RMBK Boiling Water Reactors & Chernobyl

RMBK Reactors

The reactor design at Chernobyl is a 1000-MW$_e$ Boiling-Water Graphite-Moderated Reactor [Reactor Bolshoy Moshchnosty Kanalny (RMBK)]. RMBK reactors are designed to produce ^{238}Pu for nuclear weapons as well as produce electrical power; unlike any reactors in the U.S.

The reactor uses water as a coolant and a working fluid; directly boiling water in tubes passing through the core. The moderator is graphite and heat is transferred from the graphite into the water via conduction. This combination of graphite moderation and water coolant is not found in any other reactor design. The RMBK reactor is very unstable at low power.

In order to maximize production of ^{239}Pu from ^{238}U and to minimize production of ^{240}Pu which is not suitable for nucelar warheads, the fuel rods must be removed every 30 days without shutting down the reactor. This requires a large open space above the reactor. The RMBK reactor design does not include a reinforced concrete or steel containment vessel.

The RMBK reactor is particularly unstable at low power having a positive void coefficient. Stability can be maintained with control rods, but the response time is slow. At high power, the positive void coefficient is compensated by a negative temperature coefficient.

`schematic of RMBK reactor here`

Reactivity Coefficients

The reactivity of a nuclear reactor is proportional to the nuetron flux. An increase in the neutron flux is measured by an increase in the reactivity and, subsequently, an increase in the core power.

A reactivity coefficient is how the system reactivity changes with respect to changes in power ($\dot{W}_t$), temperature, pressure, etc. Of greatest concern is the Power Reactivity Coefficient,

$$\alpha_{\text{power}} = \frac{\partial(\text{reactivity})}{\partial(\text{power})} = \frac{\partial \rho}{\partial(\text{power})}$$

For control purposes, α_{power} should be large in magnitude and negative in sign at the operating point. Under these conditions, an increase in power decreases the reactivity resulting in a stable reactor. The core reactivity is power limiting.

Another important reactivity is the Void Reactivity Coefficient,

$$\alpha_{\text{void}} = \frac{\partial(\text{reactivity})}{\partial(\%\text{ voids})} \qquad \alpha_T = \frac{\partial \rho}{\partial T}$$

should be large in magnitude & (-) in sign

which is the rate of change of reactivity with respect to percent void space in the core. Vaporization of coolant in liquid-cooled reactors results in voids in the core. The Void Reactivity Coefficient, α_{void}, should be large in magnitude and negative in sign for stable operation.

The design of the RMBK reactors is such that reactivity can rise to where the reactor is *prompt critical*; that is, the reactor is critical with neutrons produced at the time of fission and not from delayed neutrons produced during decay of the daughter isotopes. Once a reactor is prompt critical, the power level in the core (reactivity) increases extremely fast to the point of meltdown.

The RMBK reactor can become prompt critical at low powers because of boiling in the pressure tubes which reduces the neutron moderation; even though the primary moderator is graphite. The positive feedback between boiling and increase in neutron flux can be controlled by insertion of the control rods, but this takes time and prompt neutrons are produced at 10^{-14} seconds.

Typically, boiling water reactors are designed with a positive void coefficient due to thermal nuetrons, which leaves plenty of time for control rod insertion.

Chernobyl Catastrophe

The accident (understatement) occurred in a RMBK power generating facility in Chernobyl, Ukraine. There are for nuclear cores at this facility and the 1000-MW_e #4 Unit suffered an explosion and core meltdown in April 1986. A fire in combination with a breach of the reactor shell spewed radioactive material over the local area and much of eastern and western Europe. The accident occurred primarily because of human error (USSR report). Operators committed at least six serious violations of operation protocols including disabling all technical protection systems. Reactor designers never considered the conjunction of events which occurred at Chernobyl to be possible and did not account for these events in the design of the safety systems.

Operators were concerned about what would happen if there was a failure int eh offsite electrical supply. All nuclear generating stations draw operating electricity from offsite and all have backup generators in case of offsite failure In 1980, there Kursk nuclear station lost offsite electrical power. The RMBK design is particularly susceptible to offsite power loss because:

- the reactor must maintain sufficient cooling water at low power, and
- there must be computer control of the response system because of the possibility of the core becoming critical with prompt neutrons.

Engineers decided to use the kinetic energy stored in the turbine generators to supply power for the 15 to 60 seconds required to get the diesel backup generators on line. They had conducted the "turbine inertia" test before, including at Chernobyl.

Accident Timeline

April 25, 1986

01:00 operators reduced power output to half (1600 MW_t) over a 12-hour period

13:05 one turbine is shut down

14:00 emergency cooling system is disconnected

At this point, the shutdown was stopped because of demand for electricity from the grid. *This was in violation of experiment and operating protocols.*

23:00 the shutdown resumed and the test was continued; the power levels were 700 to 1000 MW_t

- Xenon gas had built up in the core
- Xenon absorbs neutrons easily and then decays (*fissions?*) into another isotope (*check this*)
- Xenon build-up takes about 10 hours to decay once the neutron flux is sufficiently low
- When the operators shut down the local automatic regulating system (control rods?) per the test plan, the Xenon absorbed the neutrons and the power output plunged to 30 MW_t.
- Operators pulled the manual control rods to raise the power output.

April 26, 1986

01:00 the power increased to 200 MW_t; reactor is precariously stable

- decided to continue with test
- two additional pumps were started with the current six pumps so that four pumps could be shut down during the test. This caused a jump in the coolant flow rate and the reactor steam level dropped towards the emergency shutdown level. *This was in violation of operating procedures.*
- the subsequent drop in steam pressure induced cavitation in the coolant system
- *operators prevented the emergency trip and ignored a printout requiring immediate shutdonw*
- because of the drop in steam pressure, all of the automatic control rods withdrew

01:23 operators blocked the closing of the emergency regulating valves so the test could be repeated if necessary; *again in violation of operating and test protocols*

01:23:40 Shift foreman ordered an emergency SCRAM

- control rods began to engage
- analysis shows that within 3 seconds of the SCRAM the power rose to above 530 MW_t fro some seconds
- increased heat likely ruptured pressure tubes; water reacted with zirconium cladding and graphite to produce hydrogen and carbon monoxide
- high pressure likely breached the seals on the pressure tube feedthroughs in the containment vessel allowing air into the reactor
- 1000 metric ton cover plate lifted and let to ignition of hot H_2 and CO in the core

01:24 Loud bang, 2 seconds later a fireball and two explosions; 31 dead

The estimates for the number of cancer deaths in Europe and the former Soviet Republics due to the radioactive release have been estimated in the range of 10,000 to 40,000 deaths over a 50 year period. To put this in perspective, 600×10^6 cancer deaths are anticipated in the same population for the same period.