An experiment that went wrong

An experiment that went wrong

Chernobyl, 26 April 1986
causes and effects

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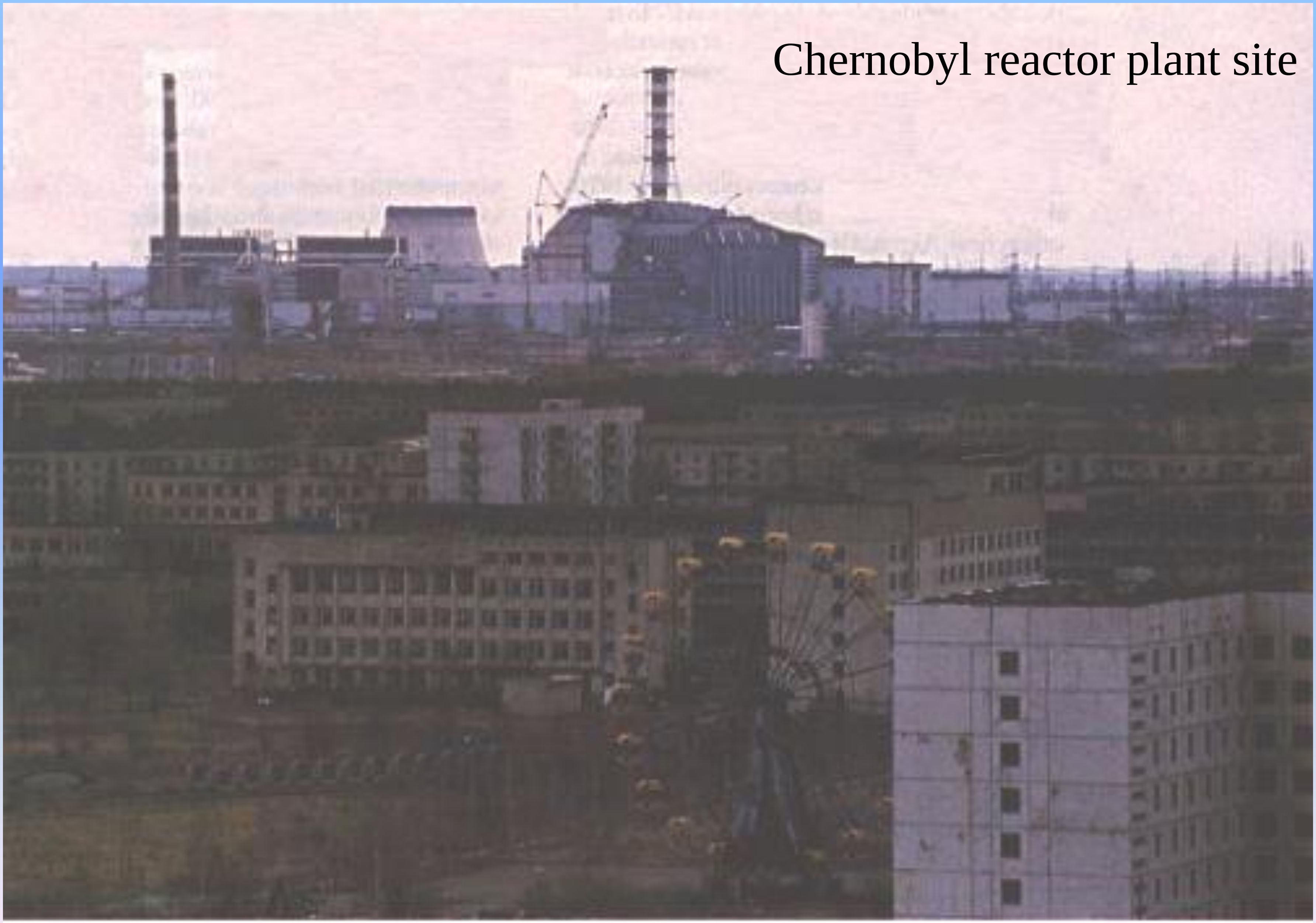
Contents

Contents

Topography


Lithuania
Belarus
Russia
Poland
Pripyat
Chernobyl
Rovno
Kiev
Khmelnitski
Slovakia
Ukraine
Zaporozhe
Hungary
Moldavia
South Ukraine
Odessa
Romania


Chernobyl reactor plant site

Chernobyl reactor plant site

1. Topography
2. **The reactor**
3. The accident
4. *Intermezzo: Natural radiation effects*
5. Emission
6. Radiation caused by the accident
7. Environmental and health effects
8. Situation in the Netherlands and Europe

Needed for fission:
1 slow (thermal)
neutron: ≈ 2 km/s

Uranium fission

$$^{235}_{92}U + n \rightarrow \text{Fission products} + 2..3\,.n$$

$$\text{Fission products}: \; ^{131}I; \; ^{137}Cs.....$$

Produced:
2..3 fast neutrons:
≈ 10 000 km/s

Neutron capture

e.g. Cadmium, Boron

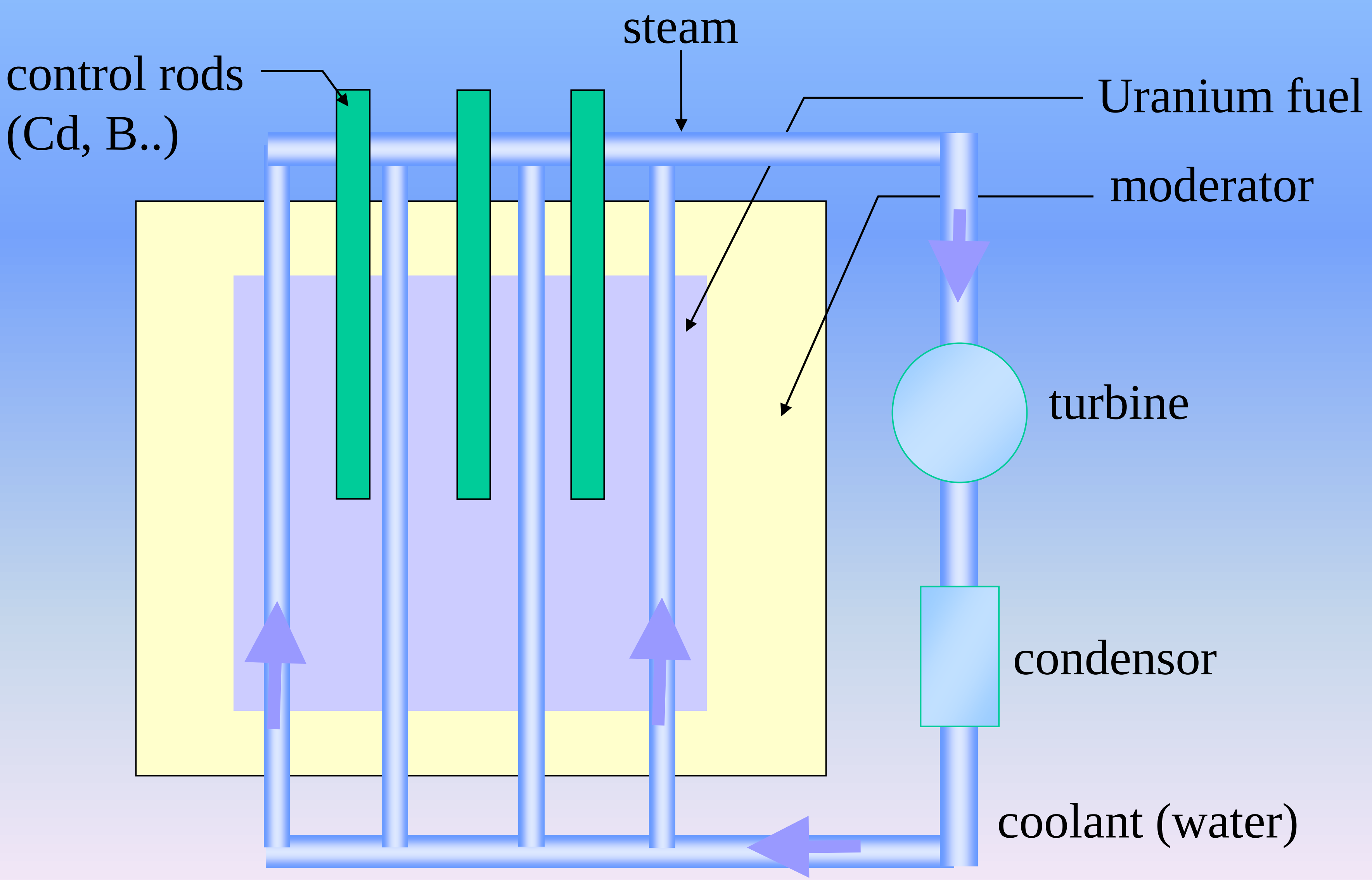
Thermal neutrons only

Neutron moderation

Needed: light nuclei: H .. C

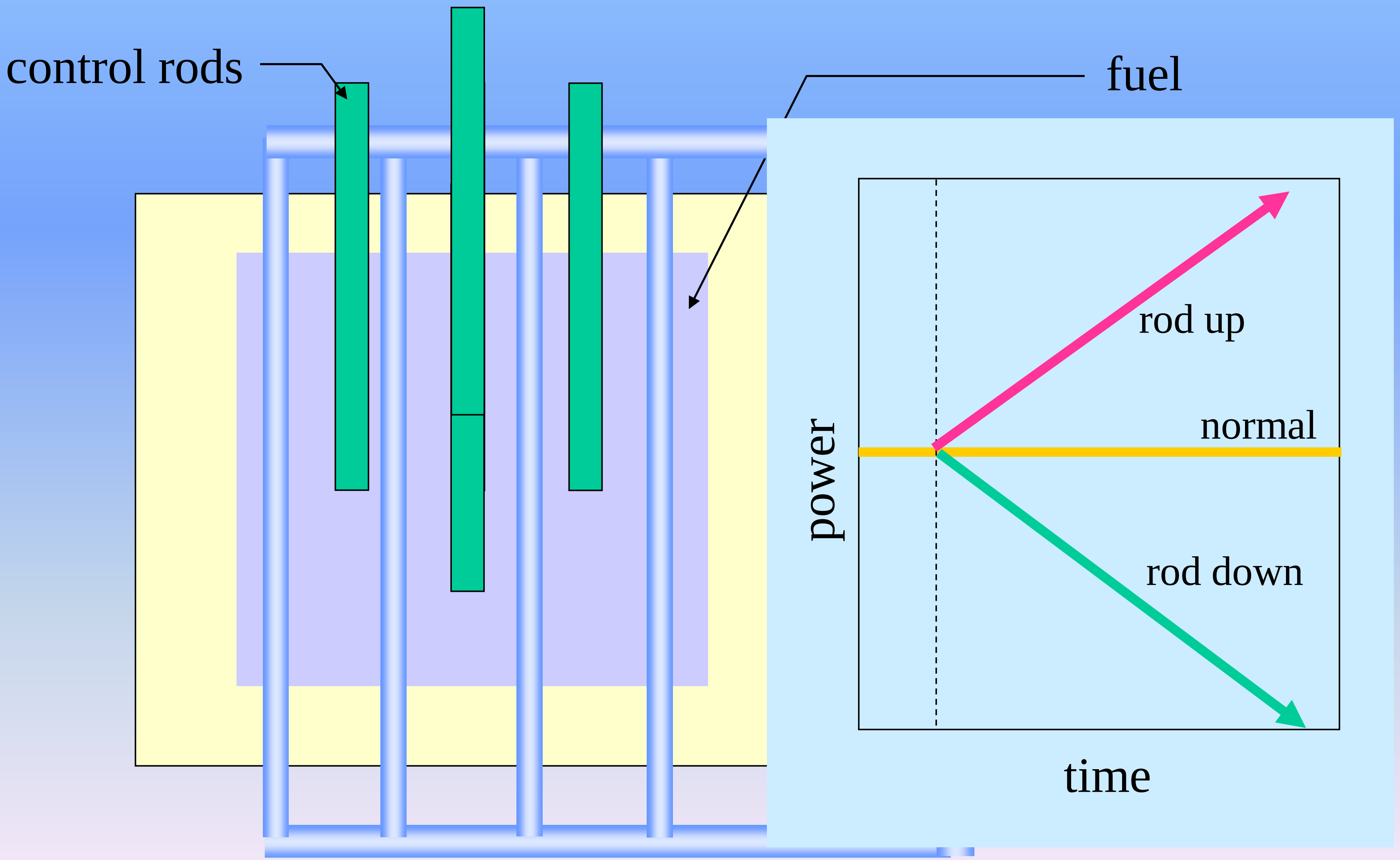
Neutron scattering

Nuclear Fission Reactor



Cerenkov effect in nuclear reactor
Photo: Research reactor (3 MW), Techn. Univ. Delft

Nuclear Fission Reactor



Nuclear Fission Reactor

How to control manually:
- a fly?
- a supertanker?

Impossible because:
- too fast
- too slow

Golden Rule in Control Technology:
- time scale of controller ≈ time scale of object

Nuclear Reactor:
- core dimensions ≈ meters
- neutron speed > 1 km/s (1 m in 1 msec)

→ time scale ≈ 1 msec

Impossible to control manually or using equipment.

Nuclear Fission Reactor

Nuclear Reactor:

- core dimensions ≈ meters
- neutron speed > 1 km/s

→ time scale ≈ 1 msec

Impossible to control manually or using equipment !

However:

Emission of a small part (≈ 0.7 %) of neutrons is delayed over 8 sec!

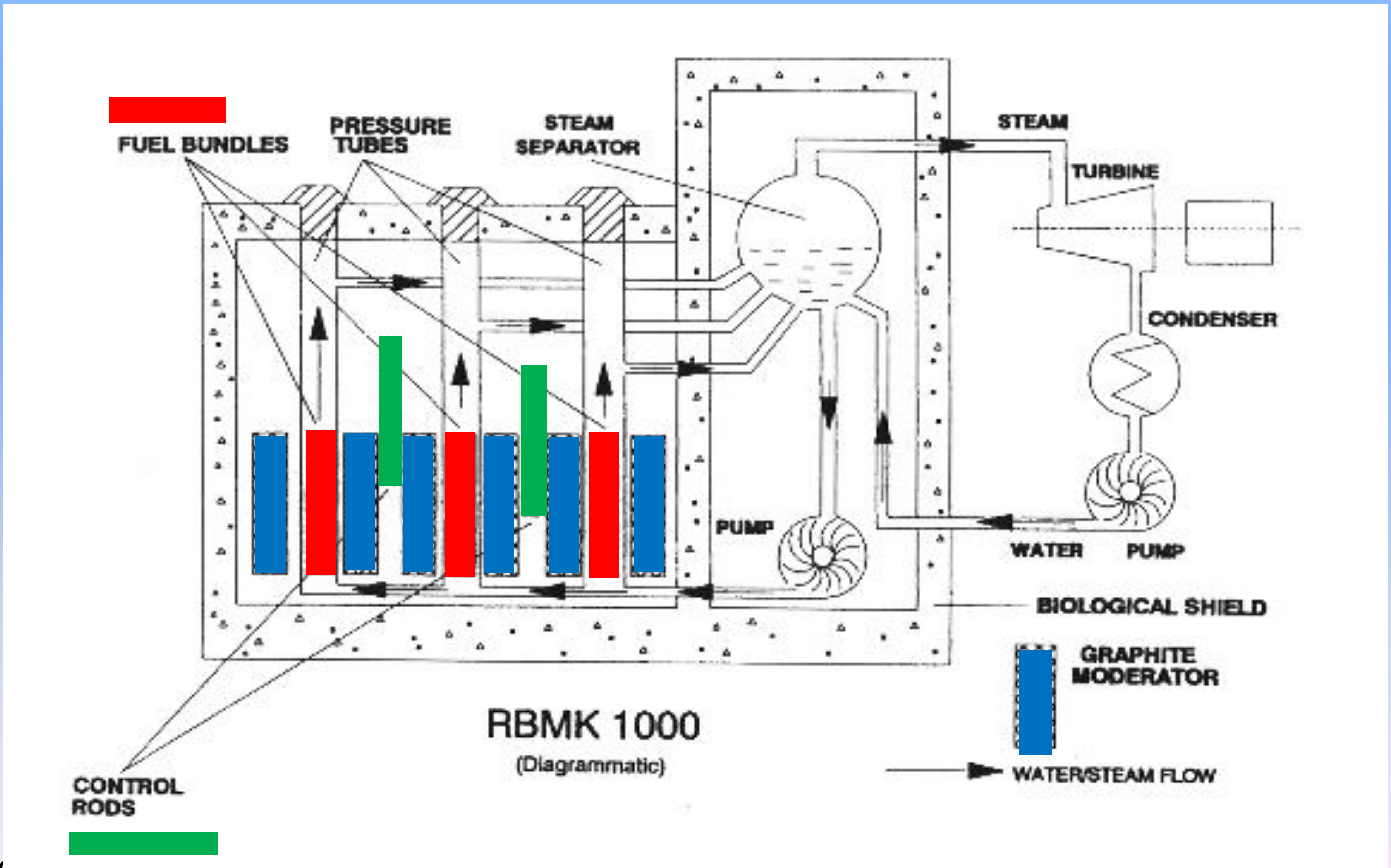
So:

This facilitates the reactor control,

provided: changes are < 0.7 % in 8 sec.

Still extremely difficult to control manually !

The Chernobyl reactor:
pressurized boiling-water reactor



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The reactor

- Boiling light water reactor, steam under pressure
- Power : 3200 MW thermal
- Contents: UO_2 – tablets in rods; 2 % enriched in ^{235}U
- Moderator: mostly graphite;
- Absorber: control rods (cadmium) and cooling water (with boron)
- Turbines: 2 x 500 MW electric,
  direct steam injection (1 circuit; no heat exchanger)
- Core: diameter 12 m ; height 7 m
- Pump system: 4 pumps ; 3 necessary
- Emergency cooling system: present
- Control: needed for stable operation: 30 control rods in the core !!!

The reactor (2)

Characteristic for this type of reactor:

= moderator and coolant separated (graphite and water resp.):

Water ↓ or power ↑

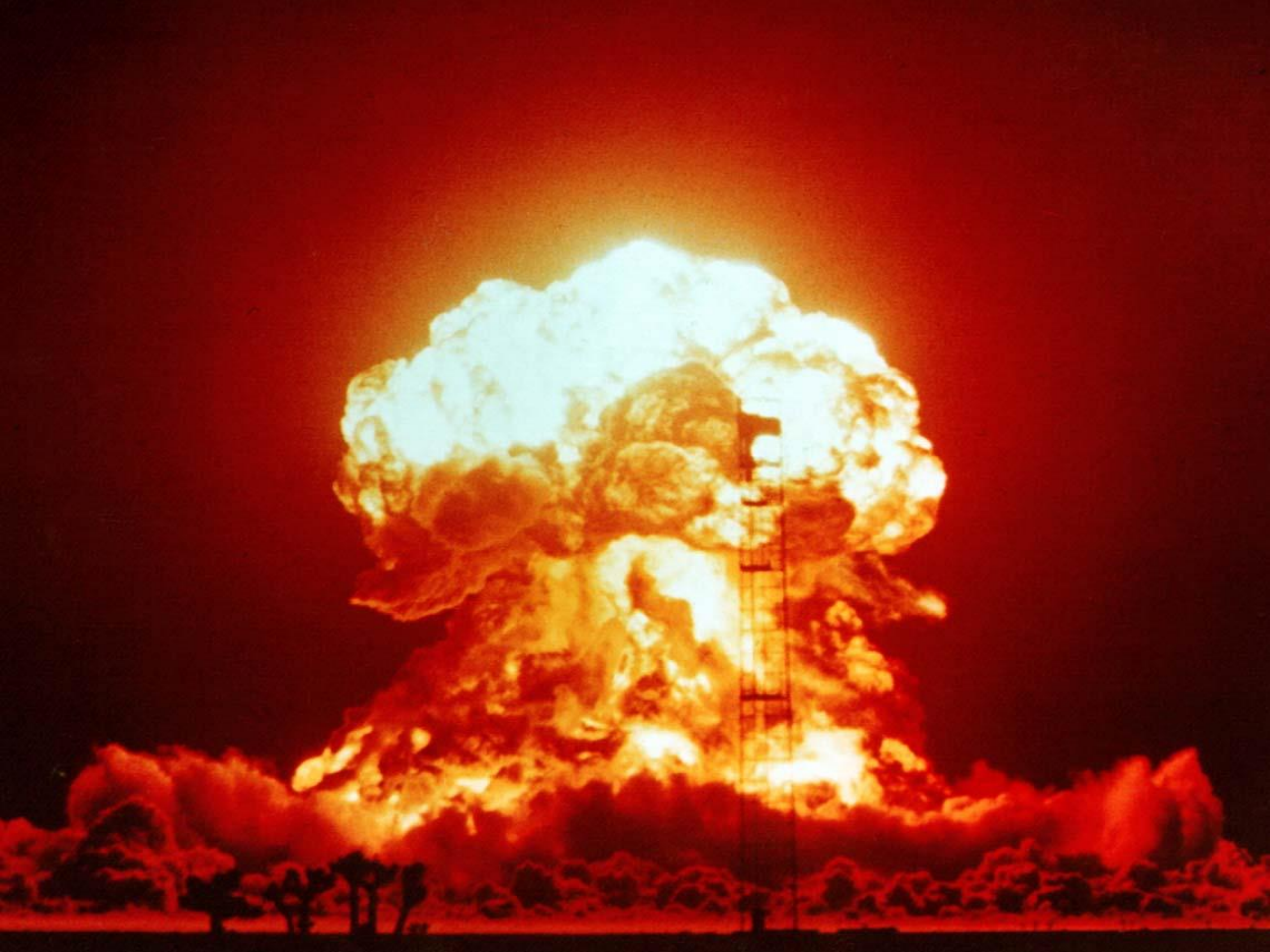
If moderator = water:
Reactor will stop

Reactor shut off
Water needed for after-cooling

If moderator = graphite:
Reactor will continue

Neutron absorption in water (+boron) : ↓

Power : ↑



1. Topography
2. The reactor
3. **The accident**
4. *Intermezzo: Natural radiation effects*
5. Emission
6. Radiation caused by the accident
7. Environmental and health effects
8. Situation in the Netherlands and Europe

The accident (1)

25 April 1986:

Plan: Stop for maintenance.

Question: can decelerating turbines produce sufficient power to operate emergency cooling pumps?

Plan for experiment:

- emergency cooling system off
- reactor switched off

The accident (2)

<u>26 April 1986</u>:

00.00 h: Reduction thermal power : 3200 → . 750 MW.

00.28 h: Reduction to 500 MW.

Control from automatic to manual **!!!**.

00.30 h: Unexpected power drop to 30 MW thermal.

Operator tries to increase power
by extraction of control rods from core

6 – 8 control rods left in the core (estimated) ; **!!!**
(essential for stable operation: > 30)

01.00 h: Power now 200 MW thermal, but very unstable.

Operator: extra water, to reduce steam pressure

The accident (3)

26 April 1986:

01.00 h: Power now 200 MW thermal, but very unstable.

Operator: extra water, to reduce steam pressure

Normal effect: "automatic stop",
but control was "manual", thus no stop.

01.20 h: Power very unstable.

Operator reduces water flow to stabilize pressure

Pressure rises again, reactor seems stable.

01.23 h: Decision: test experiment may take place.

The accident (4)

26 April 1986:

01.23 h: Decision: test experiment may take place.

01.23 h: However: steam pressure rises too fast, thus:
less water, but consequence: more power

01.23 h: Power increase now exponential.
Insertion of extra control rods: manual; far too slow.

01.24 h: Power excursion to about 100 x normal power..

01.24 h: Reactions of water and fission materials:
Pressure waves in fission tubes

Two explosions: (1) steam; (2) expansion fission

The accident (5)

26 April 1986:

01.24 h: Two explosions: (1) steam; (2) expansion of fission

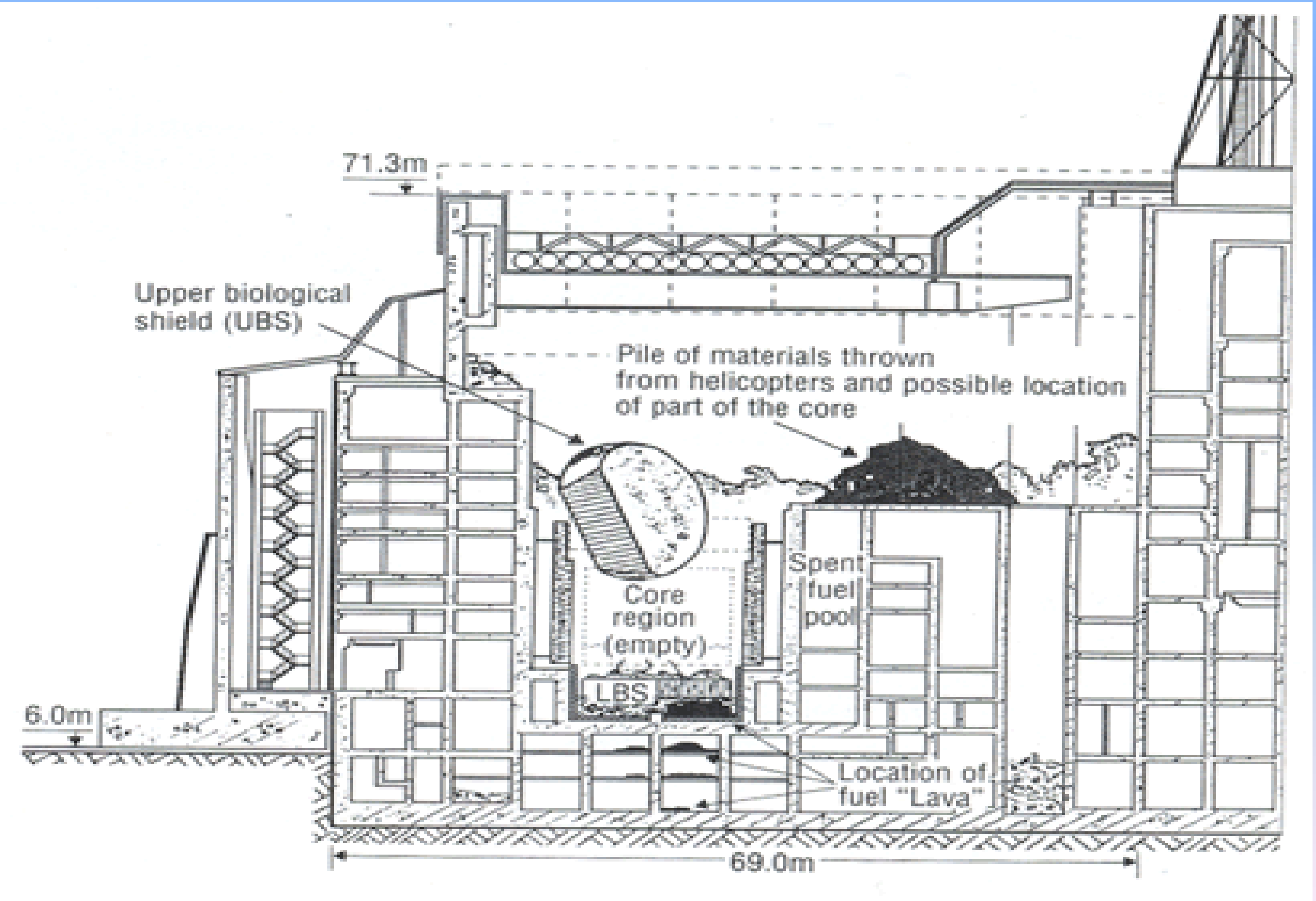
Effects:

- Cover of reactor vessel blown away,
- Entrance of air,
- Graphite + oxygen produces CO,
- CO ignites.

Following days:

- Fall-out of radioactive steam and particles.
- Spreading of radionuclides by explosions and fires.
- Remanent radioactivity produces so much heat that the fires cannot be extinguished.

The reactor after the accident



1. Topography
2. The reactor
3. The accident
4. ***Intermezzo: Natural radiation effects***
5. Emission
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8. Situation in the Netherlands and Europe

Physical variables and units

- Activity (desintegrations/sec)
- Equivalent dose (tissue; organs)

- [Bq] = [1/s]
- [Sv] = [J/kg]

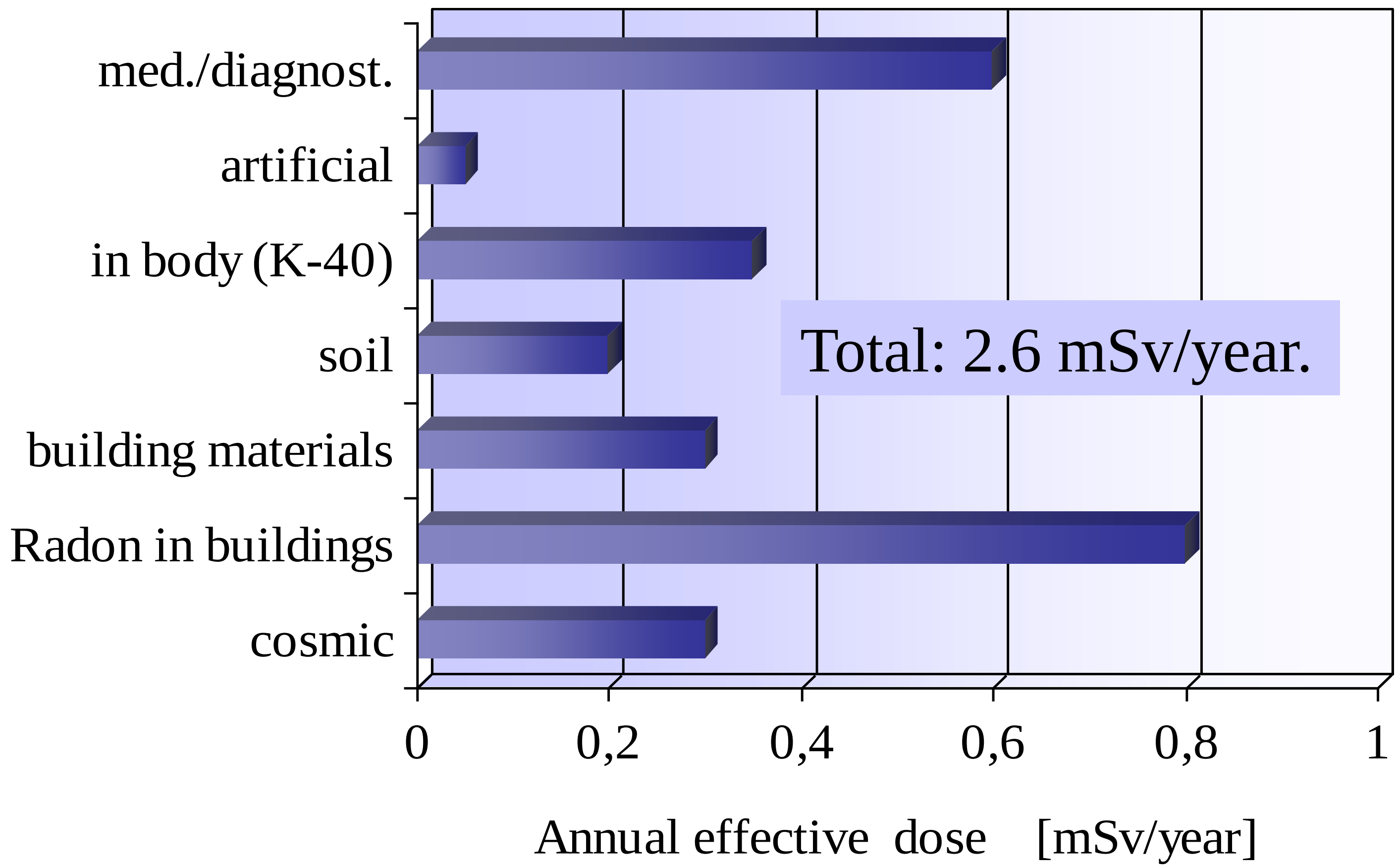
NB. J/kg = mJ/g

For biological effects: **equivalent dose [Sv]** is used

Normal background dose in the Netherlands (average):

- natural : 2.0 mSv/y
- medical diagnostical : 0.6 ,,
- total : 2.6

Netherlands: annual effective dose



Radiation from the soil

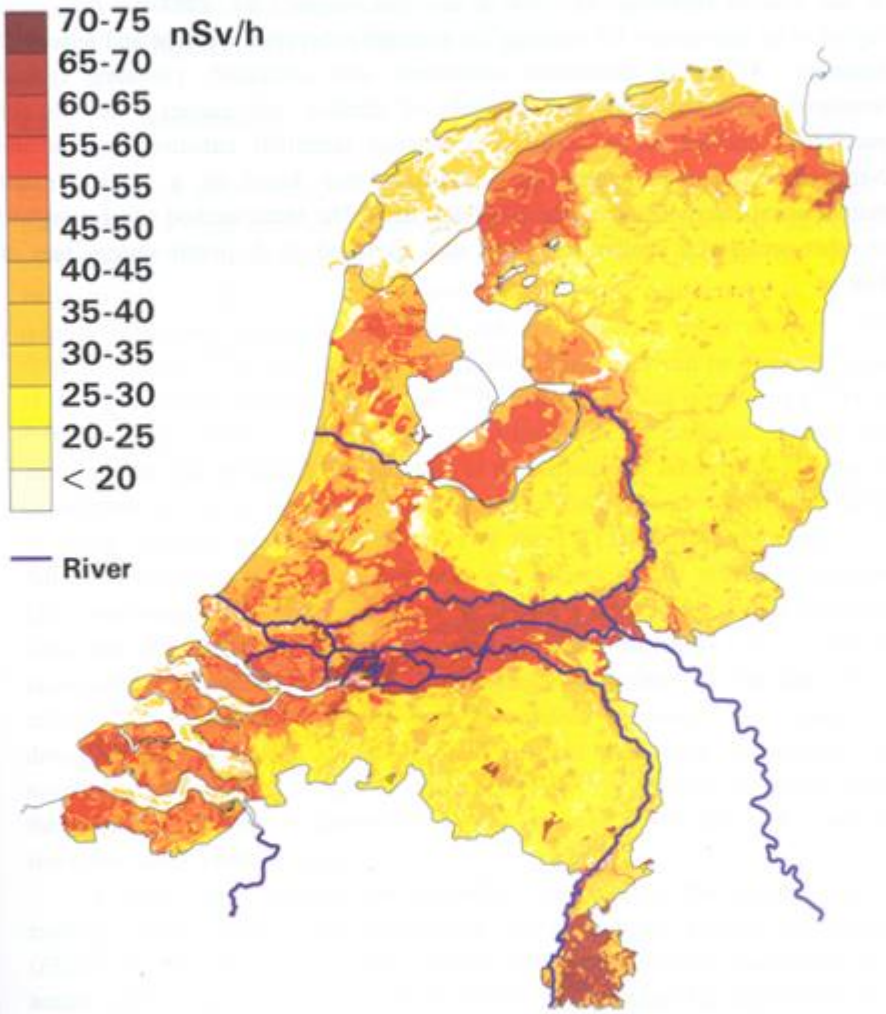
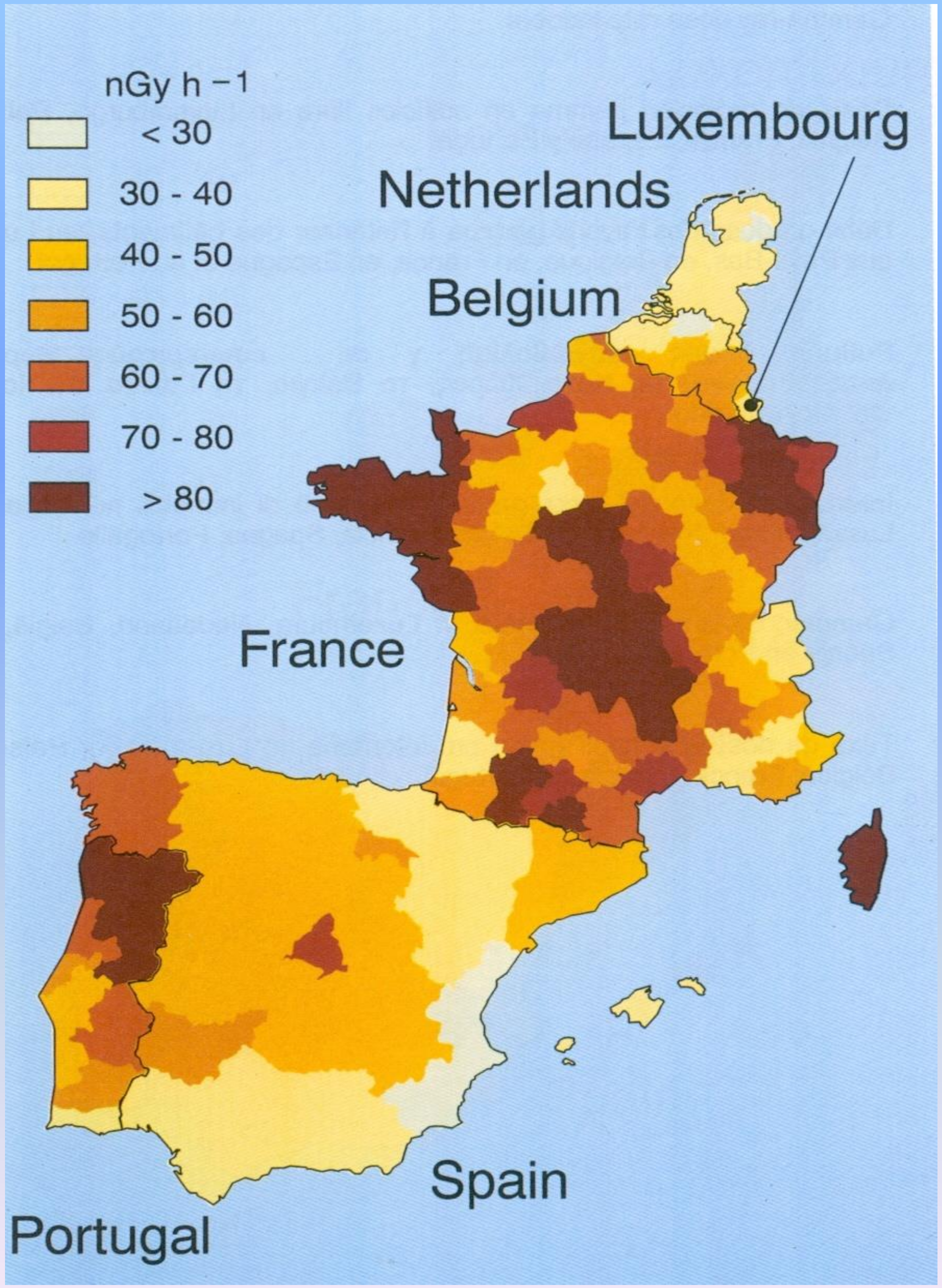


Figure 6.19B Terrestrial radiation map (ambient dose rate at 1-m height) derived from the 1:250.000 soil map [StI85], using conversion parameters as given in Appendix 2.

0.2 mSv/year

0.7 mSv/year

The Netherlands:
Averaged natural background = 2.0 mSv/year.



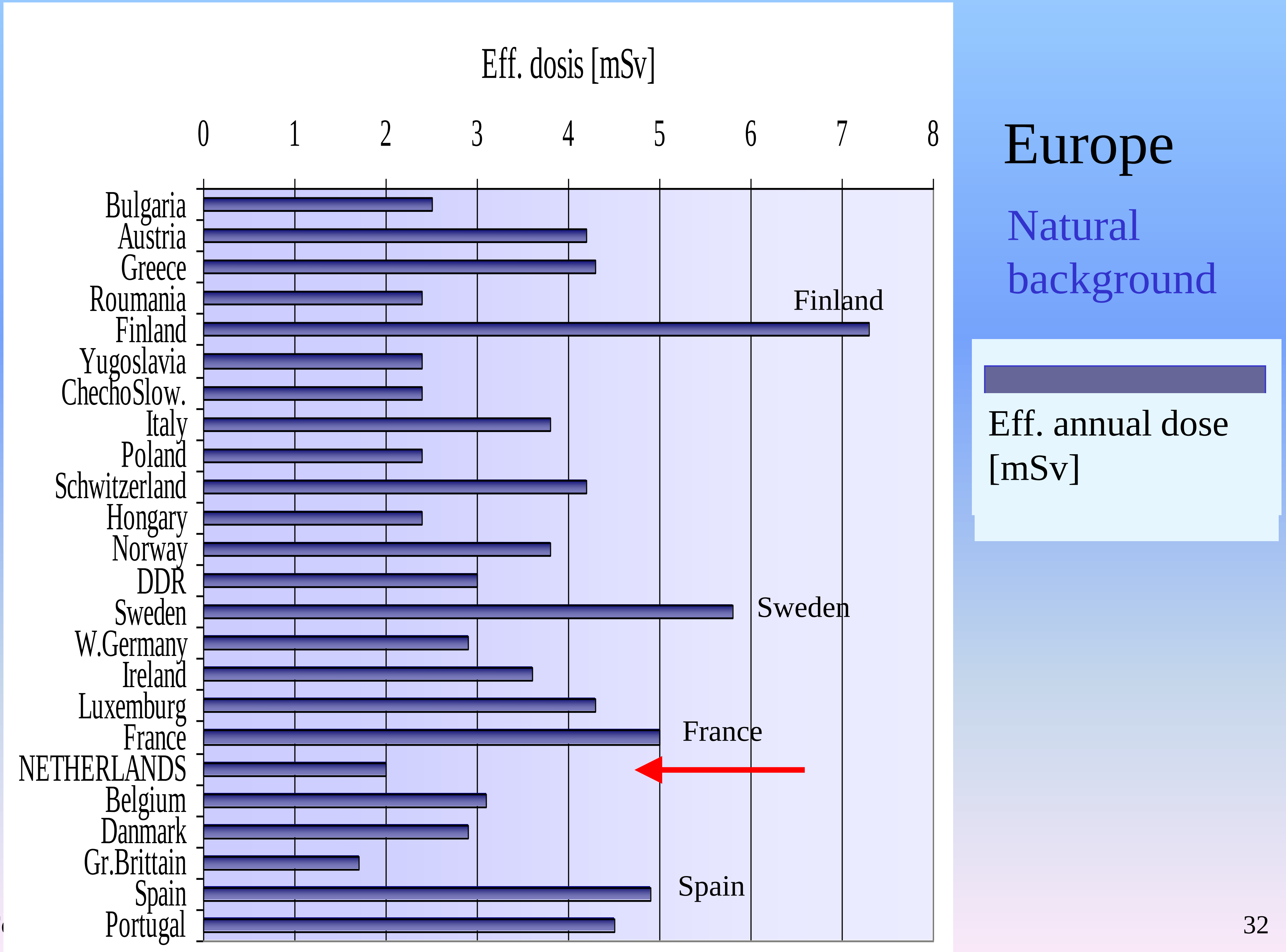
Radiation from the soil

(light yellow)	< 0.3 mSv/y
(dark brown)	> 1.0 mSv/y

The Netherlands:
Averaged natural background = 2.0 mSv/year;
From soil: 0.2 mSv/y.

Europe

Natural background



Effects of radiation

effect	probability	seriousness	dose	example
Stochastic (probabilistic)	dep. on dose (5 % per Sv)	**100 %**	all	Leukaemia, genetic (?)
Deterministic ("certain")	**100 % ,** if > threshold	dep. on dose	>**≈** 1 Sv	See below

Deterministic effects: thresholds:	dose (Sv)	mortality
Cataract	> 0.5	--
Temporary sterility	> 1	--
"Bone marrow syndrome" (blood cells)	> 2	< 50% in <1 month
Radiation disease (nausea….)	> 3	> 50% in <1 month
"Intestine syndrome"	> 10	< 1 week
"Central nerve system-syndrome"	> 50	< 1 day

NB. Natural background in the Netherlands: 2.6 mSv/y

Mortality (stochastic/probabilistic effects)

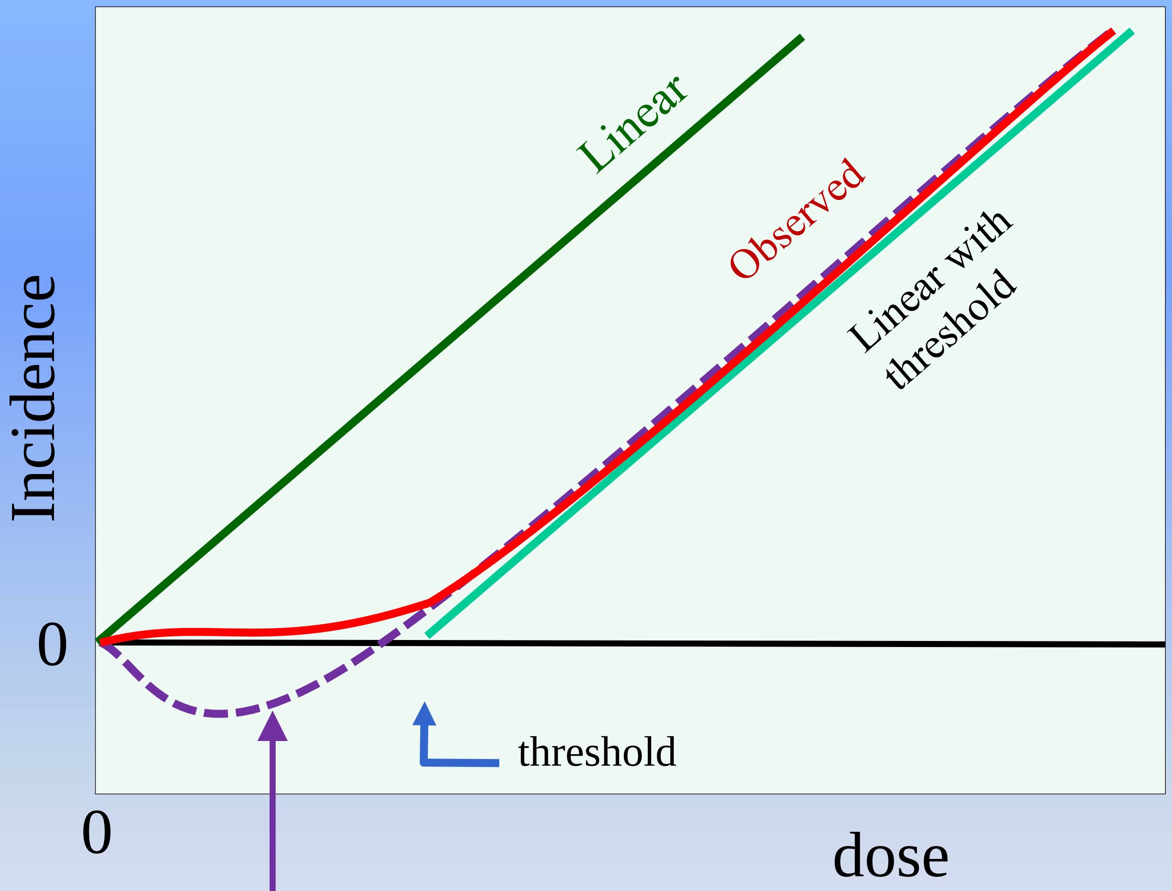
ICRP: death risk from cancer: (whole population):		**5 %** **per Sv**
The Netherlands (population 17 000 000 persons)	"Normal"	Extra (*) (Chernobyl)
• Natural dose • Medical/diagnostic dose	2.0 mSv/y 0.6 …	0.1 mSv -
Expected mortality (persons per year):		
• Natural dose • Medical/diagnostic dose	1700 (^{0}) 500	80 -

(*) Due to Chernobyl, first year only

(^{0}) 17 000 000 x 0.002 Sv/y x 5 % per Sv = 1700 persons/year

Normal deaths per year: 17 000 000 / 75 = 225 000

Effects of radiation : stochastic/probabilistic effects

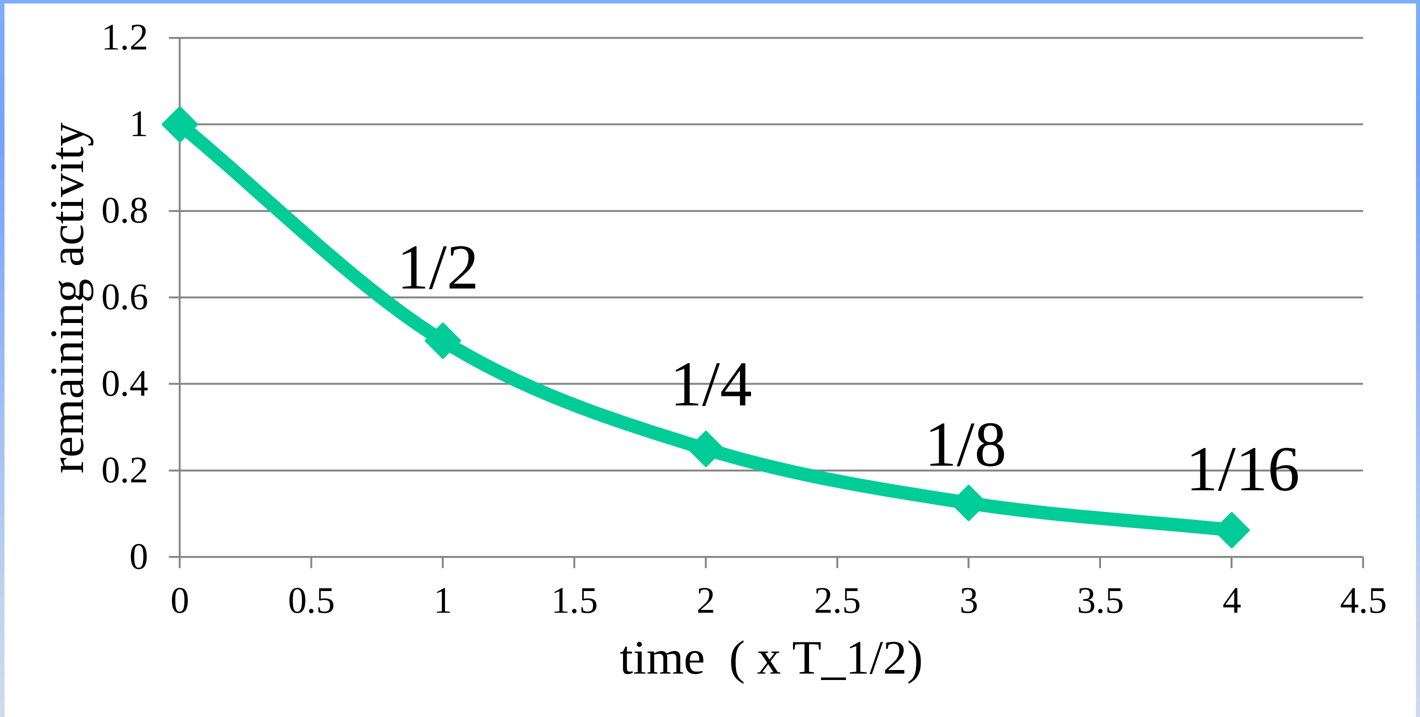


Recent ideas about low doses:
"hormese" – effect
("A little bit of radiation is good for you")

Linear relation used in dosimetry:
5 % per Sv

Decay effects of half-life time $T_{1/2}$

^{131}I : iodium-131 : $T_{1/2}$ = 8 days

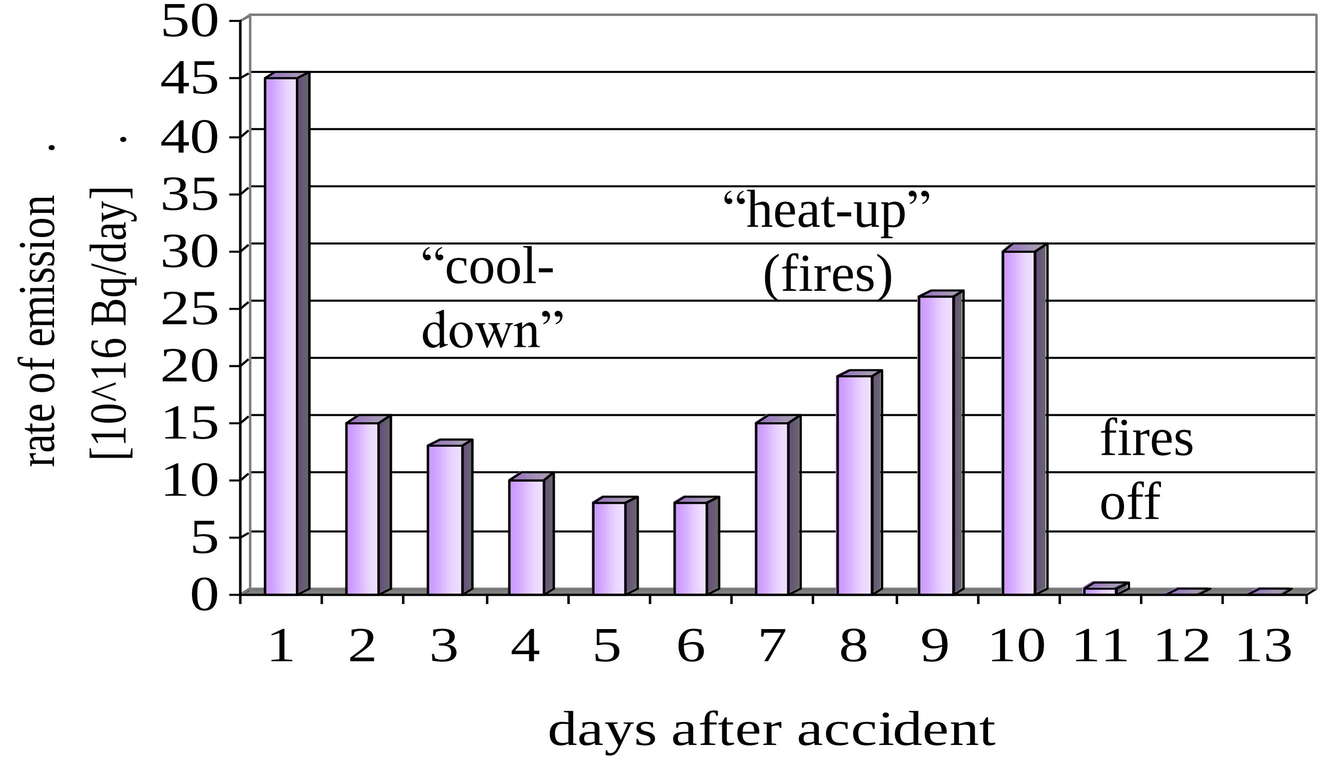


At 10 x $T_{1/2}$ (80 days; ≈ 3 months) → 1/1000 remaining

At 20 x $T_{1/2}$ (160 days; ≈ 6 months → 1/1 000 000 remaining

1. Topography
2. The reactor
3. The accident
4. *Intermezzo: Natural radiation effects*
5. **Emission**
6. Radiation caused by the accident
7. Environmental and health effects
8. Situation in the Netherlands and Europe

Chernobyl: Emission of radioactivity (*)



Total 190 x 10^{16} Bq

(*) excl. nobel gases and very-shortliving isotopes; Total ≈ 600 x 10^{16} Bq

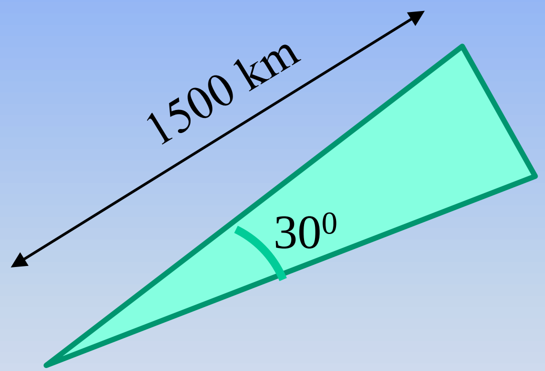
Reference: natural radioactivity

Unit: 1 Becquerel [Bq] = 1 desintegration/sec

Compare:
- (bed)rock / soil : 600 Bq/kg
- human body: 55 Bq/kg Kalium-40 => 4 000 Bq @ 70 kg

Total emission: 190 x 10^{16} Bq =
1900 000 000 000 000 000 Bq

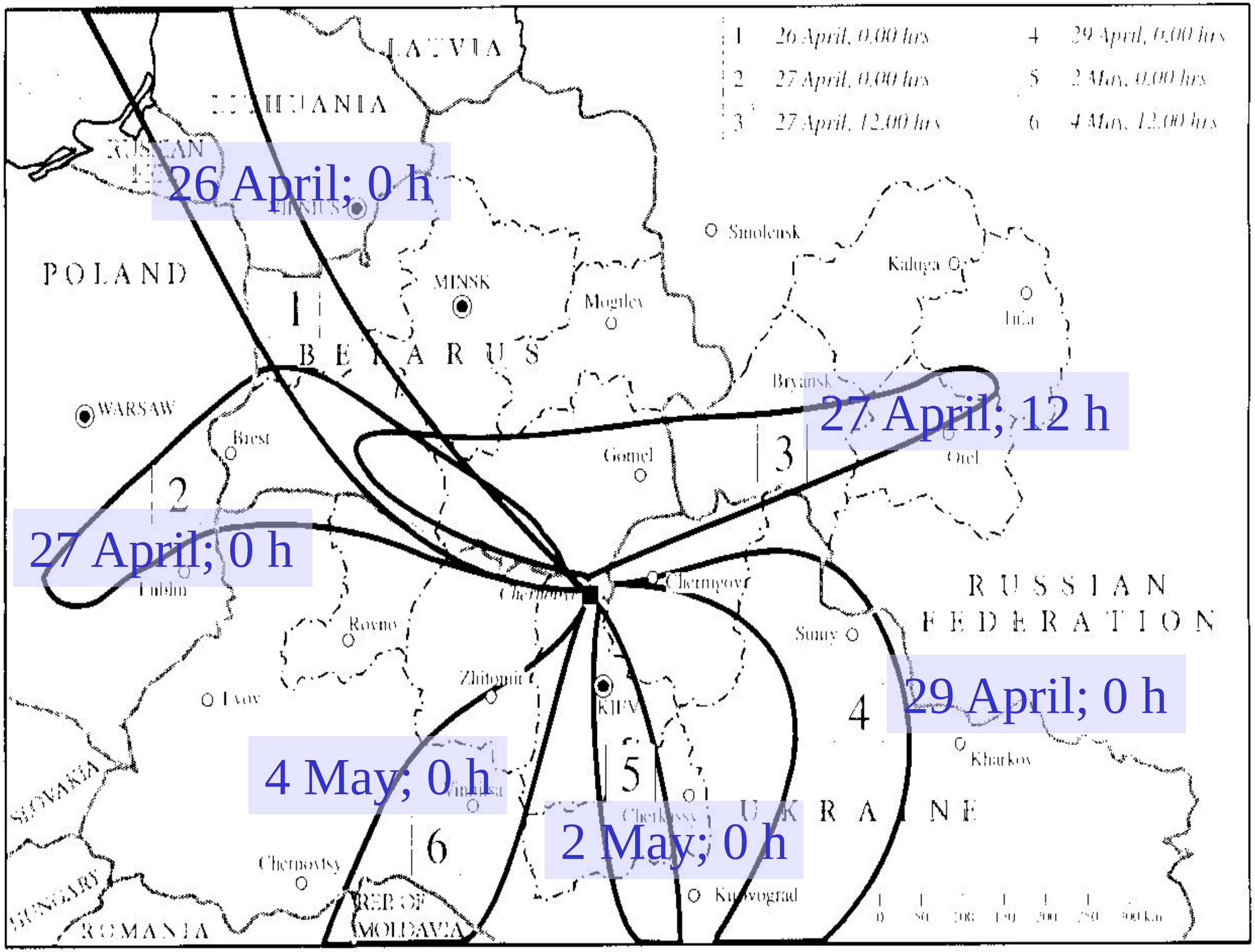
Suppose: deposited in a cone with opening angle 30^0 and length 1500 km (≈ reality):
Contamination : 3 MBq / m^2



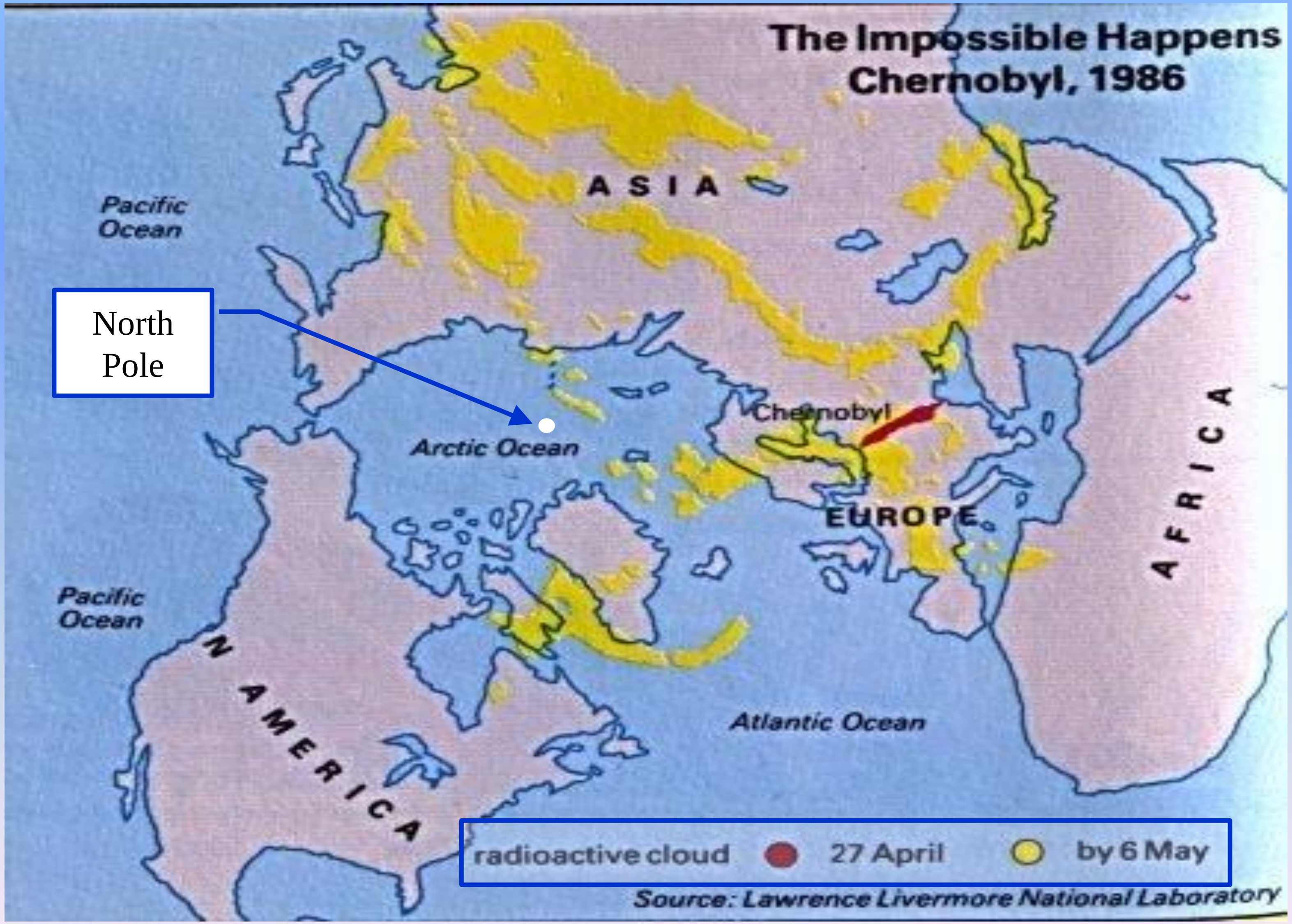
Compare: 1 MBq/m^2 → extra life dose ≈ 120 mSv
(see below)

Normal in the Netherlands:
Natural background: 2.6 mSv/y ; life dose = 2.6 x 75 ≈ 200 mSv

Wind-plume formation



Radioactive cloud
as seen from above the North Pole



Total emission: major contributions

Isotope	Half-life time	Emission (10^{16} Bq)
Fissions products:		
^{131}I : iodium	**8 d**	150
^{134}Cs : cesium	**2 y**	5
^{137}Cs : cesium	**30 y**	9
^{132}Te : tellurium	**3 d**	10
Nobel gases ($^{+}$)	**5 d**	6700
Metals (U, Pu, Sr, Np...) (^{0})	**2 d**	1700

($^{+}$) largest contribution: ^{133}Xe : xenon

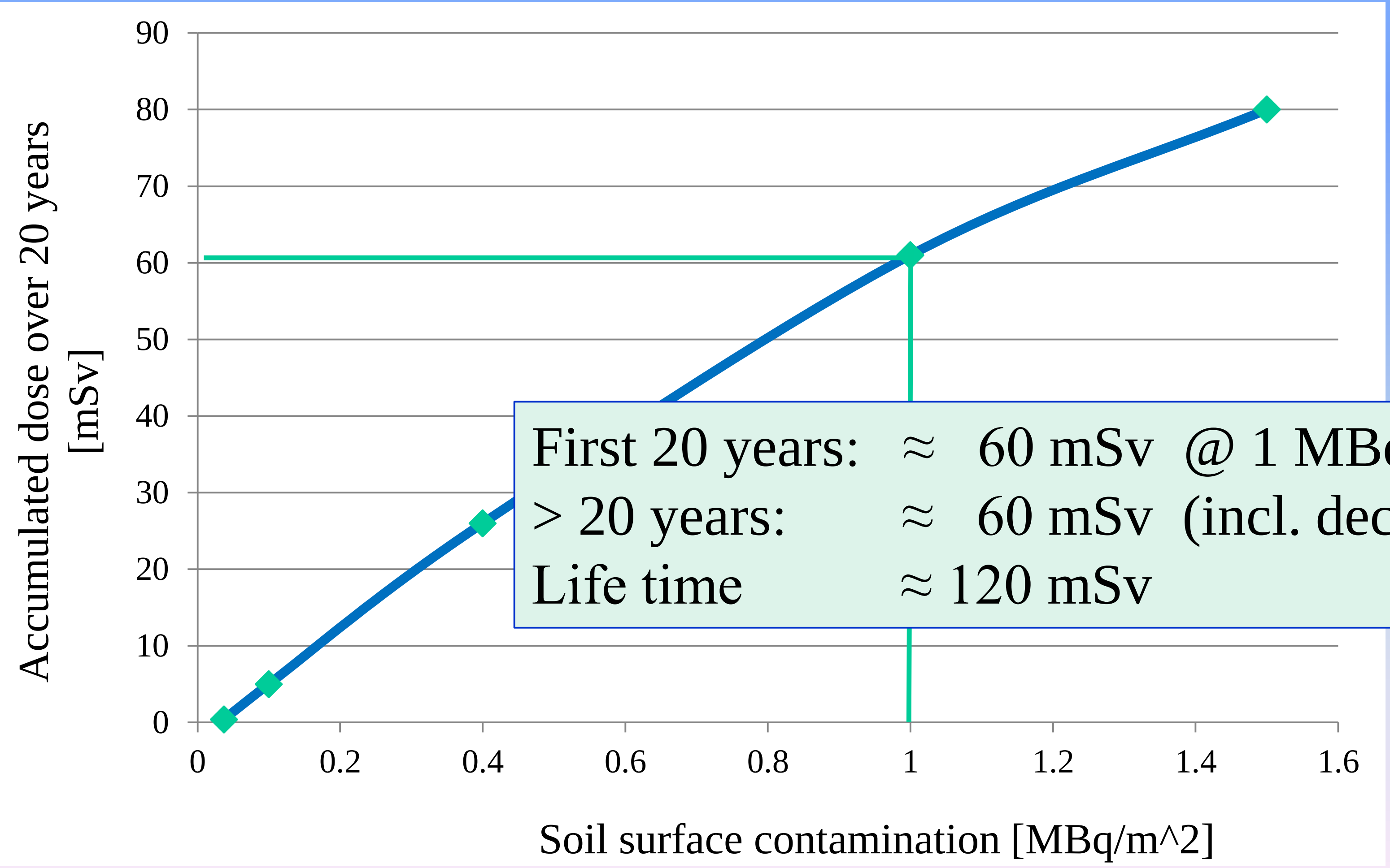
(^{0}) largest contribution: ^{239}Np : neptunium;

U : uranium, Pu : plutonium, Sr : strontium

1. Topography
2. The reactor
3. The accident
4. *Intermezzo: Natural radiation effects*
5. Emission
6. **Radiation caused by the accident**
7. Environmental and health effects
8. Situation in the Netherlands and Europe

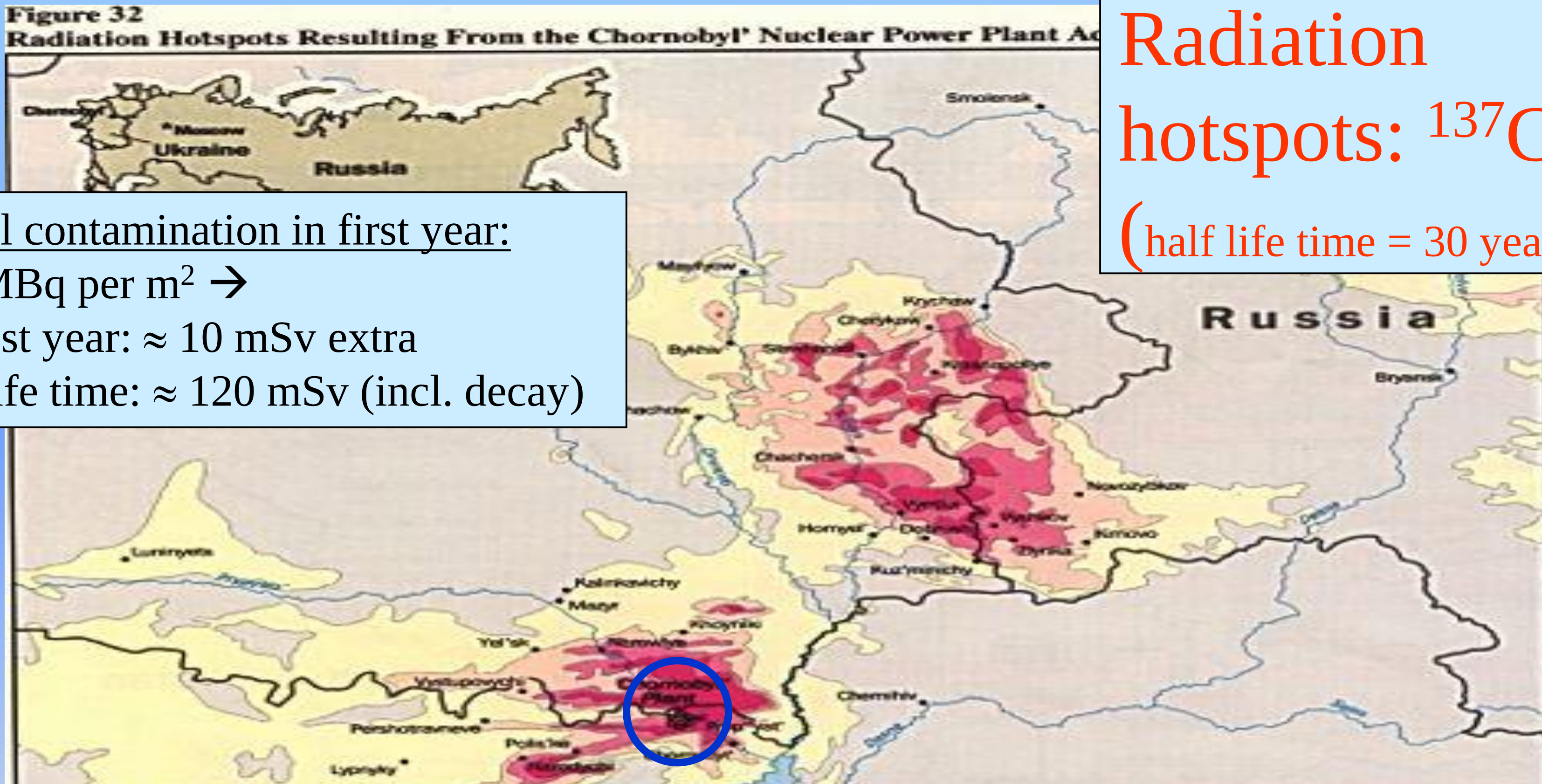
Contaminated areas (mostly ^{137}Cs : $T_{1/2}$ = 30 year):

- Soil surface contamination [MBq/m^2] vs.
- Accumulated dose [mSv] in years 1986 – 2006.



First 20 years: ≈ 60 mSv @ 1 MBq/m^2.
> 20 years: ≈ 60 mSv (incl. decay)
Life time ≈ 120 mSv

Radiation hotspots: ^{137}Cs (half life time = 30 years)



<u>Soil contamination in first year:</u>

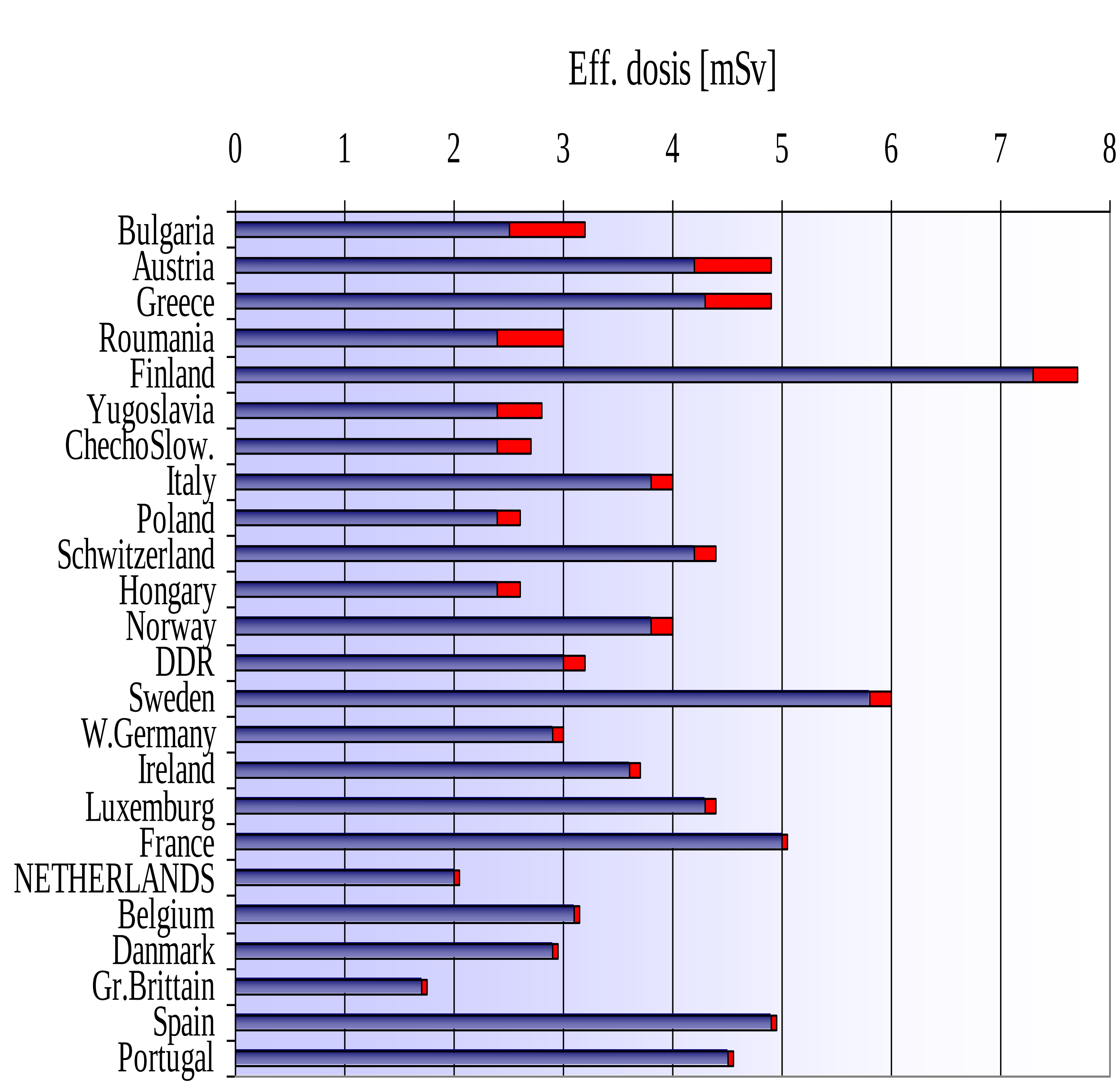
1 MBq per m^2 →

- 1st year: ≈ 10 mSv extra
- life time: ≈ 120 mSv (incl. decay)

	surface contamination		**extra life time dose (incl. decay)**
(dark red)	**>1.5 MBq/m²**	**:** closed zone	: > 180 mSv
(pink)	**0.5-1.5**	**:** permanent control zone	: 60 - 180
(light pink)	**0.2-0.5**	**:** periodic control zone	: 30 - 60
(yellow)	**0.04-0.2**	**:** no-control zone	: 5 - 30

(Compare: Life time dose in Netherlands : ≈ 2.6 mSv/y x 75 y = **200 mSv;**
in Finland: ≈ 8 mSv/y x 75 y = 600 mSv)

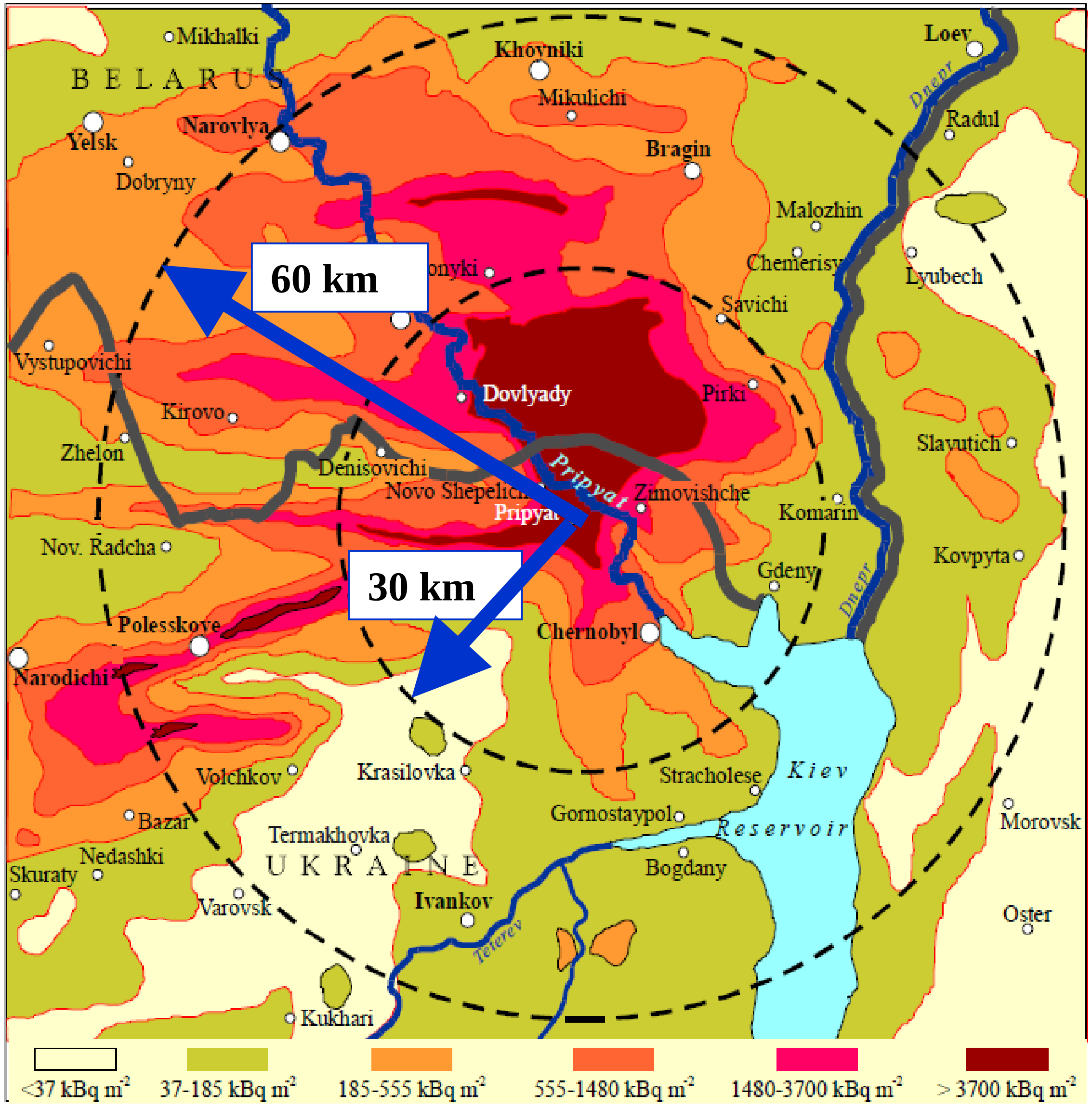
Europe



Eff. annual dose [mSv] (natural only; no medical/ diagnostics)

Extra dose in 1st year after Chernobyl accident

Zones around Chernobyl (1986) : cesium



Cs-137: $T_{1/2}$ = 30 y

Extra life time dose (mSv; incl. decay)

dark red	>500
pink	200-500
orange-red	80-200
orange	40-80
yellow-green	10-40
white	< 10

NB. Life time dose in:

Netherlands:
2.6 mSv/y x 75 y = **200** mSv

France:
6.5 x 75 = **500** mSv

Finland:
8 x 75 = **600** mSv

Figure VII. Surface ground deposition of caesium-137 in the immediate vicinity of the Chernobyl reactor [I1, I24].
The distances of 30 km and 60 km from the nuclear power plant are indicated.

Zones around Chernobyl (1986)

Zone [MBq/m²] (⁰)	**Radius [km]**	Area [km²]	**Extra Life dose [mSv]**	Measures
> 1.5	**30**	3000	**> 180**	obligatory evacuation
0.5 – 1.5	**30 – 60**	7000	**60 - 180**	obligatory evacuation
0.2 – 0.5	**60 – 100**	19 000	**25 - 60**	voluntary evacuation
0.03 – 0.2	**100 - 250**	116 000	**5 - 25**	control area
Compare: the Netherlands (normal situation: 2.6 mSv/y)		39 000	Life dose: **200 (*)**	milk and spinach

(⁰) : 1 MBq/m^2 → extra life dose ≈ 120 mSv (incl. decay).

(*) : 200 mSv = 75 year @ 2.6 mSv/year

Persons involved

Persons involved	Number	**Equiv. dose [mSv]**	Number & Percentage	**Extra cancer risk (%)**
"Liqvidators" (average dose = 100 mSv)	226 000	**>1000** **500..1000** **100..500** **< 100**	≈ 30 pers. ≈ 9000 (4 %) ≈ 22 000 (10 %) ≈ 180 000 (80 %)	**>5** **2.5...5** **0.5...2.5** **<0.5**
Assisting persons	400 000	**≈ 5**		**≈0.025**
Evacuees (average dose = 1.1 mSv)	135 000	**> 100** **50..100** **< 50**	≈ 7000 (5 %) ≈ 13 000 (10 %) ≈ 110 000 (85 %)	**>0.5** **0.25..0.5** **<0.25**

Extra cancer risk = 5 % per Sv
Normal incidence: 20-30 %

Netherlands: background: 2.6 mSv/y
… : Life time dose: 200 mSv.

1. Topography
2. The reactor
3. The accident
4. *Intermezzo: Natural radiation effects*
5. Emission
6. Radiation caused by the accident
7. **Environmental and health effects**
8. Situation in the Netherlands and Europe

Persons involved: effects

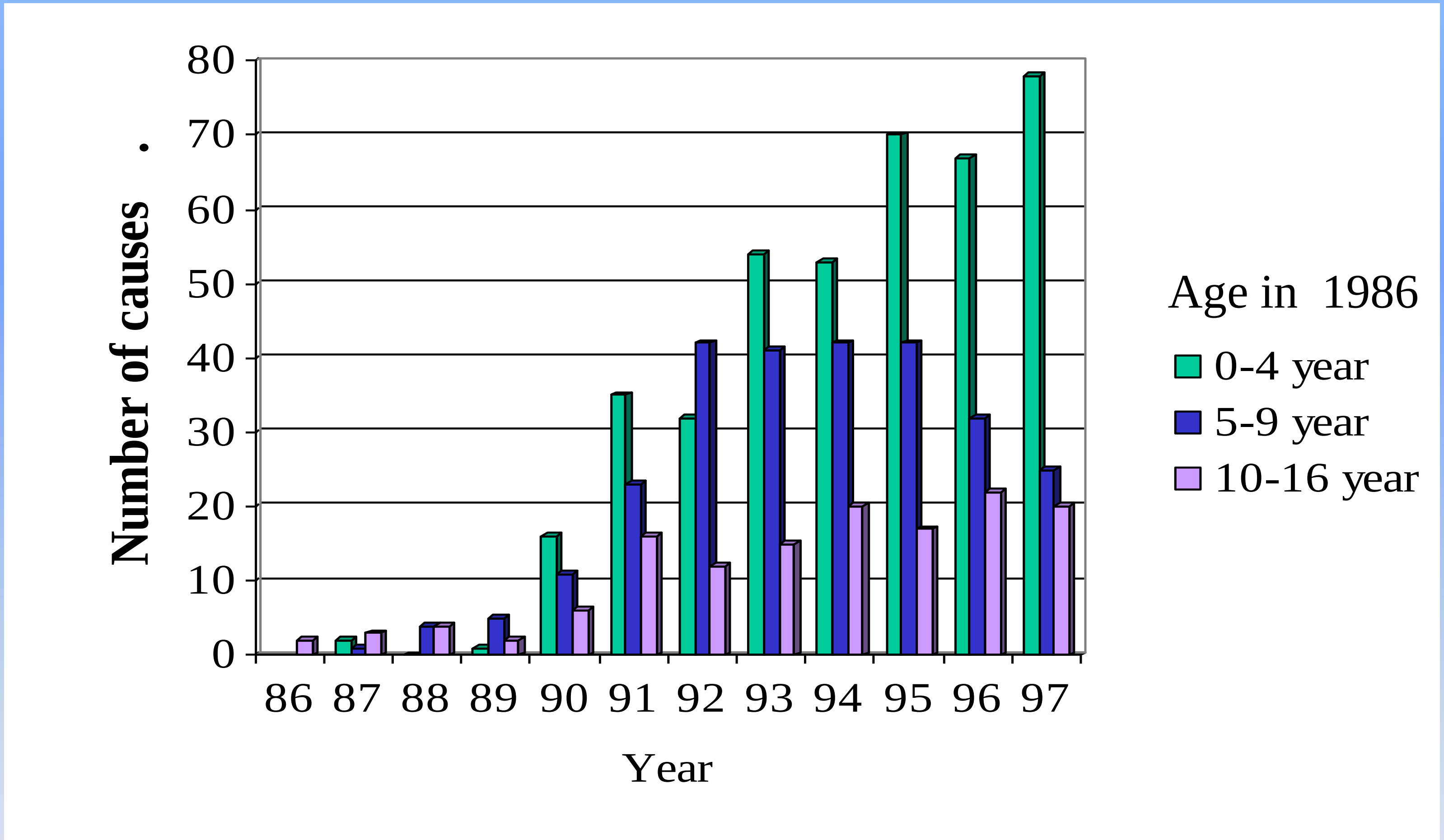
During accident:	**2** deaths
Acute hospitalization:	**237** persons
.... Suffering from ARS (*):	134 ....
.... Deceased in 1986:	28 ....
.... Deceased 1987-2004: (^{0})	19 ....
.... Alive in 2004:	190 ....

(*) ARS: Acute Radiation Syndrome:
Nausea, diarrhea, haemorrhages,
Temporary reduction of
immune system => fevers

(^{0}) Various causes: about 30% heart, 30% liver cirrhose, 10% morbid obesity, 10% tuberculosis, 10% unknown

ARS: dose	Nr. persons
< 2 Sv	41
2..4 Sv	39
4..6 Sv	50
6..15 Sv	21

Thyroid tumors in children



Average thyroid dose: 0.5 ± 0.4 Sv

(No extra effects in children born AFTER 1986)

Thyroid tumors

- Increase: - from ≈1990, latent period ≈ 4 year
  - ≈ 6000 cases until 1995, 20000 until 2017
  - predominantly: children born before 1986
  - 25 % of all thyroid tumors attributable to radiation
  - boys / girls : ≈ 7/10
- Probability: in most contaminated area (Gomel, Belarus):
  - 0-15 year: 4.5×10^{-6} (factor 8 x previous situation)
  - >15 year: factor 3 x before
- Treatment: **Medication** and/or **Thyroidectomie**
- Problem: - endemic iodine shortage (1/8 x normal)
  has stimulated intake enormously
- Deceased: - until 1996: 3 persons
  - until 2002: 9 persons (+ 6 uncertain; other causes?)
  all others recovered or recovering.

(1996) "To date, only three children in the cohort of diagnosed cases have died of thyroid cancer. These post-Chernobyl papillary thyroid cancers in children ...appear to respond favourably to standard therapeutical procedures..." (98.9 % survival).

(2011) Total number of casualties in children due to thyroid cancer is about 15.

Leukaemia and other tumors: expected

Population	Number	Average dose (^{0}) [mSv]	Solid tumors		Leukaemia		Total	
			Norm. (%)	Extra (%)	Norm. (%)	Extra (%)	Norm.	**Extra**
Liqvidators	200 000	100	24	1	0.4	0.1	50000	**2200**
Evacuees (<30 km)	135 000	10	24	0.1	0.3	0.01	40000	**150**
Inhabitants SCZ's (*)	270 000	50	24	0.5	0.3	0.04	60000	**1500**
total	*600 000*						*150000*	***3850***
Inhabitants other zones	6.8 million	7	24	0.05	0.3	0.01	2.0 million	**4080**
					grand total			***8000***

(*) SCZ: severely contaminated zone

(^{0}) Netherlands: 2.6 mSv/y ; life time dose: 200 mSv.

Leukaemia and other tumors: observed

Observations until 2005:

Population of contaminated areas and Liqvidators:

- Leukaemia and other tumors:

  "extra" cases: number << "background" of normal incidence.

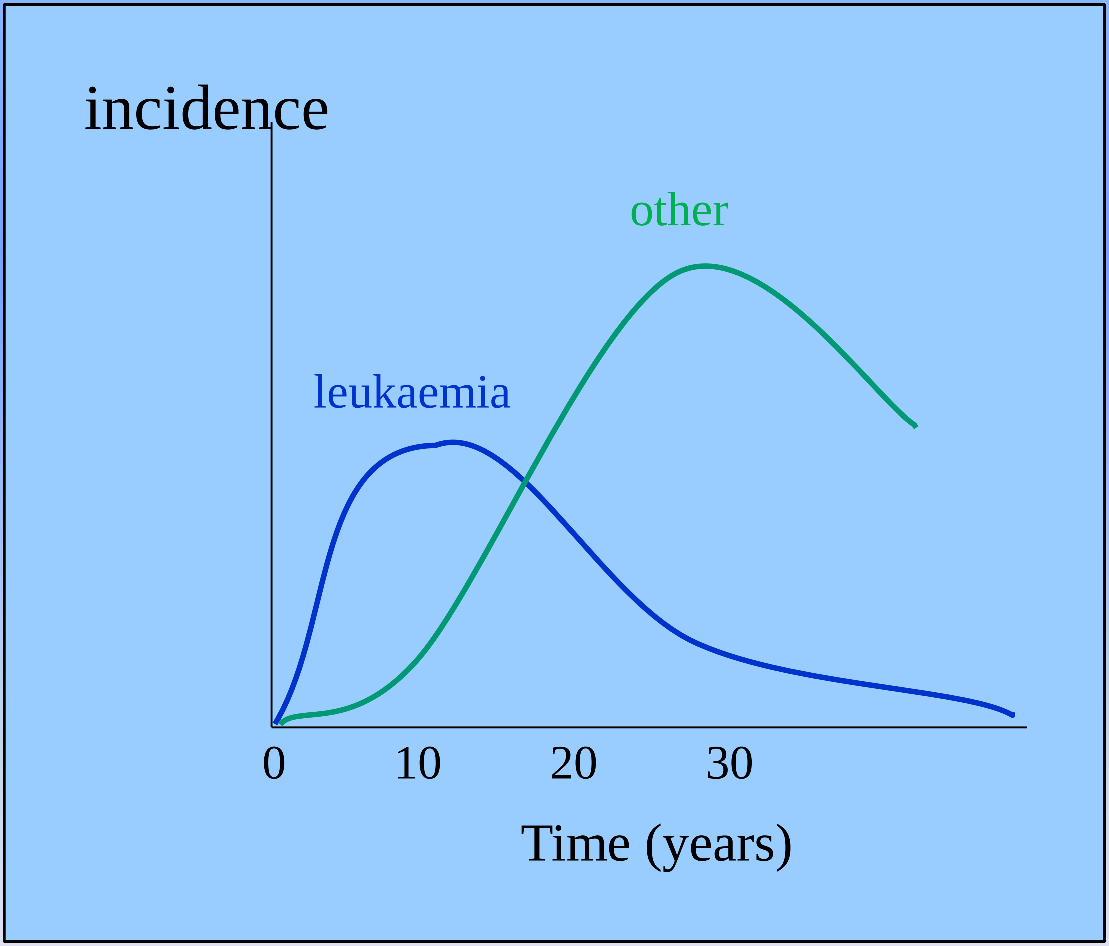
  "no increased risk for population has been found, so far"

  "slight indication of increased risk for "liqvidators",
  but latent period (≈ 20 years) has almost expired"

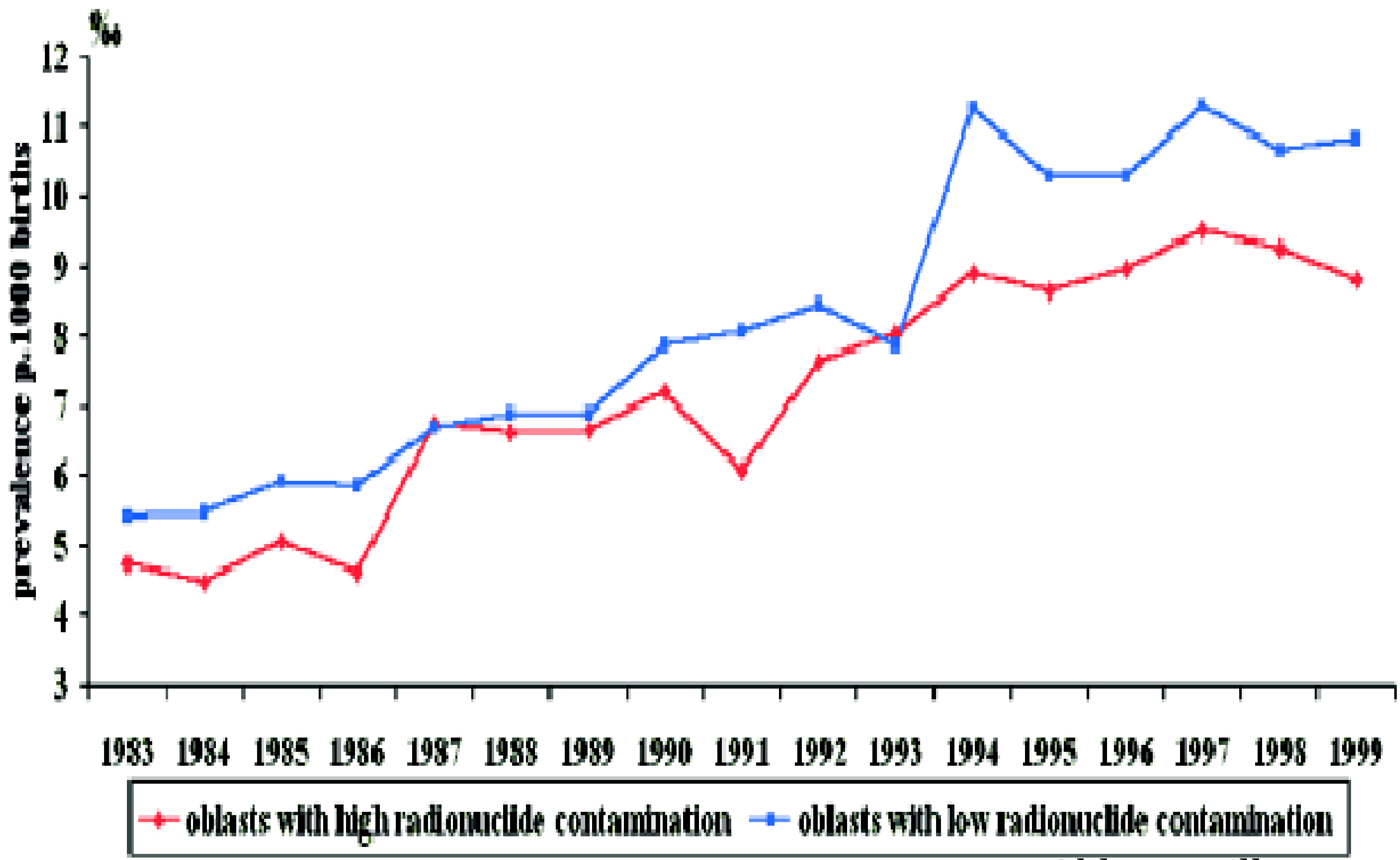
- Hereditary diseases: idem
- Malformations: slight increase over 20 years, but not radiation-dependent
- Breast cancer: slight increase, but relation with radiation level uncertain

"No consistent attributable increase has been detected either in the rate of leukaemia or in the incidence of any malignancies other than thyroid carcinoma" (UNSCEAR report).

Leukaemia and other tumors: latent period

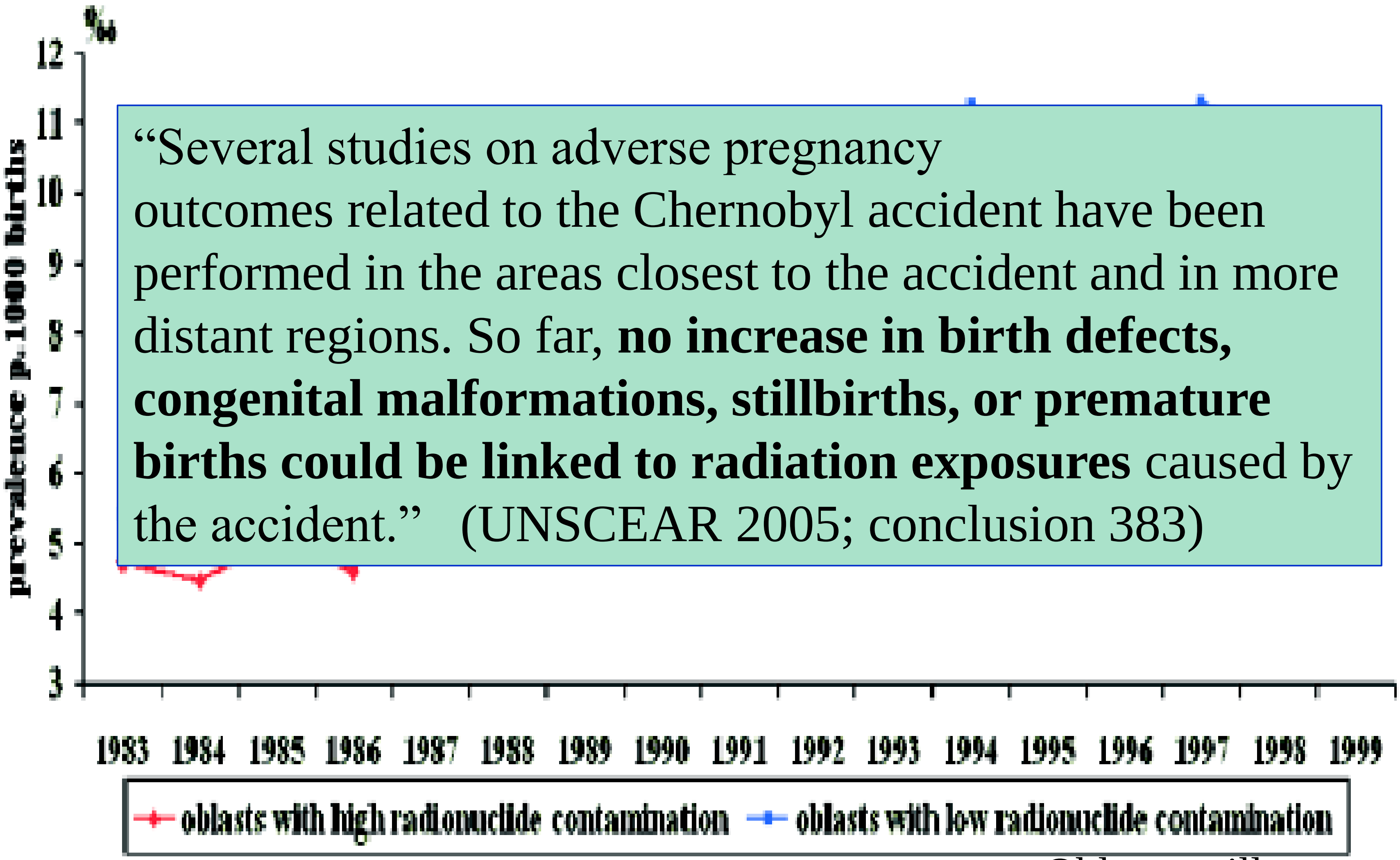


Congenital malformations



Oblast = village

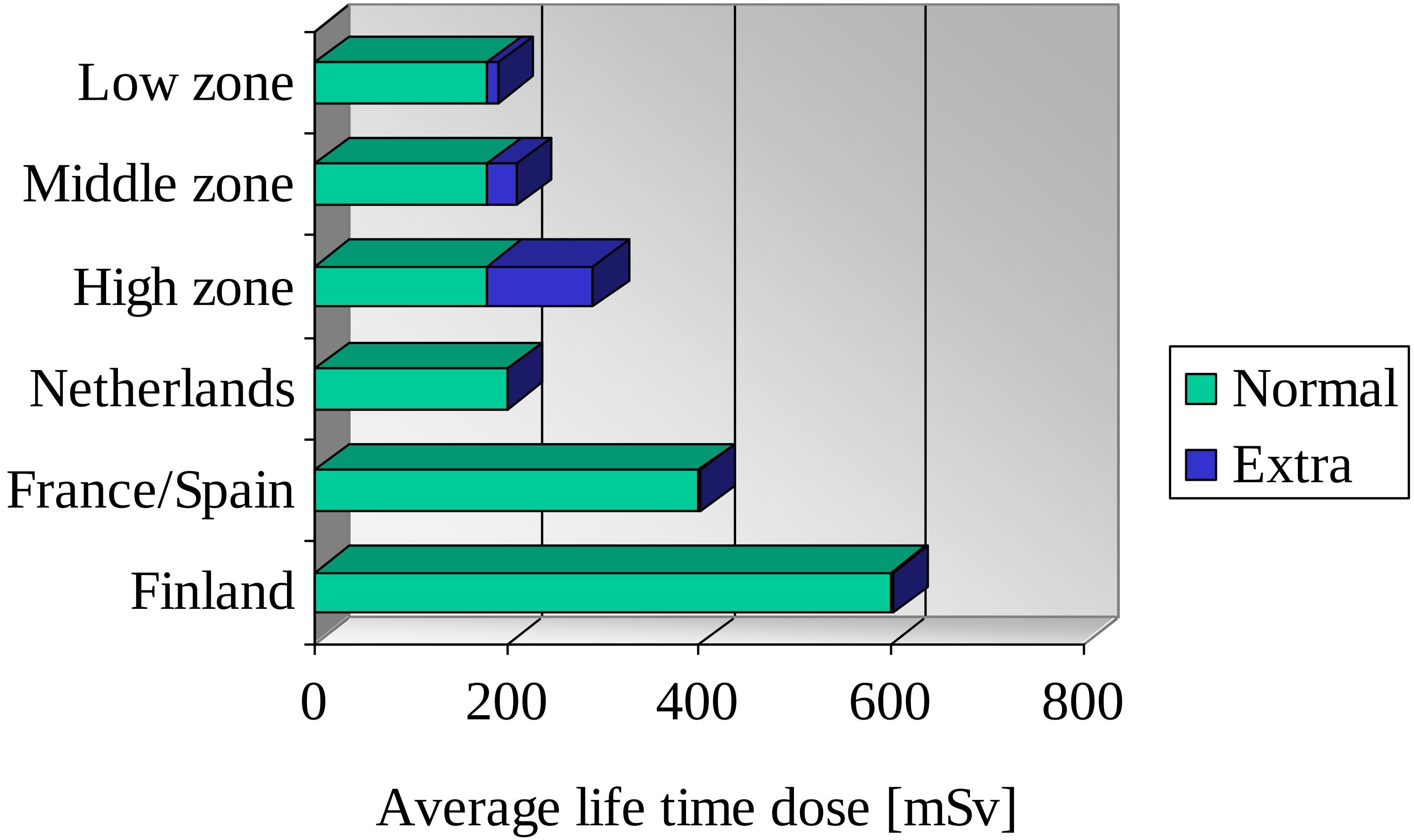
Congenital malformations



"Several studies on adverse pregnancy outcomes related to the Chernobyl accident have been performed in the areas closest to the accident and in more distant regions. So far, **no increase in birth defects, congenital malformations, stillbirths, or premature births could be linked to radiation exposures** caused by the accident." (UNSCEAR 2005; conclusion 383)

Oblast = village

Life time dose for population



Animals and Plants

- Animals (in 30 km-zone):
  - cattle: thyroid problems
  - frogs: 1/3 of eggs sterile (1.5 % in control group)
  - morphological abnormalities: not significant
  - from 1989: recuperation to ”old” situation

- Plants (in 30 km-zone):
  - trees (firs/birch): 40 % dead, 90 % damage
  - morphological abnormalities: not significant
  - from 1989: recuperation to ”old” situation

Psychological / social effects for liqvidators and evacuees

- General increase of health complaints and symptomes, but independent of contamination level
- Problems due to evacuation: unemployment, alienation
- Personal problems: despair, hopelessness, uncertainty of future health.
- Disruption of society

1. Topography
2. The reactor
3. The accident
4. *Intermezzo: Natural radiation effects*
5. Emission
6. Radiation caused by the accident
7. Environmental and health effects
8. **Situation in the Netherlands and Europe**

Milk and Spinach in the Netherlands

Question : limit for consumption after soil contamination with ^{131}I in milk and vegetables (representative example: spinach)
(initial soil contamination max. 2-11 kBq/m^2 ; normal 50 Bq/m^2)

Criterion: integrated year-dose on thyroid in baby (highest risk)
< 0.1 x yearly limit for population

	Limits	Official norm (May/Oct '86)	Actual values (May '86)
Milk [Bq/liter]	2300	500 / 125	**50**
Vegetables [Bq/kg]	6100	1300 / 250	**150**

NB. ^{131}I has half-life time = 8 days.

Statistical casualties over Europe

Inhabitants: 500 million (= 500 000 000)

Average one-time equivalent dose in 1986: 0.2 mSv (= 0.0002)

Cancer risk (stochastic range): 5 % per Sv (= 0.05 per Sv)

Expected extra casualties: **5000** (= 500 000 000 x 0.0002 x 0.05)
(onetime; latent period 20-30 years)

Compare:

- Natural cancer casualties: 20 % => **100 million**, or
  ≈ 1 300 000 / year (assume life time = 75 year)
- Natural radiation casualties @ 4 mSv / year (Europ. average):
  100 000 / year

Overview attributable casualties

Casualties (1986 - 2011)		**total**
Observed:		
- During accident	2	
- Afterwards	47	
- Thyroid in children	15 - 20	
		≈ 70
Statistical casualties:		
- Directly involved (*)	≈ 4000	
- Other involved ([0])	≈ 4000	
		≈ 8000
- Europe	≈ 5000	

(*) Liqvidators, Evacuees, Inhabitants SCZ (severely contaminated zones)
([0]) Inhabitants other zones

the end