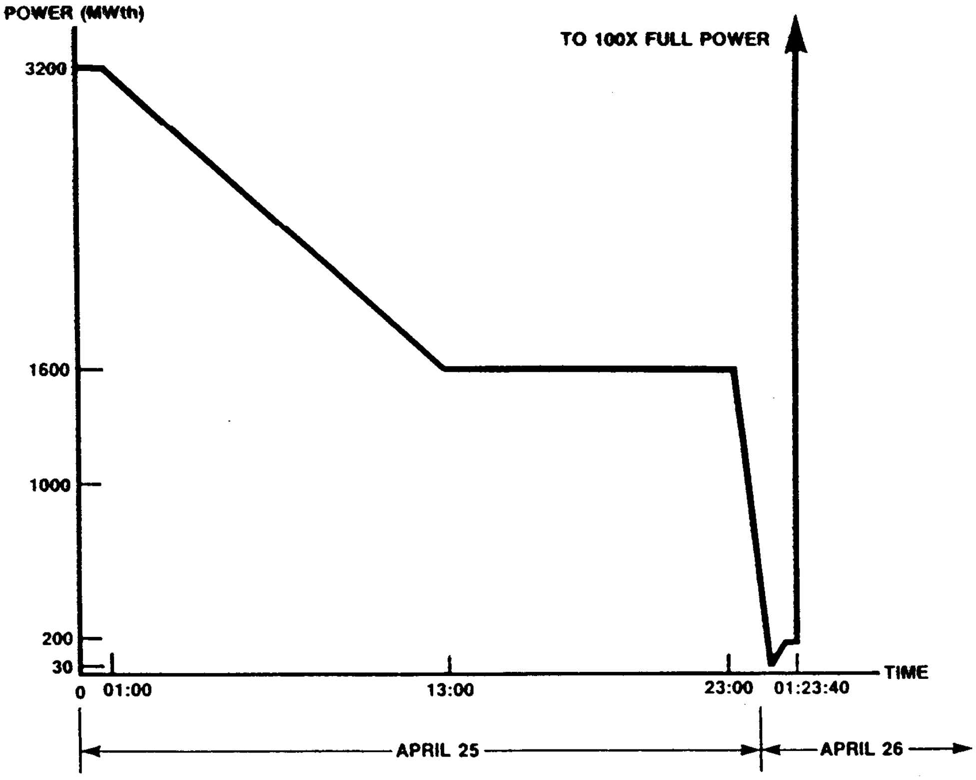
[illegible]

CHERNOBYL:

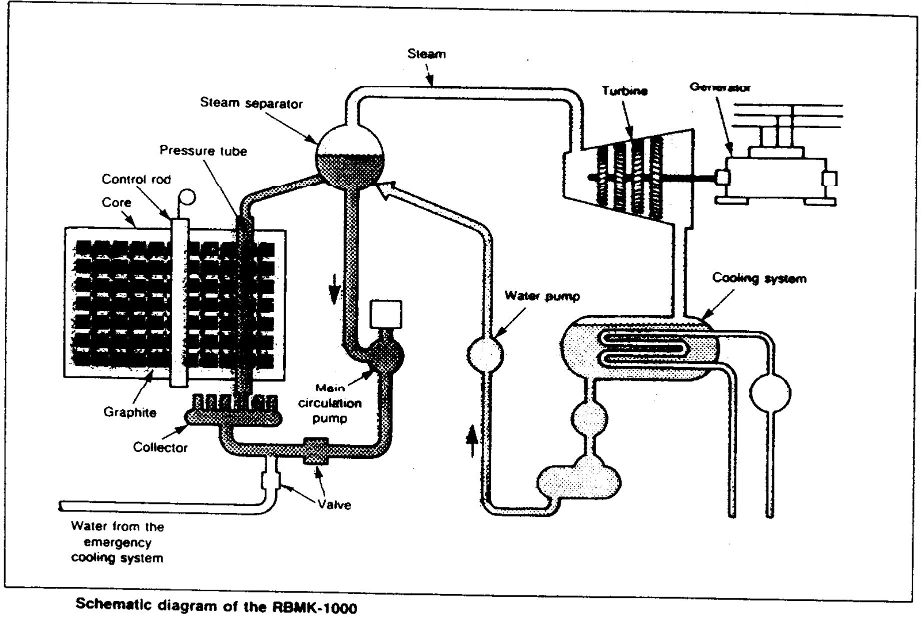
A TRAGEDY OF ERRORS

Jeremy Whitlock
AECL

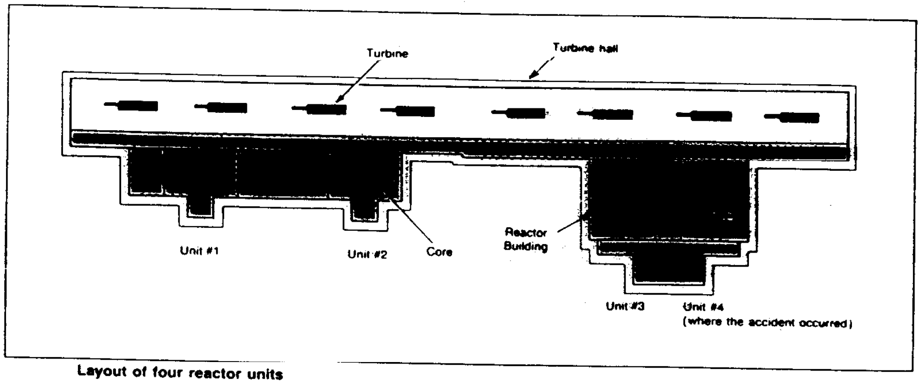


RBMK-1000:

"Heterogeneous
Water-Graphite
Channel-Type
Reactor"

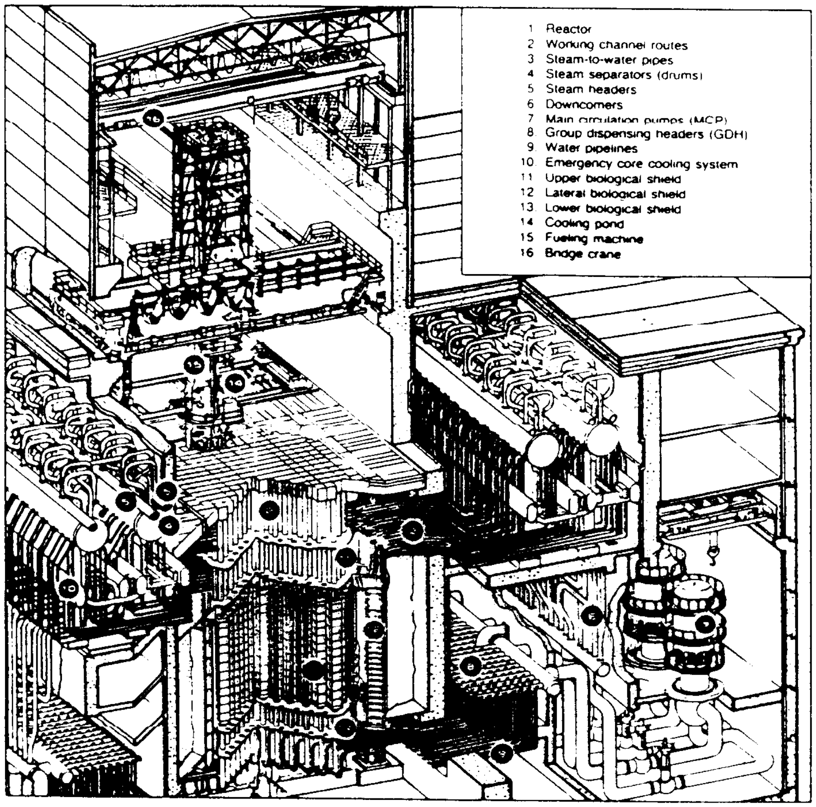


Schematic diagram of the RBMK-1000



Layout of four reactor units

- 3200 MWth (1000 MWe)
- core: 7m high, 12 m diameter
- 1661 fuel channels
- fuelled on-line
- direct cycle, steam mass quality 11-22%
- 2 loops, 3 pumps/loop + 1 standby pump/loop



FUEL

2% enriched

UO_2

2 subassemblies per channel

18 pins per subassembly

fuel pin 13.5 mm diameter

$\alpha_T = -.02$ mk/°C

COOLANT

light water

$P = 7$ MPa

$T_{out} = 285$°C

avg. steam fraction 14.5%

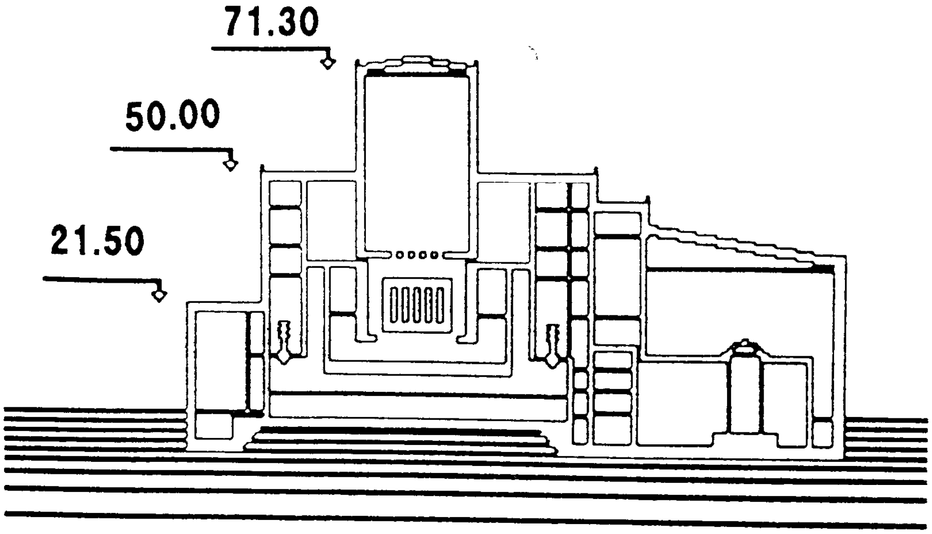
$\alpha_V = +.05/\%$ VOID

MODERATOR

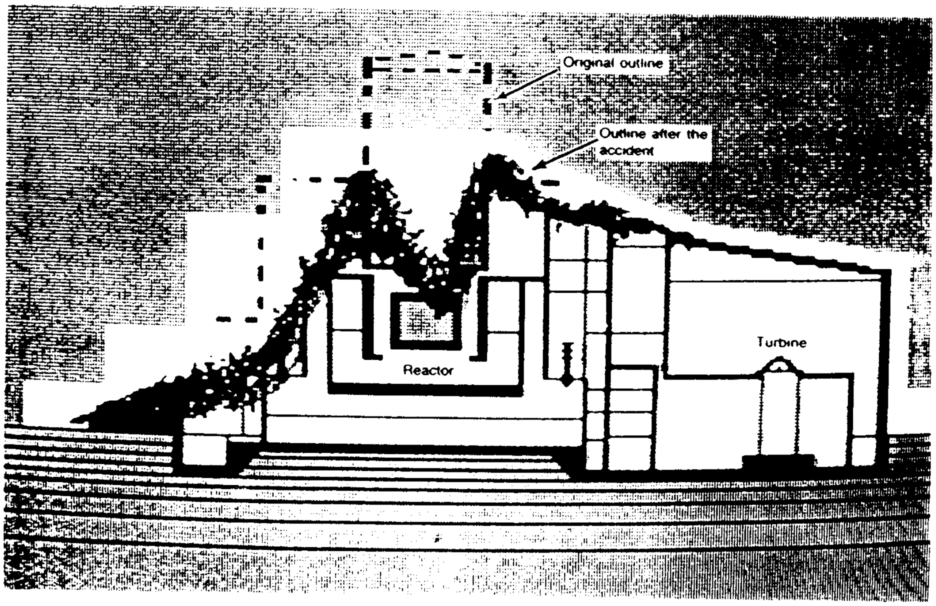
graphite

$T = 700$°C

$\alpha_T = +.06/$°C (slow)



VIEW OF THE REACTOR BEFORE THE ACCIDENT



VIEW OF THE DAMAGED REACTOR

CONTROL PROBLEMS

- at low power, small flow deviations cause large power fluctuations.

- hard to match flow and power levels at low power.

- detector feedback slow.

- control rod insertion slow (~20 sec.).

- spatial modes easily incited → less than 10% core needed for criticality; first azimuthal harmonic only 6-7.5 mk subcritical.

- significant Plutonium build-up leads to low β - values $\left(\begin{array}{l} \beta \text{ for } Pu^{239} = 2.2 \times 10^{-3} \\ \beta \text{ for } U^{235} = 6.9 \times 10^{-3} \end{array} \right)$

- operation therefore not "permitted" below 20% power, and min. reactivity insertion ~30 rods $\longrightarrow \alpha_v$ at these bounds is $\frac{.2\,\text{mk}}{\%\,\text{void}}$

SHUTDOWN

- 24 emergency rods (only system)
- effectiveness dependent on reactor operating conditions — mainly # of control rods in core and power-flow match.

- slow insertion rate.

APRIL 25, 1986

The Experiment

- design-basis accident: loss of coolant plus loss of off-site power
- reactor trips, ECC pumps powered by turbine inertia until diesels start up (~60 sec.)
- test of new voltage regulator:

  ① power reduction → 700-1000 MWth.

  ② trip one of two turbines; transfer all steam to other turbine.

cont'd ...

③ start extra pump in each loop.

④ disconnect ECC.

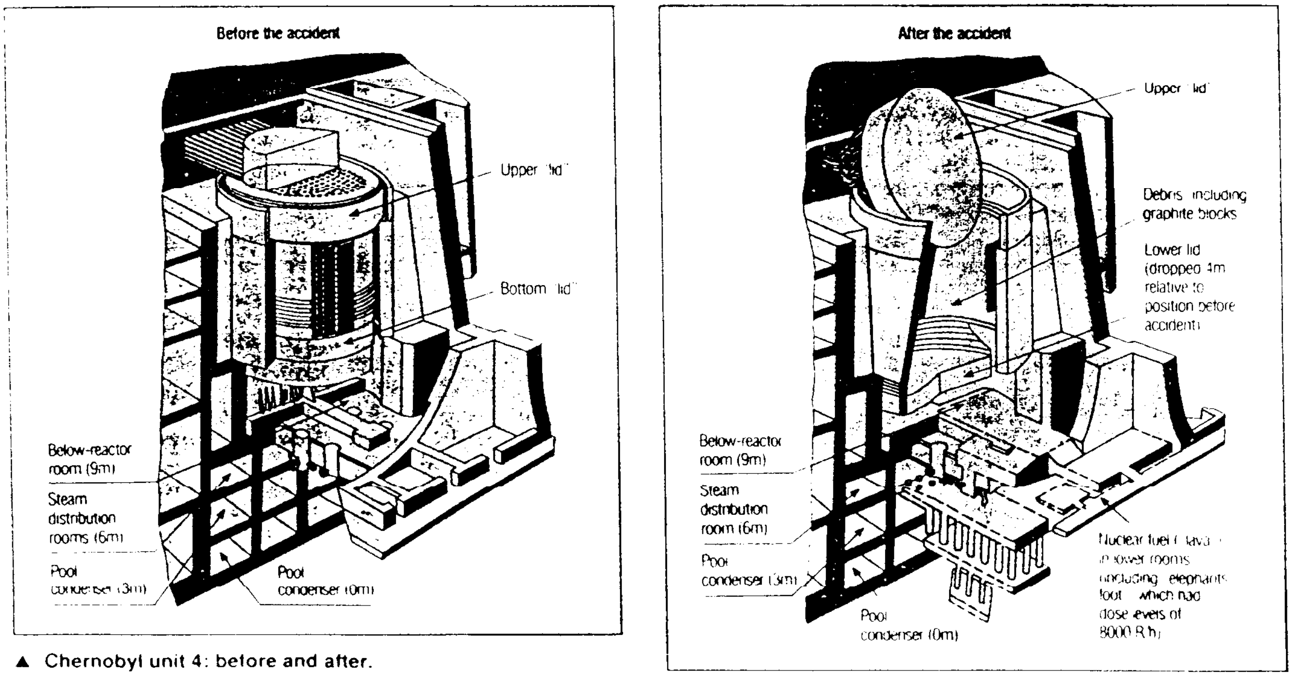
⑤ trip remaining turbine; observe voltage rundown.

The Events

TIME	REL. TIME	EVENT
~APRIL 25~ 1:00 am	0:00	Begin power reduction.
1:05 pm	12:05	Reactor at 50% power. One turbine tripped.
2:00 pm	13:00	ECC disconnected. "Hold-power" request received. ECC unavailabl
11:10 pm	22:10	Power rundown continued.
~APRIL 26~ 12:28 am	23:28	Switch from "local" to "bulk" control. ERROR: Set point incorrectly set; Power falls to 30 MWth (~1% power). RESULT: Xenon poisoning; α_v increased; reactor in unstable regime.
1:00 am	24:00	Power raised to 200 MWth (6% power). ERROR: Reactivity margin reduced to below 30 rods. RESULT: Increased α_v, instability.

TIME	REL.TIME	EVENT
1:07 am	24:07	Fourth (standby) pump in each loop started. Flow rate exceeds safe limit. Further void collapse causes drop in system pressure, separator level.
1:19 am	24:19	Feedwater flow increased to raise separator level. T_{in} decreases → further void collapse.
1:19:30 am	24:19:30	Separator level rises too high. Automatic control rods rise to limit. Manual rods raised to return auto. rods to operating region.
1:19:58 am	24:19:58	Condenser steam dump valve closed.
1:21:50 am	24:21:50	Feedwater flow abruptly reduced.
1:22:10 am	24:22:10	Steam quality begins to increase. Automatic rods lower.
1:22:30 am	24:22:30	Feedwater flow reduction stopped. Power distribution, reactivity margin printed out → 6-8 rods in core, flux "double humped".
1:22:45 am	24:22:45	Steam quality stabilizes. Pseudo-steady-state observed.
1:23:04 am	24:23:04	DECISION TO BEGIN TEST. Second turbine tripped. ERROR: Reactor "loss-of-turbine" trip blocked. RESULT: 200 MWth operation.

TIME	REL. TIME	EVENT
1:23:21 am	24:23:21	Automatic rods lower due to void-induced reactivity increase. Void determined by increasing pressure (−), decreasing pump speed (+), low feedwater flow (+). Net effect: +
1:23:31 am	24:23:31	Power begins to rise.
1:23:40 am	24:23:40	Manual trip button pushed. Rods drop 2−2.5m into core, and stop. Power surges to ~100X in 4 seconds.
1:23:48 am	24:23:48	Steam explosion, followed seconds later by second explosion (H_2, CO igniting with air).



Before the accident

After the accident

▲ Chernobyl unit 4: before and after.

The Results

- Reactor building blown away. ~30 fires on turbine hall roof, put out by 5:00 am.
- Graphite fire drives updraft for 10 days. Put out by dumping ~5000 tonnes of boron, lead, dolomite, sand, clay on core, with N_2 injection. ~10% of total (250 tonnes) burns.
- ~3.5% fuel inventory dispersed in vicinity.
- ~50 MCi noble gases + 50 MCi other species dispersed around northern hemisphere.
- ~20,000 extra fatal cancers in northern hemisphere (half in U.S.S.R.).
- 31 immediate deaths (operators, firefighters).
- units 1, 2 & 3 still operate.

CHERNOBYL

VOID COEFFICIENT

H_2O Coolant

- large absorption → ρ increases on voiding
- scattering effects (decrease in moderation; increase in "p" factor) are small.

Graphite Moderator

- moderator hotter than coolant (700 °C/285 °C)
- loss of extra neutron "cooling" on voiding increases avg. Maxwellian temp →
- U^{235} reaction rate decreases, Pu^{239} rate increases (0.3 eV resonance)
- net effect → ρ increases on voiding for high burnup fuel; decreases for fresh fuel.

Absorber Rods

- used to reduce void reactivity (80 rods → .05 mk/%)
- minimum 30 rods required partially (1.2 m) in core. (.2 mk/%)

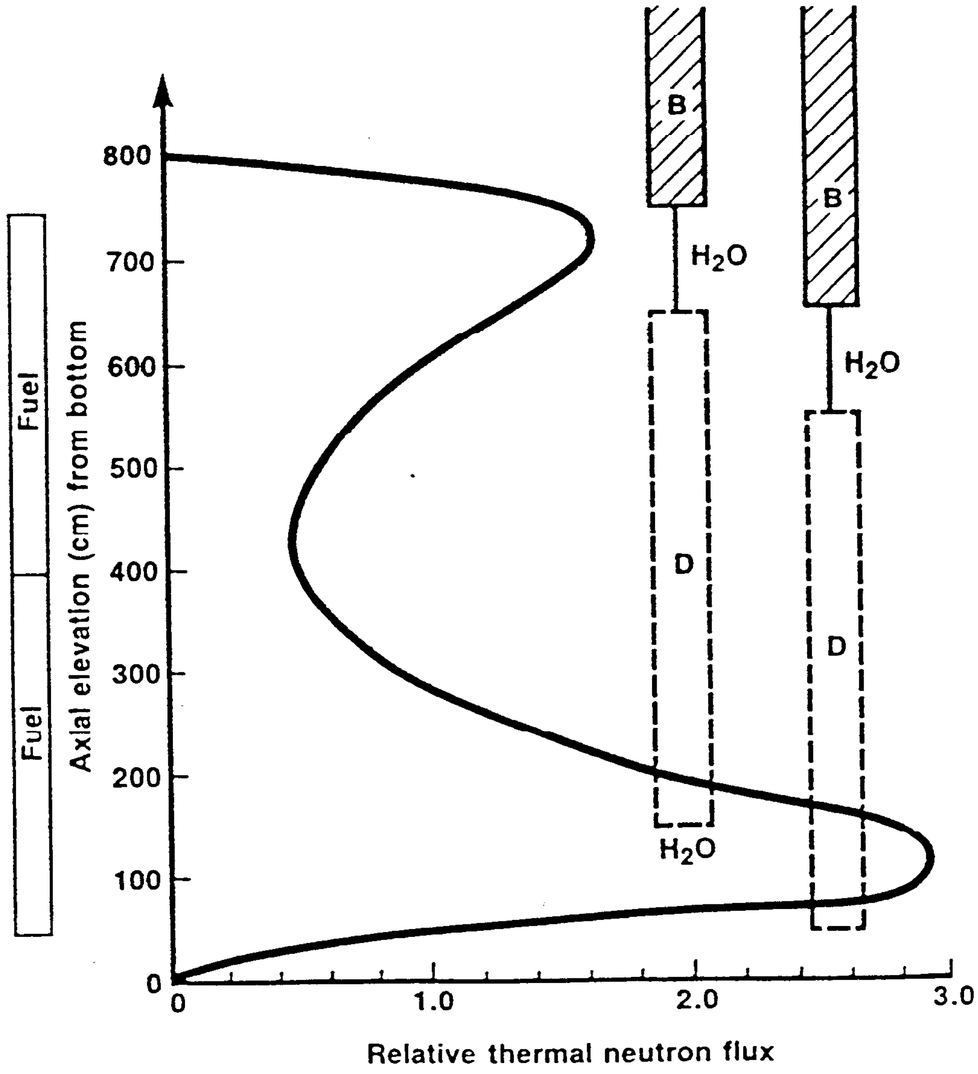
Direct Cycle

- significant operational void levels (14.5%)
- low power → low void → $\alpha_v \approx 0.2$ mk/% void

∴ Problem at low power and min rod insertion

"POSITIVE SCRAM"

AXIAL FLUX DISTRIBUTION PRECEDING ACCIDENT



B = Boron carbide absorber
D = Graphite displacer

PROPOSED CHANGES

Short Term

- Minimum rod insertion changed to 80 rods
- Limit stop switch on control rods, set for 1.2 m.
- Better knowledge of operating rules.*

Long Term

- Increase enrichment from 2.0% to 2.4%
- Faster, more independent shutdown system.
- Reactivity monitor, with reactor trip.
- Other operator info. (eg. dryout margin) more readily available.
- Longer graphite follower on control rods.
- Harder to over-ride automatic controls.

Lingering Questions ...

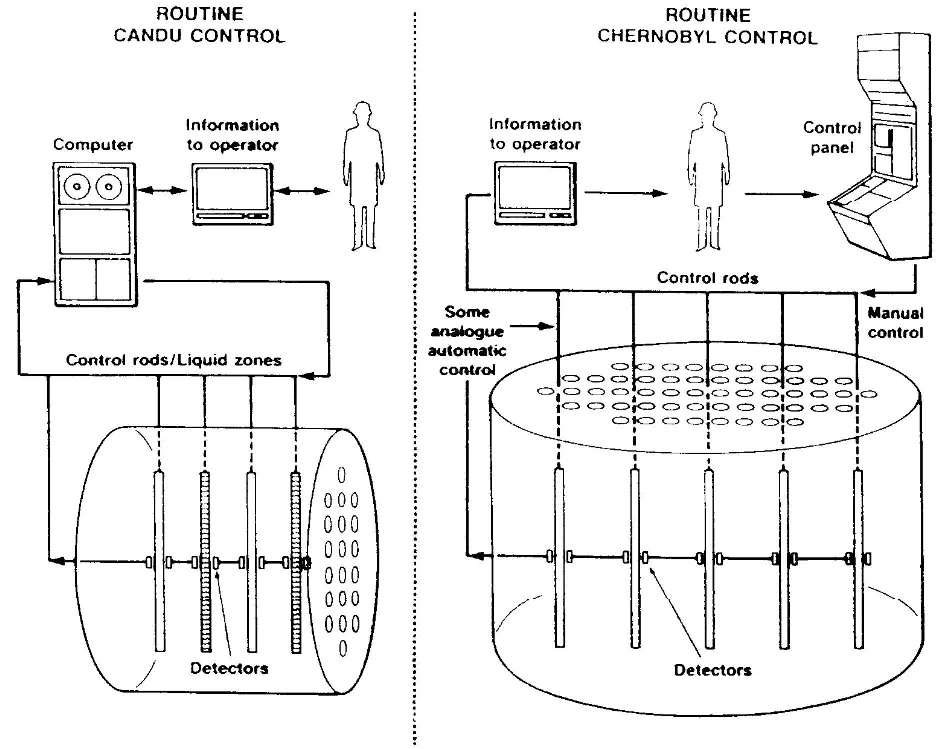
- Still inferior to Western plants.
- Initiating events → positive scram?
  → thermal shocks?
  → pump cavitation?

COMPARISON OF CHERNOBYL REACTOR WITH BRUCE-B REACTOR

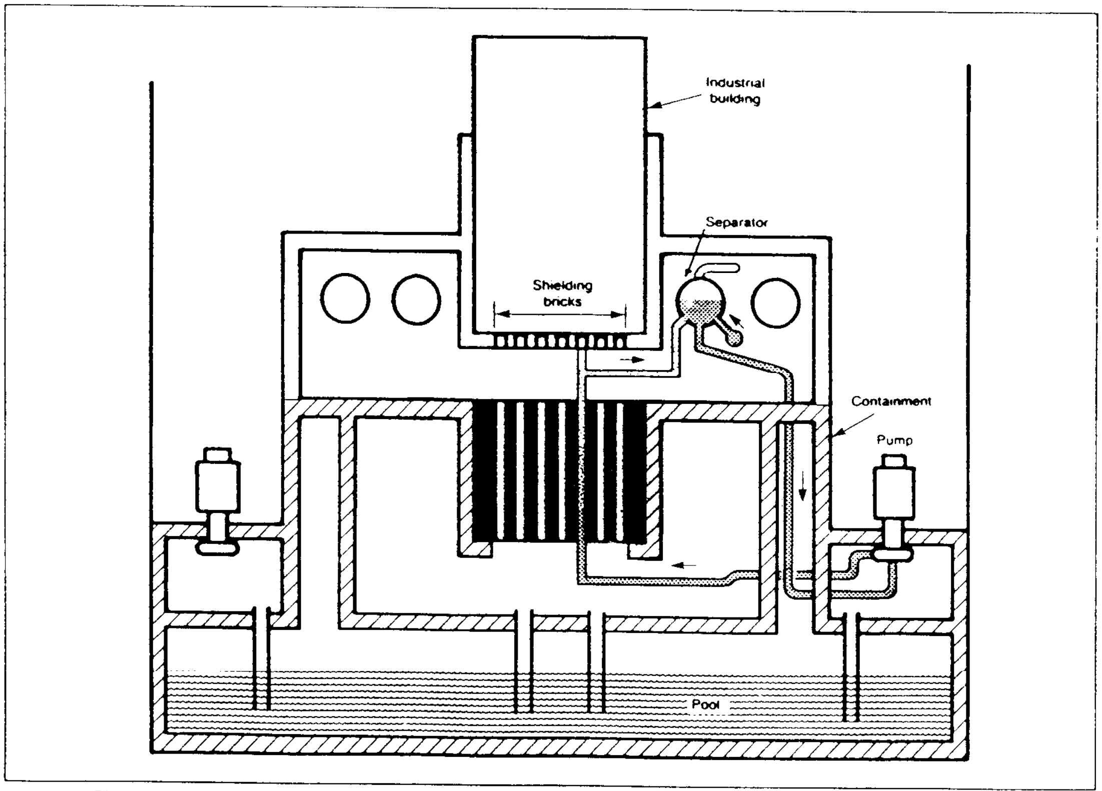
	CHERNOBYL	BRUCE-B
Type	RBMK	CANDU
Thermal Power, MW	3200	2852
Moderator	Graphite 700°C	Heavy water 80°C
Coolant	Water (boiling, x_o = 14%) 285°C	Heavy water 290°C
Cycle	Direct	Indirect
Fuel	UO_2-2% enriched	UO_2-natural
Orientation	Vertical	Horizontal
Core Outlet Pressure, MPa	7	9.3
Pressure Containment	Pressure Tubes (Zr Nb)	Pressure Tubes (Zr Nb)
Number of Fuel Channels	1660	480
Core Diameter, m	11.8	7.07
Core Height or Length, m	7.0	5.94
Re-fuelling	On power	On power
Equilibrium max. void reactivity	20 mk (~400% change with power)	11 mk (~constant with power)
Shutdown	20 seconds	2 seconds

Mitigating factors in CANDU:

better training, faster shutdown, better spatial & temporal control, containment, heavy water moderator, control & shutdown independent of operating parameters, double (independent) shutdown systems.



CONTROLLING THE POWER



Chernobyl containment