Reactor Boiler and Auxiliaries - Course 133

REACTOR CLASSIFICATIONS - TYPES OF THERMAL REACTORS

In the previous lesson reactors were classified on the basis of neutron energy and the various advantages and disadvantages of fast and thermal systems were enumerated. It was mentioned that most of the reactor systems, at present in operation, are thermal reactors.

Thermal reactors will now be classified further on the basis of core structure, the moderator used and the heat transport system used. Some reference will be made to the advantages and disadvantages of each type, but some of these considerations will be discussed later when moderator and heat transport system properties are discussed.

Homogeneous and Heterogeneous Thermal Reactors

If neutron leakage from a reactor is ignored the condition for criticality is that:

$$k = \eta \epsilon p f = 1$$

Once the choice of a thermal, as distinct from a fast, reactor has been made, the choice and arrangement of fuel, moderator, heat transport fluid and structural material must be such that this criticality condition is satisfied.

There are two possible arrangements of fuel and moderator:

(a) Homogeneous System

In this type of reactor the fuel and moderator are intimately mixed together. The uranium can be in solution in the moderator or in fine suspension called a slurry. Other possibilities, which have been considered, are uranium tetrafluoride dissolved in a molten salt such as beryllium fluoride or dissolved or suspended in a liquid metal.

In a homogeneous system the fission neutron is immediately in contact with moderator nuclei and would not have enough energy to cause fast fission in U-238. Hence $\epsilon = 1$.

The value of η depends only on the fuel composition. For natural uranium fuel $\eta = 1.32$.

Therefore, ignoring leakage, the condition for criticality is that

$$pf = \frac{1}{1.32} = 0.77$$

i.e., $pf = 0.77$ is the minimum condition for a chain reaction to be sustained in a homogeneous system.

Both p and f depend on the proportion of fuel to moderator in the homogeneous mixture. The table below shows how p, f and the product pf vary with this ratio of moderator to fuel atoms in a homogeneous mixture of graphite and natural uranium.

$\frac{\text{Mod. atoms}}{\text{Fuel atoms}}$	p	f	pf
200	0.579	0.889	0.515
300	0.643	0.842	0.541
400	0.682	0.800	0.546
500	0.693	0.762	0.528

From the table, it may be seen that the problem is that as the moderator/fuel ratio is increased, p increases, because there is better thermalization of neutrons, but f decreases, because there is more neutron capture in the moderator and less neutron capture in the fuel. The maximum value pf can have is only 0.55 whereas the value must be 0.77 to sustain a chain reaction. So a chain reaction can not be maintained with a homogeneous mixture of graphite and natural uranium.

A similar situation exists with homogeneous systems of natural uranium and either light water or beryllium. With heavy water as moderator the optimum ratio of moderator to fuel gives a maximum value of pf of 0.78, which corresponds to a maximum value of $k = 1.03$. This does not allow for neutron leakage nor does it allow for build-up of fission product poison. This means that the size of reactor required, with a natural uranium - heavy water homogeneous mixture, would be too large to be practical.

What could be done to make such a system practical? The answer lies in increasing the value of η. For a practical reactor, in which fuel consumption and poison accumulation are allowed for, k would have to be around 1.1 to 1.2. Therefore the value of η required is given by

$$\eta = \frac{1.2}{pf} = \frac{1.2}{0.78} = 1.54 \text{ for } D_2O \text{ moderator}$$

$$\eta = \frac{1.2}{0.55} = 2.18 \text{ for graphite moderator}$$

The only way to increase η is to increase the U-235 concentration (R) in the fuel, i.e., enrich the fuel. Figure 1 shows how the value of η varies with the U-235 concentration in the fuel. The U-235 concentration in natural uranium is 0.00715 (0.715%). For a D_2O moderated homogeneous system to be practical, the U-235 concentration would have to be increased to about 0.02.

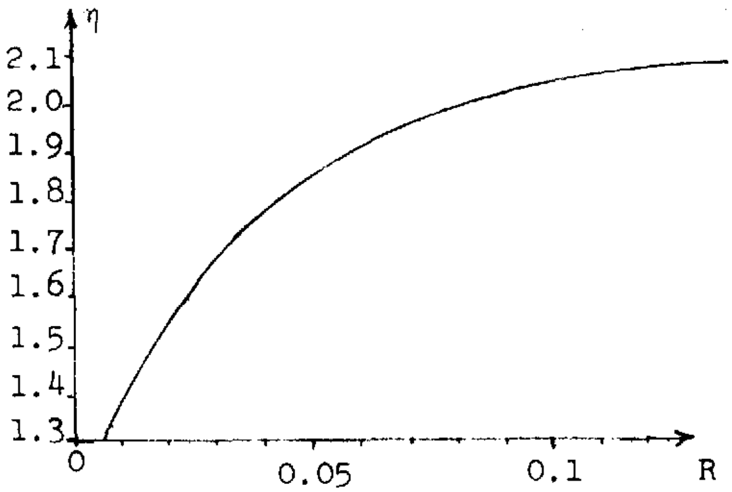


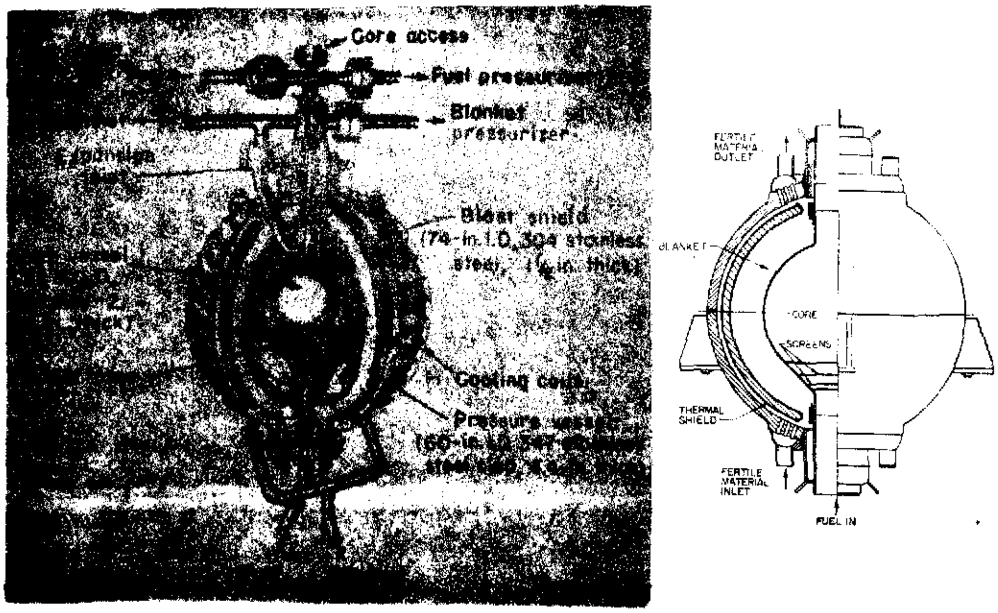
Fig. 1

It can be seen from Figure 2 that a value of η of 2.18 could not be obtained. However, as the enrichment increases, the U-238 content decreases and the value of p consequently increases. This reduces the value of η required for the graphite homogeneous system below the 2.1 value shown above. The decrease in the required value of η is such that, with a graphite moderator, the enrichment required is about a factor of 10 higher than with a D_2O moderator.

The graph shows that there is very little to be gained, in the value of η , by making R greater than 0.1 but, as mentioned above, the value of p increases with larger values of R because the U-238 concentration decreases.

Homogeneous experimental reactors have been operated successfully. HRE-I, containing a solution of highly enriched uranyl sulphate in ordinary water, operated at 1.6 Mwt at Oak Ridge National Laboratory and produced electricity in 1953. HRE-II used a dilute solution of U-235 in heavy water and operated at 5 Mwt until 1961.

What advantages would such a system have? Since the fuel is a fluid, some of the factors that limit burnup are avoided. As shown in Figure 2, the reactor vessel is a simple container with little or no structure to capture neutrons.



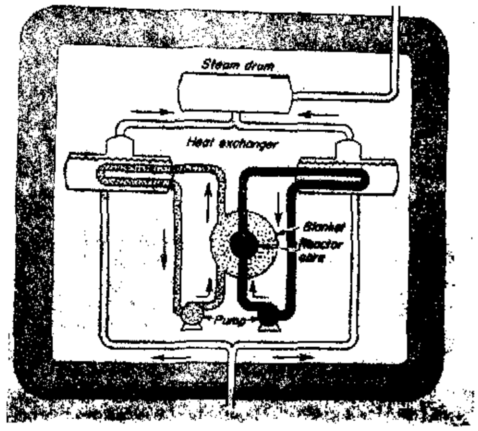


Fig. 3

Fig. 2

The HRE-II reactor vessel, shown in Figure 2, is surrounded by a pressure vessel, which was intended to contain a blanket for breeding. It actually carried heavy water. Figure 3 shows the type of circulation arrangement that would be used for a core and blanket system.

Dimensional changes due to irradiation and fission product gas pressure build-up do not occur. Also, the fuel-moderator mixture is circulated from the reactor through the external boiler and back to the reactor. It is therefore relatively simple to continuously remove fission product poisons. Fabrication costs, which are significant for solid fuel, are of little or no importance in liquid fuel reactors. All these factors offer the possibility of reducing fuel costs. In addition reactor control may be very much simplified since the reactor can be made critical or sub-critical by changing the fuel concentration. Such systems are inherently safe because they have a large negative temperature coefficient of reactivity and are, therefore, self-regulating.

There are, however, several disadvantages and several problems that still have to be solved. Because of the circulation of the fuel outside the reactor, many of the delayed neutrons are born outside the core. It is, therefore, necessary to rely on the large negative temperature coefficient of reactivity in order to have a stable system. There are drawbacks in circulating highly corrosive solutions such as uranyl sulphate and there are still unsolved problems in this area. Another disadvantage is the circulation, outside the reactor, of highly radioactive fission products and the shielding problems associated with this. Radiolytic decomposition of water and the high vapour pressure of aqueous solutions necessitates pressurization to 1000 psig or 2000 psig. The maximum practical temperatures are low (482°F for HRE-II) and so the thermodynamic efficiency of the system is limited.

(b) Heterogeneous Systems

The alternative to using a homogeneous system with enriched fuel, is to use a heterogeneous system. In such a system, shown in Figure 4, the fuel is in the form of lumps or rods arranged in a regular pattern or lattice in the moderator.

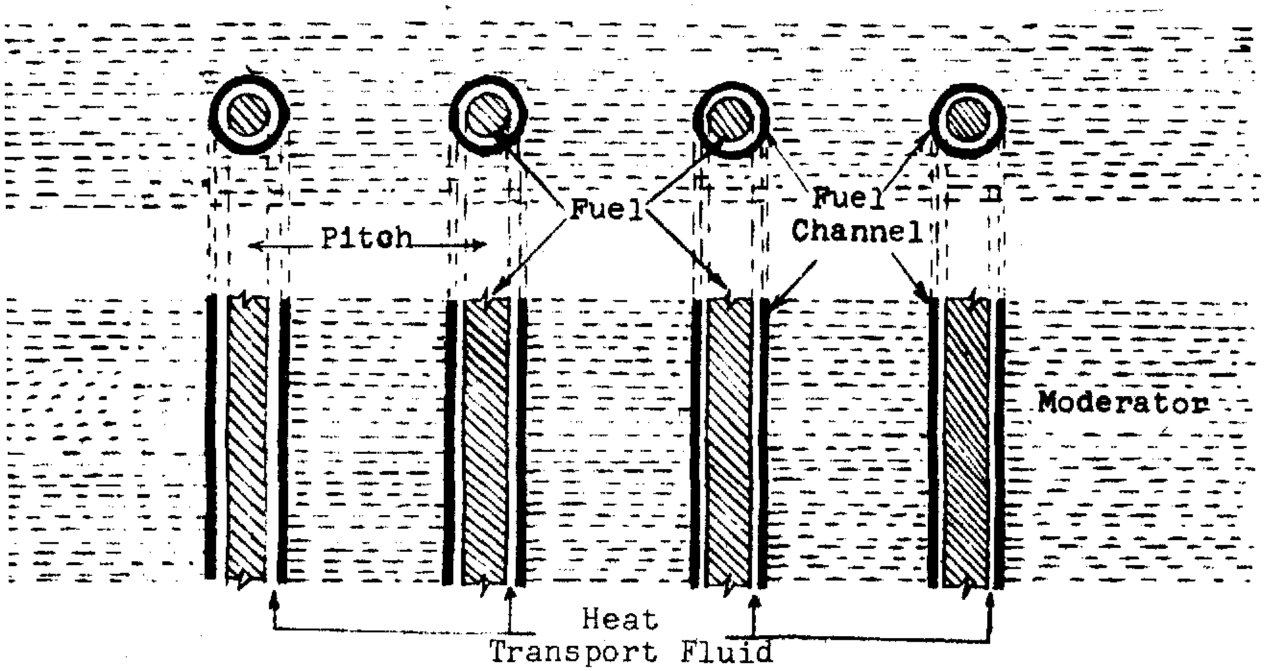


Fig. 4

The rod arrangement, inside fuel channel, is preferred since it fixes the fuel location, makes fuel changing easier and enables the heat to be removed from the fuel. This type of arrangement increases the value of ϵ because the fast neutrons are now released in the fuel and are more likely to cause fast fissions in U-238 before escaping into the moderator. ϵ will now be 1.02 to 1.03.

The value of p is increased because the neutrons, after leaving the fuel, are slowed down in the moderator before entering the next fuel rod. With correct rod separation, (or lattice pitch), most of the neutrons are thermalized before entering the next rod.

The thermal utilization factor, f, is decreased in a heterogeneous system because relatively fewer neutrons are captured in the fuel. However, unless the moderator has a large neutron capture cross section, the decrease in f is small and can still be 0.9 or greater.

Thus pf = 0.85 or more compared with 0.55 with a graphite homogeneous system and 0.78 with a D_2O homogeneous system. Hence, with natural uranium fuel and $\eta = 1.32$,

$$k = 0.85 \times 1.02 \times 1.32 = 1.14 \text{ without leakage.}$$

This value of k makes a chain reaction possible provided the moderator absorption does not decrease f too far. This will be discussed further when moderator properties are considered.

Types of Heterogeneous Reactors

The classification of heterogeneous reactors may be based on the type of moderator used or on the heat transport system employed. The basic requirements and properties of moderators and heat transport systems will be discussed at length later. It is sufficient, for the moment, to list the moderators and heat transport fluids in general use.

The moderator may be:

1. Light water, 2. Heavy water, 3. Graphite, or 4. Organic liquids.

The heat transport system may be:

1. Pressurized light water
2. Pressurized heavy water
3. Boiling light water
4. Boiling heavy water
5. Gases such as CO_2 or helium
6. Liquid metals
7. Steam or fog
8. Organic liquids

There are many possible arrangements or combinations of moderator and heat transport systems but only the combinations actually in use or to be in use will be discussed briefly. A brief reference will be made to their advantages and disadvantages.

(a) Light Water Moderated Reactors

The pressurized - light water reactor and the boiling - light water reactor are the principal types in this category. Recent developments have tended to bring the two concepts closer together.

Some local boiling is now tolerated in the pressurized-water systems and boiling-water reactors operate at elevated pressures, in any case. It is therefore better to designate them as reactors using the indirect cycle and requiring a heat exchanger or boiler to produce steam and reactors using the direct cycle, the steam being produced in the reactor and transported directly to the turbine.

The PWR and BWR types have a heat transport fluid which also acts as the moderator. Hence both moderator and heat transport fluid are pressurized and must be contained in a pressure vessel as shown in Figures 5 and 6.

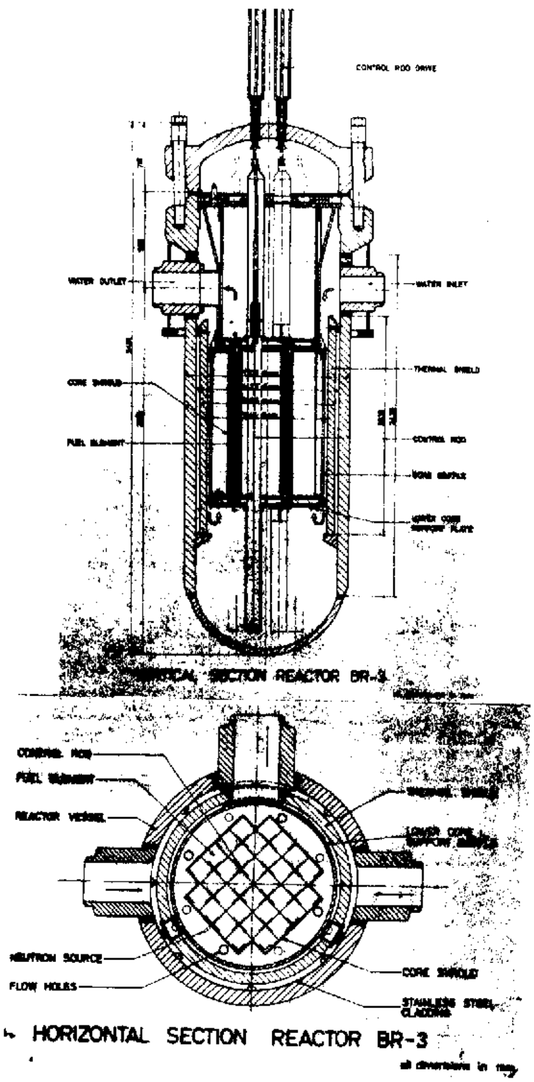


Fig. 5

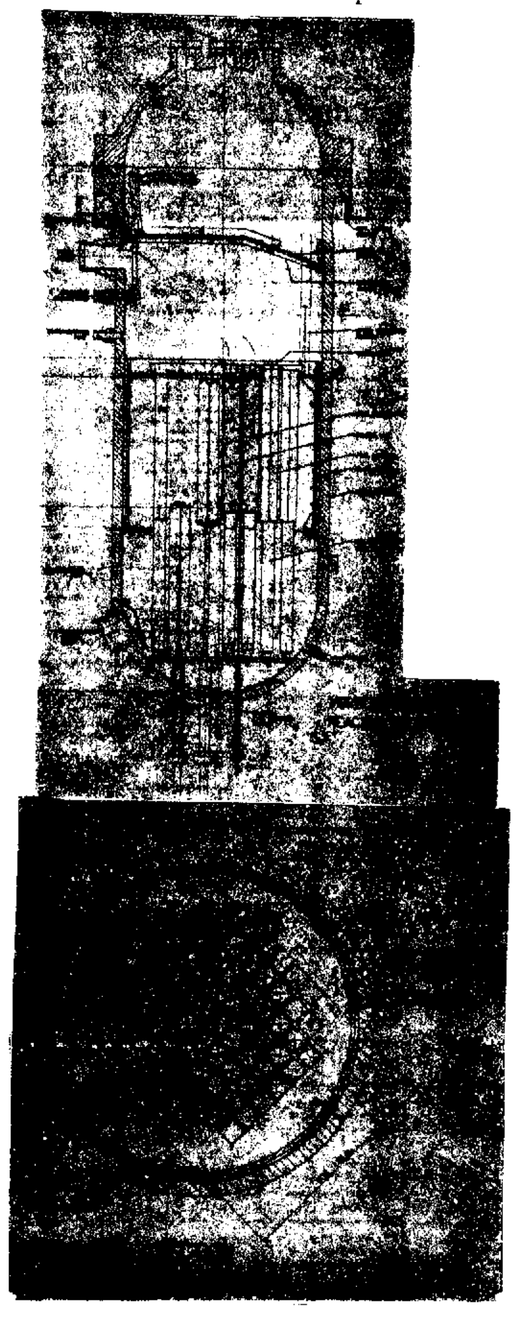


Fig. 6

Figure 5 shows the Belgian BR-3 pressurized water reactor as a typical example of a PWR type. The boiling water reactor, shown in Figure 6, is the Big Rock Point reactor in the U.S. The figures illustrate how very similar the BWR and PWR types actually are.

The use of light water moderator makes it impossible to maintain a chain reaction with natural uranium fuel. Slightly enriched fuel must therefore be used which necessitates an enrichment plant. Typical enrichment used is from 2% to 5% U-235. The critical mass required in such a reactor is around 50 or 60 kgm U-235 compared with 600 or 700 kgm U-235 or more in a fast reactor. Since enriched fuel has to be used it is possible that it might be advantageous to increase the enrichment in order, say, that stainless steel fuel sheaths and fuel channels can be used. This would give better fuel integrity, reduce corrosion and reduce the material and fabrication costs associated with zircalloy.

Because the same fluid is used for both moderator and heat transport medium, only thin tubes are required, as fuel channels, to guide the fluid over the fuel. This tends to decrease the neutron absorption in the reactor structure.

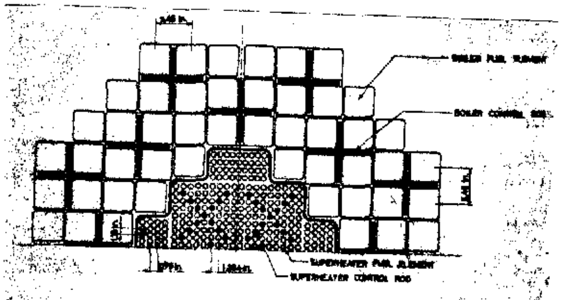
In the case of pressurized water reactors, the heat transport temperature must be kept as high as possible for good thermodynamic efficiency. To prevent boiling, even at modest operating temperatures, the heat transport pressure must be as high as 1000 psi to 2000 psi. The whole reactor vessel must withstand these high pressures. It is estimated that for a 500 Mwe reactor the vessel would have an internal diameter of 12 feet and a wall thickness of 11 inches. It is difficult to fabricate large vessels of this sort with wall thicknesses greater than 9 to 10 inches. This limits the maximum temperatures at which the heat transport systems can operate. It is also difficult to transport such vessel and 350 tons is an accepted maximum weight. This tends to restrict the maximum power. Field fabrication techniques have reduced the severity of the problems.

In the boiling water type the pressure is built up as the steam is produced in the core and the pressure is generally lower. The pressure vessel thicknesses are, therefore, smaller being around 5 inches to 6 inches. Even so, there are limitations on both operating temperatures and reactor power.

Because the pressure vessels are so thick, severe thermal stresses could be set up by radiation absorption. It is, therefore, necessary to place a thermal shield between the reactor and its containing vessel to reduce the radiation absorption in the vessel.

Finally, refueling at power is impractical with this type of reactor because of the large number of penetrations required through the vessel head. The reactor is sized so that it can operate for six months or so without refueling. The refueling is then carried out with the reactor shut down and depressurized. This means that the dome or head of the reactor vessel must be removable to permit this refueling.

Although no reactor has, as yet, been constructed which uses fog or steam as the heat transport fluid, there are two reactors which have a nuclear superheating section in the core through which steam is passed. These are the Pathfinder and Boiling-Nuclear Superheat (Bonus) reactors, the former in South Dakota and the latter in Puerto Rico. The Pathfinder reactor is illustrated in Figure 7. It may be seen that light water is boiled in the outer core region where the light water acts as moderator and heat transport fluid. The saturated steam passes through steam separators and dryers and the dry steam then passes down through the centre superheater region of the core. In this way steam at 825°F is obtained which leads to savings on turbine size and cost.



CORE ARRANGEMENT REACTOR PATHFINDER

VERTICAL SECTION REACTOR PATHFINDER

Fig. 7

(b) Heavy Water Moderated Reactors

Heavy water has a much lower neutron capture cross section than light water. The principal advantage of using heavy water as a moderator is, therefore, the neutron economy that can be achieved with it. The thermal utilization factor, f, in the four factor formula, is increased because of lower neutron capture in the moderator. Neutron economy is so much improved that, not only can natural uranium fuel be used, but that this fuel can be used in oxide or carbide form. Thus, there is no longer any need for an enrichment plant. In addition oxide or carbide fuel improve the fuel integrity and the fuel is less susceptible to distortion

Higher conversion factors and breeding ratios are possible because the factor w is smaller. This, combined with the improved fuel integrity, enables high fuel burnups to be obtained. There are promising breeding prospects using the U-233:Th-232 system because the value of η for thermal neutrons is 2.31.

A variety of heat transport fluids can and have been used with heavy water as a moderator. Most of the heavy water moderated reactors which have been constructed or are being designed us a heavy water heat transport fluid. This maintains the good neutron economy and retains the good handling and thermal characteristics of light water. The Swedish R-3/Adam Reactor, shown in Figure 8, is a pressure vessel type of reactor with the moderator and heat transport fluid being intimately mixed and at the same temperature.

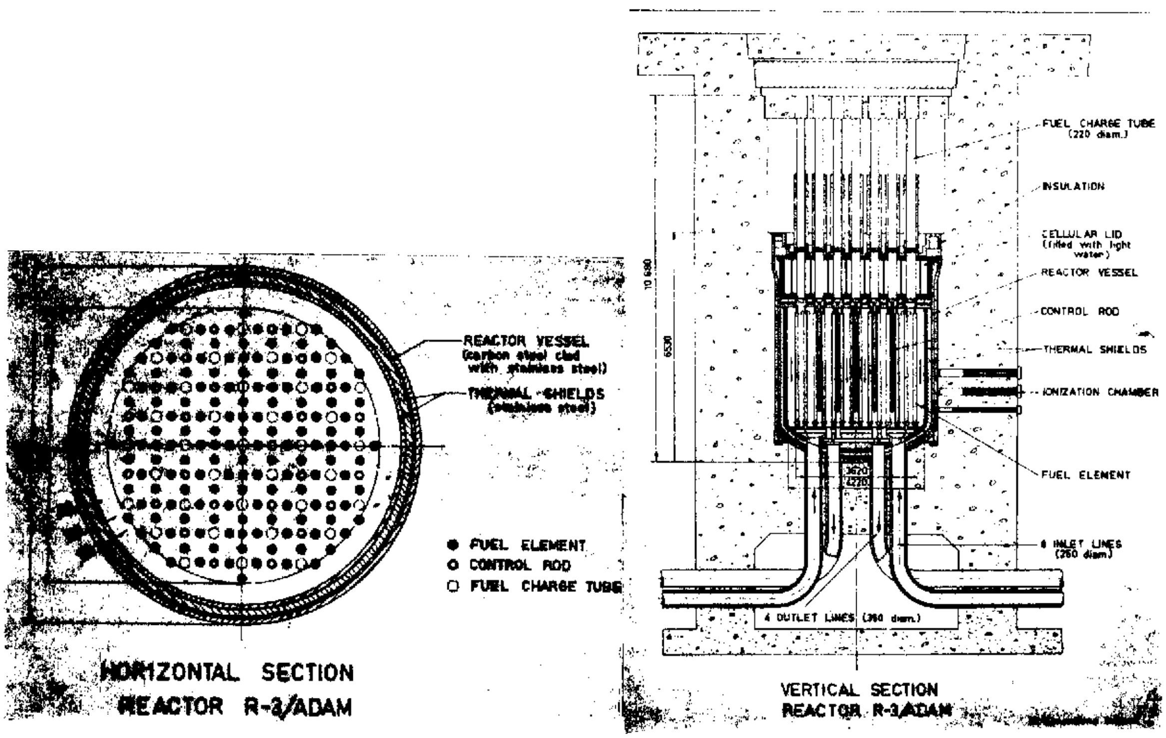


Fig. 8

The Halden Boiling Heavy Water Reactor, in Norway, uses a similar arrangement but the heavy water is allowed to boil. The only advantages offered by these reactors, over their light water equivalents, are use of natural uranium fuel and good neutron economy. However, they are still subject to the disadvantages and restrictions of the pressure vessel concept.

Thermalization of neutrons requires far fewer elastic collisions in light water than in heavy water. Thus, in heavy water the separation of fuel channels (i.e., the lattice pitch) must be greater than in light water, if the resonance escape probability, p, is to remain high. This larger fuel channel separation requirement has been utilized to advantage in the "pressure tube" reactor concept which avoids the problems inherent in the pressure vessel type of design.

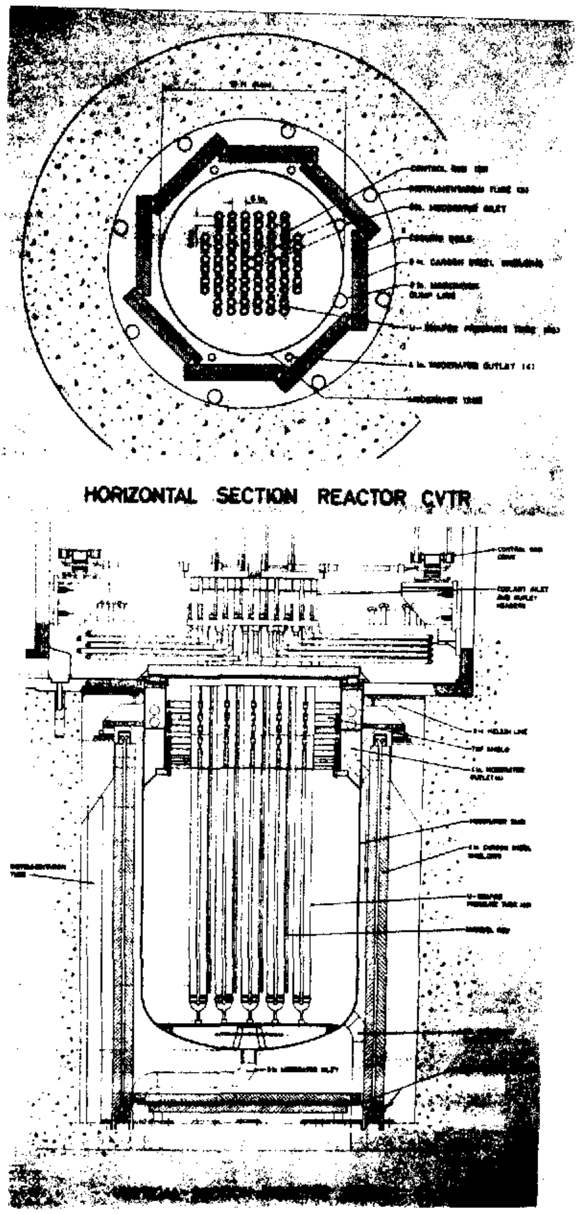


Fig. 9

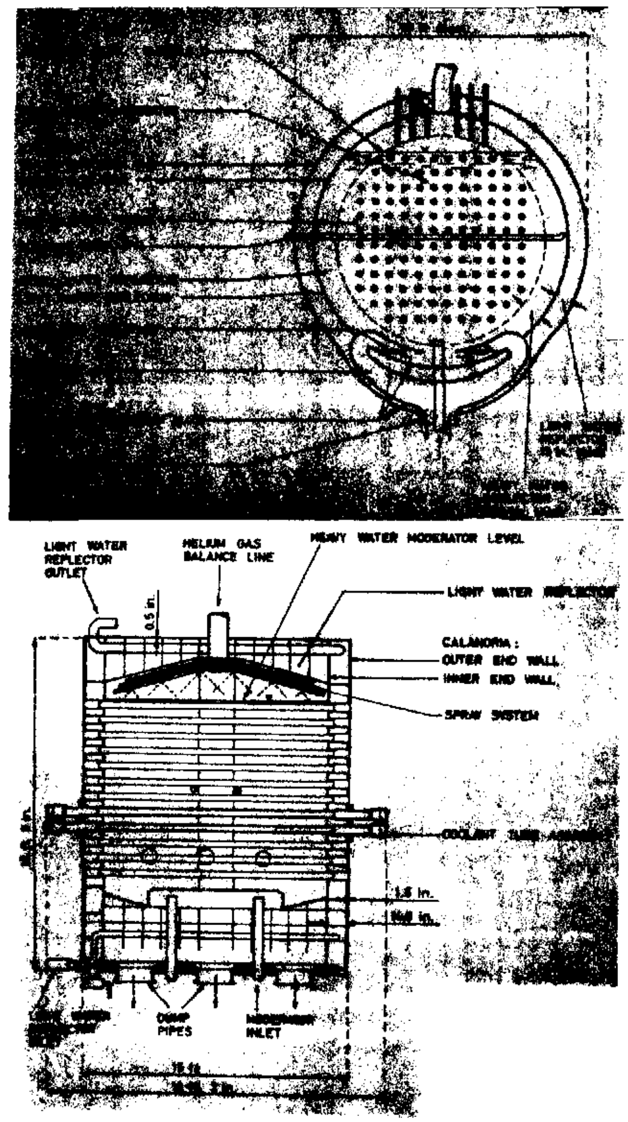


Fig. 10

In the Carolinas Virginia Tube Reactor (CVTR), shown in Figure 9, the moderator is contained in a cylindrical tank surrounding U-shaped pressure tubes containing the fuel and heavy water heat transport fluid. The pressure tubes are vertical and are suspended from a support structure resting on top of the moderator tank. Slightly enriched UO_2 fuel is used, the critical mass required being 11.2 kgm U-235. Four fuel assemblies are replaced every 6 - 8 weeks with the reactor shut down.

The Nuclear Power Demonstration Reactor (NPD), shown in Figure 10, is fairly typical of the Canadian power reactor designs. The moderator is contained in a cylindrical drum or calandria the axis of which is horizontal. Horizontal pressure tubes, containing natural UO_2 fuel and heavy water heat transport fluid, pass through this calandria.

In both these pressure tube reactors, the heat transport fluid only is pressurized. The moderator, being separated from the heat transport fluid, is also at a much lower temperature. The NPD type of reactor has the added advantage that it permits bi-directional refueling at full power. This maintains symmetrical thermal neutron flux distribution throughout the reactor and permits efficient fuel utilization without the expense of shutdowns.

The main economic disadvantage of heavy water reactors has been the high capital cost resulting from the larger size core and the high cost of heavy water. Lower costs of heavy water in the future will decrease the heavy water capital costs involved and decrease the operating costs due to heavy water losses. Some disadvantages remain, however, primarily because of the use of pressurized heavy water as a heat transport fluid. Heavy water leakage is difficult to eliminate altogether although improved engineering design and fabrication in the future will minimize such losses. In the meantime heavy water collection and recovery systems add to the capital cost of the stations. The leaking heavy water contains tritium which presents an added health hazard requiring careful control. Radiolytic decomposition of heavy water is another source of heavy water losses and presents a possible hazard because of deuterium build-up. Recombination units are used to recover the losses and keep the deuterium concentration within acceptable limits.

Other reactor concepts, using heavy water as moderator, have been and are being given consideration. The CANDU-BLW station, to be built near Gentilly, Quebec, is a vertical pressure tube reactor using boiling light water as the heat transport medium. This station is expected to be producing power in 1971. This may well lead to a future concept in which the steam produced in one region of the reactor is superheated in another region. The problem involved is to increase the fuel heat rating without using sheathing and pressure tube material which will necessitate fuel enrichment. Organic liquids have also been proposed as heat transport fluids and the WR-1 reactor at Whiteshell, Manitoba, is designed specifically for engineering studies and development of organic heat transport fluids. Organic liquids would allow much higher temperatures to be achieved with little or no pressurization.

Figure 11 shows a heavy water moderated reactor, using carbon dioxide as heat transport fluid. This HWGCR (Heavy Water Moderated Gas Cooled Reactor) is being constructed in Czechoslovakia and has a heat output of 590 Mwt. It uses natural uranium fuel and has a designed outlet gas temperature of 425°C (797°F). This will enable better steam conditions to be obtained than would be possible with pressurized or boiling water systems.

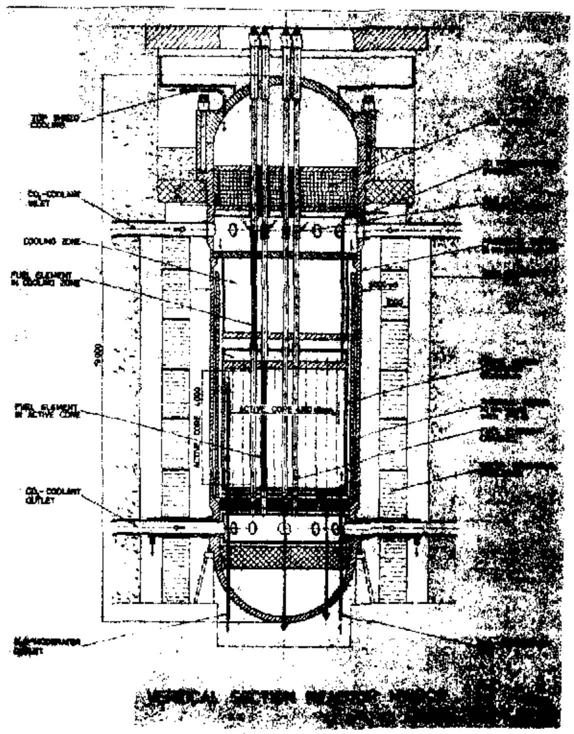


Fig. 11

(c) Graphite Moderated Reactors

The major portion of the nuclear power being produced today is generated in graphite moderated reactors with gas as the heat transport fluid. The Hinkley Point reactor, shown in Figure 12, is a typical example. The fuel used is natural uranium metal clad with Magnox, a magnesium alloy. The heat transport fluid is carbon dioxide gas at a pressure of 150 to 250 psia. A chain reaction could not be sustained using oxide fuel and a graphite moderator. Even with uranium metal, very high grade graphite must be used and 2000 tons of this are required. This introduces structural problems of locating and constraining the graphite and controlling differential expansion between it and the pressure vessel in which it is contained. The Hinkley Point vessel is 67 feet in diameter and this factor alone limits the vessel thickness and consequently the operating pressure. In comparison, the Douglas Point calandria is less than 20 feet in diameter and the Dresden boiling light water reactor vessel is around 12 feet in diameter. The resulting high capital cost is compensated for to some extent by the lower fuel costs.

The temperature of the fuel, and therefore of the CO_2, is also limited because of the alpha to beta phase change that occurs in the uranium metal fuel and because of the temperature limitation on Magnox. Steam temperatures are, therefore, limited to about 740°F. A chemical reaction also occurs between the CO_2 and the graphite at higher temperatures. Gases have poor heat transfer characteristics and have high pumping power requirements, so that up to 20% of gross plant power may be needed for gas circulation.

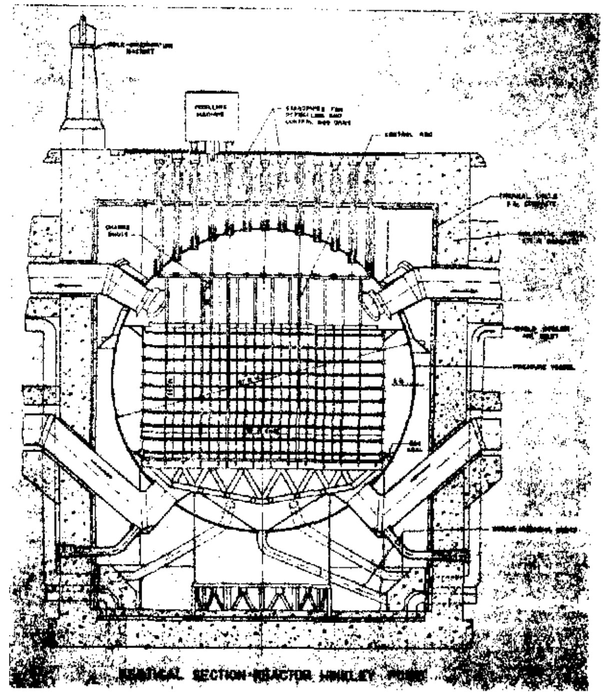


Fig. 12

There is considerable incentive to develop satisfactory methods for using carbon dioxide at higher temperatures since this also reduces the pumping power requirements. The Advanced Gas-Cooled Reactor (AGR) in the U.K. used slightly enriched UO_2 fuel in stainless steel cladding with graphite moderator. The CO_2 temperature is 1070°F at the outlet, giving 850°F steam at 650 psi. The use of enriched fuel reduces the diameter of the pressure vessel to 21 feet. Chemical reaction between the CO_2 and the graphite is inhibited by adding methane to the CO_2. The fuel channels also have removable liners.

It would still appear that there are better prospects of higher heat transport temperatures and, therefore, better steam conditions if a fluid other than CO_2 is used as the heat transport medium. The Peach Bottom High Temperature Gas-Cooled Reactor uses an Uranium-Thorium fuel combination and helium as the heat transport fluid. The fuel is in the form of carbides dispersed in graphite and clad in a dense, impervious graphite. The reactor is also graphite moderated. It is hoped to obtain a heat transport temperature of 1380°F, providing 1000°F steam at 1450 psia and a net thermal cycle efficiency of 35%. It is also hoped to have fuel burnups approaching 75,000 Mwd/tonne by Th-232 conversion.

An alternative heat transport fluid has been used in the Hallam Nuclear Power Facility shown in Figure 13.

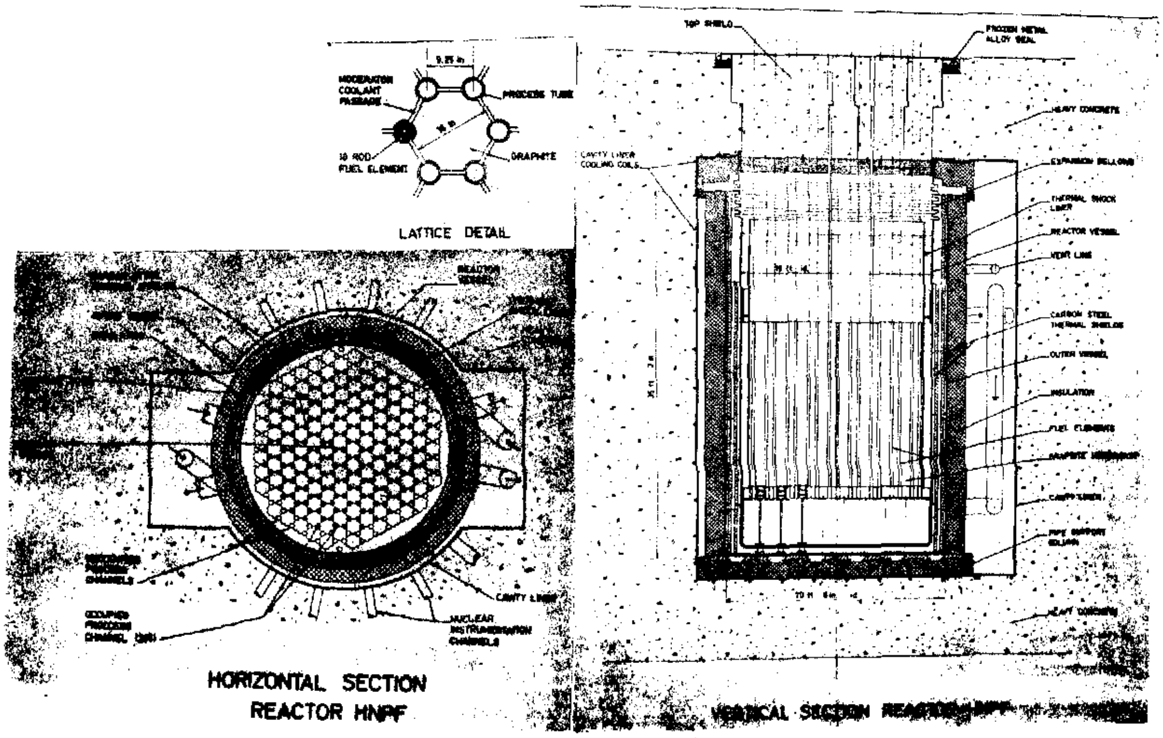


Fig. 13

The core is composed of hexagonal graphite "logs" canned in stainless steel. The fuel channels, containing slightly enriched uranium, are located at the corners of the hexagons. Sodium is used as the heat transport fluid and an intermediate heat exchanger is used to transfer the heat to a secondary sodium circuit which is connected to the boiler. A core outlet temperature of 945°F is achieved and superheated steam at 833°F and 850 psig produced.

(d) Organic Moderated Reactors

The advantages of organic liquids as heat transport fluids have been mentioned already. The moderating properties of an organic, such as diphenyl ($C_{12}H_{10}$) are not very different from those of light water. Both require some fuel enrichment to make a self-sustained chain reaction possible. There seems to be no advantage, then, in using an organic moderator unless both the moderator and the heat transport fluid are of the same material and the pressure vessel concept is used.

The Piqua Nuclear Power Facility, shown in Figure 14, uses this concept. The fuel used is an alloy of 1.94% enriched uranium metal with 3.5% by weight of molybdenum and about 0.1% by weight of aluminum. The combined moderator and heat transport fluid is a mixture of terphenyls. An outlet temperature of 575°F can be obtained with a pressure of only 120 psia. The use of inexpensive materials and the fairly low pressure requirements lead to comparatively low capital costs, which are partially offset by the cost of purification and replacement to make up for radiolytic and thermal decomposition of the organic liquid. Organics are flammable in air at temperatures above 415°F and the highest operating temperatures, regardless of pressure, is about 800°F.

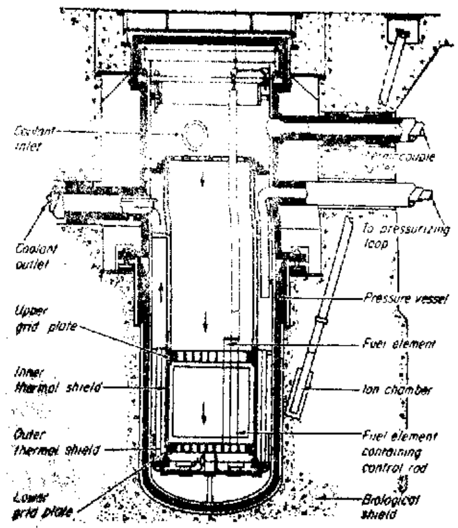


Fig. 14

ASSIGNMENT

1. Explain why fuel enrichment is required in a homogeneous reactor system and indicate the degree of enrichment required with heavy water and graphite moderators.

2. Briefly enumerate the advantages and disadvantages of a homogeneous reactor system.

3. What factors are affected and in what way are they affected by using a heterogeneous, as distinct from a homogeneous, arrangement of fuel and moderator?

4. What similarities exist between pressurized and boiling light water reactor and in what principal ways do they diffe

5. (a) How are some of the basic disadvantages of the boiling water reactors overcome by using a system such as that used in the Pathfinder reactor?

   (b) What basic problem is involved in applying the same principle in a reactor using natural uranium fuel?

6. Briefly state the principal advantages of using heavy water moderated reactors and the principal disadvantages if heavy water is also used as a heat transport fluid.

7. What advantages are inherent in the horizontal pressure tube concept?

8. Specify the problems inherent in the Hinkley Point type of reactor and the reasons for the temperature limitations imposed in such a system.

9. What are the alternative heat transport fluids that could be used in a graphite moderated reactor and what effect would they have on the above limitations?

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