Reactor Boiler and Auxiliaries - Course 133

REACTOR CLASSIFICATIONS - FAST & THERMAL REACTORS

Development of nuclear power in various countries has depended on a variety of factors not the least of which is the availability of either water resources or fossil fuel for the production of power economically. No country has unlimited water resources that can be developed and the transmission cost of hydro electric power from the point of generation to the load centre will continue to increase and become a major factor in the overall cost of power. Fossil fuel resources are also limited and the costs of production and transportation of such fuel are continually increasing as the availability decreases. There seems little doubt that nuclear sources of energy will have to be extensively utilized for power production. More engineering design and development is required to demonstrate that nuclear electric generation is really competetive with fossil electric generation.

It would be ideal if a number of reactor concepts could be developed ahead of time so that the most suitable or most economic concept could be chosen when the need arises. However the cost of experimental facilities, and the cost of scientific, technological and industrial development prohibit development on a broad front except in such countries as the United States. Most countries have concentrated on developing one, or perhaps two, reactor concepts.

It was seen, in the previous lesson, that there are many variables involved and, consequently, many types of reactors have been or are being developed. They may be classified in a number of ways and the following classifications will be considered in these lessons:-

(a) Classification on the basis of the energy of the neutrons causing fission.

(b) Classification according to core structure,ie, homogeneous or heterogeneous.

(c) Classification on the basis of the moderator used.

(d) Classification on the basis of the heat transport fluid used.

The classifications are by no means as clear cut as the list above would suggest, since there are some factors common to some or all of the classifications. The discussion will be confined to power reactors as distinct from experimental facilities.

Classification of Power Reactors on the Basis of Neutron Energy

Each fission process produces 2½ new neutrons and, for a chain reaction to be maintained, at least one of these must produce a further fission. So for every 100 neutrons, produced in one neutron generation, at least 40 must cause further fissions so as to produce 40 x 2½ or 100 neutrons in the next generation.

Now the neutrons produced at fission are fast neutrons with an average energy of 2 Mev. If the fissions occur in natural uranium fuel, 99.3% of the nuclei are U-238 which will only fission with neutrons having energies greater than 1.2 Mev. Therefore only half the fission neutrons can cause U-238 fissions. So of 100 neutrons produced at fission, only 50 can cause U-238 fissions. The inelastic scattering cross-section of U-238, at these neutron energies, is 10 times greater than the fission cross-section. So, of the 50 neutrons that could cause fission in U-238, only 5 will do so and 45 will be scattered and lose so much energy that they can no longer cause U-238 fission. The fast fission cross-section in U-235 is only 1.44 barns and, with so little U-235 in natural uranium, U-235 fast fissions can be ignored.

Therefore, of 100 fast neutrons, produced at fission, only 5 will cause further fissions and produce 5 x 2.5 or 12.5 new neutrons. Thus, even if leakage and radiative capture are ignored the chain reaction can not be maintained by fast neutrons in natural uranium. One of two alternatives are available which lead to a power reactor classification as follows:-

(a) Fast Reactors

The U-235 content of the fuel can be increased, ie, the fuel is highly enriched in U-235 with a substantial decrease in U-238. The U-235 fast fissions are thus, considerably increased and a fast reactor results such as the Enrico-Fermi reactor. Some reduction in neutron energy does occur due to inelastic collisions of neutrons with nuclei of the fuel and structural material but most of the fissions are caused by neutrons of energies greater than 0.1 Mev. The curves in Figure 1 show how the mass of U-235 required for the reactor to be critical varies with amount of U-235 enrichment. Curve A refers to a core with fuel only whereas curves B and C apply to cores with the following compositions by volume:-

B - 50% fuel, 33.33% sodium, 16.67% stainless steel

C - 25% fuel, 50% sodium. 25% steel

In each case the core is surrounded by a depleted uranium blanket.

In all cases the critical mass of fissile material required increases rapidly below 15% to 20% U-235 enrichment. To avoid large fuel inventories a practical fast reactor, such as case C above, would require fuel containing at least 20% U-235 by volume. The Enrico-Fermi fuel is an alloy of 28% U-235 with 10% by weight of molybdenum. Incidentally the critical mass of U-235 in a fast reactor is considerable greater than ~~in a fast reactor is considerably greater than~~ in a thermal reactor with the same fuel composition.

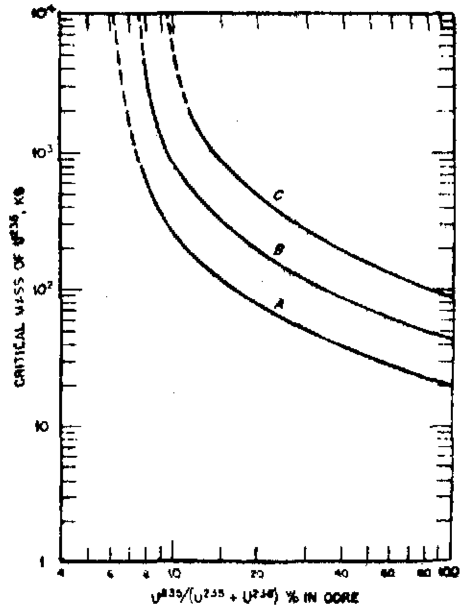

Fig. 1

The highly enriched fuel and absence of moderator results in a small core, the size of the Enrico-Fermi core, for instance, being 31 inch in diameter and 31 inch high with a thermal power production of about 200 MW. Therefore, fast reactors have high power density cores. The average heat flux in the Fermi reactor is 650,000 Btu/hr/ft^2 compared with 100,000 Btu/hr/ft^2 for a pressurized water reactor of similar thermal output. It is therefore essential that a heat transport fluid with good thermal properties be used. The choice is also limited to a non-moderating fluid and liquid metals seem to satisfy both requirements.

The capture cross-sections of most elements for fast neutrons are small and since there is a relatively large mass of U-235 in the reactor, the macroscopic capture cross-sections of structural material and fission products are small compared with the macroscopic fission cross-section of the U-235.

Consequently there is more flexibility in the choice of materials and stainless steel can be used instead of aluminum or zirconium. Fission product poisoning is not significant and for this reason, (and the fact that temperature coefficient of reactivity is low), the excess reactivity required in a fast reactor is small.

A large amount of fuel subdivision is required to provide a large heat transfer area and this increases fabrication problems and manufacturing costs. The core of the Fermi reactor is made up of subassemblies of fuel pins each 0.158 in outer diameter. However the liquid metal heat transport fluid and the use of stainless steel allows for high outlet temperatures and good steam conditions. The heat transport outlet temperature in the Fermi reactor is 800°F giving steam conditions at the turbine of 740°F and 600 psi. This compares with NPD steam conditions of 450°F and 400 psi.

The prompt neutron lifetime is only 10^{-7} secs. compared with 10^{-3} secs. in a thermal reactor but fast reactors can be controlled satisfactorily on delayed neutrons in the same way as thermal reactors. It is true that, if the reactivity becomes equal to the delayed neutron fraction and the reactor becomes prompt critical, the power excusion would be severe. However serious damage would result if a thermal reactor went prompt critical and this is less likely to happen in a fast reactor since the excess reactivity that has to be built into the core is much less than in a thermal reactor.

The chief advantage of the fast reactor concept lies in the possibility of using it for breeding or conversion, ie, for obtaining Pu-239 from U-238 or U-233 from Th-232. As shown in the previous lesson, the values of η-1 (which could be called the BREEDING POTENTIAL) is generally higher, for all three fissile materials, with fast neutrons than with thermal neutrons. The variation of this breeding potential with neutron energy is shown in the following table.

Nuclide	Breeding Potential (η - 1) for neutrons in energy range				
	Thermal	1 to 3000 ev	3 to .10 Kev	0.1 to 0.4 Mev	0.4 to 1.0 Mev
Pu-239	1.03	0.62	0.93	1.61	1.88
U-235	1.08	0.68	0.90	1.12	1.46
U-233	1.31	0.88	1.29	1.30	1.54

It may be seen, from the table, that it is desirable to have as little moderation of the neutrons as possible in order to maintain as high a value of η - 1 as possible. Since the initial breeder must use U-235 as fissile material, it is even more important to keep the neutron energy as high as possible. Therefore a non-moderating heat transport fluid is essential. Even the use of carbide or oxide fuel can cause some moderation.

Fast reactors have another important advantage as far as breeding potential is concerned. Radiative capture in reactor material is lower with fast neutrons than with thermal neutrons. This decreases the value of w in the equation

$$c = \eta - w - 1$$

w is decreased still further by surrounding the core with a blanket of fertile material as shown in the Enrico-Fermi reactor in Figure 2. The blanket then serves as a neutron reflector to decrease leakage and those neutrons that do escape are captured in the fertile material to produce fissile material.

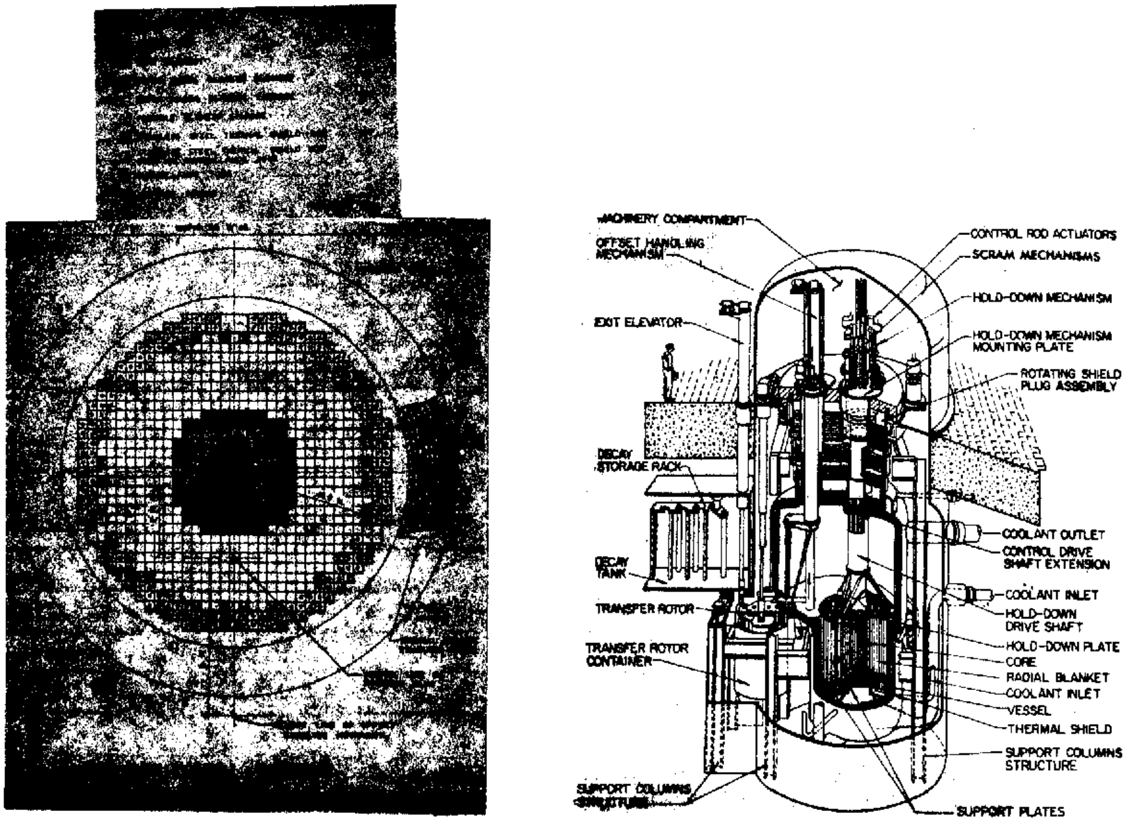

Fig. 2

In order to maintain steady-state conditions in a breeder operating at constant power, the blanket must be processed at such a rate as to provide fissile atoms to compensate for those consumed in the core. It should not be necessary to obtain fissile material from an outside source after the initial loading.

Fast breeder reactors can only be utilized if enrichment and fuel processing facilities are available. Such facilities, on the other hand are only economic if enough reactors can be serviced by them. The cost of fuel and the cost of nuclear power must allow for the capital cost of such facilities.

(b) Thermal Reactors

Since a chain reaction can not be maintained with fast neutrons without considerable enrichment, the alternative is to reduce the neutron energy until the fission cross-section of U-235 is sufficiently increased. If the neutrons are reduced to thermal energies (ie, thermalized), the U-235 fission cross-section is 580 barns whereas the radiative capture cross-section is 106 barns. Thus, even allowing for the low percentage of U-235 in natural uranium, the thermal neutron fission cross-section in natural uranium is 4.2 barns whereas the radiative capture cross-section is 3.5 barns.

Thus, for every 77 neutrons captured in natural uranium about 40 will cause fission and produce 40 x 2½ or 100 new neutrons. For 77 neutrons out of every 100 to be captured, fewer than 23 neutrons can be lost by escape or radiative capture in other reactor material. Under these conditions a chain reaction could be sustained. In thermal reactors the fission neutrons are thermalized by slowing them down in a moderator. Most of the power reactors in existence are thermal reactors.

Thermal reactors have several advantages over the fast reactors:-

(1) They can use any form of fuel from natural uranium to pure fissionable material. This permits a wide range of reactor sizes depending on fuel and enrichment availability.

(2) Since the fuel used is normally natural or slightly enriched uranium, the reactor is relatively large and this simplifies the design of the calandria and associated instrumentation.

(3) Fuel changing is very much simplified because the fuel diameter is greater and the fuel channels are further apart.

(4) The power density is lower in a larger reactor with lower U-235 concentration so that heat removal is less of a problem. This allows for a wider choice of heat transport fluids especially as the fluid can have moderating properties.

However, thermal reactors have the following disadvantages compared with the fast reactor:-

(1) The larger reactor size increases the shielding costs.

(2) The choice of reactor structural material is more limited because of the higher capture cross-section of thermal neutrons. This may limit the temperature of the heat transport fluid and result in poorer steam quality.

(3) There is a high Xenon and Samarium poison load during normal operation which necessitates having enough excess reactivity in the reactor to overcome this.

(4) On reactor shutdown the Xenon load builds up above its normal equilibrium level, resulting in the so called Xenon transient. It is impractical and uneconomical to have sufficient excess reactivity to overcome this transient. Thus, unless the reactor is started up again within 10 or 15 minutes it will be incapable of starting up for several hours, this delay being known as the poison-out time. The poison-override time, during which the reactor can start up after a shutdown, can be extended by booster fuel rods but this necessitates a higher fuel inventory.

ASSIGNMENT

1. Explain why fission neutrons can not maintain a chain reaction in natural uranium.
2. How is the chain reaction maintained in a fast reactor?
3. What are the two requirements for the heat transport fluid in a fast reactor?
4. Give two advantages of fast reactors over thermal reactors.
5. Explain why a fast reactor concept offers breeding or conversion possibilities.
6. Why is a chain reaction maintained in natural uranium by thermal neutrons?
7. List two advantages and two disadvantages of a thermal reactor as compared with a fast reactor.

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