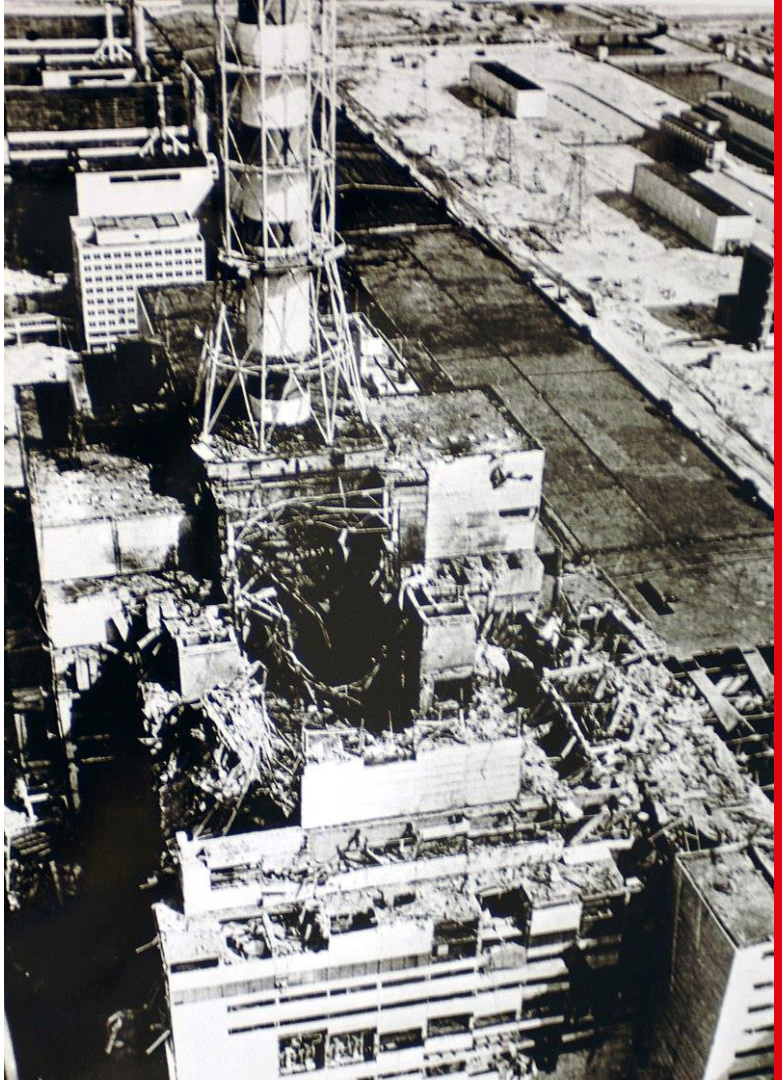
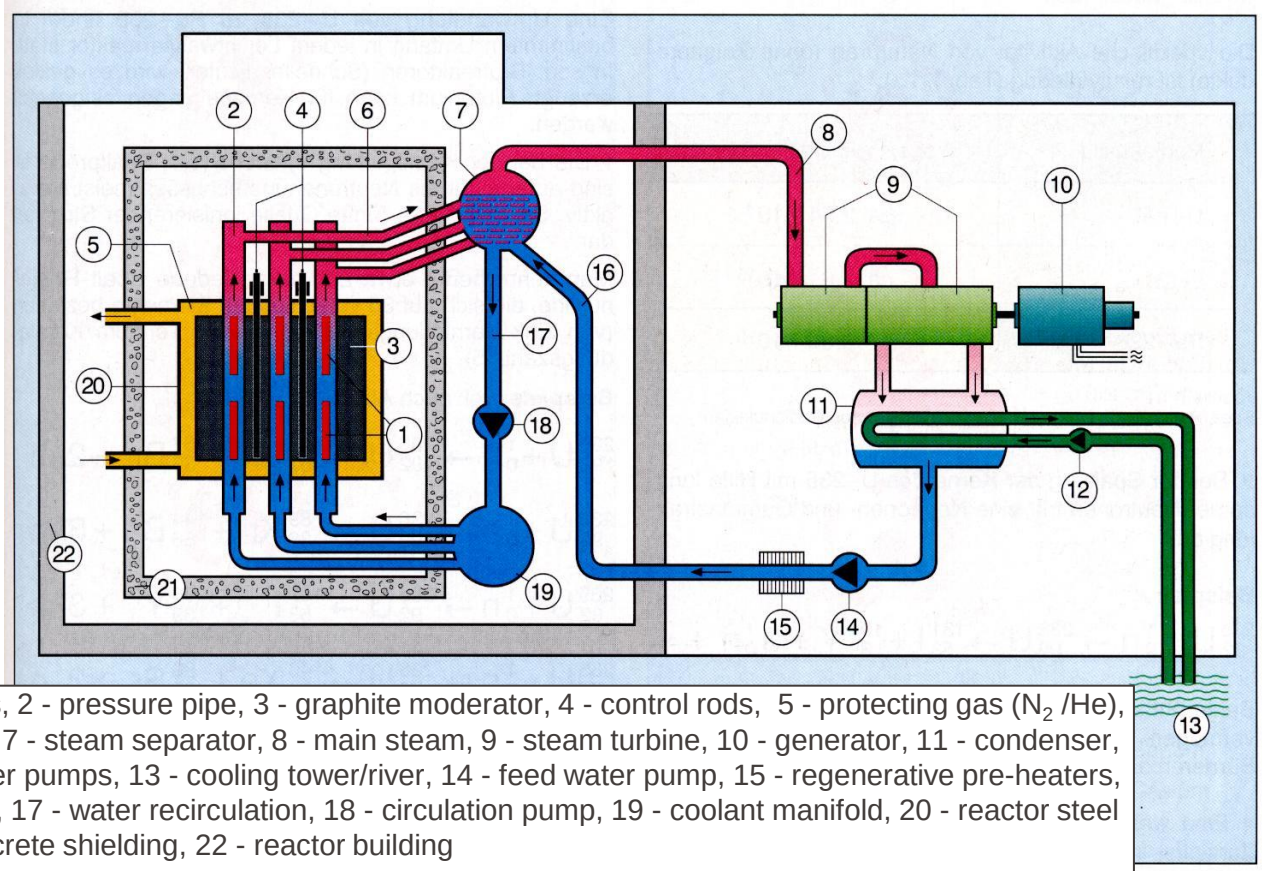


Severe Accidents: Chernobyl

The accident at Chernobyl

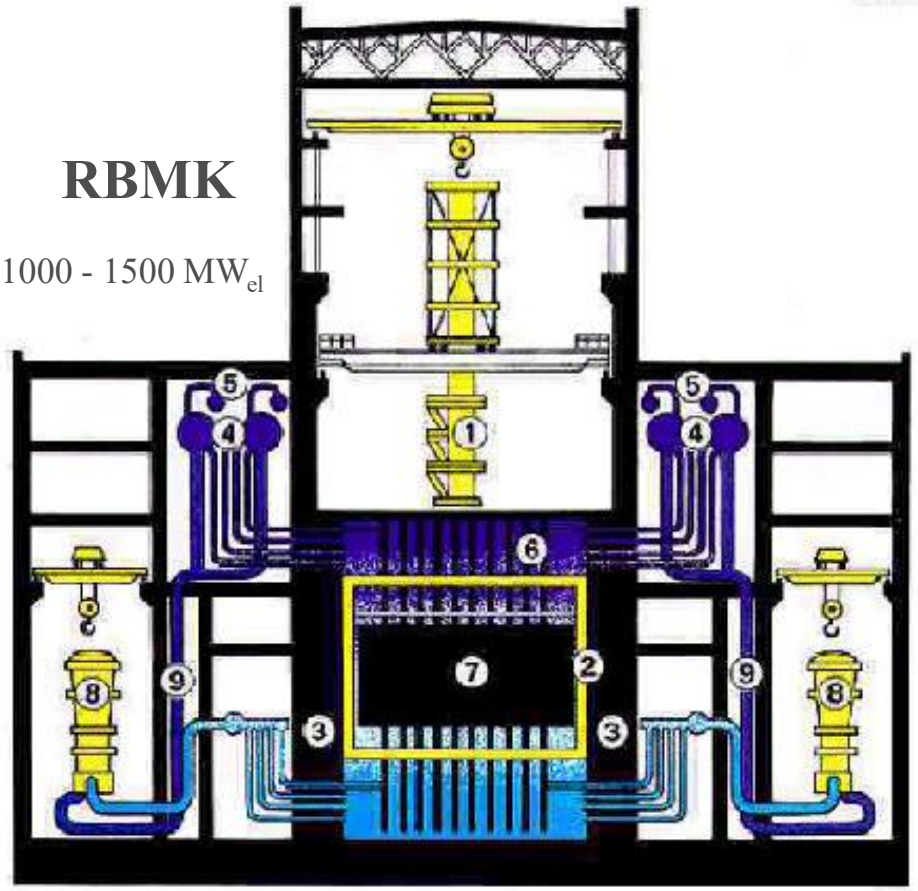
- Accident happened **at night**, on 26 April 1986 at 01:24:
  - Reactor 4 at the Chernobyl power plant exploded **during a technical test.**
- The plant had been in service since 1983.
- It was a **RBMK type reactor**, a Soviet model designed in the 1960s:
  - Reactor core made up of a very large block of graphite containing vertical channels in which pressure tubes were placed.
  - Each pressure tube contained several fuel assemblies.
  - **Graphite functioned as a moderator**; cooling was provided by boiling water flowing through the pressure tubes in contact with the fuel.

Graphite moderated BWR of "pressure tube" type (RBMK, Chernobyl)



1 - fuel elements, 2 - pressure pipe, 3 - graphite moderator, 4 - control rods, 5 - protecting gas (N_2 /He), 6 - steam/water, 7 - steam separator, 8 - main steam, 9 - steam turbine, 10 - generator, 11 - condenser, 12 - cooling water pumps, 13 - cooling tower/river, 14 - feed water pump, 15 - regenerative pre-heaters, 16 - condensate, 17 - water recirculation, 18 - circulation pump, 19 - coolant manifold, 20 - reactor steel vessel, 21 - concrete shielding, 22 - reactor building

RBMK plant – No containment!



1. Fuel loading machine
2. Hermetic protection gas tank
3. Radiation shielding
4. Steam separators (drums)
5. Main steam line
6. Reactor cover lid
7. Reactor core
8. Circulation pump
9. Coolant line

Core dimensions:

Height:	7 m
Diameter:	12 m
Fuel elements:	ca. 2000
Enrichment:	1.8 %

Main design flaws

- The initial design of RBMK reactors had some significant weaknesses from a safety standpoint:
  - **Positive moderator feedback** from water boiling → highly unstable at low power ranges.
  - **No containment** around the reactor.
  - Graphite can ignite (and the fire is difficult to extinguish)

- However, one can say that the main problem was **how the personnel and people in charge behaved:**
  - No sufficient preparation and lack of time for the planned test, but pressure to perform it in any case…
  - … this meant that operators did not follow all the operating rules!
    - They even violated them by suppressing some important safety systems.

Event sequence (1/3)

- Objective of the planned test:
  - Show that during a turbine trip the inertia of the turbine could drive the pump, while the diesel generators are being switched on. The test had already failed before.

- The test was supposed to be performed at low power and in the morning of 25 April, operators began the power reduction procedure.
  - Between 13:00 and 23:00, the reactor was held at half-power at the request of the electric power distribution centre. At about 23:00, power reduction was resumed

- **The reactor state was now inappropriate for the test to be performed:**
  - The core was very difficult to control with the systems available;
  - You could not keep the reactor on unless you removed the control rods (mostly because of Xenon poisoning).

- **The reactor should have been stabilised at this stage… but operators were in a hurry to catch up the delay in the schedule, and decided to perform the test regardless**

Event sequence (2/3)

- On 26 April at 01:23:04, the test was launched, and the turbine steam supply valves were closed. The temperature rose in the core, causing reactivity to increase
- The reactor started to go critical and out of control. At this point, the operators realized the seriousness of the situation…
- At 01:23:40, the chief operator ordered an emergency shutdown. All control rods began to enter the core, but did not have time to stop a runaway chain reaction.
- At 01:23:44, power peaked, exceeding the reactor's nominal power by a factor of more than 100x.

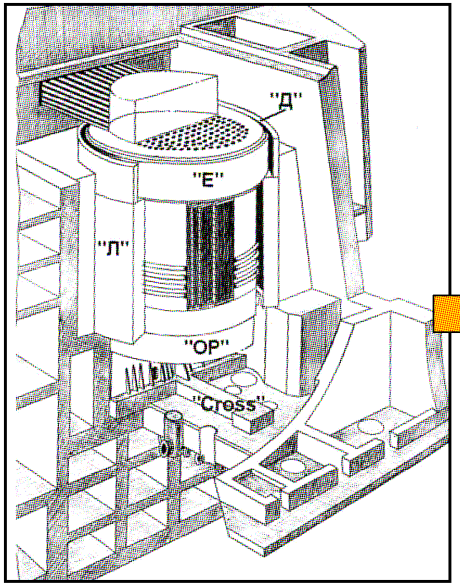
Event sequence (3/3)

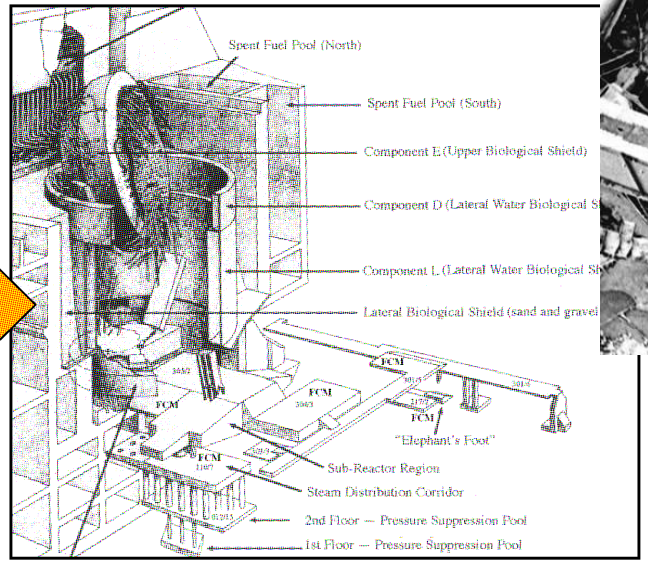
- High pressures reached in the pressure tubes caused them to rupture:
  - The fuel rods in the core disintegrated violently.
  - An explosion lifted the upper reactor cover, weighing about 2000 tonnes, off the reactor.

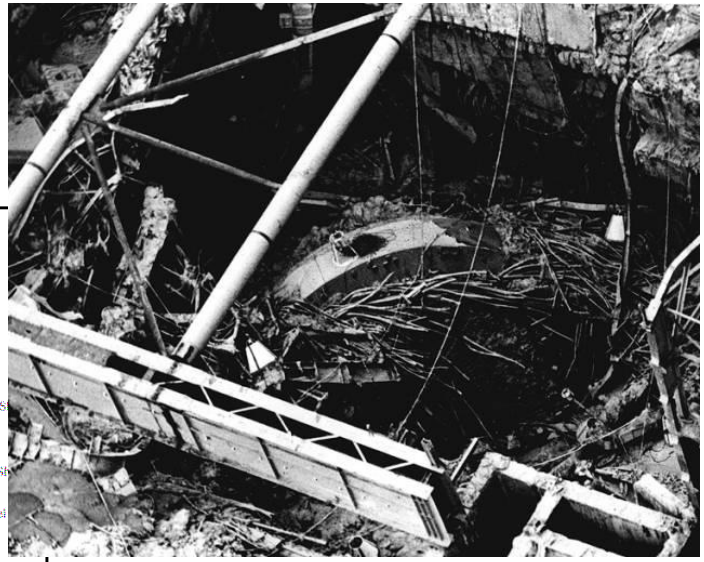
- The top of the reactor core was exposed to the open air. The **graphite ignited** and a number of fires broke out in the facility:
  - The graphite fire was not fully extinguished until 9 May
  - Between 27 April and 10 May, 5000 tonnes of material (sand, boron, clay, lead, etc.) were poured onto the reactor by helicopter to cover it

Aerial view of the reactor in flame

Final state of reactor and containment (1/2)







Upper reactor support plate with torn cooling channels

Final state of reactor and containment (2/2)

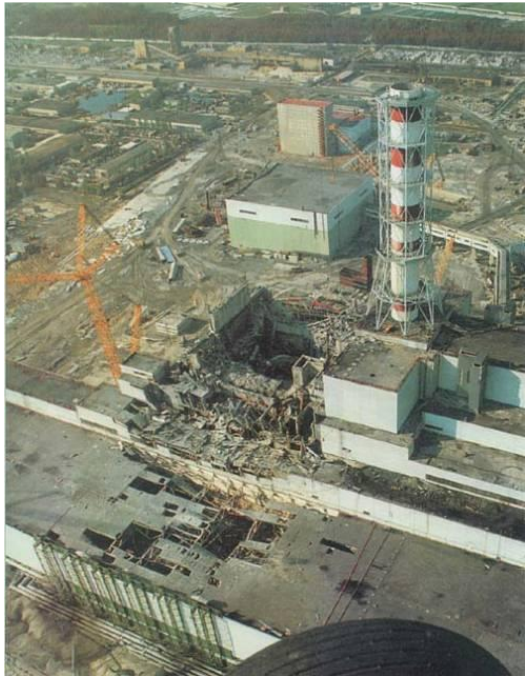
Refrozen corium melt "Elephant' s foot"

Refrozen corium melt (steam removal valve)

Fuel debris

Refrozen fuel 'lava' and debris was found in the rooms under the lower biological shield

General view



Fission product release from Chernobyl

Core inventory on 26 April 1986			Total release during the accident	
Nuclide	Half-life	Activity (PBq)	Percent of Activity	Activity (PBq)
^{133}Xe	5.3d	6500	100	6500
^{131}1	8.0d	3200	50-60	~1760
^{134}Cs	2.0y	180	20-40	~54
^{137}Cs	30.0y	280	20-40	~85
^{132}Te	78.0h	2700	25-60	~1150
^{89}Sr	52.0d	2300	4-6	~115
^{90}Sr	28.0y	200	4-6	~10
^{140}Ba	12.8d	4800	4-6	~240
^{95}Zr	65.0d	5600	3.5	196
^{99}Mo	67.0h	4800	>3.5	>168
^{103}Ru	39.6d	4800	>3.5	>168
^{106}Ru	1.0y	2100	>3.5	>73
^{141}Ce	33.0d	5600	3.5	196
^{144}Ce	285.0d	3300	3.5	~116
^{239}Np	2.4d	27000	3.5	~95
^{238}Pu	86.0y	1	3.5	0.035
^{239}Pu	24400.0y	0.85	3.5	0.03
^{240}Pu	6580.0y	1.2	3.5	0.042
^{241}Pu	13.2y	170	3.5	~6
^{242}Cm	163.0d	26	3.5	~0.9

- The explosion propelled radioactive materials into the atmosphere, to altitudes of over 1200m.
- Most of the radioactive materials were discharged at the time explosion…
- … but a fraction continued to be released until 5 May mostly as a result of the fire and residual heat.

[NEA3508]

Dispersal of the radioactive plume

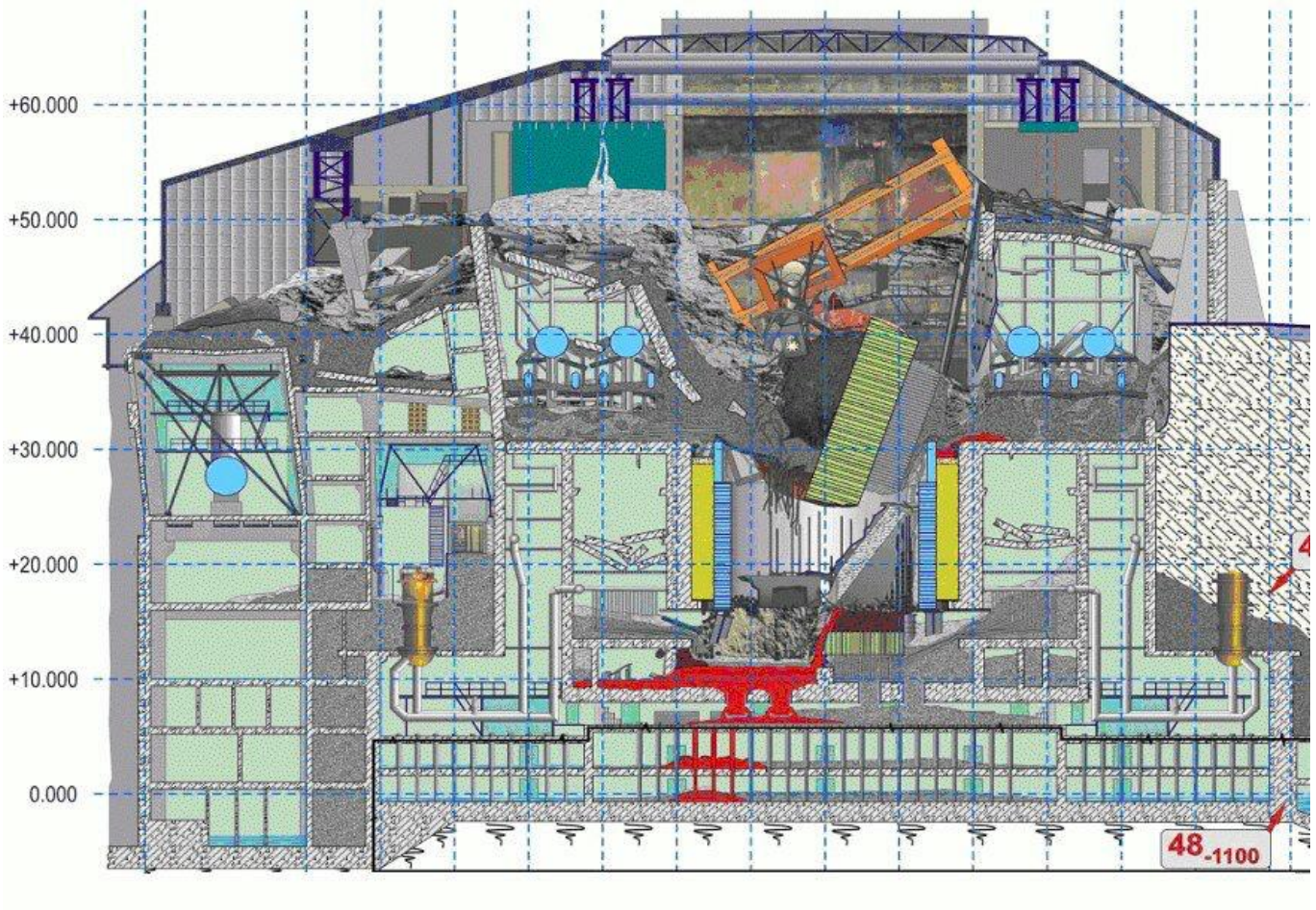
- Nuclear fuel debris and pieces of the reactor were thrown into the environment around the power plant. Radioactive dust, fine particles (aerosols) and gases rose to high altitudes and formed a plume which was carried over great distances in air masses by changing winds

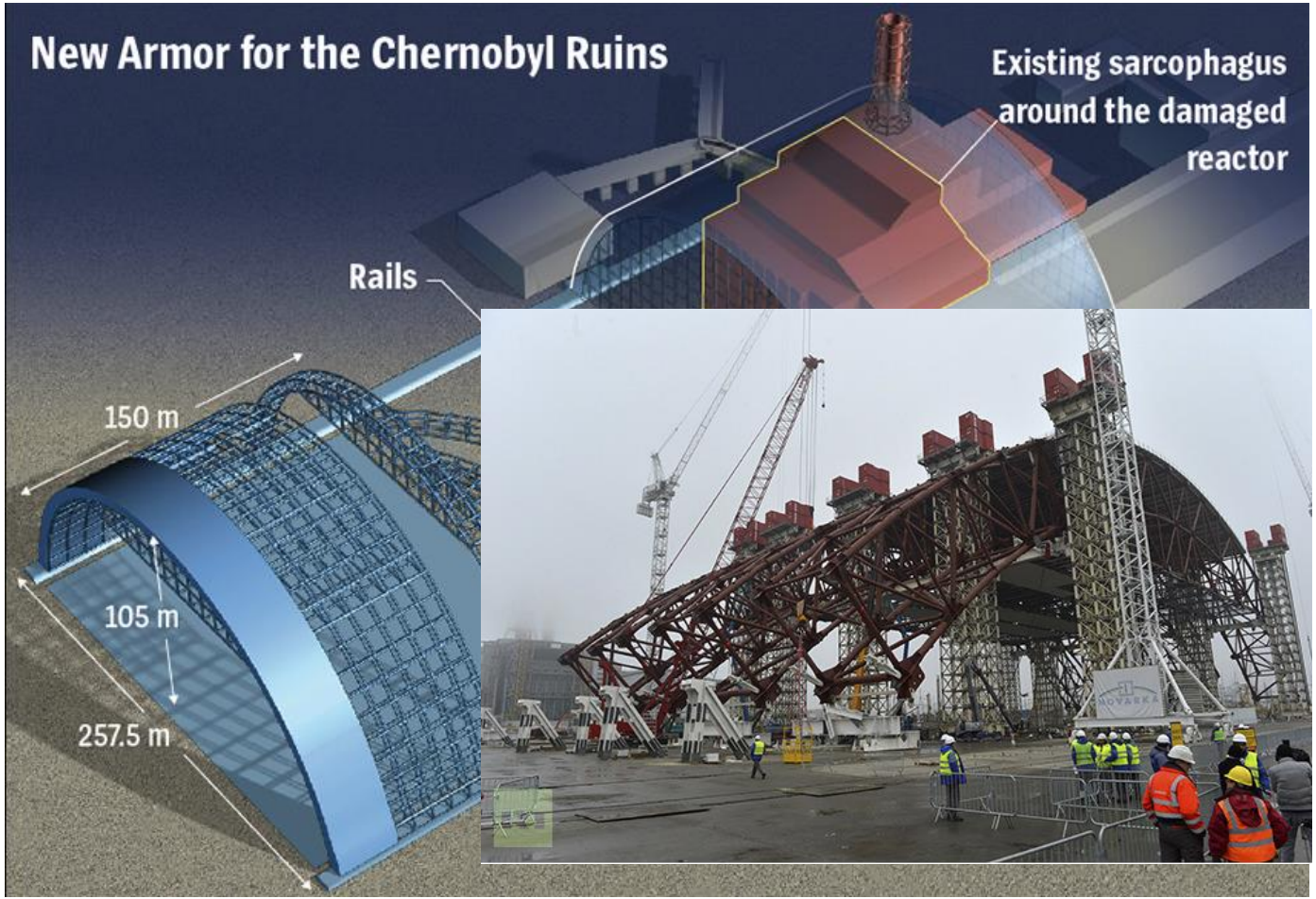
- Between 26 April and mid-May 1986, the radioactive plume scattered radioactive elements such as ^{131}I (half-life 8d), ^{132}Te (78h), ^{129m}Te (33d), ^{103}Ru (39d), ^{137}Cs (30y), ^{134}Cs (2y), ^{140}Ba (13y), over most of the countries in Europe

- As time passed, this dispersion resulted in the dilution of the radioactive elements in the air.

- Some of the aerosols were deposited along the way, gradually depleting the radioactive cloud. Finally, the radioactive elements with a very short half-life (a few hours) disappeared quickly as a result of radioactive decay in the plume

Cross section view of reactor ruins with a sarcophagus




New Armor for the Chernobyl Ruins
Existing sarcophagus around the damaged reactor
Rails
150 m
105 m
257.5 m

Liquidators clearing the roof of Block 4

Consequences - Sources

- World Health Organization, 2006. Health effects of the Chernobyl accident and special health care programmes (https://www.who.int/publications/i/item/9241594179)

- World Health Organization, 2016. 1986-2016: CHERNOBYL at 30. https://www.who.int/publications/m/item/1986-2016-chernobyl-at-30

- UNSCEAR. The Chernobyl accident. https://www.unscear.org/unscear/en/chernobyl.html#:~:text=Notwithstanding%20the%20influence%20of%20enhanced,two%20decades%20after%20the%20accident.

Consequences – from UNSCEAR

- Of 600 Chernobyl workers, 134 received high doses (0.8-16 Gy), leading to 28 deaths within three months and 19 more from 1987-2004 from various causes. Among survivors, health normalization took years.

- Approximately 530,000 workers were exposed to 0.02-0.5 Gy from 1986 to 1990, with ongoing monitoring for late effects like cancer. Emerging evidence shows a slight increase in leukaemia among Russian workers with higher exposures.
- By 2005, over 6,000 cases of thyroid cancer were reported, largely attributable to radioiodine exposure due to the accident, with less than 1% mortality (can be treated).

- While there is a significant increase in thyroid cancer and some rises in leukaemia and cataracts among workers, no solid evidence links radiation to other cancers or non-malignant disorders in the affected populations.

- The accident caused widespread psychological distress primarily from radiation fears, rather than direct radiation exposure.

Consequences

Population	Population size/average dose	Cancer type	Period	Background number of cancer deaths		Predicted excess cancer deaths		
				Number	Percent	Number	Percent	AF[a] (%)
Liquidators, 1986-1987	200,000 100 mSv	Solid cancers Leukaemia	Lifetime (95 y) Lifetime (95 y) First 10 years	41,500 800 40	21 0.4 0.02	2,000 200 150	1 0.1 0.08	5 20 79
Evacuees from 30 km zone	135,000 10 mSv	Solid cancers Leukaemia	Lifetime (95 y) Lifetime (95 y) First 10 years	21,500 500 65	16 0.3 0.05	150 10 5	0.1 0.01 0.004	0.1 2 7
Residents of SCZs	270,000 50 mSv	Solid cancers Leukaemia	Lifetime (95 y) Lifetime (95 y) First 10 years	43,500 1,000 130	16 0.3 0.05	1,500 100 60	0.5 0.04 0.02	3 9 32
Residents of other "contaminated" areas	6,800,000 7mSv	Solid cancers Leukaemia	Lifetime (95 y) Lifetime (95 y) First 10 years	800,000 24,000 3,300	16 0.03 0.05	4,600 370 190	0.05 0.01 0.003	0.6 1.5 5.5