Chernobyl Accident

Events on 25–26 April 1986

- Just 24 hr. before shut down – 3200 MW (Th).
- Annual maintenance shut down.
- Test: how long the power station's steam turbines could generate electricity after steam supply stopped
- Technicians (Operators) did not discuss with physicists or safety staff.

* Switch off the ECCS

1 Am Friday 25th April, – Start power reduction
2 pm " " " – 1600 MW.
– Received call from Kiev to back-up power

Operated without ECCS

Procedure Voilation (PV)

11.10 pm (Friday 25/4/86) Start reducing power
Operator Forgot to set power Regulator.

Operator Error (O.E)

0.28 Am (Saturday 26/04/86)
30 MW instead of 700 MW
Too low power! – abandon test
but decided increase power.

Xe-poison problem.
pulled more control rod to increase power – only 6–8 left
minimum 30 – 15 occasionally permitted.

O.E/PV

1.00 AM – 200 MW (still low)

Started at 1.03AM & 1.07 AM – Two extra circulation pumps in addition to 6
– High Cooling.

OE/PV

Water & steam level changing drastically in reactor - could not control (close to saturation - flashing).

1:20 A.M. - steam pressure & water level decreasing
- deactivate automatic shutdown system (Trip system disabled)

1:23 Am Test started.

Switched off last safety system
↳ would act when turbine shut

- Reactor without control - 30 seconds.

Shift manager - alerts - asked to drop control rods.

Rods fell - core too hot!

Power jump - Prompt Critical!
7 to 100 times increase

* 2 Explosions Heard.
- Steam flashing?
- H_2 explosion?

Graphite ignition - fire

Containment - 27 psi →

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Kinetics:

$$\frac{dn}{dt} = \frac{\rho - \beta}{l} n + \sum_i \lambda_i C_i$$

$l \sim 1$ ms. $\beta \sim 0.0065$ – ^{235}U, $.0002$ for ^{239}Pu –
Average $\beta = 0.5\%$

If $\rho >> \beta$, – prompt neutron

$$\frac{dn}{dt} = n \frac{\rho - \beta}{l}$$

$$\therefore n = n_0 e^{t/T}$$

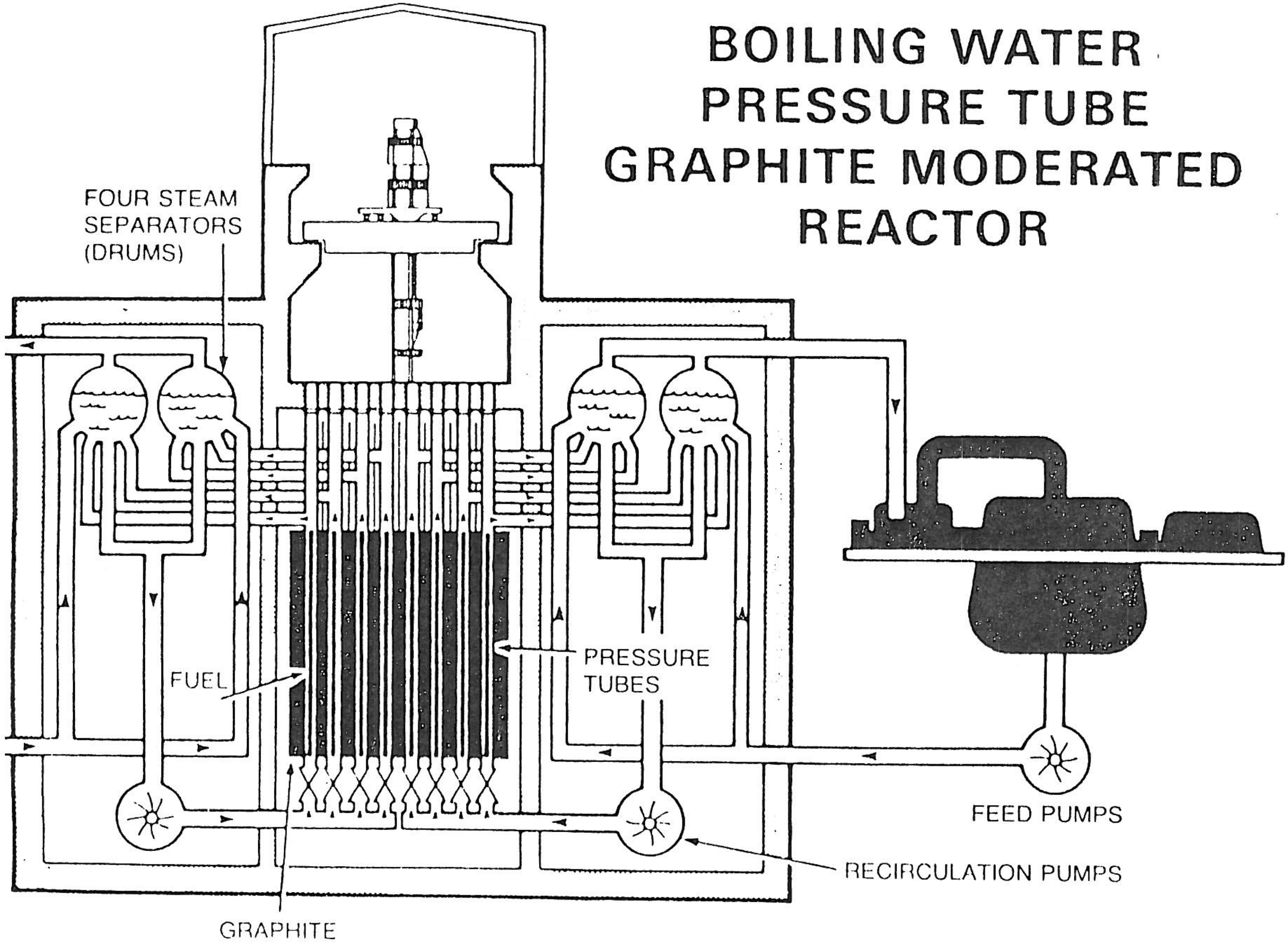
$$T = \frac{l}{\rho - \beta}$$

Void coefficient +ve in Chernobyl,
at 0.03% per percent of void.

If void change 10% to 60% – 50% increase
then reactivity increase 1.5%
This is 1% above β
Time constant $T = 10^{-3}/10^{-2} = 100$ ms
power increases 2.7 times in 100 ms
and in 1 second 22,000 time

Fuel temp coeff. (0.001%/°C) – negative – but too small.
Thermal time constant of the fuel 5 to 6 seconds.

BOILING WATER PRESSURE TUBE GRAPHITE MODERATED REACTOR



;chematic diagram of the RBMK-1000, a heterogeneous water-graphite channel-type
eactor

TABLE I

THE MOST DANGEROUS VIOLATIONS OF OPERATING PROCEDURES AT CHERNOBYL-4*

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

*From the Soviet Union summary of its report to the IAEA.

Table 2 Detailed Sequence of Events

Time	Event	Interpretation: Result of event	Interpretation: Significance
25 April			
1:00:00	Reactor power reduction started	Initial steps of test program and planned maintenance outage	The slow reduction in power would help reduce the effects of the buildup of xenon poison
13:05:00	Reactor power reduction stopped at 50% of full power. Turbogenerator (TG) No. 7 switched off. Electric power requirements for unit's needs switched to TG No. 8 (four main circulating pumps, two feed pumps, plus other equipment)		These components would run down with the TG during the test. Pump configuration at this time is four running from TG No. 8, two running from grid, and two on standby connected to grid
14:00:00	The emergency core cooling system (ECCS) was isolated	Isolation done in accordance with the test plan because crew wished to avoid spurious triggering	Safety principle violation, but blocked ECCS played no role in transient to point of core disruption
	Load dispatcher halted the power reduction		The long hold in power would further reduce the buildup rate of xenon at test power level
23:10:00	Power decrease continued toward the target level of 700 to 1 000 MW(t)		In accordance with test procedure, this level was chosen to be above the minimum allowable operating power of the reactor [~700 MW(t)]
26 April			
0:28:00	*Operator error occurred: transfer from local (LAR) to global power (AR) control; hold power at required level was not entered*	*Power reduced to 30 MW(t)* owing to inability of the automatic control rods and lack of prompt operator action to compensate for the void collapse	Negative reactivity was added to system, and more manual rods were withdrawn to compensate
1:00:00	Reactor was stabilized at a power of 200 MW(t)	*Reactor operating below the minimum permissible power level; required reactivity reserve margin violated*	No excess reactivity was available to raise power
1:03	The fourth main cooling pump powered from the grid was connected to the left loop of the heat transport system	Owing to low power and increased flow rate of coolant in the heat transport system, the coolant inlet temperature approached saturation	This added negative reactivity to the system, necessitating withdrawal of more rods to compensate. The system was put into a more vulnerable condition with respect to void/power stability
1:07	The fourth main cooling pump powered from the grid was connected to the right loop of the heat transport system	*Flow rate in some of the main cooling pumps exceeded the permissible value*; significant deviations of the water level and steam pressure in the steam drums	Flow vibration limits were violated based on potential cavitation problems. Addition of both pumps caused further control rod withdrawal and further decrease in reactivity reserve margin

(Table continues on the next page.)

Table 2 (Continued)

Time	Event	Interpretation: Result of event	Interpretation: Significance
26 April (Continued)			
1:19:00	Operator increased feedwater flow. About this time *operator blocked the shutdown signals associated with steam drum level and pressure*	Core subcooling increase, which resulted in more void collapse; control difficulties throughout this period	
1:19:30	Rise in water level began in steam drum. The feedwater flow exceeded three times balanced value	Feedwater entering the system exceeds the steaming rate; the cooler water reached the core and reduced the steam quality and core void	Steam drum level increased
	The automatic control rods went up to the upper tie plate		Calculated core average void was then zero
	The manual control rods were raised		Addition of negative reactivity was compensated by rod withdrawal
	The onset of steam drum steam pressure drop		
1:19:58	The steam bypass valve was closed	Slowdown in the rate of drop of the steam pressure	
1:21:50	The feedwater flow exceeded four times the balanced flow rate	Steam drum level still rising; pressure still falling	Control rod position was constant as modeled. Reduction in pressure produces enough void to compensate additional feedwater flow
	Operator abruptly decreased the feedwater flow		
1:22:10	Steam quality started rising, automatic control rods started driving in, and water level i.. steam drum stabilized	A rise in average core void produced by warmer water reaching core inlet; control rods drive in to compensate	
1:22:30	Feedwater flow is reduced to two-thirds of the balanced flow rate	Operator unable to stop feedwater flow rate at desired level owing to coarseness of control system, not designed for this operating regime	Control rods had moved in to compensate added reactivity of increased voiding
	The distribution of power density and the positions of every control rod were printed out	Printing was done to establish the flux distribution and reactivity margin before beginning the test	*Confirmation that the operational reactivity reserve margin was half of the minimum permissible, and the operator should have initiated immediate shutdown based on the computer printout*

Table 2 (Continued)

Time	Event	Interpretation: Result of event	Interpretation: Significance
26 April	(Continued)		
1:22:45	Feedwater flow rate stabilized	Stabilizing of steam quality in the core; pressure starts rising	
1:23:04	*Personnel blocked the two-TGs-trip signal.* Emergency stop valve to the turbine was closed. The reactor continues operating at a power of 200 MW(t)	*Start of TG No. 8 test*	Last process safety system trip was *removed to allow test to be repeated.* Operator was aware he was inducing transient which required shutdown (this was not provided for in the test program)
1:23:10	One group of automatic control rods starts driving out	Decrease in core void because of increasing system pressure	
1:23:21	*Two groups of automatic control rods begin reinsertion*	Reduction of the coolant flow rate and the approach of the warmer water to the core	Both of these results led to positive reactivity addition to the core. Control rods tried to balance this addition
1:23:31	Net reactivity, increasing with subsequent slow increase in reactor power	Control rods unable to balance added reactivity any longer	Power slowly rose; positive power coefficient accelerated reactivity imbalance
1:23:40	*Operator pushes AZ-5 button* (reactor trip)	No apparent effect	
1:22:43	The triggering of the high power and short period alarms		*The emergency protection was not efficient enough to prevent the reactor runaway*
	The sharp growth of the calculated fuel temperature		Heat transfer crisis occurred
1:23:44	Rapid increase in power		

An estimate from the Vienna meeting sets it at about 0.6% increase over the normal incidence rate in those evacuated from the 30-km area around Chernobyl and less than 0.15% in the rest of European U.S.S.R. Epidemiological studies may never be able to detect these low levels of increase in the normal cancer incidence rate.

Although the specific sequence of events (Table 2) is believed to be impossible in U.S.-designed reactors, there can be lessons to learn. We believe that these lie mostly in the areas of human factors, human–machine interfaces, accident management, and emergency response. The Chernobyl accident appears to us to be a case in point supporting recent calls for designs of more "forgiving" systems that have inherent passive safety features that cannot be defeated by either deliberate or unintentional actions.

REFERENCE

1. U.S.S.R. State Committee on the Utilization of Atomic Energy (Comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material,* report presented at the International Atomic Energy Agency Experts' Meeting, Aug. 25-29, 1986, Vienna.