D. Design Features of Reactor Control

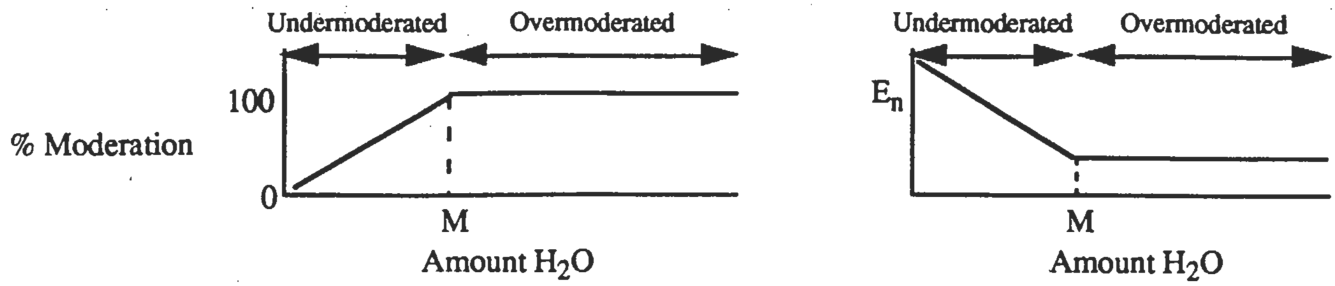
All non-Soviet reactors are designed to have a negative temperature coefficient. This makes the reactor self-regulating and stable against many perturbations. The lack of such a coefficient was one factor in the Chernobyl accident. Another factor was that the reactor was deliberately operated in such a way as to render the temperature coefficient positive. Hence, a loss of liquid water would cause a power excursion.

What causes a negative temperature coefficient? Neutrons are created from fission at high energy. In order to sustain a chain reaction, they must be slowed down. This is achieved by moderating them — they collide with light water (the hydrogen) and lose energy with each collision. This use of a moderator leads to two design options.

(a) Under-Moderation – There is not enough water to thermalize or moderate every neutron. So, we have some inefficiency in that some neutrons are wasted. But, there is also a huge advantage. If the water heats up, as it would at the outset of a power excursion, it becomes less dense. Hence, there will be fewer thermalizing collisions. This has two consequences. First, the average energy of a neutron increases. This is called spectral shift. Second, more neutrons leave the reactor core without interacting. This is called increased leakage. Both effects result in fewer neutrons to continue the chain reaction. So, the power level decreases and the excursion stops.

(b) Over-Moderation – There is more than enough water to thermalize every neutron. So, there is no loss of efficiency. We can build the smallest possible core. But, there is also a huge disadvantage. If the water heats up as the result of an incipient power excursion, nothing stops it. The neutrons remain fully moderated despite the loss of some water. So, the reactor overheats.

The following figure illustrates (in a simple way) the difference between over- and undermoderated. On the left is the amount of moderation versus the amount of water. On the left is the neutron energy versus the amount of water. A high neutron energy implies an undermoderated core.

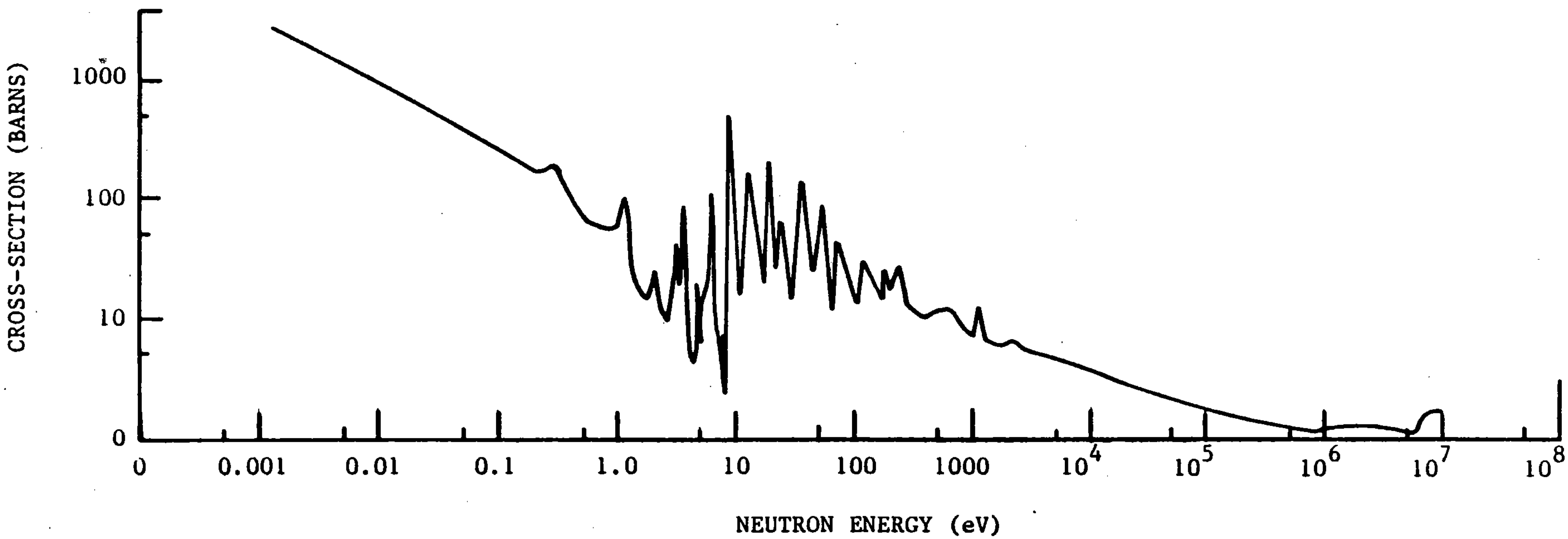


If the amount of water in the core is initially less than M, the core is undermoderated. If the coolant density goes up, the amount of water decreases, and the reactor moves along the sloping part of the curve into a state of increasingly less moderation. Fewer neutrons slow down, the neutron energy spectrum "hardens" (i.e., neutrons do not thermalize), and the power level drops. If the amount of water in the core is initially greater than M, the core is overmoderated. If the coolant density goes up, the amount of water decreases but nothing happens to the neutron energy spectrum because there is still enough water present to thermalize every neutron.

What happened at Chernobyl? The Chernobyl accident was the result of both design and operational errors.

a) Design – Chernobyl was a graphite-moderated boiling water reactor. It was designed to moderate its neutrons completely. That is, the core was over-moderated. Hence, if the coolant heated up and became less dense, there would be no effect on the neutron spectrum. In contrast, all non-Soviet reactors are designed to be under-moderated and hence, as the coolant heats up, there is a negative feedback effect. Namely, fewer neutrons are moderated and this slows the rate of power increase.

b) Operational – Light water both scatters and absorbs neutrons. Because the Chernobyl core was over-moderated, the dominant effect of its light-water coolant was neutron absorption. This in itself would have been acceptable because the coolant was normally maintained at a certain quality (mixture of liquid and vapor) and control blades were used to absorb the neutrons and keep the reactor exactly critical. But, prior to the accident, the operators had been trying to do an experiment to evaluate a new energy storage mechanism. As a result, the reactor's sequence of power maneuvers was unusual and the operators ended up with (1) the control blades fully out, and (2) the coolant almost 100% saturated liquid. So, the coolant was absorbing the excess neutrons from the neutron chain reaction. The operators then began to raise the reactor power. The coolant flashed to steam and hence its density decreased rapidly. This eliminated the neutron absorption and created a positive feedback effect – the power rose faster and faster and the reactor was destroyed.



Fission Cross-Section of Uranium-235 (BNL-325)

Courtesy of Brookhaven National Laboratory.

NEUTRON MODERATION

- Neutrons slow down or lose energy most rapidly if they collide with nuclides of similar mass. Materials that slow down neutrons are therefore those with low atomic numbers. These include light water, polyethylene, beryllium, heavy water, and graphite.

- The material of choice in the United States, Japan, and Europe is light-water. This is referred to as the neutron moderator or moderator. (Note: Canada uses heavy water for a moderator.)

- Light water, like all other materials, can both scatter and absorb neutrons. U.S., Japanese, and European reactors are designed so that the scattering effect is the dominant mode of interaction. Loss of the light water therefore causes the chain reaction to stop and the reactor to shut down.

Conclusion:

- The tendency for a reactor to shut down on loss of its moderator is referred to as a "negative power coefficient". This is an inherent (i.e., passive) safety feature that is required of all U.S. nuclear reactors.

NEGATIVE POWER COEFFICIENTS

- Negative power coefficients make reactors self-regulating. Consider the sequence of events that occurs during a power increase:

(a) A licensed operator causes the neutron chain reaction to increase.

(b) Additional fissions occur. This releases additional energy.

(c) The moderator (i.e., light-water) heats up. As it does, its density decreases. Then, there is more space between the water molecules.

(d) The fact that there is more space between the water molecules means that fewer neutrons collide with the water. So, there is less neutron thermalization. Fewer neutrons slow down.

(e) As fewer neutrons slow down, there are fewer fissions and the reactor power stops rising and, in most cases, starts to decrease.

Figure removed for copyright reasons.

Schematic diagram of the RBMK-1000, a heterogeneous water-graphite channel-type reactor (source: Soviet report to IAEA)

CHERNOBYL DESIGN FEATURES

Several design features of the Chernobyl Reactor stand out as being distinct from reactors of U.S., Japanese, Canadian or European design. These are:

Core Size - The huge size of the core makes it difficult to control. Each subregion of the core can be a critical reactor functioning independently of the rest of the core.

Positive Power Coefficient - The graphite fully moderates the neutrons produced from fission. As a result, the net effect of the light-water coolant is neutron absorption. If the density of the coolant decreases, fewer neutrons are absorbed and the fission rate rises. So, there is positive feedback. An increase in power causes a further, automatic increase in power. (Note: This effect is present only at power levels of 20% or less. It was the fundamental cause of the Chernobyl accident.)

Shutdown System - It takes 20 seconds to shut down a Chernobyl-type reactor under emergency conditions. Contrast this with a fraction of a second for U.S. reactors.

Containment System - The Chernobyl reactor had a containment around its primary piping and steam-producing components. The core itself was NOT within a containment.

Graphite Temperature - The graphite temperature is maintained several hundred degrees °C higher than recommended by Western authorities.

CAUSES OF THE CHERNOBYL ACCIDENT

Design Features

1. Positive power coefficient.

2. Lack of containment.

3. Little or no use of automatic systems to prevent incorrect operator actions such as withdrawing the rods too far.

4. Slow response of shutdown system.

5. Possibility of excessive withdrawal of the control blades.

Procedural Errors

1. Conducting a research test on a commercial reactor.

2. Lack of a procedure for the test.

3. Reactor was kept operating while the test was performed.

Operator Training

1. Emphasis on keeping reactor in operation rather than on safety. The Chernobyl crew was rated #1 in the Soviet Union based on the hours that they kept their reactor at power.

2. Lack of understanding of the physics of reactor operation.

Operator Errors

1. Bypassing any and all systems that might have impacted on their ability to conduct the test. Ten major errors of this type.