Chernobyl Disaster 25th Anniversary
RBMK Reactor & Sequence of Events

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A6

RBMK Reactors

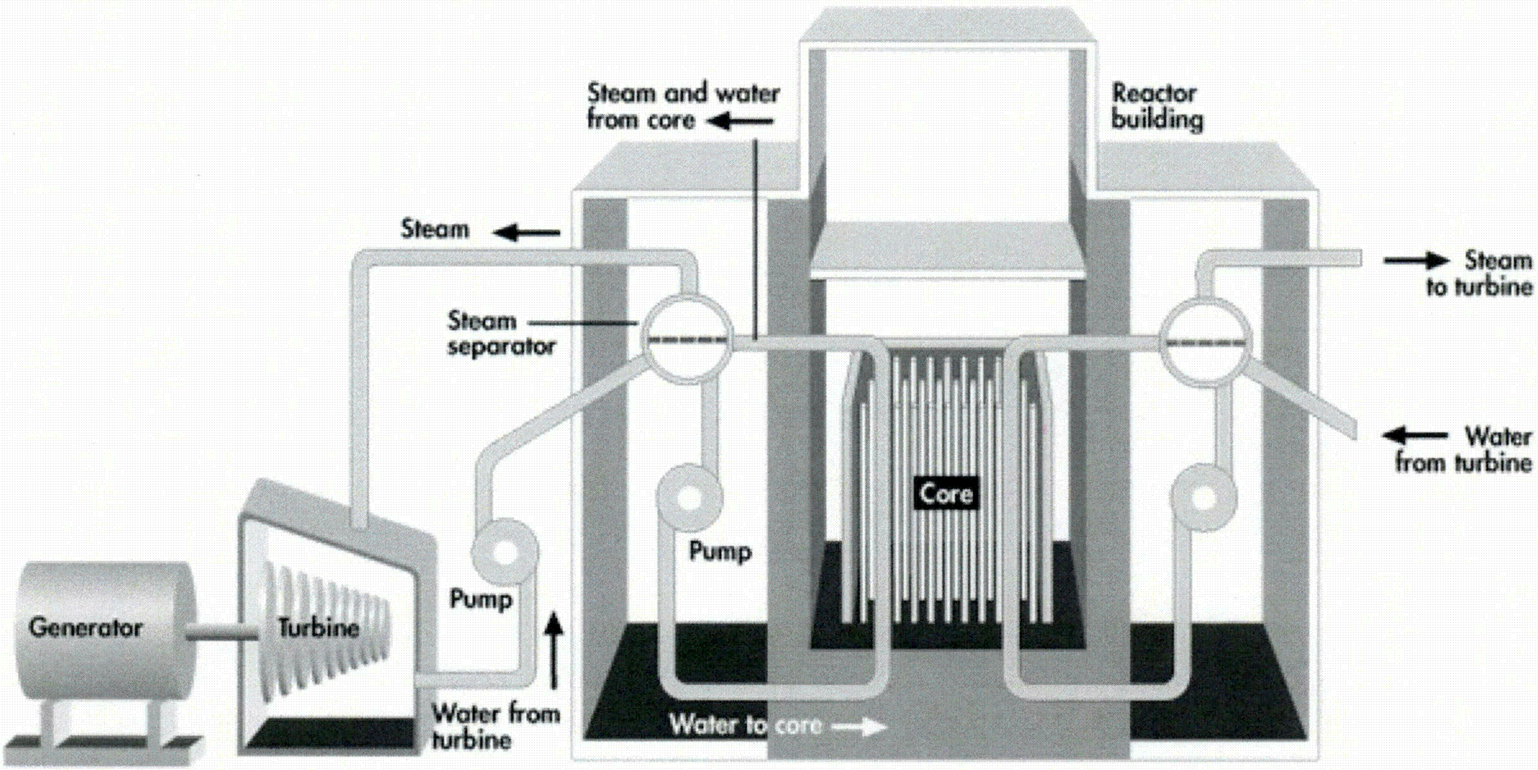
- Graphite-moderated
- Boiling light-water cooled
- Pressure tube design
  - 1661 vertical pressure tubes
  - UO_2 fuel
  - Zirconium alloy cladding
  - 1000 psig pressure
- Evolved from lower-power plutonium production reactors

Significant Distinguishing Features

- Use of computerized control system
- Positive void coefficient under most operating conditions
- Poor reactivity control
  - Rods move slowly
  - Rods insert positive reactivity upon initial entry
- Low coolant-to-fuel ratio

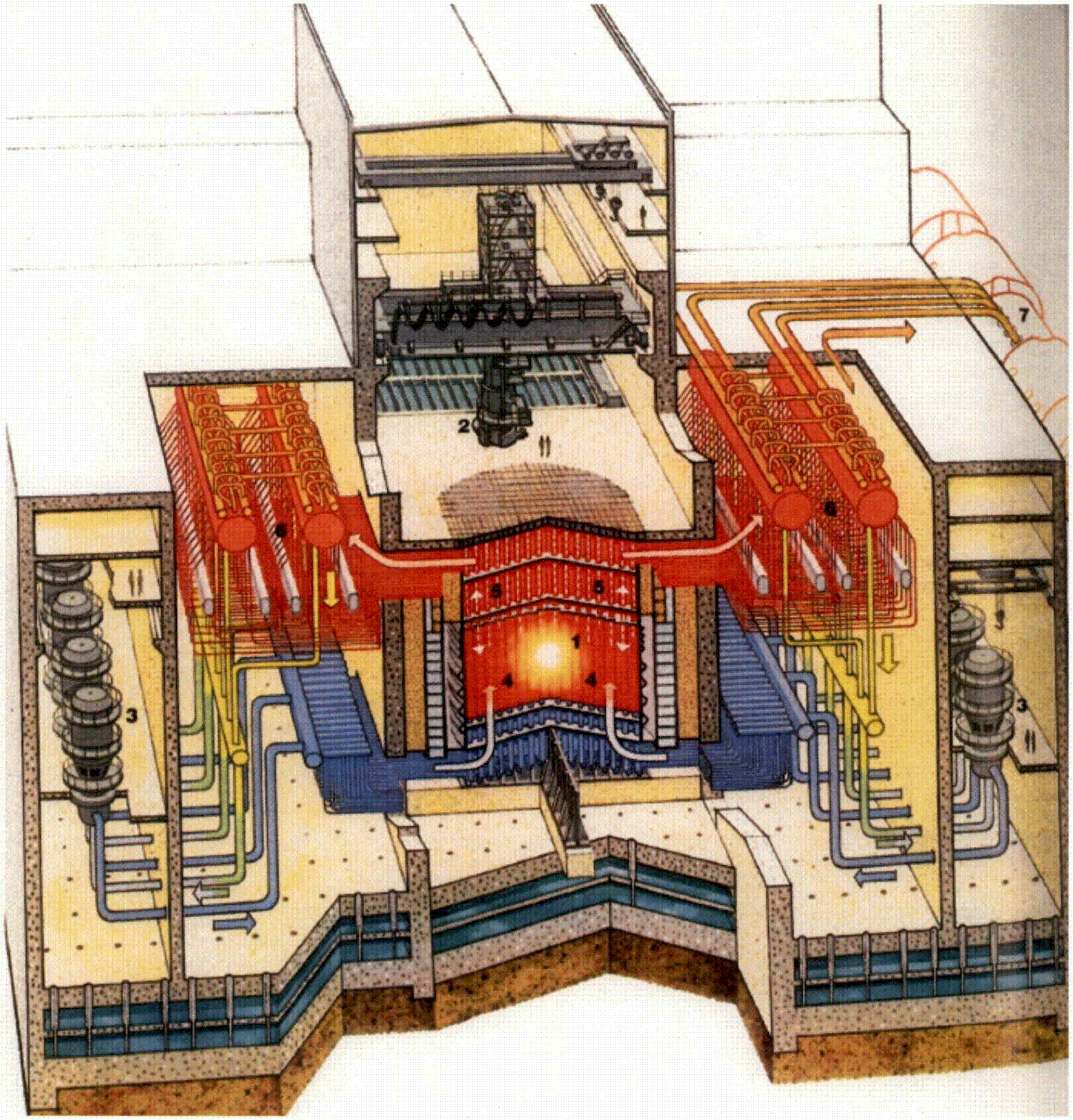
- No containment

RBMK Diagram

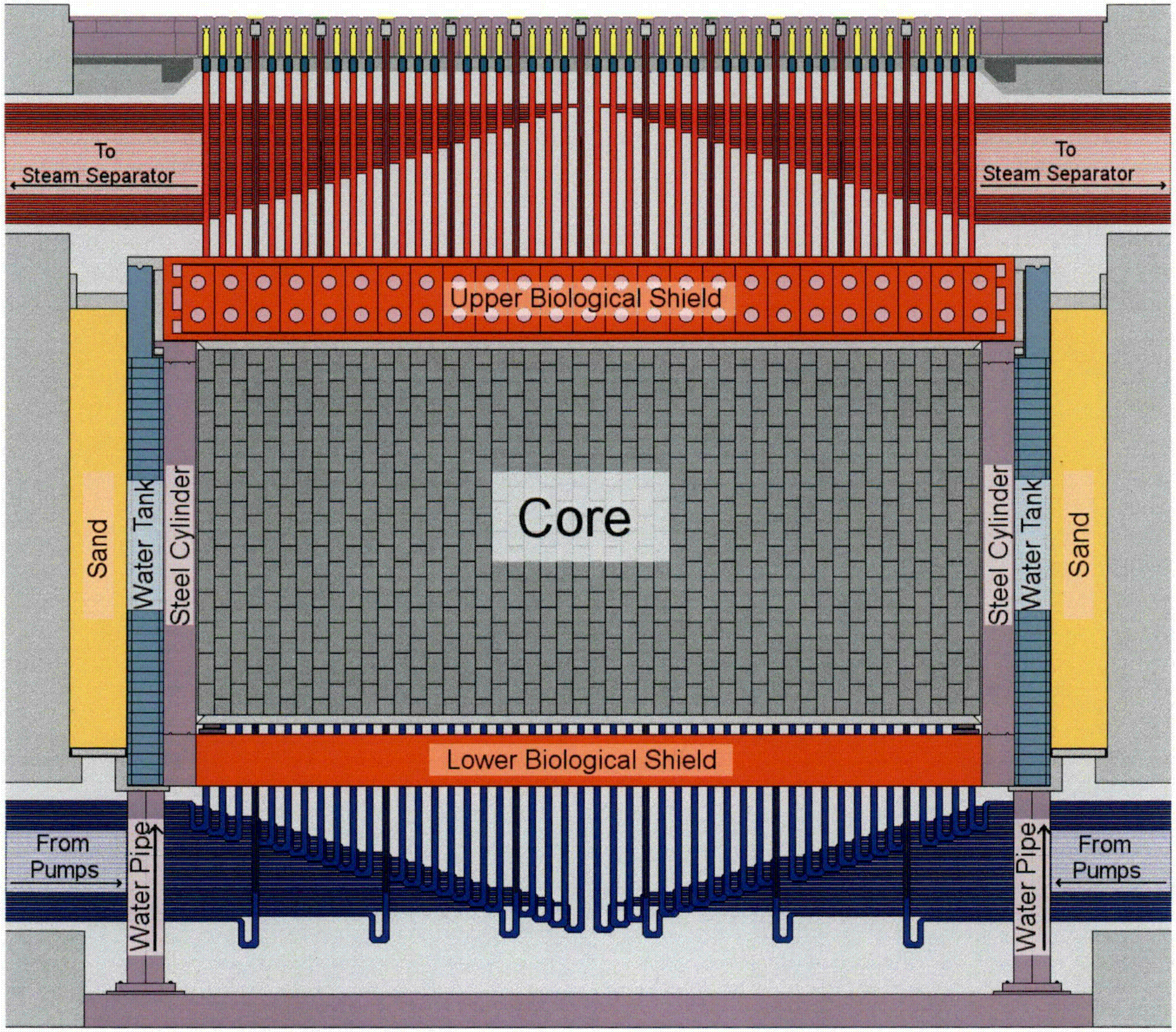


Source: Nuclear Energy Institute

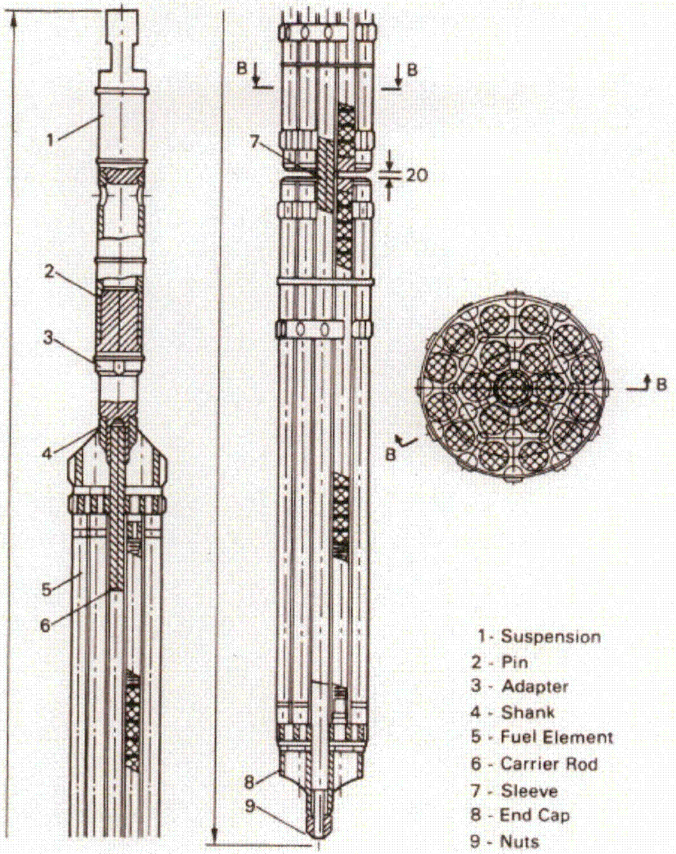
RBMK Plant Layout



Core Diagram

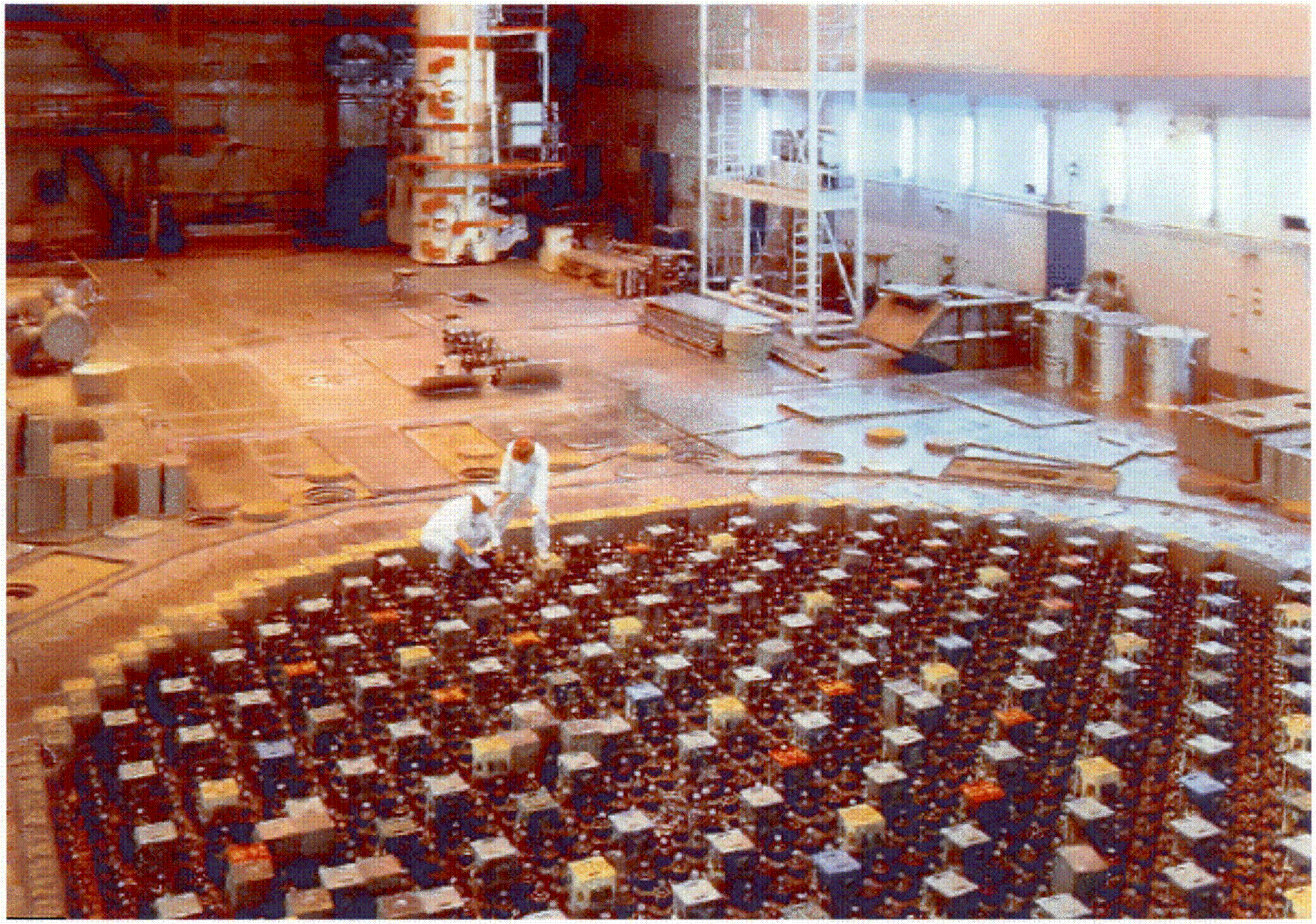


RBMK Fuel Design



- Zirconium cladding used
- Fuel rods 3.65m (11.97 ft) long
- 18 rods form a fuel bundle.
- Two bundles joined together and capped at either end by a top and bottom nozzle, form a fuel assembly.
- Assembly length 10m (32.81 ft)
- Since 1990, the fuel has been modified
  - enrichment increased from about 2% to average 2.8%
  - Burnable poison added to UO2.

RBMK Reactor Hall



Reactor Hall at Ignalina NPP, Lithuania

Chernobyl Design Specifics

- Four RBMK units at site
- 1000 MWe units (about 3200 MWt)
- Unit 4 began operation in December 1983.
- Graphite moderator: 39 foot diameter, 23 foot high
- 1659 fuel assemblies, avg burnup of 10.3 MWD/kg
- 2 turbines, 8 main circulation pumps

Chernobyl Event Summary

- Violent reactivity excursion with a vapor explosion/hydrogen combustion/graphite fire
- Safety systems disabled for test
- Worst-ever nuclear power plant accident
- Plume spread into Europe and detected worldwide
- Large land area off limits, food supply impacted
- Added to nuclear controversy in U.S.

Initiation of Chernobyl Event

- Purpose of test was to show that turbine coastdown could provide power to safety systems until EDGs load
  - Relieves rapid EDG startup
  - Applies to loss of offsite power events
  - not an un uncommon procedure in Russia
- Virtually no additional safety measures
  - procedure to follow plant instructions – nothing specific
  - ECCS deactivated to prevent complications during test

Event Sequence

- 1:00 am on April 25 – power reduced to 50% by 1:05 pm
- One turbogenerator shut down (#7), plant systems switched to remaining turbogenerator (#8) to be used in test
- 2:00 pm – ECCS isolated to prevent inadvertent actuation during test – violated operating procedures but unclear if this would have changed accident
- Electricity dispatcher delayed test for another 9 hours (while ECCS was deactivated)
- 11:10 pm – test preparation resumed

Sequence (continued)

- Operators attempted to further reduce power to 700 – 1000 MWt range specified for the test
- Problem with control systems allowed an overshoot to 30 MWt
- 1:00 am on April 26 – power back to 200 MWt
  - Xenon poison buildup – large negative reactivity
  - Operators had to manually withdraw control rods beyond safe operating limits to increase power
  - Skewed flux distribution
  - 6-8 control rod equivalents, minimum reserve margin is 16

Sequence (continued)

- 1:03 and 1:07 am – two standby main circulation pumps started, along with 6 pumps already running
  - Massive flow, up to 35,000 gpm per pump, in violation of procedures
  - Created near-saturation flow in the core
  - Low steam pressure and water levels, but protection signals blocked to continue test
- 1:19 am – feedwater increased 4 times normal to restore level in steam drums
  - This lowered inlet temperature and reduced steam production
  - Negative reactivity effect, automatic rods fully withdrawn
  - Operators withdrew manual rods but overcompensated, and automatic rods began to re-enter core

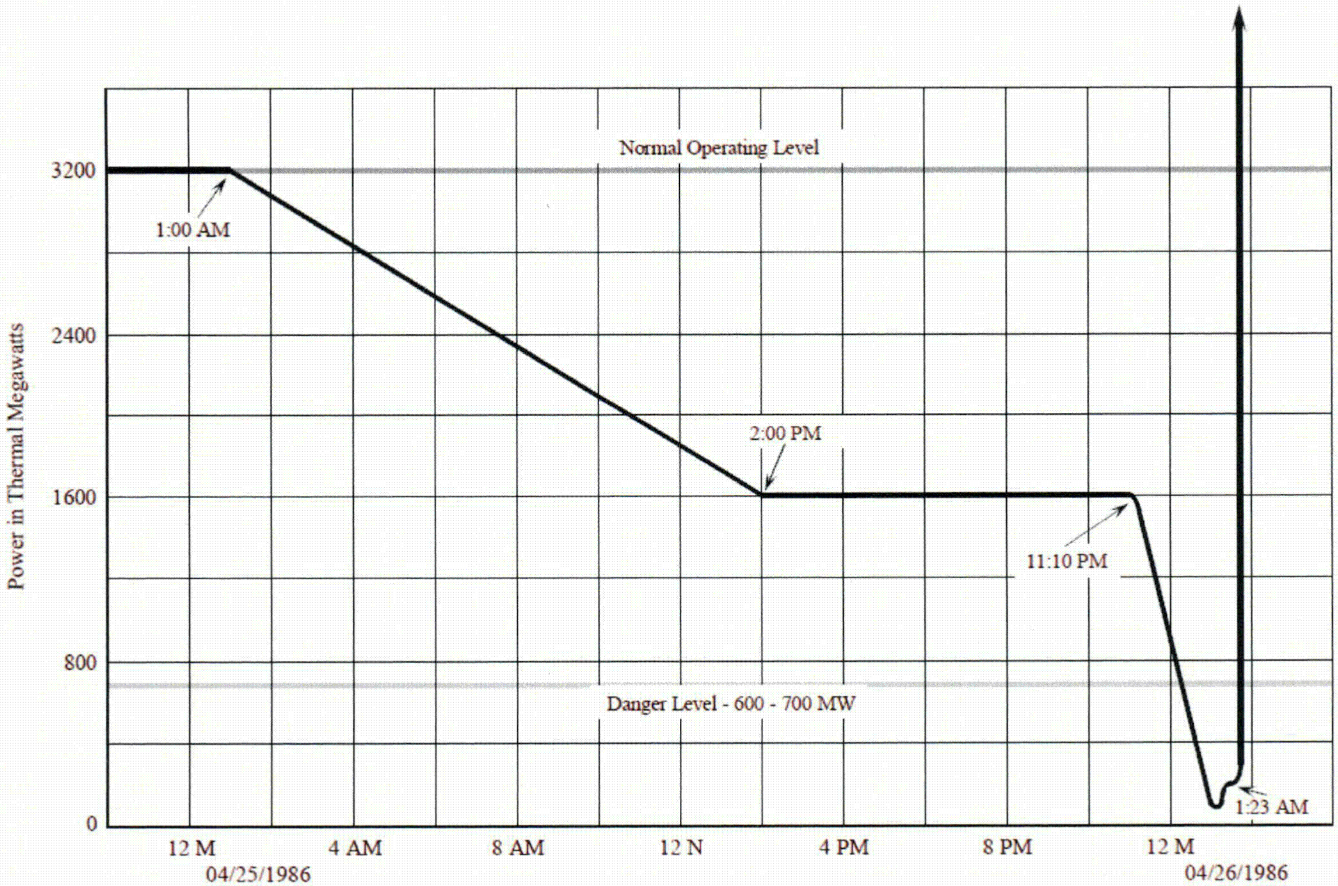
Sequence (continued)

- 1:22 am – reactor approximately stable, decision made for operators to proceed with test
  - Reactor trip protection signal from turbine stop valve bypassed to allow possible fast repeat of test
  - Reduced feedwater flow just before test initiated, which brought system to near saturation conditions.
  - Steam voiding was low due to high recirculation flow
- 1:22:30 am – reactivity evaluation required immediate shutdown of reactor
  - Requirement ignored so test could be completed
  - Rods basically worthless
  - Skewed flux shape

Sequence (continued)

- 1:23:04 am – turbine stop valve closed to begin test
  - Four main circulation pumps on the generator bus bar began to coast down
  - Power remained at 200 MW because auto reactor shutdown was disabled
  - Reactor power began to increase rapidly
- 1:23:40 am – scram button pushed at direction of unit shift manager
  - Reason unclear – because of reduced shutdown margin, rods would have to travel well into core to be effective
  - Shocks felt in control room
  - Operator determined rods had not inserted
  - Rods deactivated to hopefully fall by gravity
- Observers outside report two explosions

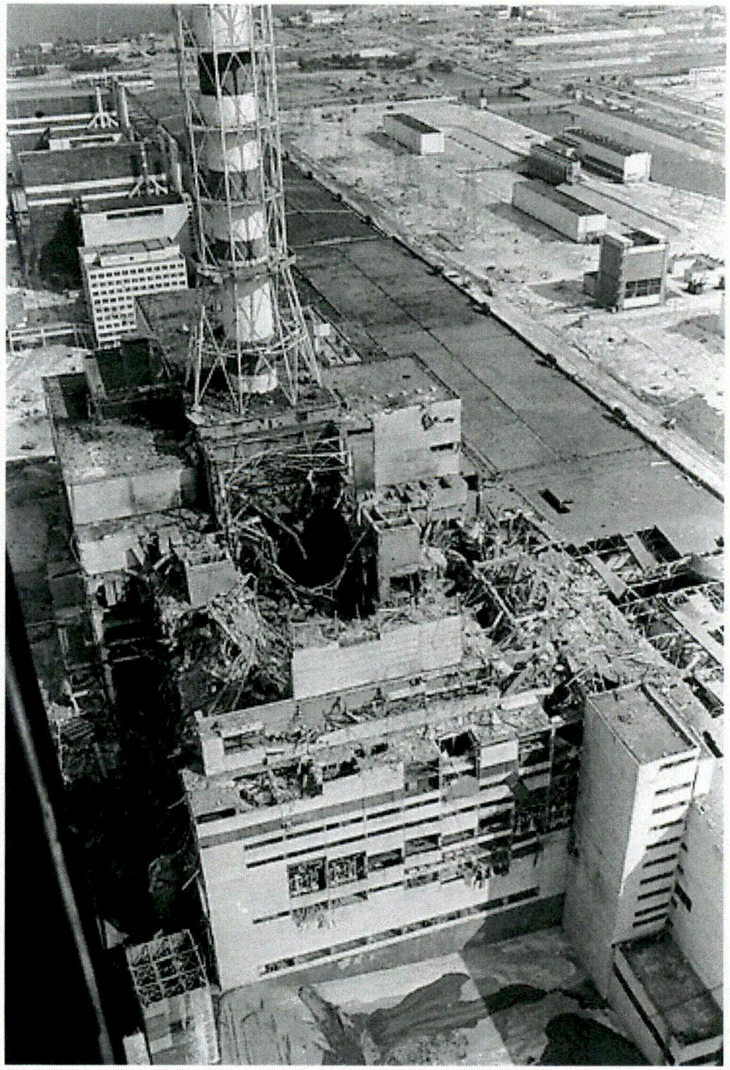
Unit 4 – Reactor Power vs Time



Reactor Response

- Initial explosion
  - Prompt critical reactivity excursion
  - Power level exceeded 100 times full power
  - Fuel pellet temperature – 3,000 degrees C – fuel melted and expanded causing cladding failure
  - Massive energy release to coolant, along with particles of destroyed fuel
  - Massive steam explosion
- Second explosion 3 to 4 seconds later
  - Possible hydrogen and carbon monoxide explosion
  - Blew roof off of reactor building, and started 30 fires
- Graphite fires burned for 10 days

Chernobyl Unit 4



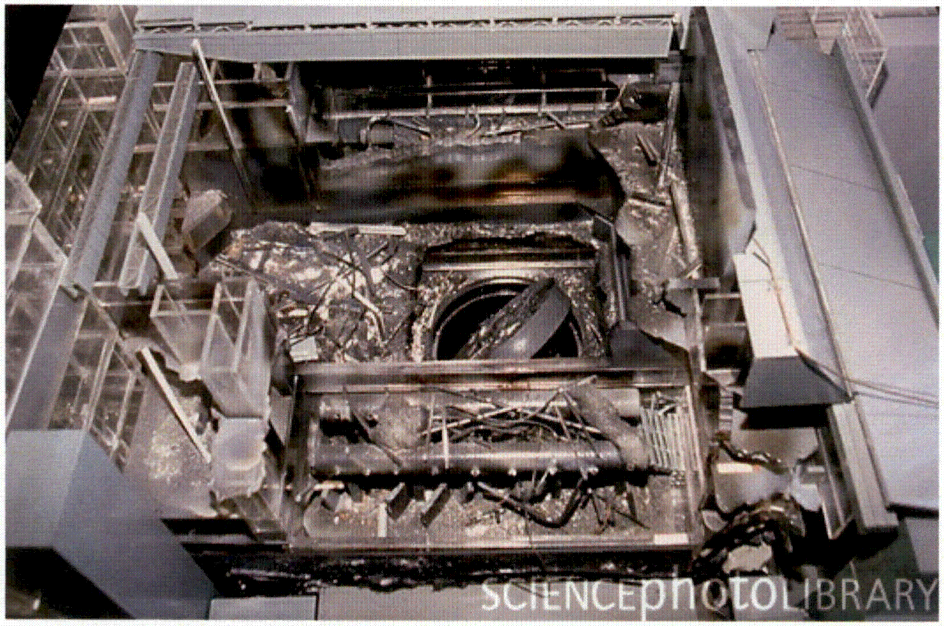
Total Release

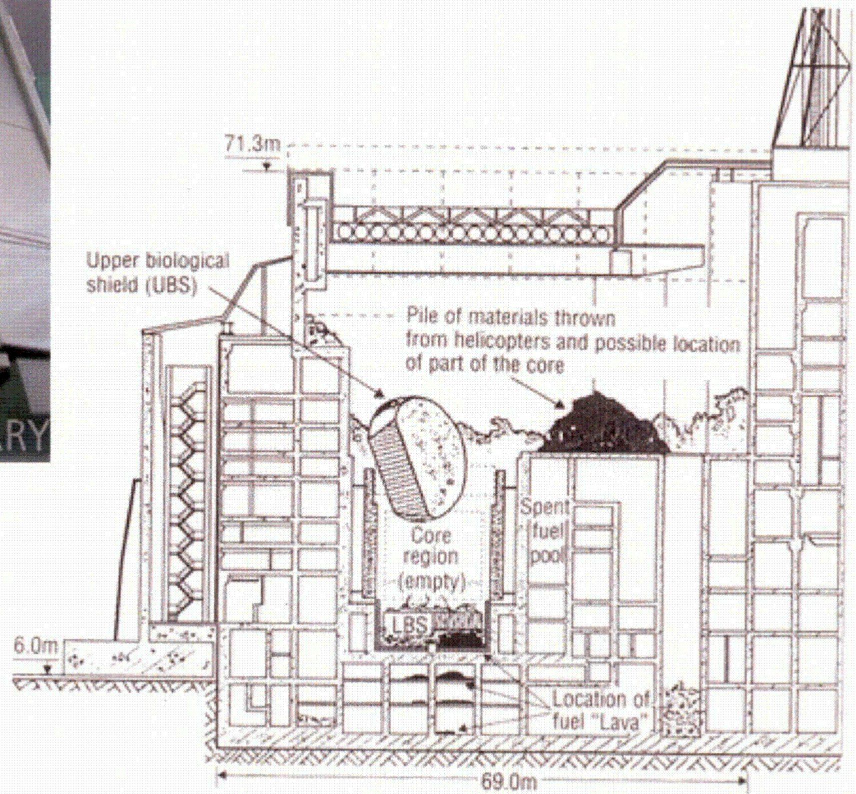
- Calculated inventories vary by factor of 2, mainly for short-lived nuclides
- Estimated releases vary by 10% to factor of 2
- Total release about 50-100 MegaCuries
  - Noble gas – full release
  - Volatiles – I, Cs, Te – 1/3 released
  - All else – 3%
- Rated Level 7 (Major Accident) on the INES

Mitigative Actions

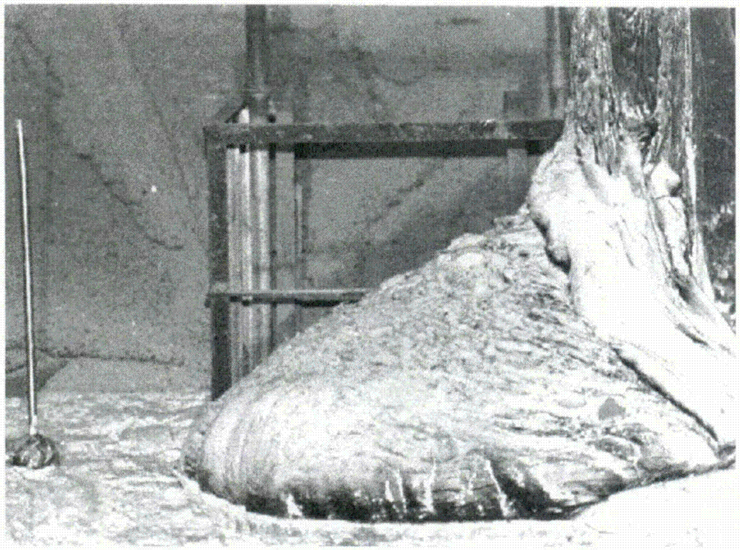
- 5,000 tons dropped by helicopter in the direction of the reactor
  - Boron – to minimize criticality
  - Lead – to cool the core and for shielding
  - Sand – to quench the fire and filter release
  - Clay – to quench the fire and filter release
  - Dolomite – absorb heat and generate CO2 to limit fire
- After 5 days, core temperature began to increase due to blanketing effect of materials
- Miners tunneled below and used several tons of liquid nitrogen to cool core debris
- Workers shoveled debris into building

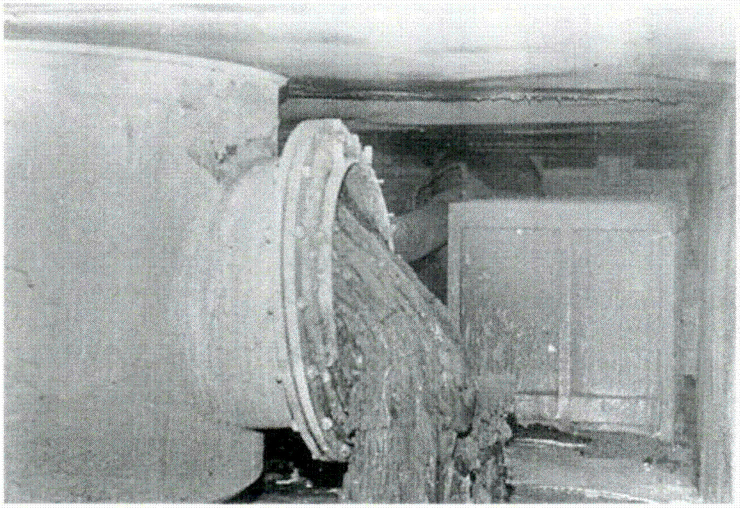
Model and Drawing of Chernobyl 4 Post-Accident





Corium Photos





Significant Violations of Operating Procedures

Violation	Motivation	Consequence
Reducing operational reactivity margin below permissible limit	Attempt to overcome xenon poisoning	Emergency protection system was ineffective
Power level below that specified in test program	Error in switching off local auto-control	Reactor difficult to control
All circulating pumps on with some exceeding authorized discharge	Meeting test requirements	Coolant temperature close to saturation
Blocking shutdown signal from both turbogenerators	To be able to repeat tests if necessary	Loss of automatic shutdown possibility
Blocking water level and steam pressure trips from drum	To perform test despite unstable reactor	Protection system based on heat parameters lost
Switching off emergency core cooling systems	To avoid spurious triggering of ECCS	Loss of possibility to reduce scale of accident

Implication for U.S. Plants

- Different designs – RBMK very unforgiving
- Additional training, more respect for procedures
- Containments (may not have helped in this case)
- Main insights related to need for procedures, training and understanding the technology
- Human performance aspects not unique
  - Focus on "success" instead of safety
  - Overconfidence in capabilities
  - Lack of protection of design and operating margins

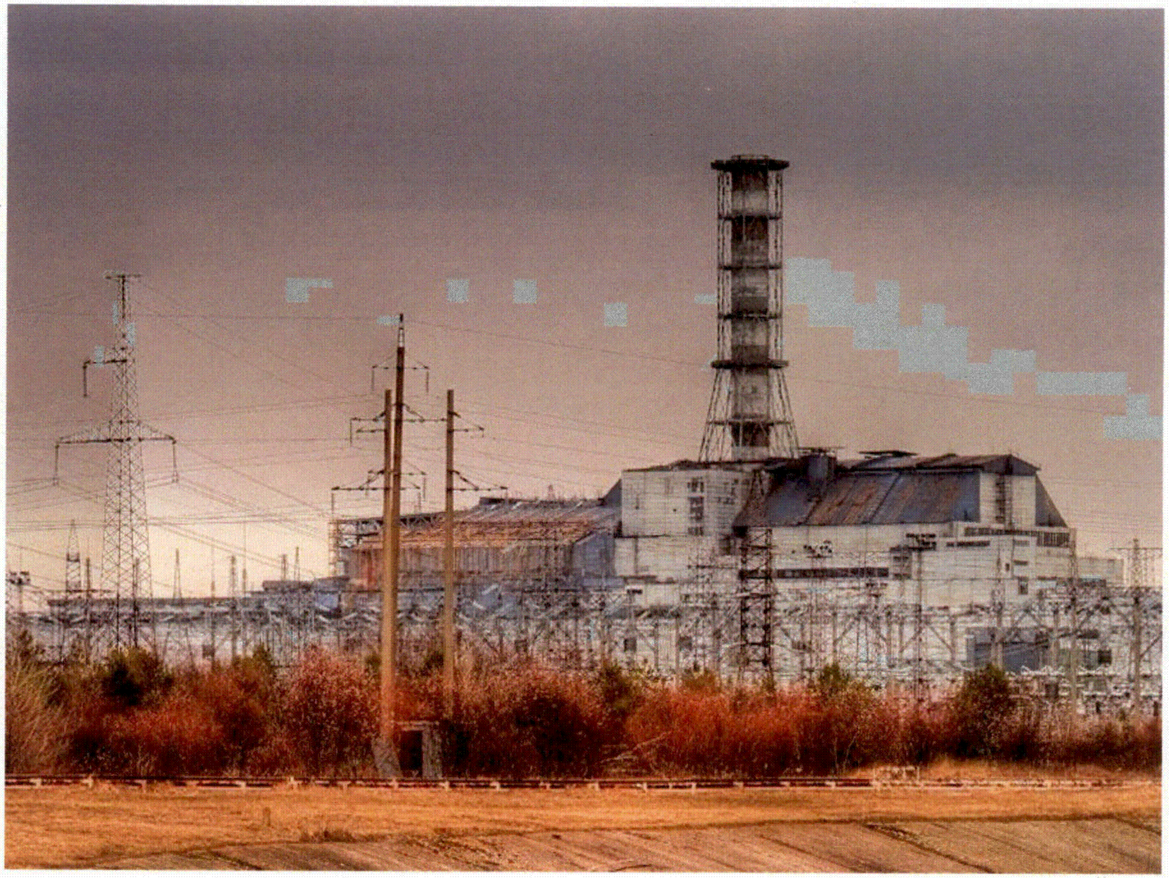
Note on RBMK Designs

- Many (11 as of 2010) RBMKs still in operation
- Many changes have been made
  - Control rods
  - Safety systems
  - Procedures
  - Training
- Controversy over their continued operation

References

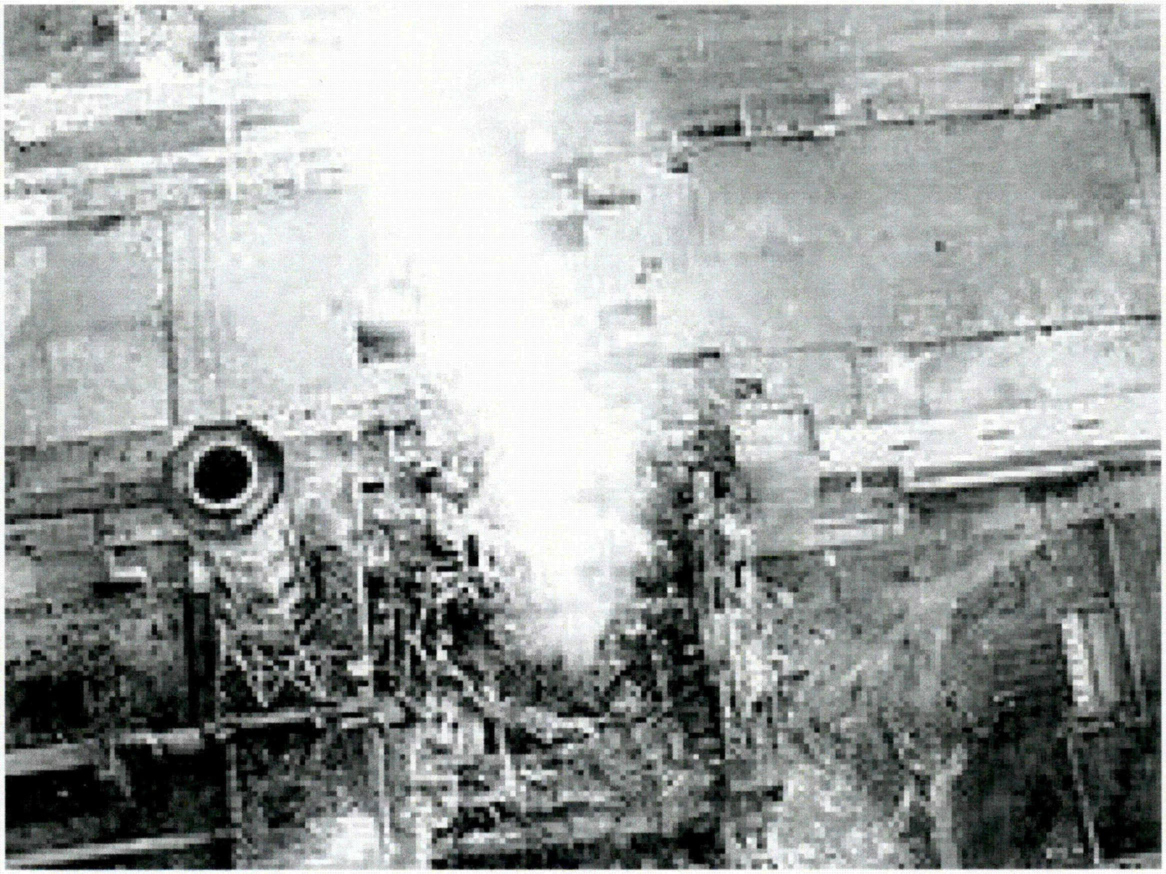
- NUREG-1250, “Report on the Accident at the Chernobyl Nuclear Power Station”

- NUREG/CR-6042, Rev. 2, “Perspectives on Reactor Safety”



CHERNOBYL – 25 YEARS LATER

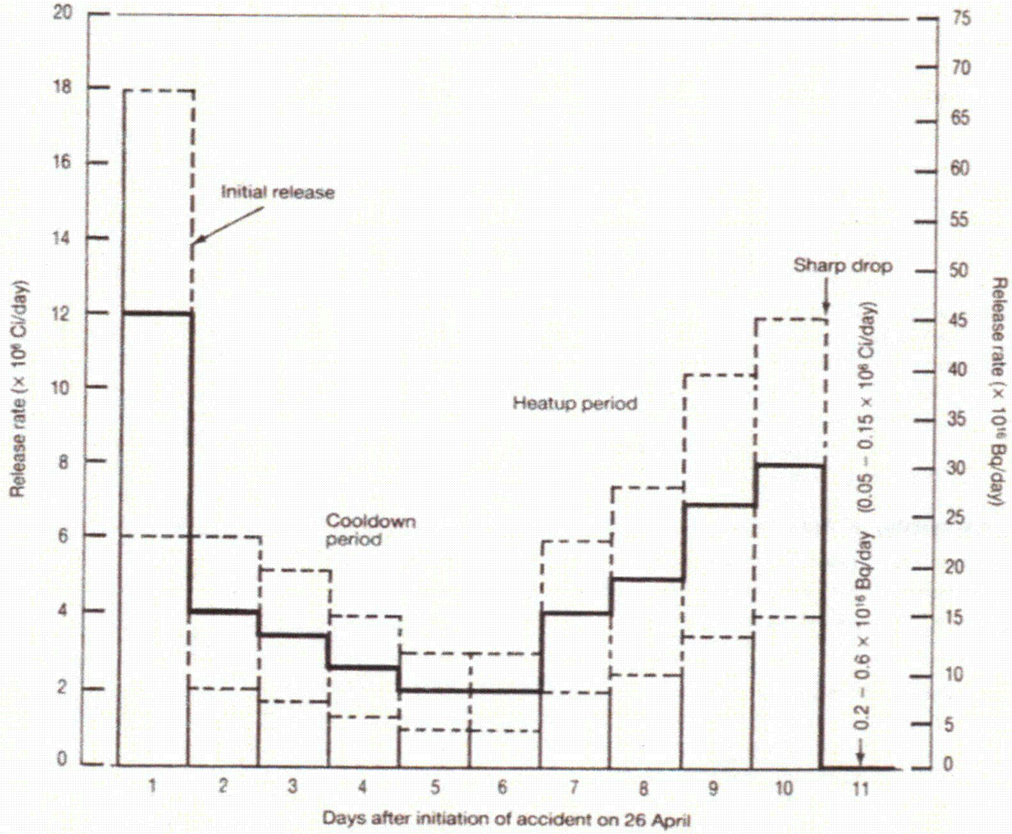
Frank J Congel



AERIAL VIEW OF BURNING CORE

Photo Taken During First Days of Accident

Figure 2. **DAILY RELEASE OF RADIOACTIVE SUBSTANCES TO THE ATMOSPHERE DURING THE CHERNOBYL ACCIDENT**
(not including Noble Gases)



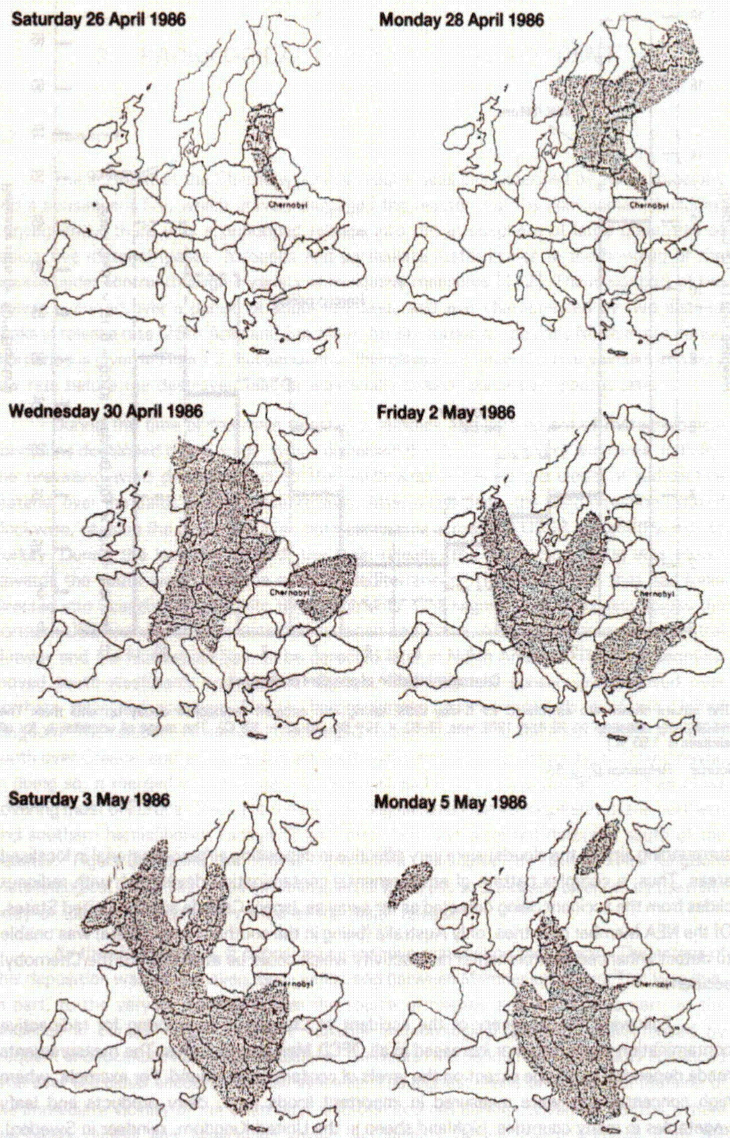
[The values shown are calculated for 6 May 1986, taking into account radioactive decay up until then. The radioactivity released on 26 April 1986 was 75-80 × 10^{16} Bq (20-22 × 10^{6} Ci). The range of uncertainty for all releases is ±50 %.]

SOURCE - NEA REPORT

Dotted Lines Denote Error Bars

MAP OF EUROPE

FOR COMPARISON TO WIND MAPS



WIND PATTERNS

REACTOR SITE ENVIRONS DOSE RATES AND DOSES TO EARLY RESPONDERS

Dose Rates varied substantially in and around the reactor complex.

Burning graphite and sections of reactor fuel littered the area.

Other debris of various material composition were also scattered throughout the area, all radioactively very "hot".

Early hand-held dosimeters were off-scale or inactive because of the extremely high dose rates. Readings were regarded as inaccurate or otherwise ignored.

Many individuals (~200) received very high doses (> 200 rem).

Thirty-one workers, mostly firefighters with burns and extreme radiation exposures died within two months.

RADIOLOGICAL EFFECTS
Closest Population Center
PRIPYAT
~2km NW of Reactor Site

Principally Total Body Dose From Passing Radioactive Plume

Evacuation Started About 36 hours After Reactor Destruction

Doses Not Lethal Only Because of Plume Lofting

Measured Dose Rates Reached 500mrem/hour in Some Outdoor Locations of the City Before Evacuation

Accumulated Individual Doses Were Highly Variable

Iodine Deposition Leading to Thyroid Doses

Regions in the Ukraine, Belarus, and Poland received Substantial Deposits of Radioiodines. Children were particularly Susceptible to Thyroid Health Effects from Consuming Locally Produced Milk and Vegetables.

Thyroid Doses above 100's of Rems Were Estimated for Some Recipients.

Intervention Was Impossible Because of the Delays in Announcing the Magnitude of the Accident by the Soviet Officials.

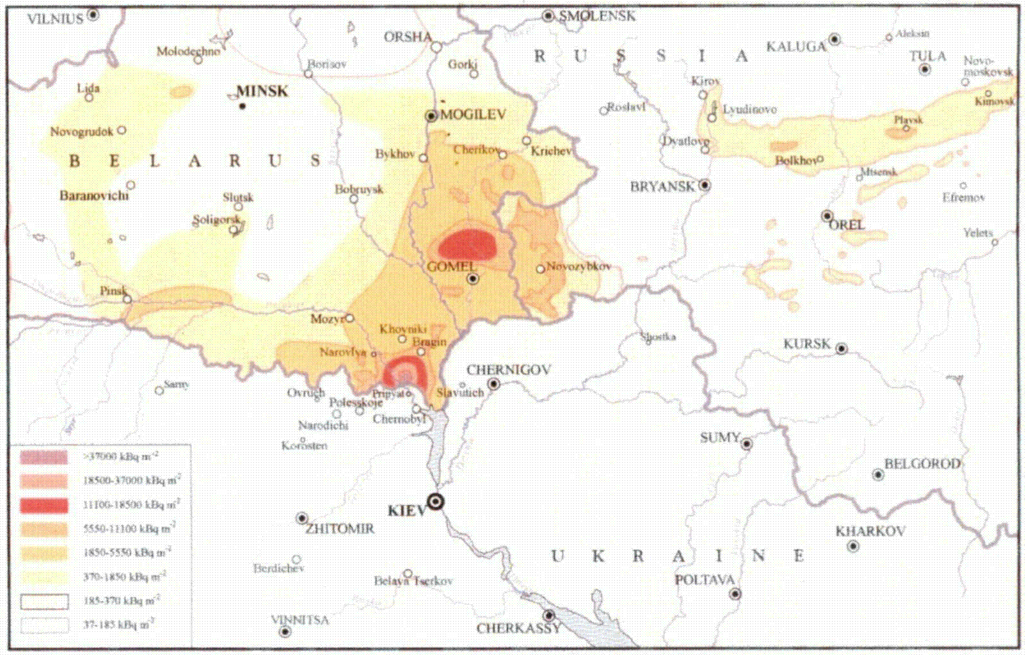
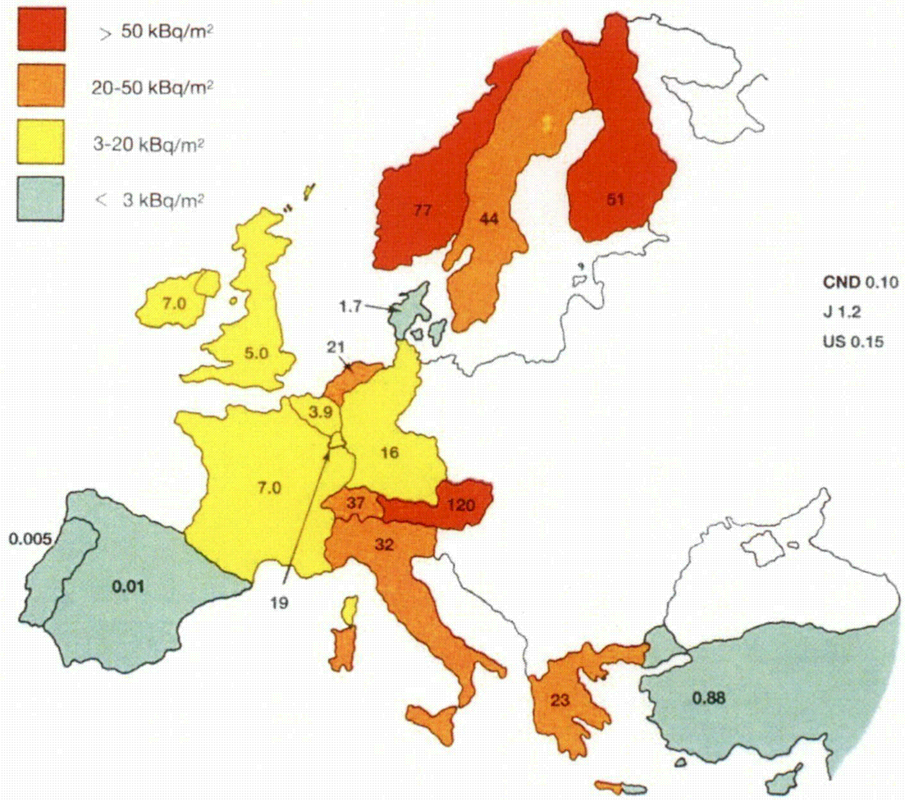


Figure X. Estimated surface ground deposition in Belarus and western Russia of Iodine-131 released in the Chernobyl accident [B25, P19].

I-131 SPREAD OVER WIDE AREA
SIMILAR DISTRIBUTION FOR CESIUM 134 & 137

Figure 4. **AVERAGE VALUES OF THE TOTAL DEPOSITION OF IODINE-131 FOLLOWING THE ACCIDENT (kBq/m²)**



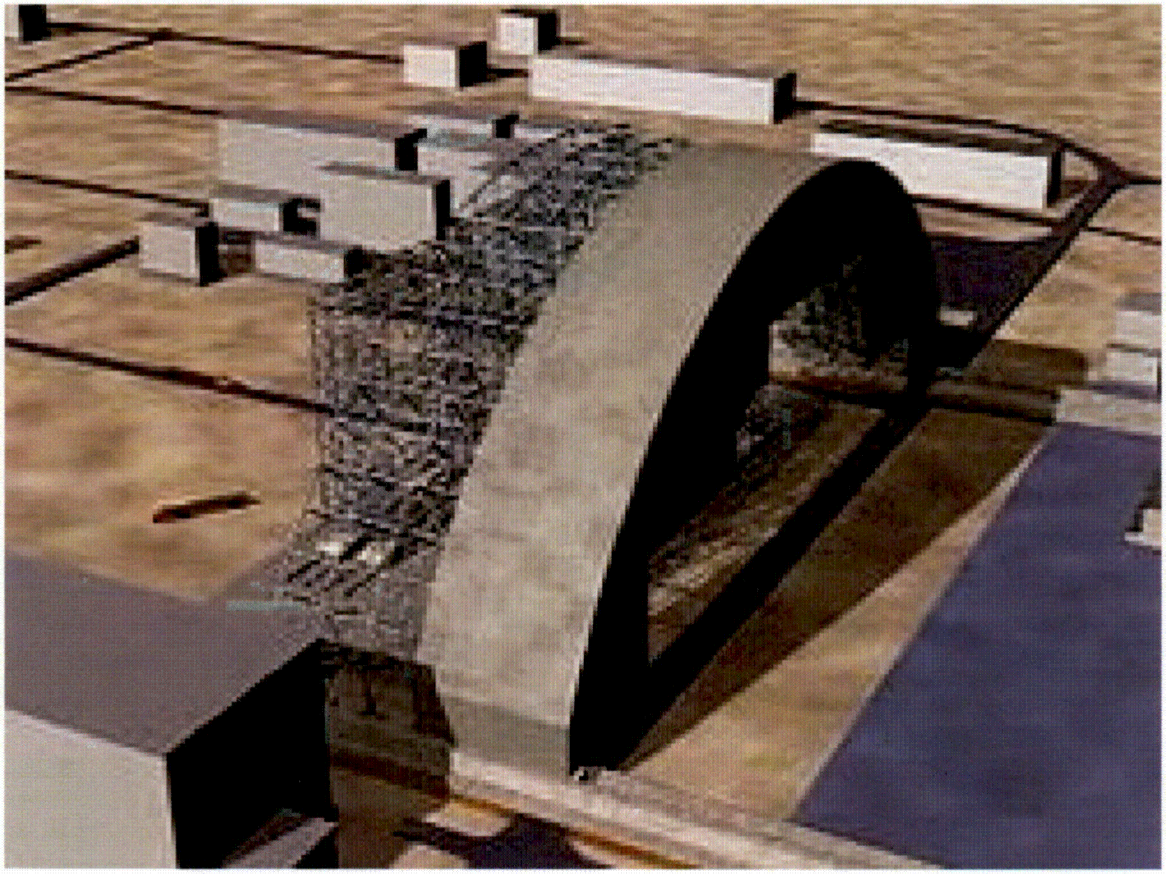
Average Individual Thyroid Doses
Highest: 200 -300 mrem
(From Radioiodines)

Conversions

50 kBq/sq meter - ~140 pico Ci/sq cm

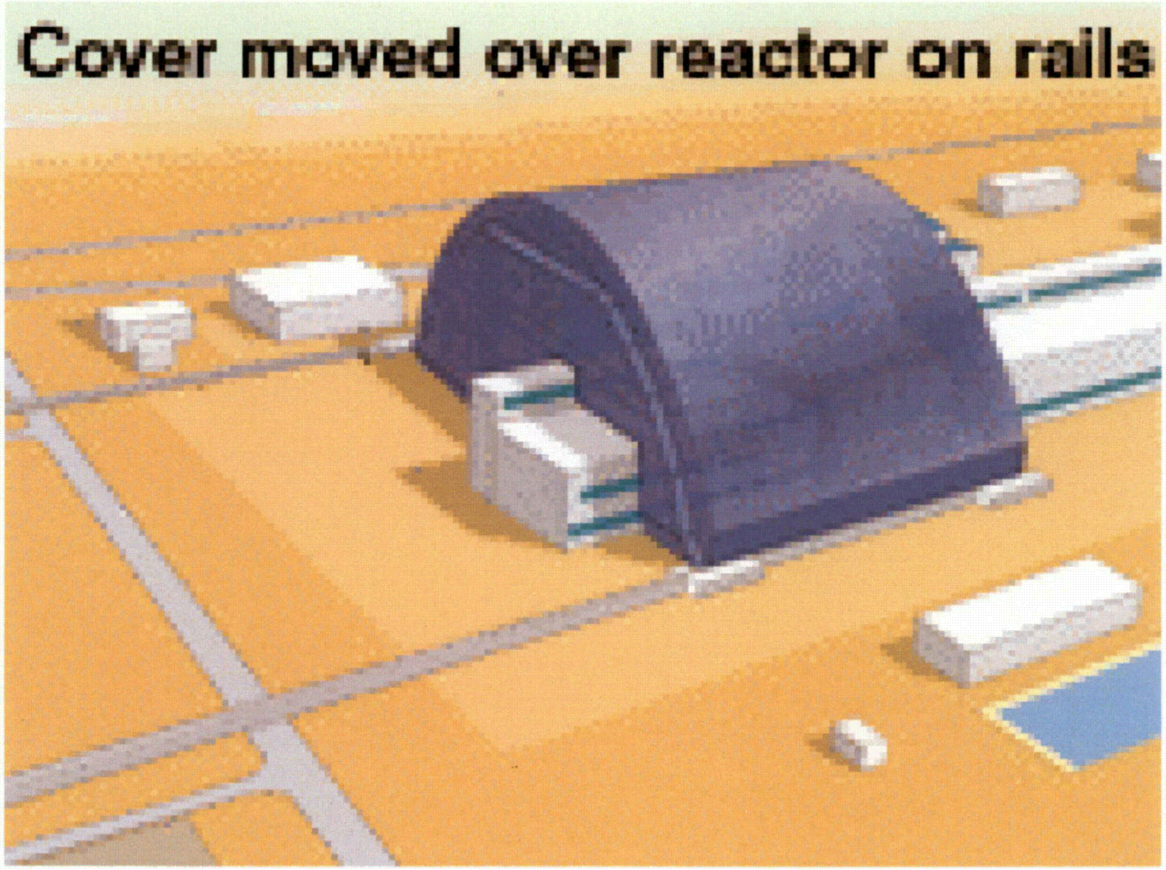
20 kBq/sq meter - ~56 pico Ci/ sq cm

3 kBq/ sq meter - ~ 8 pico Ci/ sq cm



ARTIST RENDERING OF FUTURE SARCOPHOGUS

THE CURRENT BUILDING SURROUNDING CHERNOBYL 4 IS CRUMBLING.
REPLACEMENT EXPECTED WITHIN NEXT FOUR YEARS



NEW REACTOR SHIELD

SEE VIDEO AT

http://www.wimp.com/encasechernobyl/