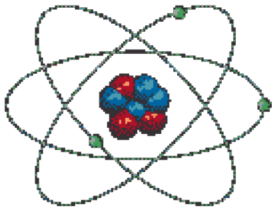
MINISTERIO
DE EDUCACIÓN
Y CIENCIA

CONSEJO SUPERIOR
DE INVESTIGACIONES
CIENTÍFICAS

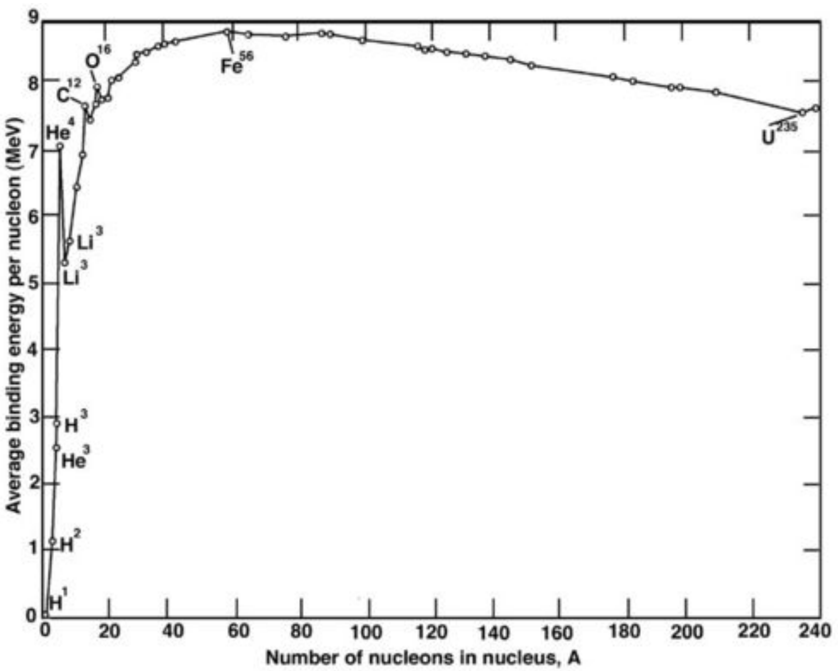
Olof Tengblad

Chernobyl 20 years later

- introduction to nuclear reactors
- the Chernobyl accident
  - what happened
  - the reactor
  - consequences



How to obtain energy



Natural systems tends to minimise their energy so the reason for nature to form nuclei is that the mass of the combined system is less than the sum of the masses of the constituents.

$\mathbf{M}(\text{ZXN}) < Z\,\mathbf{m}_p + N\,\mathbf{m}_n$

Binding Energy

B.E. $= [\,Z\,\mathbf{m}_p + N\,\mathbf{m}_n - m(Z,N)\,]\,c^2$
$= [Z\,\mathbf{M}(1H) + N\,\mathbf{M}(n) - \mathbf{M}(\text{ZXN})]\,c^2$

as the electron masses evens out and the e- binding energy is negligible

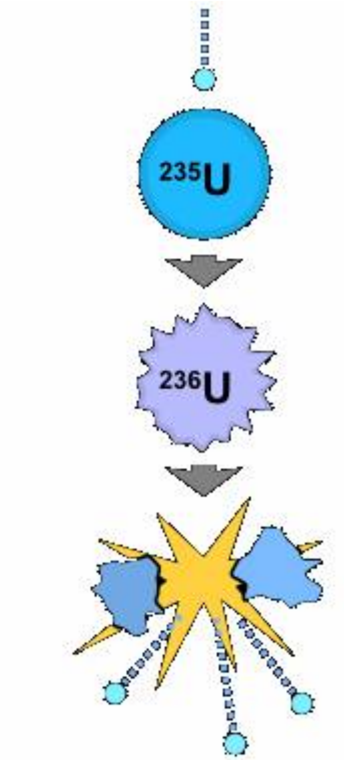
Spontaneous Fission

Certain heavy nuclei can break spontaneously into two comparably sized fragments.
The Binding Energy per nucleon for Uranium is about 7.6 MeV, if we assume symmetric fission, the two fragments will have masses of about 120 and in this region the

B.E. = 8.5 MeV → 238(8.5 - 7.6) = 215 MeV

As the heavy nucleus has a neutron excess relative the lighter nuclei, 2 - 3 neutrons are emitted in the process, this reduces the available energy to about 200 MeV.

However, the rate for this process in natural existing nuclei is very small, and thus of no interest for energy production.



Induced Fission

One can increase the fission rate by bombardment with particles. The fission rate will then depend upon the nature of the bombarding particle, the energy and the intensity of the particles.

Induced fission is thus a *reaction process* rather than a decay, so relevant parameter is cross section not half life.
The more interesting case is when a Compound Nucleus is formed, and this to happen is more probable using neutrons.
The relative fission barrier the projectile has to excite the system to overcome is that of the Compound system

$E_n > E_b - S_n$

- E_n - neutron energy
- E_b - fission barrier
- S_n - neutron separation energy

^{238}U(99.3%), ^{232}Th(100%): fission threshold = 1 MeV

^{235}U(0.7%), and the artificial ^{233}U, ^{239}Pu and ^{241}Pu
Sn > Eb why fission occurs with **thermal neutrons**

Chain reaction

Very important is that there are more than 1 neutron emitted in each fission. As each of these emitted neutrons can induce fission in another fissile nucleus, one can have a self-sustained chain reaction which, beginning with a single fission event, would grow exponentially until the sample is consumed.

ν - Mean nº of neutrons emitted per fission

η - Mean nº of n emitted per n absorbed

β - Fraction of delayed neutrons

α - ratio of (#,γ) to (#,fission) = σ_γ / σ_f

so $\eta = \nu / (1+\alpha)$ and if $\eta > 1$ we can have a **chain reaction**

	fission cross section σ	# of n emitted per fission ν	# n emit per # n absorbed η	fraction of delayed n β
^{233}U	528	2.48	2.27	0.27
^{235}U	569	2.42	2.06	0.65
^{239}Pu	785	2.86	2.06	0.22
^{241}Pu	2.92	2.17	0.54	

Fuel and moderator

- **Kinetic energy loss suffered colliding is greater the lighter the body it hit.**
- **The absorption cross section for thermal neutrons has to be small**
- **D_2O can sustain a chain reaction with natural Uranium**
- **H_2O requires a 3-4 % enrichment of the ^{235}U**

20 % enrichment NO moderator is needed --> breeder reactor.

Element	**Number of collisons 2 $\rightarrow$ 0.025 MeV**	Elastic/absorbtion Cross section
H_2O	20	61
D_2O	36	4320
Be	87	137
C	115	223
Al	252	0.44
U	2170	0,0109

The neutron cycle in a fission reactor

N neutrons absorbed in the fuel --> { **radiative capture (n,γ)** / **N * σ_f / σ_a will fission**

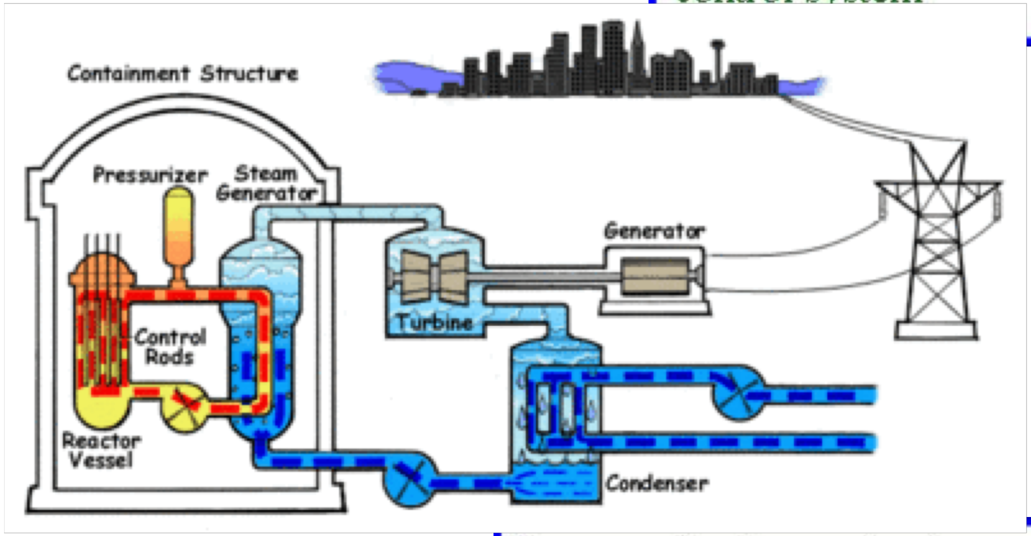
we get n new neutrons per fission -> $\eta = v\ \sigma_f / \sigma_a$ fission neutrons.
Some will induce fission before thermal -> fast fission factor ε
During the slow down some will be absorbed in
^{238}U the resonance-passage-factor p
Finally the amount absorbed in the fuel → f --> $\eta\,\varepsilon\,\pi$ f N

$\eta\,\varepsilon\,\pi$ f N = k N and we have the multiplication factor k
this is for a reactor of infinite size as the reactor has a finite size we introduce a leakage factor and get k_{eff}

$k_{eff} < 1$ sub critical	**neutron amplifier**
$k_{eff} = 1$ critical	**can sustain chain reaction at constant effect**
$k_{eff} > 1$ over critical	**the effect will increase for each n-cycle**

Fission Reactor

Nuclear fuel	-	UO_2 enriched to 3.5 % ^{235}U
Moderator	-	H_2O, D_2O or C
reflector	-	the same as the moderator
cooling system	-	to transport the "energy" to the turbine
pressure chamber	-	to contain the "reactor" and keep the high pressure needed
radiation shield	-	cement
gas tight building	-	to prevent leakage of radioactive gases in case of accident
control system	-	neutron absorbing rods of B or Cd



For security the reactor has a negative temperature coefficient, which means that if the temperature increases the k_{eff} decrease. In a light-water reactor this is automatically as the water density changes with temperature so that the moderator effect decrease with increasing water temperature.

Facts and History

- 1938 Induced fission discovered by Hahn and Strassman when they observed that Ba was produced when U was irradiated with neutrons. Meitner and Frisch gave the explanation
- 1941 Spontaneous fission discovered
- 1942 first critical reactor in Chicago by Fermi
- 1954 first electric producing reactor Obninsk
- 1954 first atomic submarine
- 1979 Harrisburg accident
- 1986 Chernobyl accident
- 1 GW reactor uses 20 ton UO_2 per year
- Which is equivalent of 1.000 ton natural Uranium, this give 250kg of plutonium isotopes (58% ^{239}Pu).
- For a nuclear bomb one need 4.9 kg of ^{239}Pu
- 442 nuclear power plants in operation with a total net installed capacity of 370 GW(e) about 18% of total el-power

Artificial thermonuclear fusion

The fusion process is what keeps our sun running.
To achieve it artificially we will need very high temperature and high density.

he interesting reactions are:

			$^{3}He + n + 3.3$ MeV
DD	$\mathbf{^{2}H + ^{2}H}$	$\Rightarrow$	$^{3}He + ^{1}H + 4.0$ MeV
			$^{4}He + 23.8$ MeV tiny cross section
	$^{3}He + ^{2}H$	$\Rightarrow$	$^{4}He + ^{1}H + 18.3$ MeV
DT	$\mathbf{^{3}H + ^{2}H}$	$\Rightarrow$	$\mathbf{^{4}He + n + 17.6}$ **MeV**
	$^{1}H + n$	$\Rightarrow$	$^{2}H + 2.2$ MeV

$\Rightarrow$ Total **$4 * {}^{2}H \Rightarrow 2 * {}^{4}He + 47.7$ MeV** **Non radioactive!**

a factor 6 more compared to the release in fission

The self-sustained reactor

10^{10} J of energy from 1 litre of town water = 300 litre of petrol

Water supply is infinite
HOWEVER, the ignition temperature of the
DD reaction is 4 10^8 K
DT 4 10^7 K

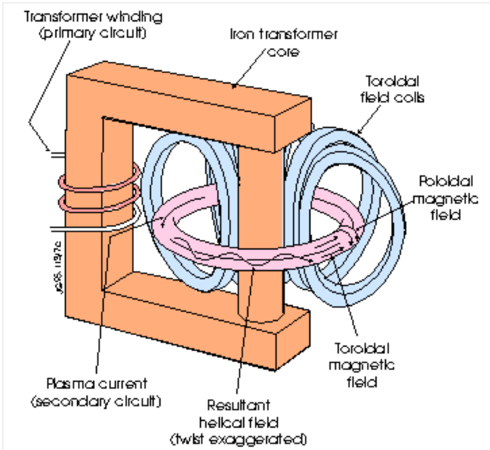
⇒the DT reaction will be the one and only used

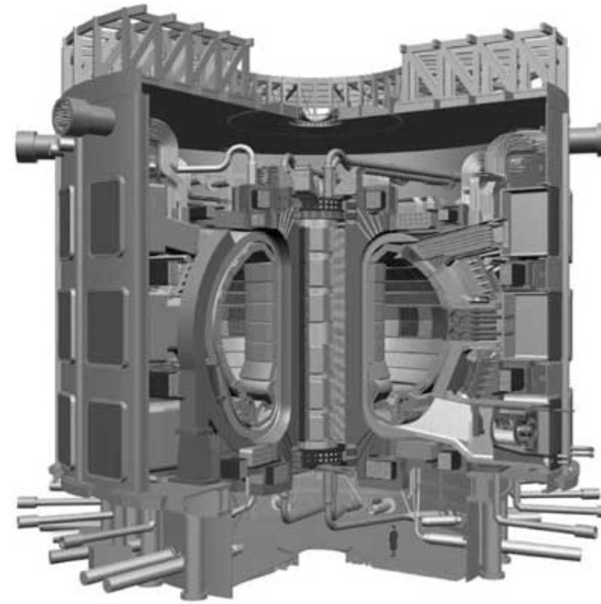
⇒ How about the TRITIUM supply!
By surrounding the reactor with
Lithium cloth one can breed Tritium

$$n + {}^{6}Li \Rightarrow {}^{4}He + {}^{3}H$$
$$n + {}^{7}Li \Rightarrow {}^{6}Li + 2n - 7.2\ MeV$$

The neutrons from the DT reaction have 14 MeV so OK.
In fact one will generate more T than consumed.
The Lithium supply is about the same as the oil, gas supplies

The Tokamak





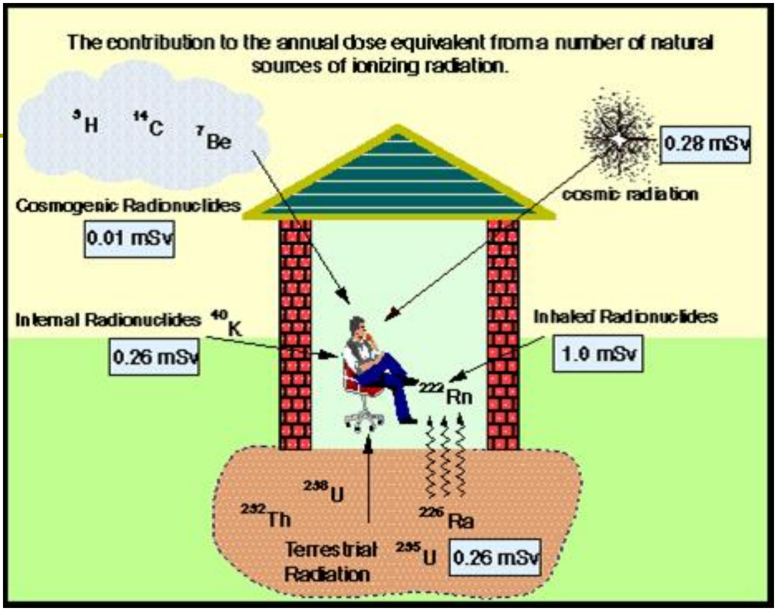
The basic components of the Tokamak's magnetic confinement system are:

The toroidal field which is produced by coils surrounding the vacuum vessel.

The poloidal field produced by a current in the plasma; the plasma current is induced by transformer action.

Background radiation

Radiation source	Absorbed dose in µGy/year muscle	bone
External		
Cosmic rays	300	300
from ground and air	500	500
Internal		
40K	200	60
Radium	2	40
Radon	3	3
14C	7	9
Total	1000	900



One *gray* (1 Gy) is the absorption of one joule (1 J) of energy, in the form of <u>ionizing radiation</u>, per Kg of <u>matter</u>

$$1\ \mathrm{Gy} = 1\ \frac{\mathrm{J}}{\mathrm{kg}} = 1\ \frac{\mathrm{m}^2}{\mathrm{s}^2}$$

Absorbed dose Gy	Effect in human of momentarily full body radiation
0 - 0.25	NO immediate effect, delayed with very low frequency
0.25 - 1	Short period of decreasing blood-cells but recovery, might get delayed effects
1 - 2	Tiredness, uneasy feelings, 3 month recovery for full blood cell production
2 - 6	Vomiting, diarrea, in 1-2 weeks time loss of hair and fever 2.5 Gy 50% probability of complications leading to death within 30 days 50% will need half a year recovery time
>6 >8 10 Gy locally	visual effects on the skin Death wounds with very bad healing

Ekvivalent Dose given in Sivert (Sv → Biologisk effect:

Biological effects of radiation

the ionising radiation excite atoms in the cells.
The defects induced depends on the type of radiation, the energy, the intensity, the irradiation time and in which part of the body.
Blood producing organs as well as the red and white blood cells are very sensitive as they have a short lifetime, nerves which last the life out are much less sensitive to radiation.
If a human receives a deadly dose of 10 Gy full body irradiation the energy the body received is about 800W i.e. a 40W bulb used for 20s.
So it is the ENERGY CONCENTRATION along the path of the ionising radiation that is the danger, i.e. the shorter range the particle has the more concentrated is the energy deposit.

As the body is mainly water the main effect of radiation in human;
H_2O --> OH + H ---> H_2O_2 + H_2
H_2O_2 is a very strong cell-poison.

Ekvivalent Dose → Biologisk effect:
given in Sivert (Sv): Sv=$\varepsilon * Gy$

e^- & γ	ε = 1
Neutrones	ε = 5 -20
alphas	ε = 20

Radiation	Range in body of 5 MeV radiation	Effect in cell, 1 cell = 10 μm
α	0.04 mm	absorbed by 3 cells, 4000-9000 ion pairs / μm
β	2.5 cm	100 ion pairs / μm produced
γ	>50% pass 25 cm	20 ion pairs / μm

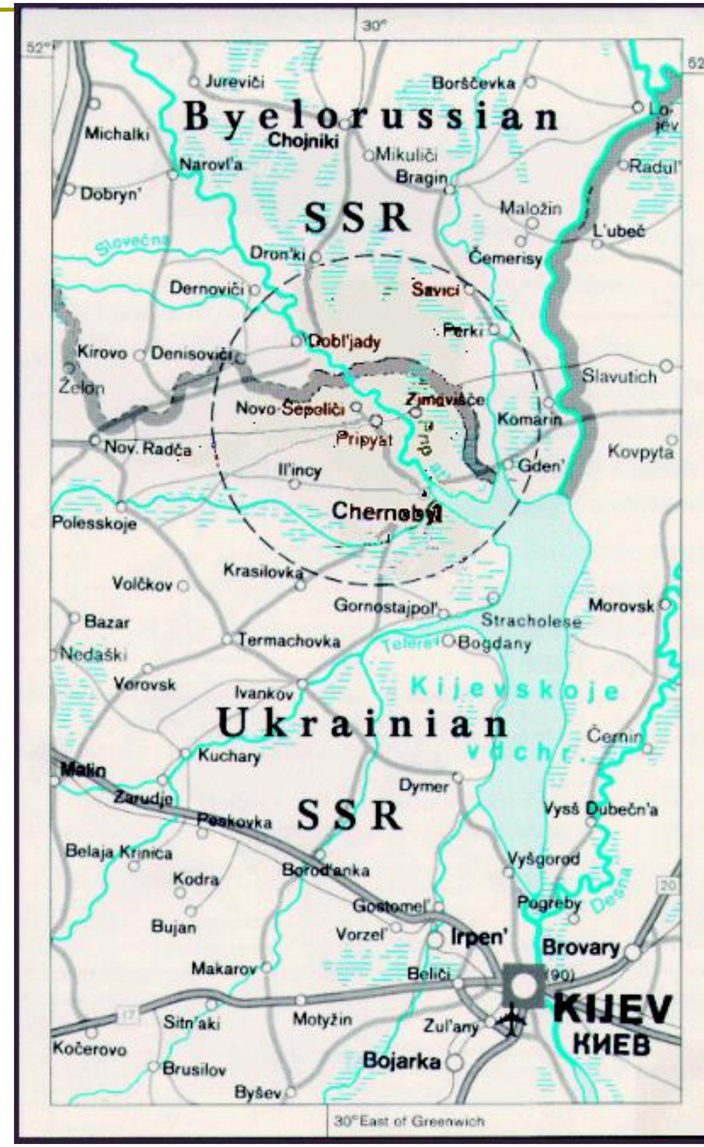
Chernobyl accident 26 of April 1986

The site: Ukraine

within 30 km radius a population of 120.000

nearest town:

<u>Pipyat</u> 3 km from the reactor with a population of 49.000

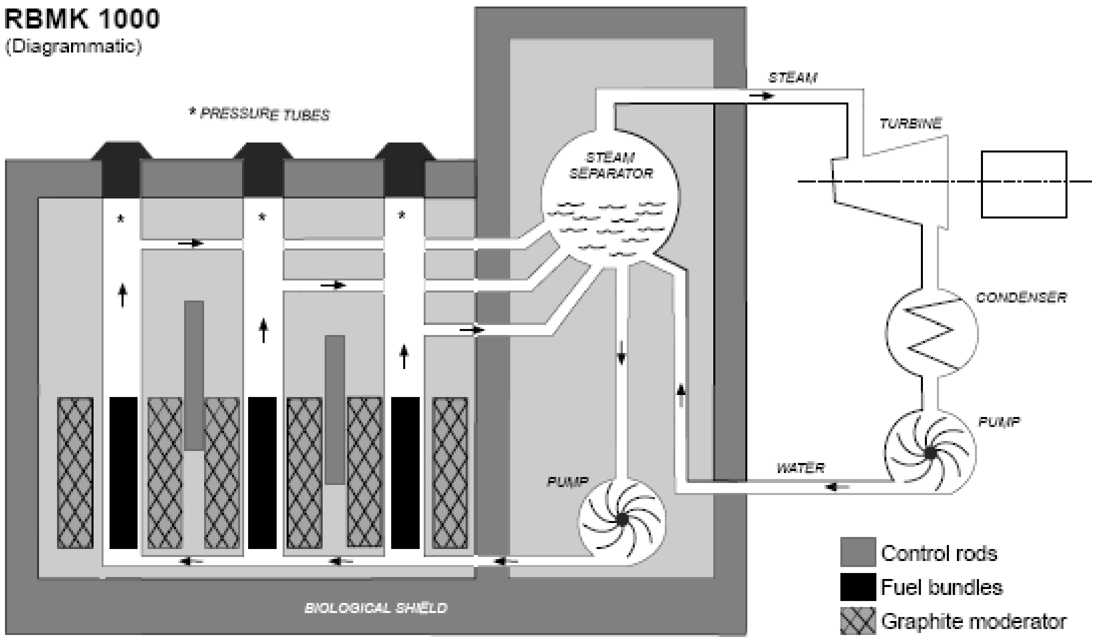


The Chernobyl reactor

Reactor: 3.200 MW(t) → 1.000 MW(e)
Fuel: UO_2 enriched to 2% ^{235}U
Moderator: Graphite
Cooling: Light water
Core: 7 m high 12 x12 m^2 wide
Direct steam feed two 500 MW(e) turbines.
Water pumped to the bottom of the fuel channels, boils as it progress up the tube producing steam to drive the two turbines.

SAFETY - system: **Pos.temp.coef.**
power increase or water flow decrease → increased fission
balanced by
Neg.fuel.coef.
increase in fuel temp → reduced n-flux

Normal effect	neg.fuel.coef.	dominates →	SAFE
< 20% effect	pos.temp.coef.	dominates →	UNSTABLE

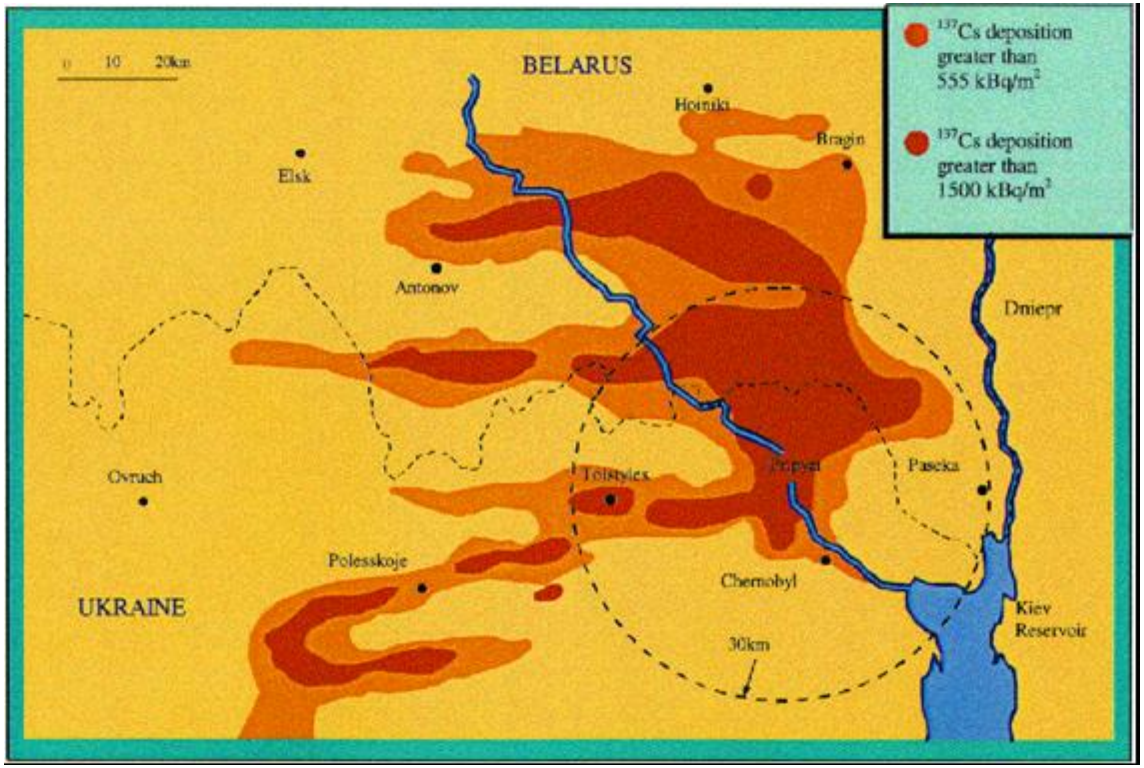


Events leading to the accident

- Routine shutdown 25 april 1986, during which a test was performed
- Could in case of loss of staion power the slowing turbines still produce enough electricity for the emergency system?
- To make test safety system de-coupled
- Test at 1000 MW before shutdown. Bad comunication and operator error → power fell to 30MW → pos.temp.coef dominate
- 01:00 operator stabilize the reactor at 200MW turning of automatic regulation
- Now only 6-8 control rods in use (30 recomended)
- Increase in coolant flow → drop in steam, automatic control would have closed down the reactor BUT operator instead withdraw remaining control rods to maintain power → reactor unstable, operator reduces the coolant flow to compensate
- The pos.temp.coef takes over → run off→ power increases a factor 100 → fuel particles reacts with the cooling water → STEAM EXPLOSION → reactore core destroyed
- Time 01:23 Saturday 26 April 1986
- Fire starts → the coolant Graphite takes fire
- 05:00 fire brigade arrives
- One dropped BoronCarbide and sand from helicopters to stop the fire
- 9 May the fire was out

The cloud

The explosion sent a shower of hot radioactive particles 1 km up into the air.
6 tonnes of fragmented fuel was released
7 GBq of ^{137}Cs 50% of the reactor inventory
30 km zone up to 1.5 MBq /m^2 of ^{137}Cs

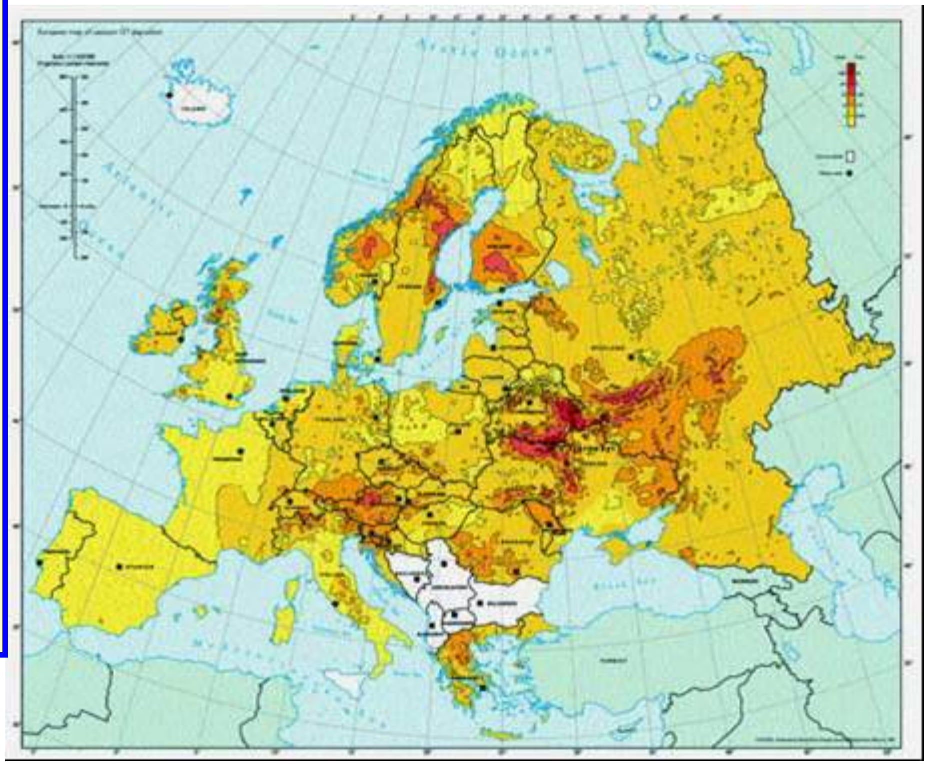


Outside Russia

The accident got first known outside Soviet when workers entering a Swedish power plant were found contaminated.

One immediately started searching for a leak but realised fast that the activity had come from elsewhere.

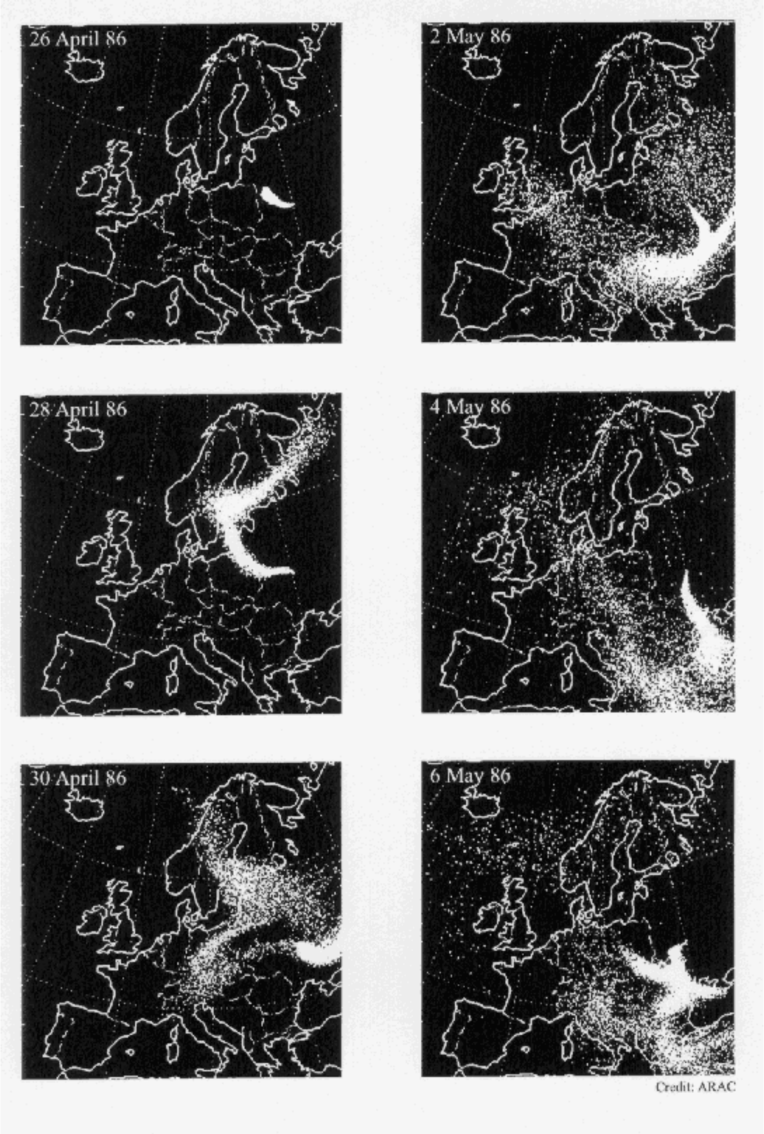
However except around nuclear plants all sensors are set for Nuclear war and could not detect these "low" quantities.



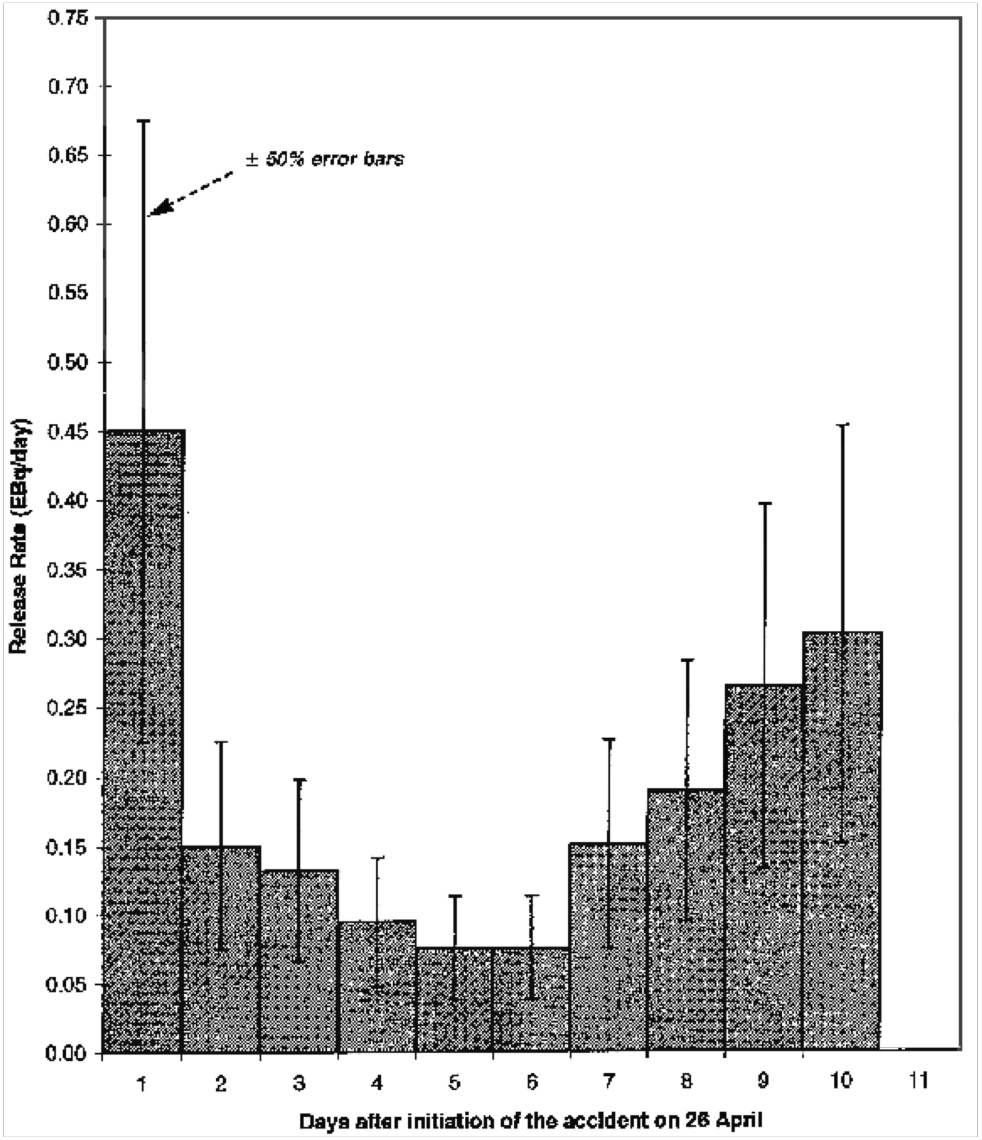
To compare numbers:
In Sweden before the accident (due to Russian, American, French bomb tests in the -60) there was 2 kBq / m2
In Portugal after the accident one measured 20 Bq / m2

The cloud passing over Europe

26/4 | 2/5
28/4 | 4/5
30/4 | 6/5



Release of radioactive material per day after accident



Evacuation and Dose

- Pipyat 3 km from accident 49.000 inhabitants
  - 26:th in the evening one took decision to evacuate
  - 27:th 11:00 one announced the evacuation order
  - 14:00 evacuation started
  - 16:30 last person left Pipyat
  - In total 135.000 were evacuated from teh 3km zone
- On the night 26 there were 400 workers on site
  - 237 sent to hospital
    - 140 whole body irradiation 1-2 Gy
    - 55 2-4 Gy
    - 21 4-6 Gy
    - 21 (20 died) 6-16 Gy
- 800.000 people worked during 1986-1990 to clean up
  - 50% military personal these people took in average
  - 170 mSv 1986 max. 250 mSv allowed
  - 130 mSv 1987
  - 30 mSv 1988
  - 15 mSv 1989
- Among the evacuated
  - 15 mSv whole body
  - 1 Sv Thyriode uptake in small children
  - 70 mSv Thyriod uptake in adults

Acute health impact

- 31 dead — 1 in the explosion; 1 of heart attack; 29 during treatment at hospital
- Thyroid centre in Minsk

<1986	5 cases reported
1986-89	2-6 cases/year
1990	29
1991	55
1992	67
→1999	2.000 cases in total
→ 2006	4.600 cases in total survival percentage 99%

→ No change leukaemia rate found

→ No change in pregnancy outcome

The 30km zone has become a “wild animal parc”

A wall 3.5 km long and 35 m deep was built around the reactor to protect Kiev water reservoir

Equipment and soil from clean up has been digged down inside the 30km zone

UNSCEAR 2008; http://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf

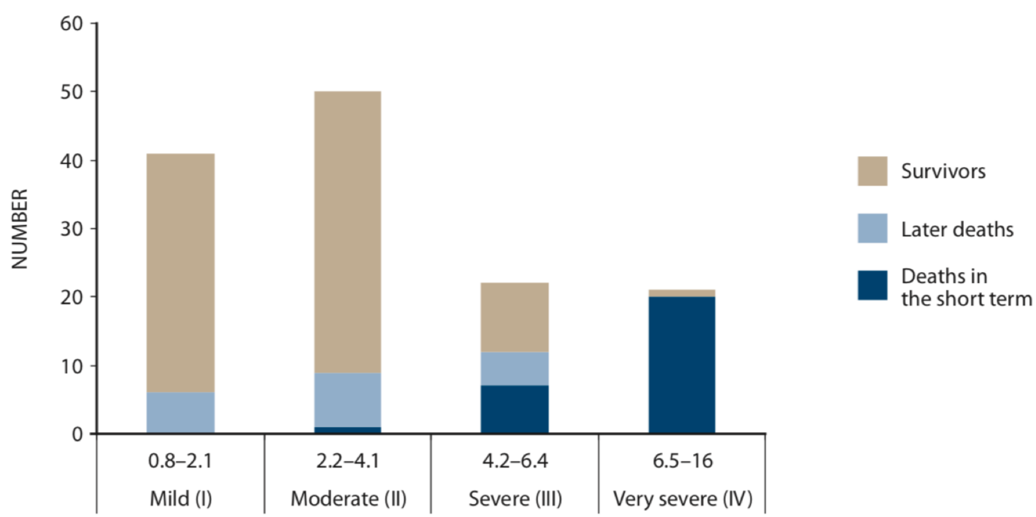
A. Acute radiation syndrome in emergency workers

48. The first information on the early severe health effects due to high acute levels of radiation exposure was presented to the international community in August 1986 [I31]. Analyses of clinical data were presented in the appendix to annex G, "Early effects in man of high doses of radiation", of the UNSCEAR 1988 Report [U7]. Updated information on the early health effects among emergency workers was provided in annex J, "Exposures and effects of the Chernobyl accident", of the UNSCEAR 2000 Report [U3]. There are no substantive new data regarding the early health effects, so only a short recapitulation is provided here (more detailed information is provided in appendix C).

49. A total of 237 emergency workers were initially examined for signs of ARS. Within several days, ARS was verified in 104 of these individuals, and in a further 30 at a later date. Of these 134 patients, 28 died within the first four months, their deaths being directly attributable to the high radiation doses (two other workers had died from injuries unrelated to radiation exposure in the immediate aftermath of the accident). Figure VII presents the outcome for the ARS patients.

Figure VII. Outcome for patients with ARS

While the figure indicates the numbers of later deaths for each category of ARS, most of the cases are not attributable to radiation exposure



Year 2000

Table C1. Data for the 134 patients with acute radiation syndrome [U3]

Degree of ARS	*Absorbed dose range (Gy)*	*Number of patients*[a]	*Number of early deaths*[b]	*Number of survivors*
Mild (I)	0.8–2.1	41	0 (0%)	41
Moderate (II)	2.2–4.1	50	1 (2%)	49
Severe (III)	4.2–6.4	22	7 (32%)	15
Very severe (IV)	6.5–16	21	20 (95%)	1
Total	0.8–16	134	28	106

a Acute radiation syndrome was not confirmed in a further 103 treated workers.
b Percentage of treated patients in parentheses.

C8. During the first two days, analyses were conducted to ascertain the degree of radioactive contamination of the skin and the activity of the radionuclides (including radioiodine and radiocaesium) taken into the body. These analyses were carried out on 75% of the total number of patients. The majority of patients did not show radionuclide body burdens above 1.5–2.0 MBq (40–50 μCi). Some 6% of the patients had internal burdens approximately 2–4 times higher than this. The patients were also analysed for the presence of ^{24}Na, to ascertain the neutron exposure. Neutron exposure, however, was found to contribute only a very small part of the total exposure of the patients. Data on internal and external exposures are presented in table C2.

Chernobyl accident 26 of April 1986

The main consequences were;

- **Fall out of radioactive elements covering a big areas:**
Russia, Ukraina and Bellarussia , Scandinavia

- **300.000 people were moved from there homes in the nearby region of the accident**

- **Among the people working on stopping the fires during the accident**
  164 got acute radiation damages taking doses up to 16 Sv
  31 died within a few month after the accident
  11 more have died between 1987 - 1998

- **Thyroid cancer among the group that were (<18) at time of the accident has increased dramatically. The total amount of cases 1990-1998 about 2.000 and until 2006 about 4.600. Survival rate 99%**

- **For children born after 1987 the statistics is as before the accident.**
- **No increase in any other cancer form has been detected**

- **about 40% of the forest nearby died, but has recovered**

Very difficult to make estimates on the wild animals as when people moved out animals have moved in from other ends of Russia and almost Created a animal paradise

In November 1986 the reactor 4 had been enclosed in the "sarkofag"

Reactor 2 closed in 1990, reactor 1 in 1997 and reactor 3 was closed 15 December 2000.

References

- http://www.iaea.org/NewsCenter/Focus/Chernobyl/
- http://www.unscear.org/unscear/en/chernobyl.html
- nea3508-chernobyl.pdf
- Kärnkraftsolyckan I Tjernobyl SSI report 2001:07 Leif Moberg