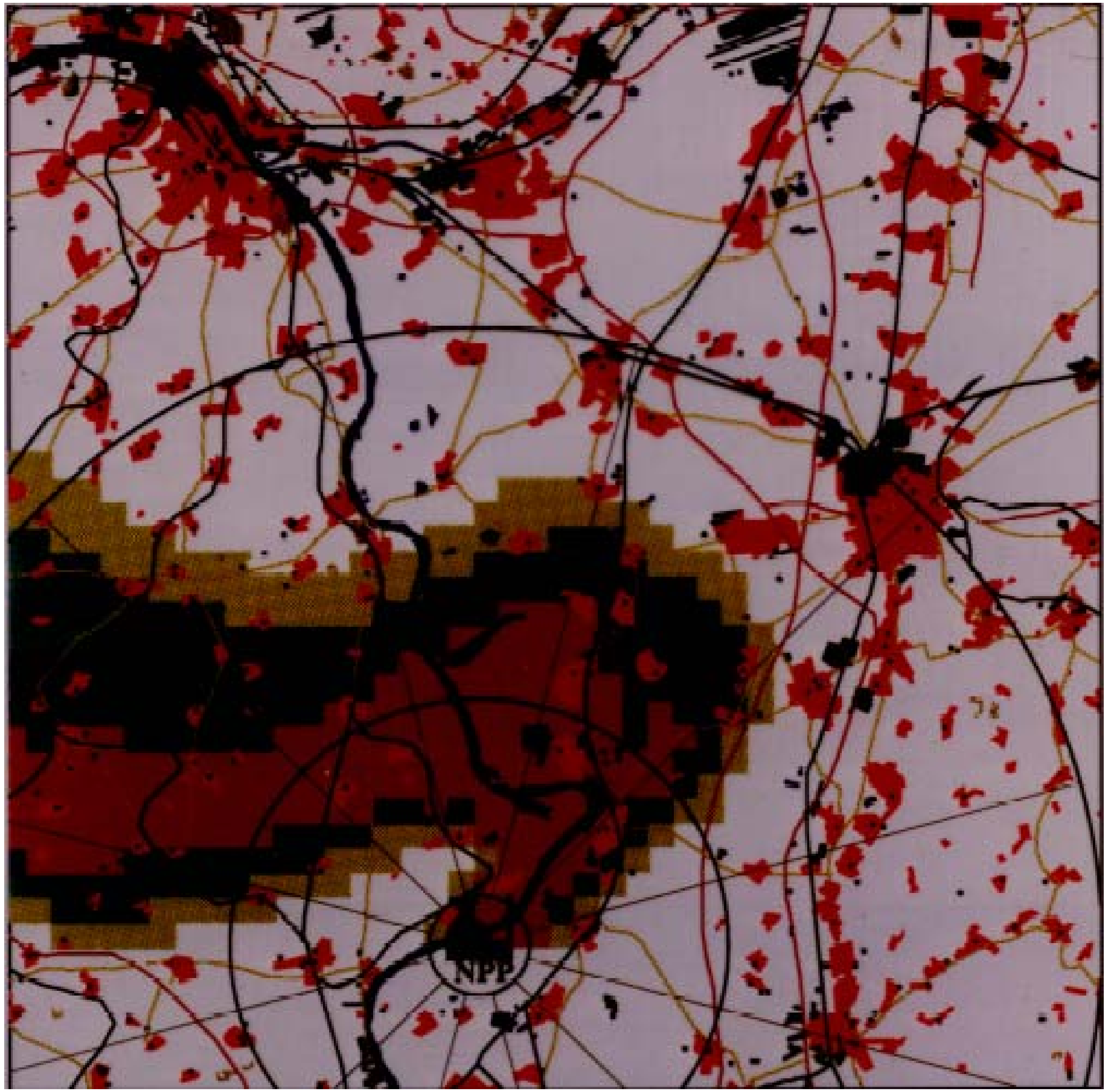

FREQUENCY (EVENTS / YEAR)
10
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
TOTAL MAN CAUSED
AIR PLANE CRASHES TOTAL
FIRES
DAM FAILURES
EXPLOSIONS
AIR PLANE CRASHES PERSONS ON GROUND
CHLORINE RELEASES
100 NUCLEAR POWER PLANTS (LATE FATALITIES)
100 NUCLEAR POWER PLANTS (EARLY FATALITIES)
10
10 2
10 3
10 4
10 5
10 6


MIXED OXIDE FUEL FABRICATION
TRANSPORTATION
REPROCESSING
WASTE REPOSITORY
MINING AND MILLING
NUCLEAR POWER PLANT


INITIATING EVENT:
PIPE BREAK
ELECTRIC POWER
ECCS
FISSION PRODUCT REMOVAL
CONTAINMENT INTEGRITY
RADIOACTIVE RELEASE
SEQUENCE FREQUENCY
f_m
$(1-p_1)$
AVAILABLE
p_1
FAILS
$(1-p_2)$
AVAILABLE
p_2
FAILS
$(1-p_3)$
AVAILABLE
p_3
FAILS
$(1-p_3)$
AVAILABLE
p_3
FAILS
$(1-p_4)$
AVAILABLE
p_4
FAILS
$(1-p_4)$
AVAILABLE
p_4
FAILS
$C_{m,1}$ (VERY SMALL)
$C_{m,2}$ (SMALL)
$C_{m,3}$ (SMALL)
$C_{m,4}$ (MEDIUM)
$C_{m,5}$ (LARGE)
$C_{m,6}$ (VERY LARGE)
$C_{m,7}$ (VERY LARGE)
$F_{m,1} = f_m$
$F_{m,2} = f_m \cdot p_4$
$F_{m,3} = f_m \cdot p_3$
$F_{m,4} = f_m \cdot p_3 \cdot p_4$
$F_{m,5} = f_m \cdot p_2$
$F_{m,6} = f_m \cdot p_2 \cdot p_3$
$F_{m,7} = f_m \cdot p_1$



Inversion Layer
z
Wind Profile
h_{mix}
σ_z
σ_y
h_{eff}
y
u
h_s
Reactor Building
x



Sheltering Area – 0.005Sv

Evacuation Area – 0.1Sv

Evacuation Area – 0.3Sv

Evacuation Area – 0.5Sv

4 Hours Radiation Release

25% – Noble Gases

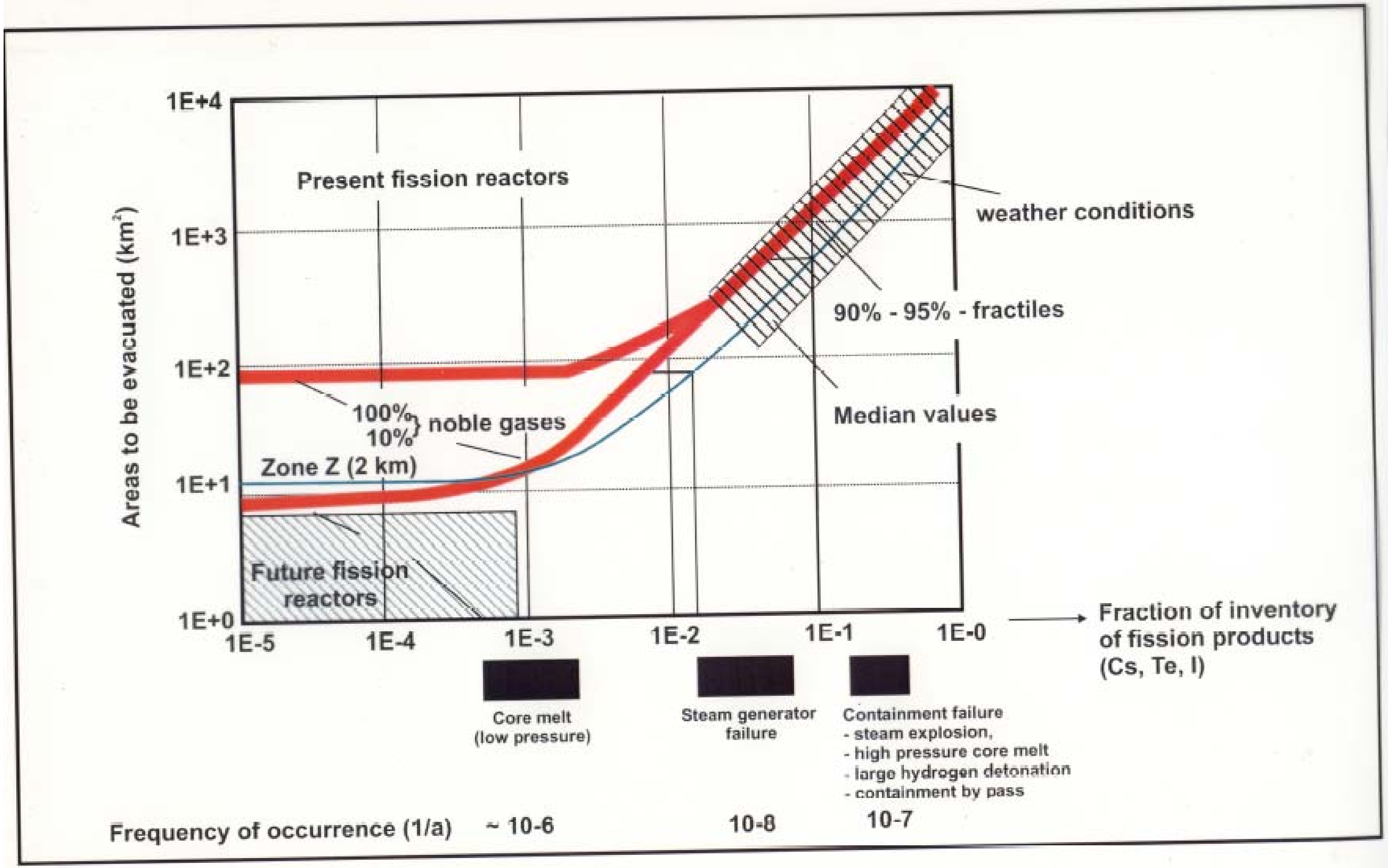
5% – Aerosols

Wind Velocities – 2.5m/s

RODOS Calculations

Action	Reference dose	Lower Reference value [mSv]	Upper Reference value [mSv]
Remain in house sheltering	Effective dose through inhalation and external radiation	5	50
	Lung and each individual organ	50	250
Evacuation	Effective dose through inhalation and external radiation	100	500
	Lung and individual organ	300	1500
Relocation	Effective dose through inhalation and external radiation	50	250
Food ban	Effective equivalent dose by ingestion over 1 year	5	50

Reference dose values for initiation of protection and countermeasures


1E+4
1E+3
1E+2
1E+1
1E+0
Areas to be evacuated (km²)
Present fission reactors
weather conditions
90% - 95% - fractiles
Median values
100%
10%
} noble gases
Zone Z (2 km)
Future fission reactors
1E-5
1E-4
1E-3
1E-2
1E-1
1E-0
Fraction of inventory of fission products (Cs, Te, I)
Core melt (low pressure)
Steam generator failure
Containment failure
- steam explosion,
- high pressure core melt
- large hydrogen detonation
- containment by pass
Frequency of occurrence (1/a)
~ 10-6
10-8
10-7

Amendment of GERMAN ATOMIC LAW (1994)

Future Fission reactors can only obtain a license for construction and operation , if they are built such that also …

severe accidents (core melt) do not lead to catastrophes or protection measures (evacuation, relocation) of the population outside the nuclear plant.

Radiological Objectives

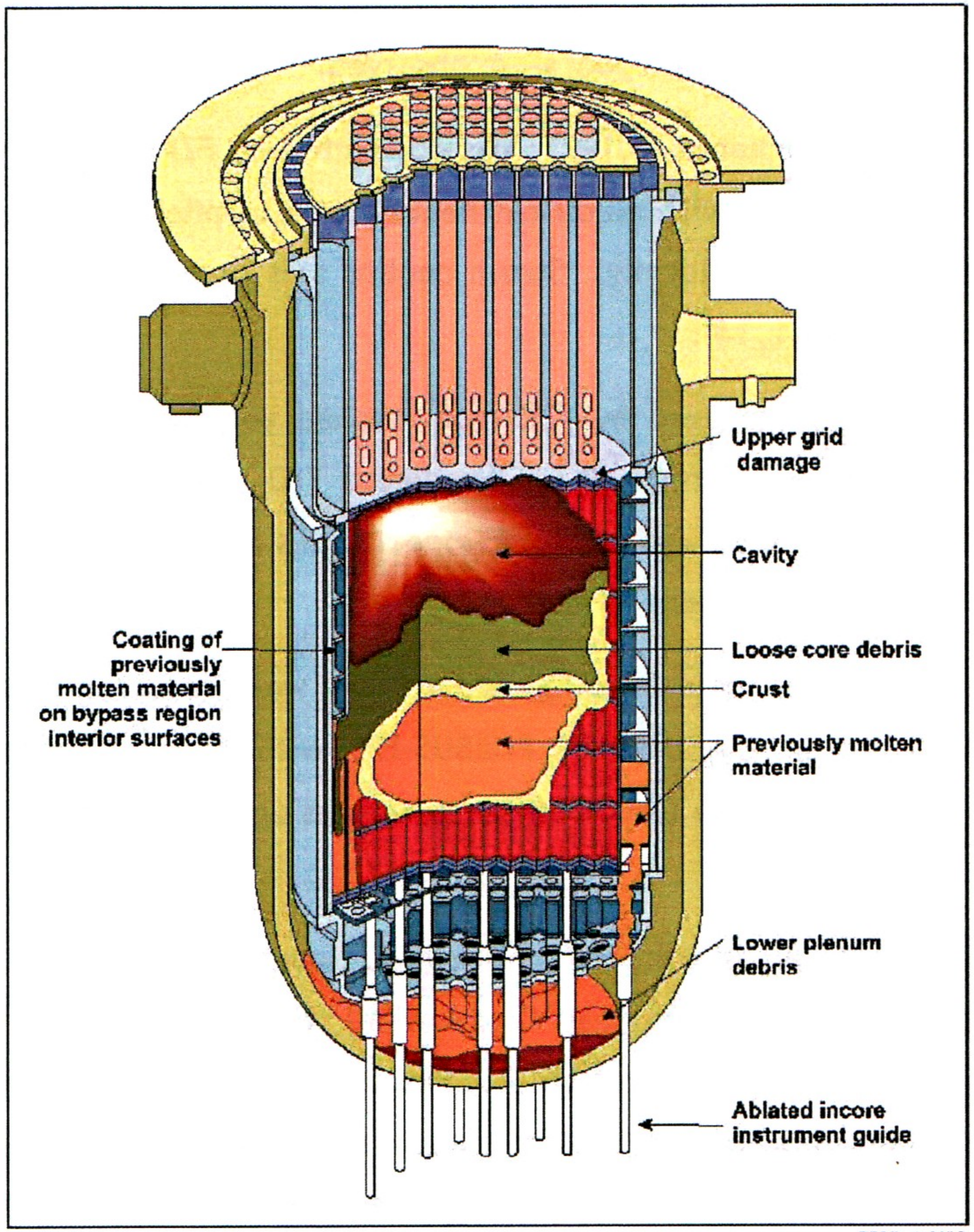
In case of severe accidents: only very limited protection measures

- limited sheltering only
- no evacuation outside the immediate vicinity of the plant
- no permanent relocation
- no long-term restrictions in food consumption

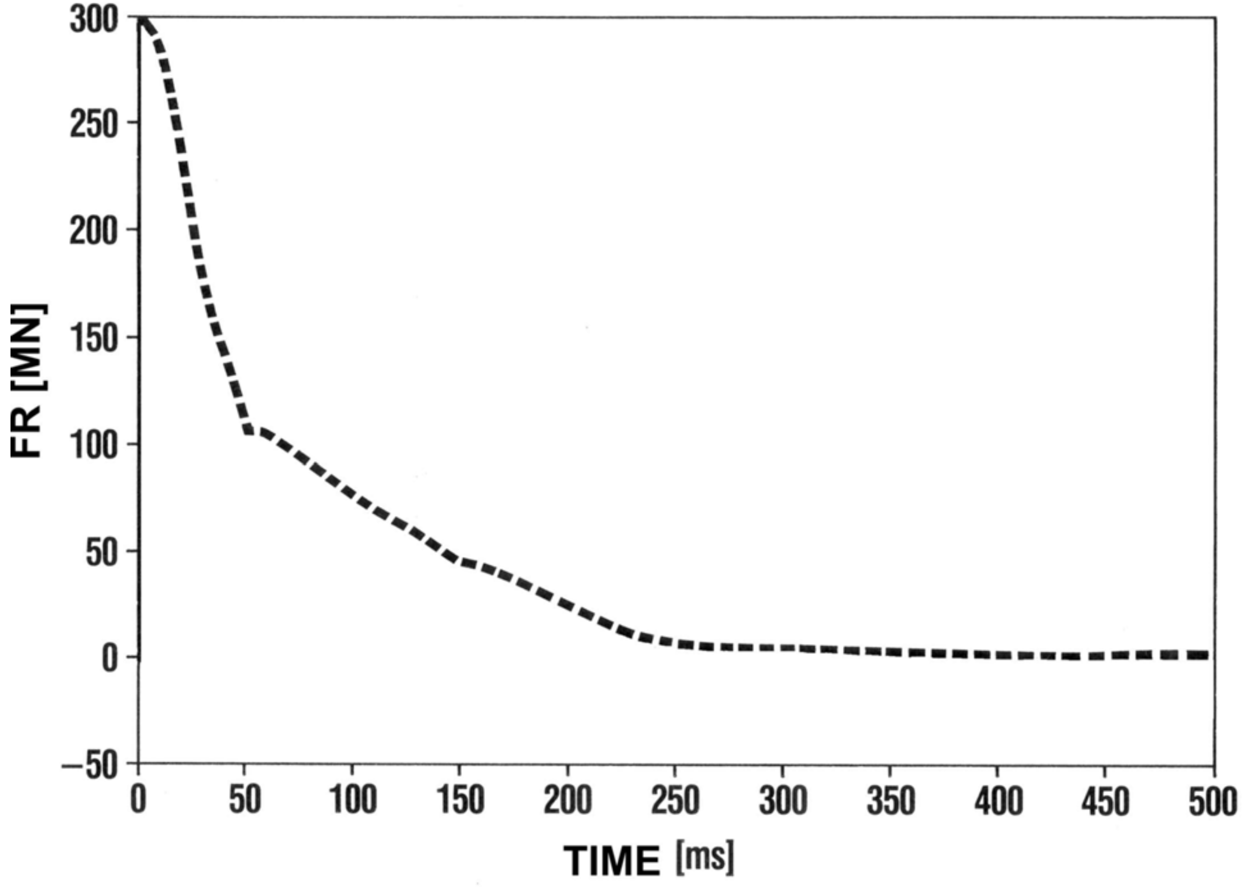
Largest radioactivity releases
after containment failure
caused by

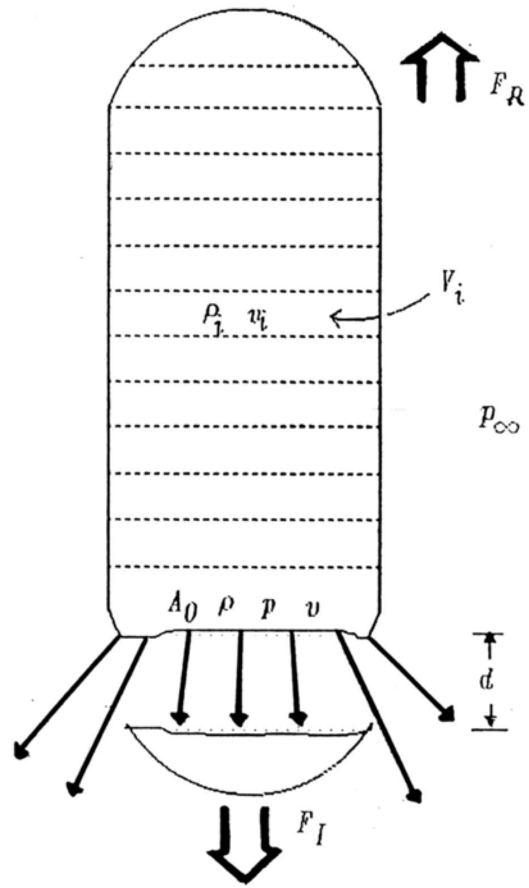
- steam explosion
- large hydrogen detonation
- high pressure core melt through
- containment bypass (pipes)

(These phenomena were assumed in Probabilistic Risk Analysis to lead to containment failures)



DCS/95 9486/LP


300
250
200
150
100
50
0
−50
FR [MN]
0
50
100
150
200
250
300
350
400
450
500
TIME [ms]


F_R
V_i
ρ_i v_i
p_∞
A_0 ρ p v
d
F_I

Result Analysis

High pressure melt through

- present structures around reactor pressure vessel hold 100 bar internal pressure

- structures can be reinforced to hold 155 bar internal pressure

- 2 high pressure safety valves can be opened within ½ h

(TMI-2 core did not melt through)

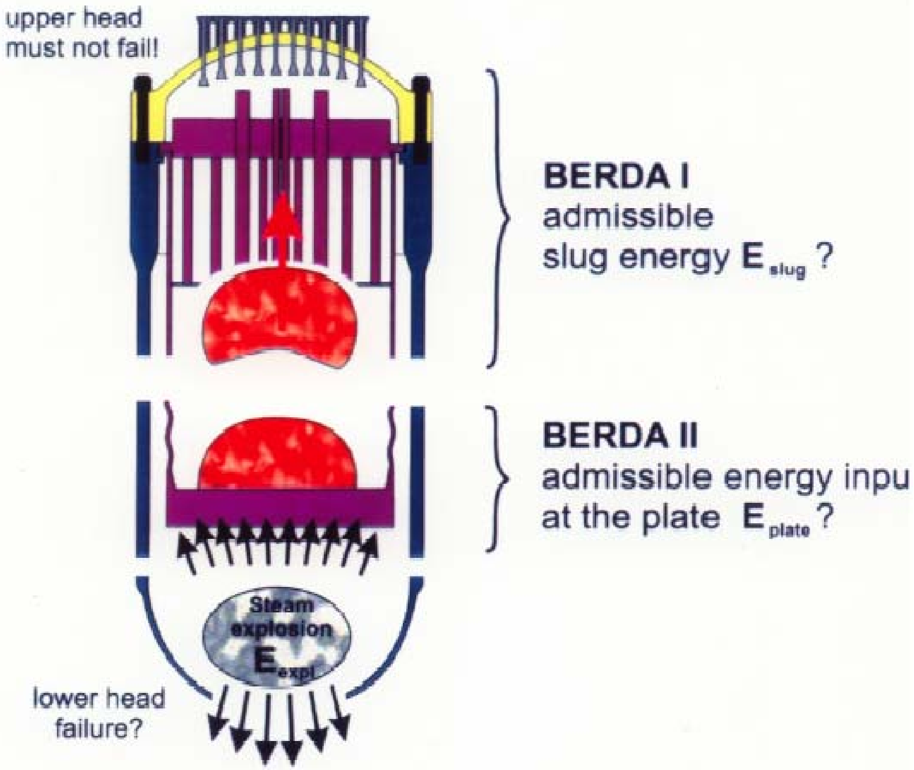
(High pressure coolant pipe could fail because of high steam temperatures)

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
Institut für Reaktorsicherheit

BERDA

Behaviour of the Reactor Pressure Vessel Head during a Postulated Steam Explosion

Investigation Program

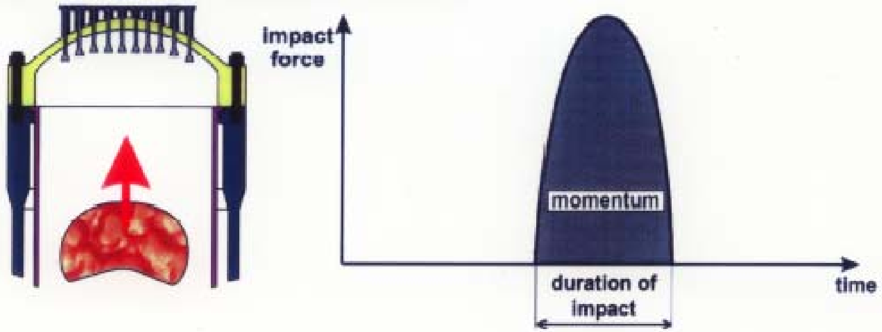


If $E_{expl} \leqq E_{plate}$, then upper head integrity is confirmed

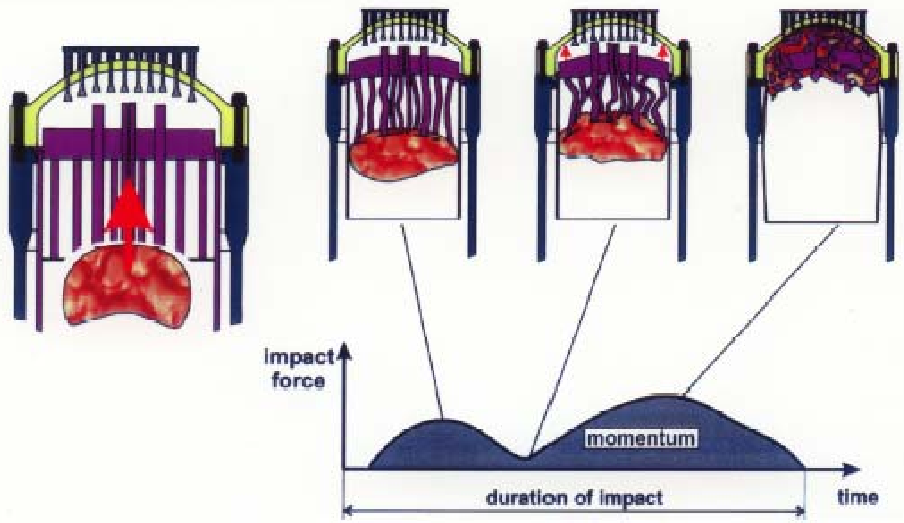
BERDA

Slug Impact Scenarios BERDA I

without upper internal structures

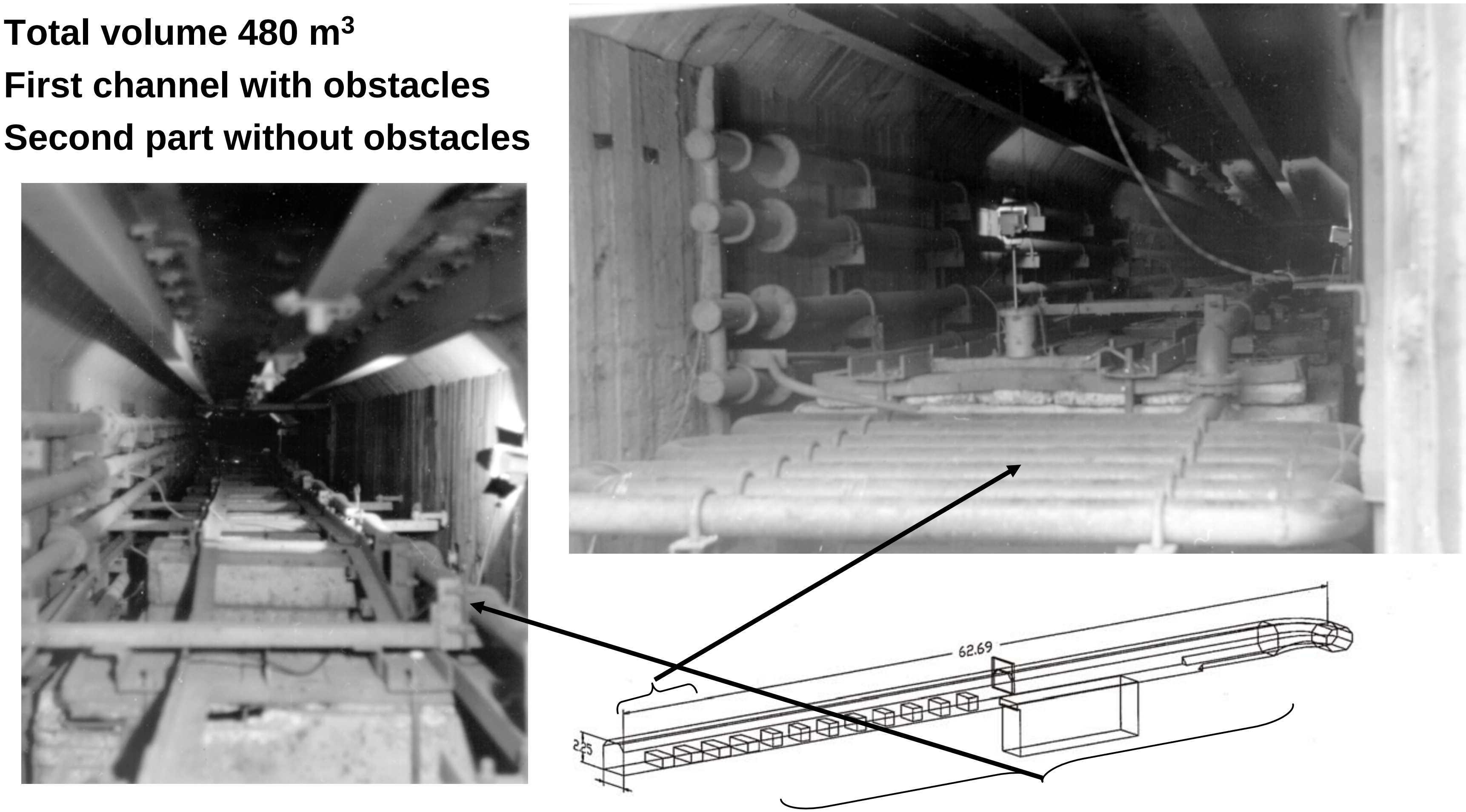


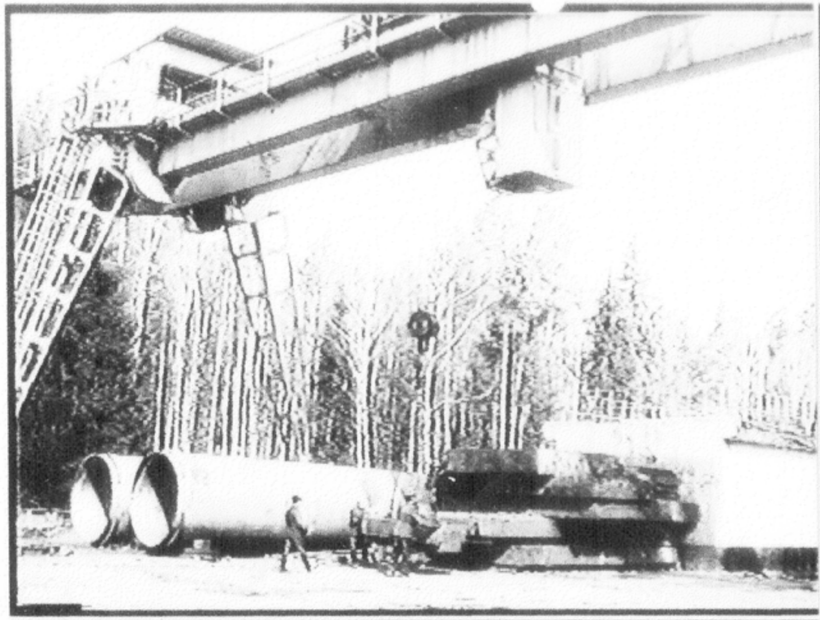
including upper internal structures

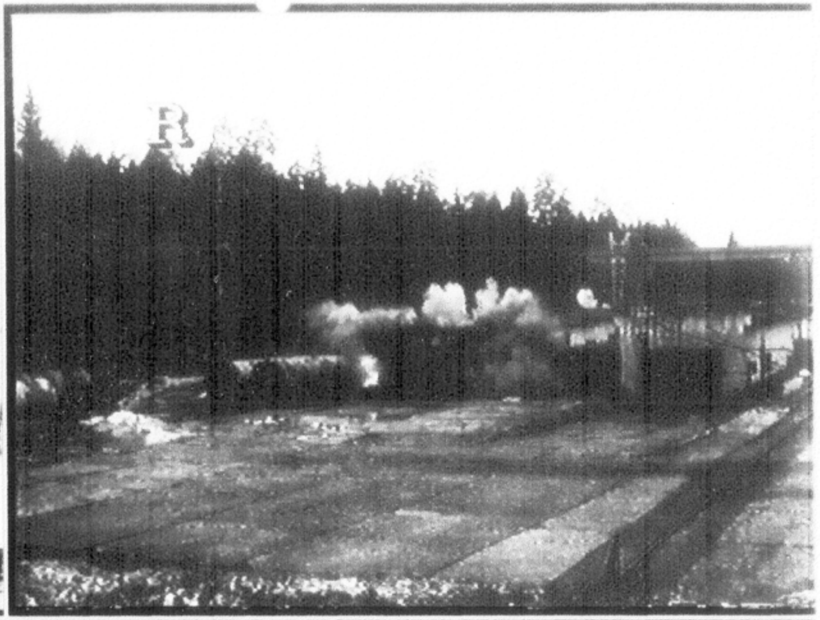


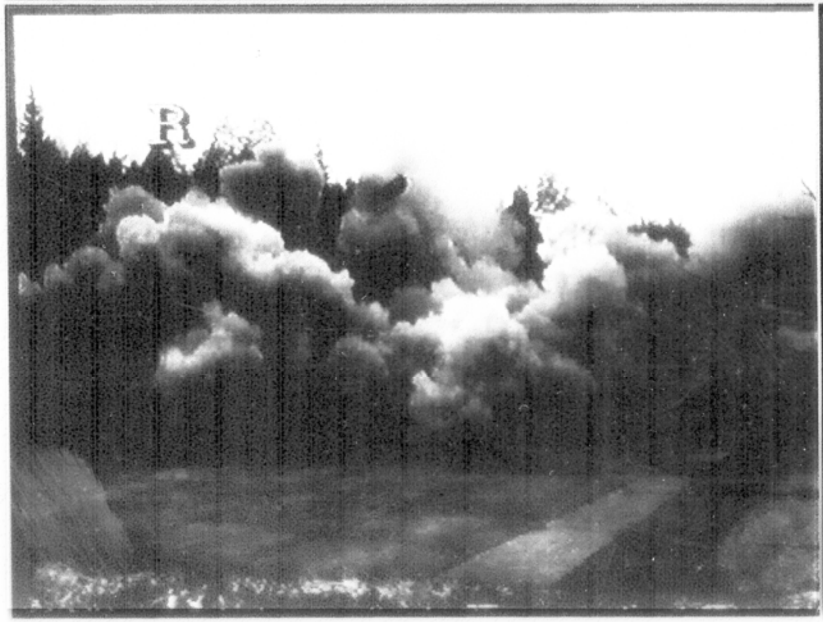

COM3D verification (1)

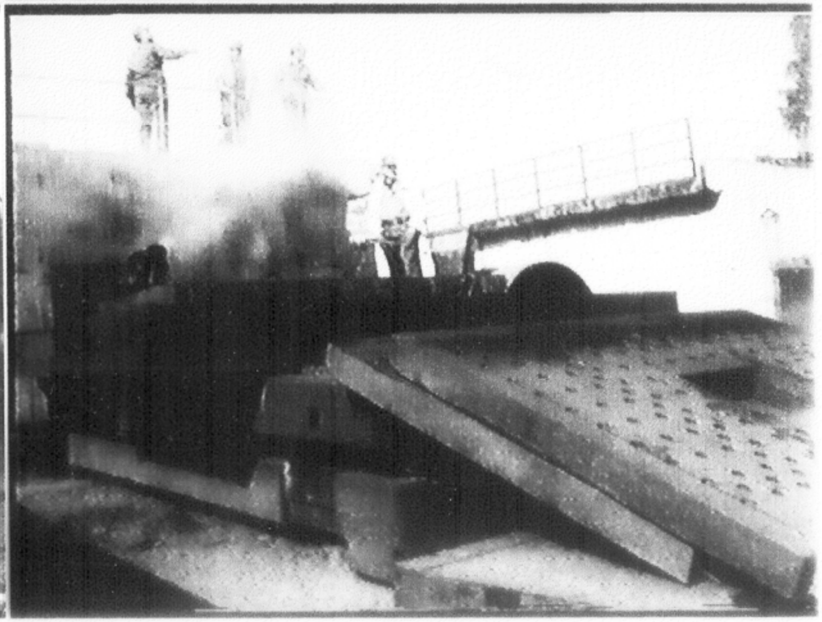
- **Large scale experiments performed in RUT facility near Moscow (FZK, CEA, partly NRC), H_2-air, H_2-air-steam**
  - **Total length 62 m**
  - **Total volume 480 m^3**
  - **First channel with obstacles**
  - **Second part without obstacles**



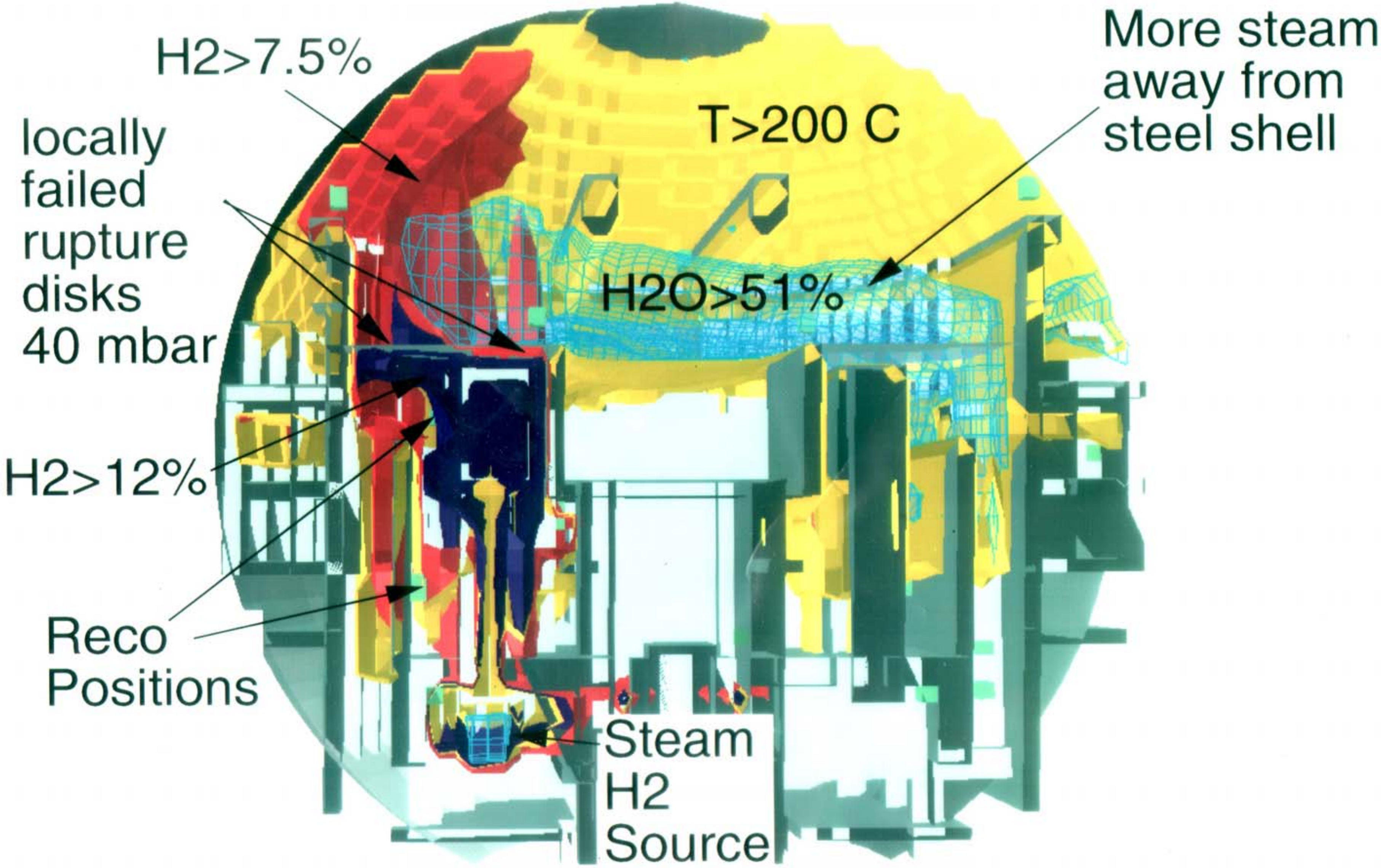




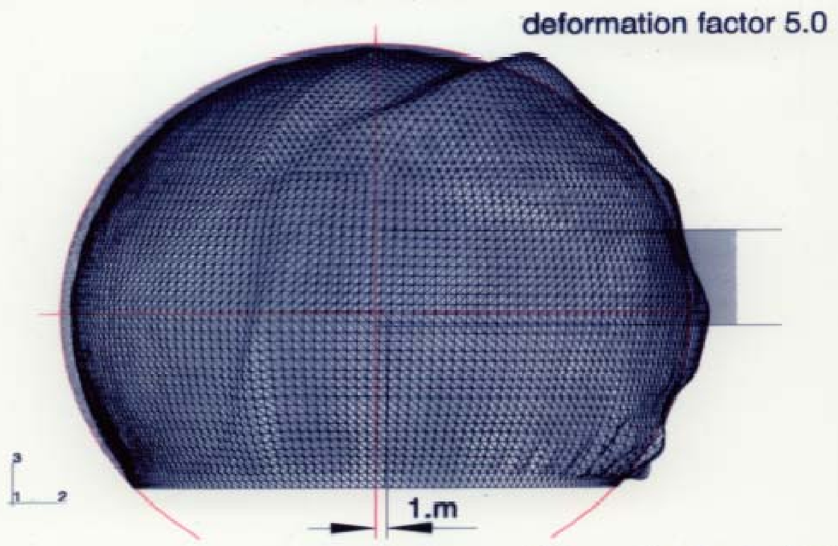


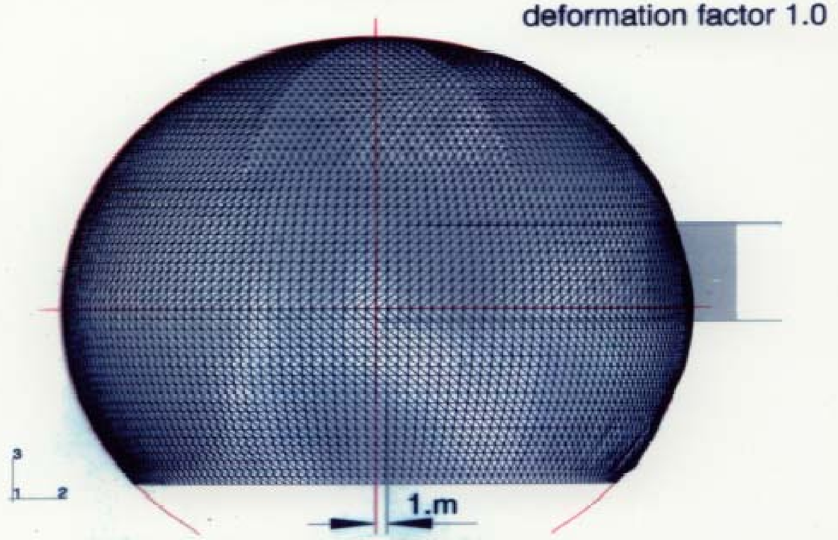


rut_ddt



H2, H2O clouds and temperature plume GKN at 5932s


deformation factor 5.0
1.m


deformation factor 1.0
1.m

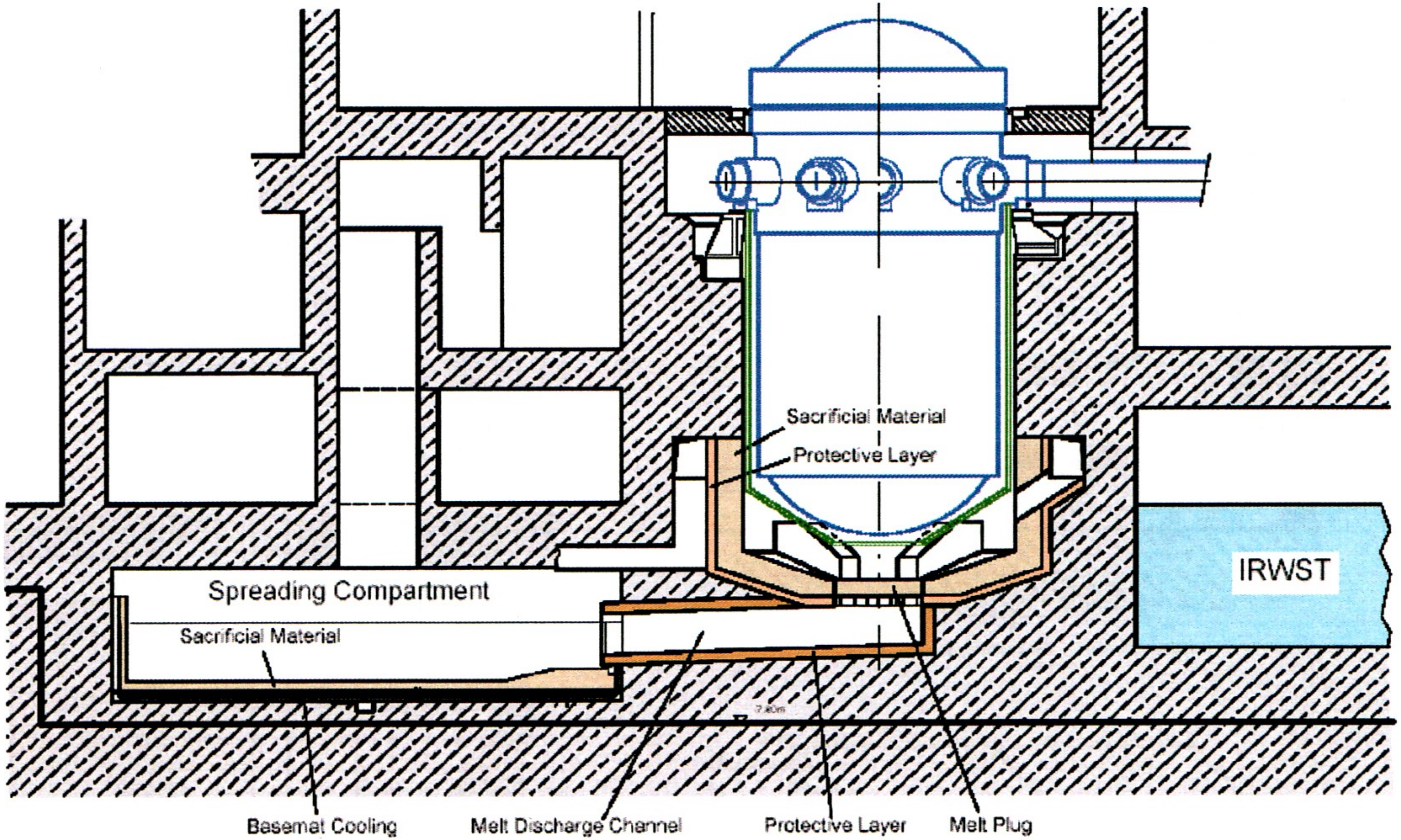
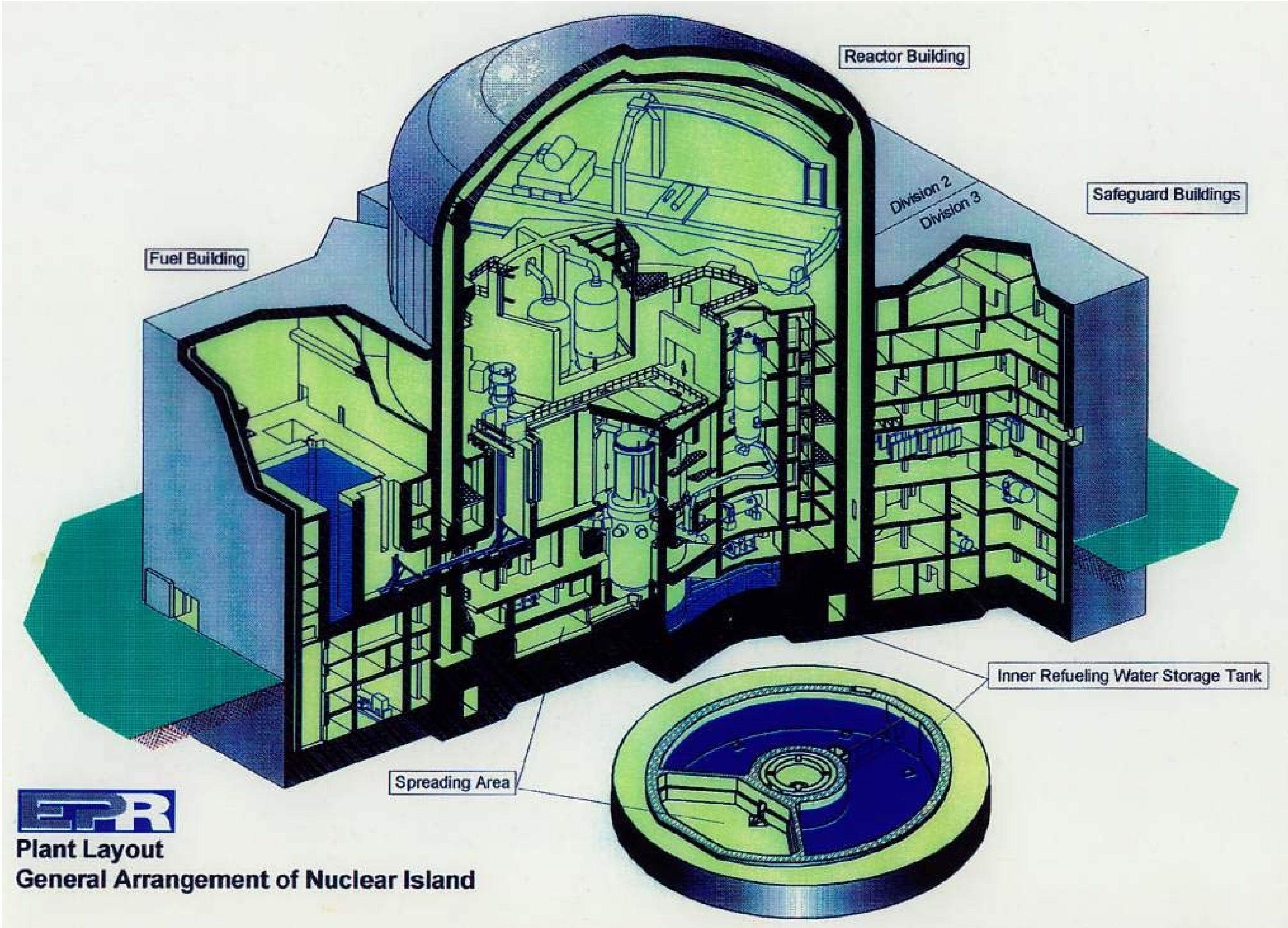
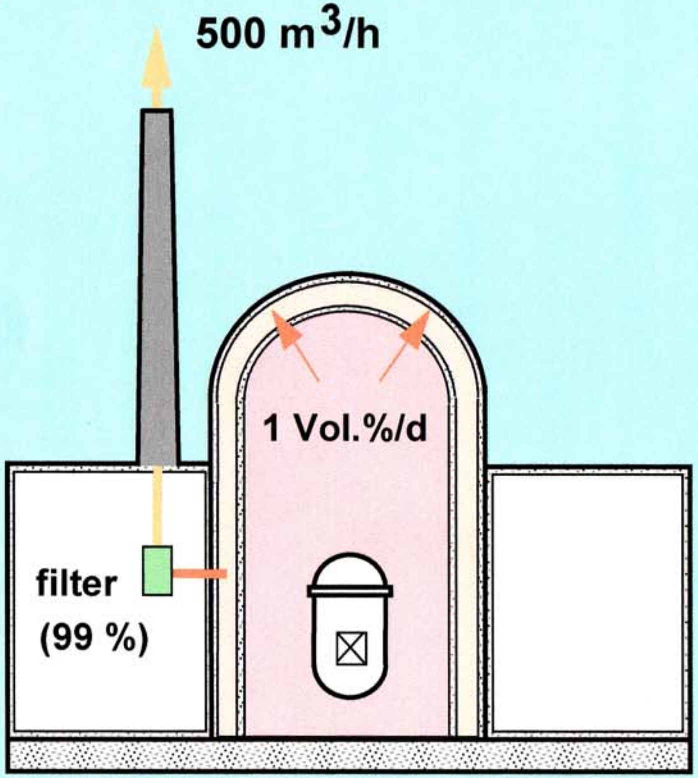


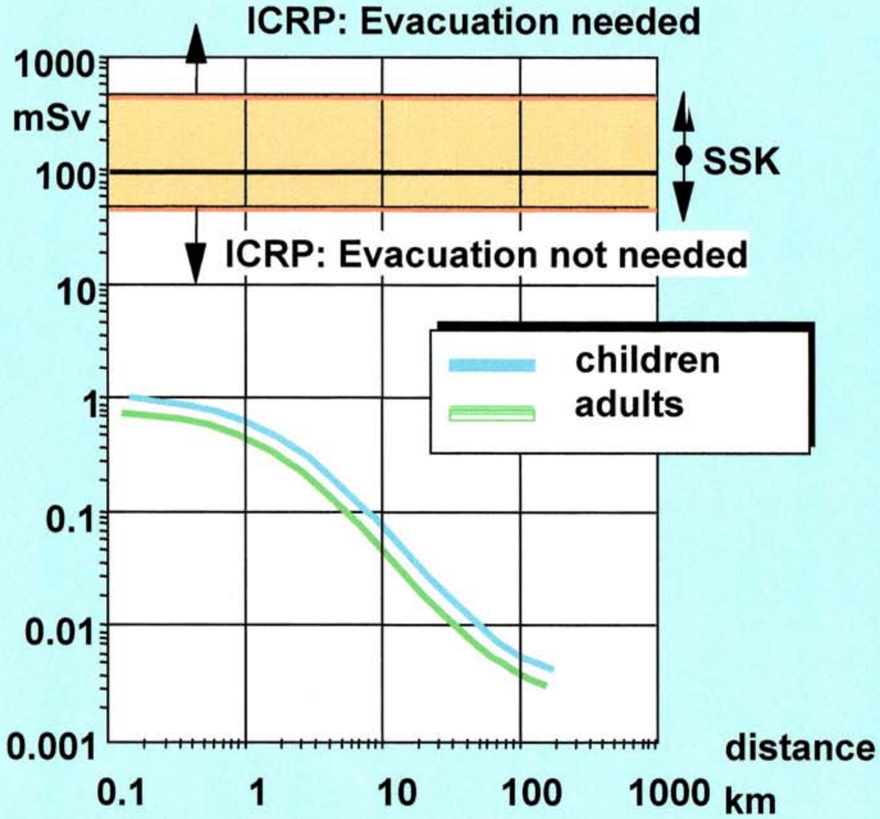
Figure 6.4-1: The main components of the EPR core catcher



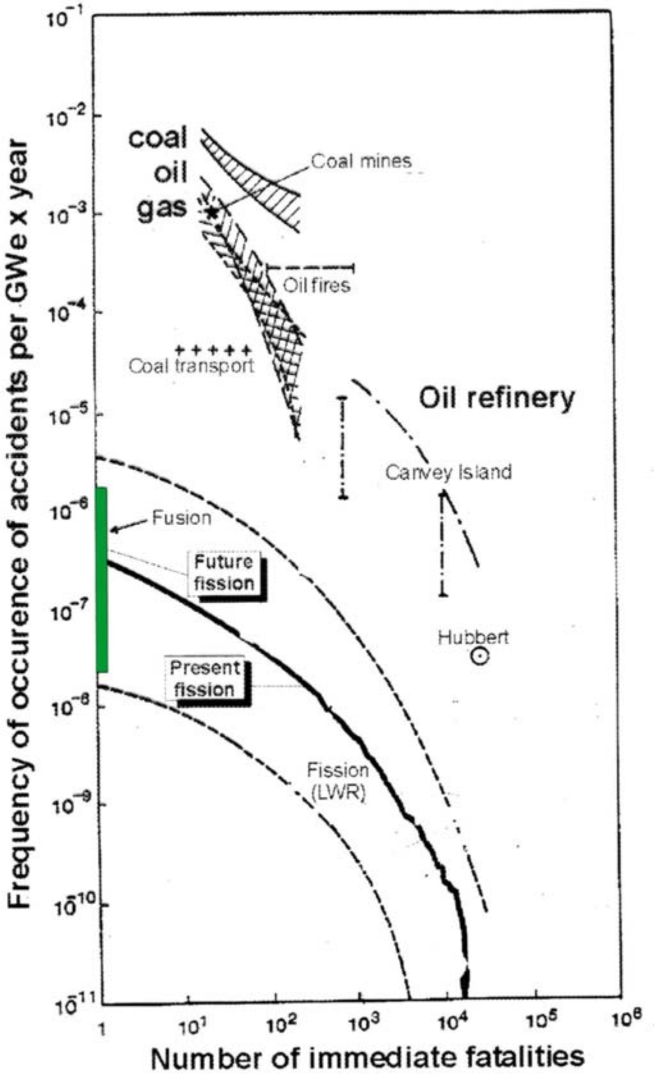
Plant Layout
General Arrangement of Nuclear Island



Release path into atmosphere



Effective dose due to inhalation and direct radiation from the cloud


Frequency of occurence of accidents per GWe x year
Number of immediate fatalities
coal
oil
gas
Coal mines
Oil fires
Coal transport
Oil refinery
Canvey Island
Hubbert
Fusion
Future fission
Present fission
Fission (LWR)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1
10^1
10^2
10^3
10^4
10^5
10^6