Reactor Boiler and Auxiliaries - Course 133

REACTOR CONSTRUCTION

As was seen, in the previous lesson, there are many different concepts for power reactors involving different combinations of fuel arrangements, core arrangements, moderators and heat transport fluids. Consequently there are many possible variations in design and construction of power reactors. Some of the associated problems may be common to more than one concept. Other problems may be specific to a particular type of reactor. The major problems will be discussed in this lesson, particularly those involving the choice of reactor structural materials.

Reactor Components

It has already been said that the basic function of a reactor is to contain the required combination of fissile material (or fuel) and moderator to sustain a chain reaction. A further objective is to obtain the maximum burn-up possible from the fuel and a third objective is to transport the heat from the fuel in as useful a form as possible, (i.e. at as high a temperature as possible.)

The principal components that may be required to fulfill these functions or objectives are:-

a. Fuel which includes the fissile material and fertile or alloying materials that may cause dilution of the fissile material.

b. Fuel cladding or sheaths if the fuel is solid, the main purposes of which are to prevent dispersion of fuel throughout the heat transport system, to prevent release of fission products which would contaminate the system and to prevent a possible chemical reaction between the heat transport fluid and the fuel material.

c. Heat transport fluid to transport the heat from the fuel.

d. Fuel channels or tubes to position the fuel in the reactor, and so simplify fuel changing, and to direct the heat transport fluid over the fuel.

e. The moderator, in a thermal reactor, to thermalize the fission neutron.

f. The reactor vessel to contain or position any or all of the above components.

g. Reactivity mechanisms used to vary the excess reactivity in the reactor either for power regulation, to compensate for reactivity changes or to shutdown the reactor.

h. A reflector to reduce neutron leakage which may also be a blanket used for breeding.

It may be necessary to provide some means of thermally insulating the moderator from the heat transport fluid. The reactor vessel may also contain structural material to strenghthen the vessel itself, to support the moderator and reflector or to guide the reactivity mechanism. A thermal shield may be located inside the reactor vessel to reduce heat generation in the vessel.

The components such as the fuel, fuel cladding, heat transport fluid, moderator, reactivity mechanisms and reflector will be discussed in later lessons. In this lesson the discussions will be confined to reactor and reactor vessel structural components.

<u>Structural Material Requirements.</u>

The requirements of a reactor structural material will vary to some extent, with the type of reactor and with its specific purpose in the reactor. In particular it will depend on whether or not the material is inside the reactor core. The reactor core may be defined as the region, within the reactor vessel which contributes directly to the production of energy and the removal of the energy from the fuel. It will, therefore, include all materials or components, such as fuel, cladding, heat transport fluid, fuel channels and moderator, up to the outer boundaries of the moderator or within the reflector, i.e. in the region where neutron conservation or economy is a primary consideration.

Structural material requirements may, however, be stated as follows:

(a) They must have small neutron capture cross-sections, particularly in the core region. This reduces neutron capture in materials other than fuel and increases the thermal utilization factor, f. It also reduces the factor w and, thereby, increases the conversion factor or breeding ratio. The following table lists the thermal neutron absorption cross-sections, σ_a, in structural materials or elements to be found in structural materials.

Material	σ_a (barns)	Material	σ_a (barns)
Magnesium	0.069	Inconnel	~ 4.1
Zirconium	0.185	Monel	~ 4.2
Aluminum	0.24	Nickel	4.6
Aluminum (2S)	~ 0.26	Vanadium	5.0
Aluminum (3S)	~ 0.36	Titanium	5.8
Tin	0.6	Manganese	13.2
Niobium	1.2	Tungsten	19.2
Molybdenum	2.7	Tantalum	21.3
Iron	2.6	Cobalt	37.0
Chromium	3.1	Hafnium	105
Stainless Steel	~ 3.1		
Copper	3.8		

The materials above the first dotted line have absorption cross-sections below 1 barn and they, or their alloys, could be considered for use in a thermal natural uranium reactor. The group below the second dotted line have cross-sections in excess of 10 barns and could not, in general, be considered as core structural materials in a thermal reactor. The materials with intermediate cross-sections might be used in a thermal reactor using enriched fuel.

The absorption cross-sections for fast neutrons are substantially smaller than for thermal neutrons e.g. σ_a = 0.006 for iron at 1 Mev. Also the quantity of fissile material, relative to structural material, in a fast reactor is much greater than in a thermal reactor. Therefore, the neutron utilization factor tends to be higher. As a result, structural material, which could not be considered in a thermal system, can be used in a fast reactor. Other material properties are then more important and stainless steels, niobium, molybdenum, tantalum and tungsten would appear attractive, the latter two because of their high melting points.

There is, of course, a much wider choice of materials for structural components outside the reactor core, since neutron absorption cross-section is no longer important.

(b) They must be able to resist radiation damage effects. Absorption of radiation and scattering of neutrons in materials causes changes in the physical properties of the material. Changes in strength, ductility and thermal conductivity occur in metals. Organic materials may have their essential properties drastically changed.

This resistance to radiation damage is particularly important in the reactor core because of the higher radiation intensities but radiation damage, particularly decrease in strength, may be serious in the reactor vessel itself. Because of the adverse effects of intense nuclear radiation on most organic materials, reactor structural components are predominantly metallic in construction.

(c) They should not become radioactive as a result of neutron capture or, if they do become radioactive, the radioactive nucleus should have a short half-life and, preferably, emit no gamma radiation. Corrosion or erosion causes small quantities of structural material to be circulated around the moderator and heat transport systems. If these corrosion products become radioactive as they circulate through the reactor and gamma ray emitters result, then the equipment associated with these systems will not be accessible during reactor operation. Shielding will be required to protect personnel from the radiation emitted. The radioactive corrosion products may well plate out on pipes, pumps and other equipment and the presence of long half-life nuclei would cause serious maintenance problems. The radioactive nuclei that would present the most serious problems are those given in the following table:-

Nucleus	Cr-51	Mn-56	Fe-59	Co-60	Zn-65	Zr-95	Mo-99	Ta-182
$t_{\frac{1}{2}}$	28d	2.6h	45d	5.3y	250d	63d	67h	112d
γ energy (Mev)	0.32	2.1	1.3	1.3	1.1	0.75	0.78	1.1

(d) Their mechanical properties, such as tensile strength, impact strength and rupture stress, must be adequate for the operating conditions. The reactor vessel and its internal components constitute a mechanical structure which must support itself under elevated temperature and possibly under elevated pressures.

(e) They must be able to maintain stability under severe thermal stress. Considerable internal heating of reactor components may occur as a result of radiation absorption or slowing down of fast neutrons. The removal of heat from the exterior of such components results in high temperature gradients within the material. Thermal stresses may be particularly severe during reactor startup, power changes or reactor shutdown.

(f) They should have high thermal conductivity so that there is efficient transfer of the heat generated in the components.

(g) They must have good corrosion resistance so that they are not chemically attacked by the moderator or heat transport fluid.

(h) The coefficient of thermal expansion must be low or well matched to that of other materials.

(i) They should have good fabrication characteristics.

(j) They should be readily available in pure form. Small amounts of impurities could cause large increases in the neutron absorption cross-section and impair the ductility.

(k) The cost should be reasonable.

Properties of Possible Structural Materials

From a consideration of absorption cross-section only Magnesium, Aluminum, Tin and Zirconium are attractive as possible materials in a thermal natural uranium reactor. Tin must be rejected, as a structural material, because of other considerations. Magnesium is too reactive chemically although its alloy, Magnox, is used as cladding material in reactors using CO_2 as heat transport fluid.

If enrichment can be tolerated then the most attractive materials are the iron and steel alloys, mainly because of cost. Many other materials can be considered for high temperatures particularly in fast reactors.

The most common materials, Aluminum, Zirconium and steel, will be considered in details and brief reference will be made to some of the other possibilities.

(a) Aluminum and its Alloys

Aluminum has a low thermal neutron capture cross-section. In addition it is relatively cheap and easily produced and fabricated. It is relatively easily rivetted, welded, forged and machined and cast shapes can be produced if proper care is taken to prevent porosity. It has good corrosion resistance at low temperatures but this resistance decreases even at moderately elevated temperatures. It is particularly susceptible to galvanic corrosion and pitting if small particles of foreign material are present. So care must be taken to keep aluminum surfaces free from other metals, particularly copper.

The pH of water in contact with the metal must be carefully controlled between 5.5 and 7.0, since it is subject to acidic and basic corrosion.

The thermal conductivity of aluminum is particularly good (around 121 Btu/hr-ft-$^{\circ}$F). Its coefficient of linear expansion is 14.8×10^{-6} per $^{\circ}$F between 20°C and 400°C. It has moderate mechanical strength (13000 psi with 30 - 35% elongation) and it is not subject to appreciable radiation damage. It melts at 1220°F.

Both the mechanical strength and the corrosion resistance can be substantially improved by alloying with silicon, iron manganese etc. The addition of copper, however, reduces the corrosion resistance. Most aluminum alloys suffer severe reduction in tensile strength at temperatures as low as 400°F. There is therefore a temperature limitation on the use of aluminum or its alloys.

(b) Zirconium and its Alloys

Zirconium has a unique combination of properties which makes it a useful metal in reactor construction. In the pure state it has a thermal neutron absorption cross-section of only 0.185 barns which is even lower than that of aluminum. It occurs with hafnium in nature and it has similar properties to hafnium. This makes the removal of the hafnium difficult and expensive and it is imperative that it be removed since it has an absorption cross-section of 105 barns.

The melting point of Zirconium is 3355°F.its thermal conductivity is around 12 Btu/hr-ft^2-°F (about one-tenth of that of aluminum) and its coefficient of linear expansion about 3×10^{-6} per °F. It has good structural properties compared with aluminum (50,000 - 60,000 psi tensile strength with 24 - 30% elongation). As a pure metal it is ductile and easily fabricated.

Annealed Zirconium is significantly affected by neutron irradiation the yield and tensile strengths being increased about 10,000 psi. Cold-worked zirconium, however, is not significantly affected. The strength of zirconium decreases rapidly with temperature but it is still greater than that of aluminum.

Alloys of zirconium are generally used in reactors but the alloying elements have to be carefully chosen so as not to increase the neutron absorption cross-section. Thus, the addition of nickel, iron or chromium would greatly diminish the usefulness of zirconium as a reactor material. Tin, which has a small absorption cross-section, could be used as an alloying element. Alloys of zirconium, such as zircalloy-2, 3Zl and zircalloy-4, have better room-temperature and elevated-temperature strength than pure zirconium. These alloys are much superior to aluminum in the intermediate temperature range but do not have sufficient strength for operation at high temperatures. For instance, at 900°F, the creep strength of zirconium alloys is only one-fifth of that of stainless steels.

Pure zirconium has outstanding corrosion resistance to high temperature water and steam. Zirconium suffers less attack in water at 400°F than stainless steel. It also has good resistance to liquid sodium up to 1100°F. Small amounts of impurities can seriously impair its corrosion resistance to high temperature water, nitrogen, oxygen and carbon being particularly harmful. Fortunately, alloying elements such as tantalum, niobium and tin, offset the detrimental effects of nitrogen, carbon and oxygen and improve the corrosion resistance.

Although Zircalloy-2, has excellent corrosion resistance, one problem, associated with it, occurs as a result of its retention of hydrogen. The hydrogen forms a brittle hydride which *precipitates, during cooling from 600°F, in the form of thin* plates. The plates cause brittleness and the whole effect is known as hydrogen embrittlement. Thus the effect of the hydrogen absorption is not noticed except at lower temperatures. Consequently there are restrictions on fuel changing at low temperatures. Another alloy, Zircalloy-4, has been developed in which nickel has been eliminated in an attempt to prevent hydrogen embrittlement.

Another problem recently encountered with the zircalloys is the accelerated creep rate believed to occur in high fast neutron fluxes. A new zirconium-niobium alloy has now been developed which, it is hoped, will not be subject to this accelerated creep. The pressure tubes of the Gentilly reactor will be made of this material.

The main disadvantages of using zirconium alloys are the high costs involved and the temperature limitations. These materials cannot be used above 750°F (400°C).

(c) Carbon Steels

Carbon steel is an important reactor material for use in pressure vessels and other components where corrosion resistance and low neutron absorption are not important, but where an ability to withstand thermal stresses is desirable. Where some corrosion resistance may be required, the vessel may be clad on the inside with a protective layer such as of stainless steel.

Steels for thick-walled pressure vessels could be more accurately described as high strength, low-alloy steels rather than as carbon steels. Small amounts of alloying materials, such as manganese, silicon or molybdenum, may be present to improve mechanical properties. Tensile strengths up to 100,000 psi and yield strengths up to 50,000 psi, with 20% or so elongation, may then be obtained.

Prolonged exposure of low-alloy steels to high fast neutron fluxes (the equivalent of 1 year's exposure to a flux of 10^{13} neutrons/cm^2/sec) can cause an appreciable increase in the tensile strength and an appreciable decrease in the ductility. What is, perhaps, more important is the increase in the brittle-to-ductile transition temperature. Although loss of ductility reduces the ability of the steel to accommodate thermal stresses, the increase in the transition temperature could be much more serious. After prolonged exposure to fast neutron irradiation, a drop in temperature might cause the vessel to suffer brittle fracture because of this increase in the transition temperature. The effects of radiation damage may be annealed out at higher temperatures but too little is really known about this to rule out a brittle fracture possibility.

(d) Stainless Steels

Stainless steels are a familiar group of materials, being known for their excellent corrosion resistance and their strength retention at high temperatures. Since the thermal efficiency of the system increases with heat transport temperature, the use of stainless steel is an attractive possibility. However, a neutron absorption cross-section of 3 barns, limits the use of stainless steel in thermal reactors to reactors using enriched uranium fuel. They are particularly suited for use in fast reactors.

Stainless steel melting points are in the range 2500 - 2750°F. Their thermal conductivities vary from about 7 to about 21 Btu/hr ft^2-°F and are generally rather low. This poor heat conductivity tends to give rise to high thermal stresses and indicates the unsuitability of stainless steels for thick structural components. They have excellent mechanical properties at high temperatures, the tensile strength of 1200°F being 50,000 psi. Thus, they are far superior in this respect to aluminum and zirconium and their alloys. They show substantial increase in hardness due to fast neutron irradiation.

Stainless steels are readily fabricated into a variety of shapes and they can also be cast. As has been said they are very corrosion resistant at room temperature and will maintain this resistance to 1600°F or 1800°F depending on the chromium content. They are not generally desirable for containing liquid metals but they are particularly resistant to liquid sodium or Sodium-potassium alloy.

The nickel used in stainless steel manufacture should have a low cobalt content because of the high absorption cross-section of cobalt and the formation of radioactive Co-60. This, however, tends to increase the price of the resulting steel.

Chlorine causes stress-corrosion cracking of stainless steel, particularly under stagnant conditions. The corrosion resistance of the steel is adversely affected. It is, therefore, imperative that stainless steel be kept free of any chlorine. It should be noted that chlorine can be introduced from chlorides in solvents sponges, organic gaskets and packings and in some types of insulations.

(e) High-temperature Materials

From the standpoint of neutron economy, most high-temperature materials would find use mainly in fast reactors. Titanium, vanadium, inconnel and the Hastelloys (nickel-molybdenum alloys) are examples of such materials. There is a special interest in titanium because of its high strength-to-weight ratio up to 842°F. It makes it attractive for use where weight-saving is important. Many of the alloys in this group, such as vitallium (chromium-cobalt - nickel - molybdenum), are much superior to stainless steel at high temperature. However, they are generally expensive and may also present fabrication problems.

Design and Construction Considerations

The design and constructional considerations required and the choice of materials for a reactor will be largely determined by the type of reactor being built. Such considerations will, therefore, be discussed as they pertain to each general type of reactor.

(a) Fast Reactors

No moderator is used in fast reactors and the only neutron slowing down process is the inelastic scattering in fuel, structural material and heat transport fluid. Highly enriched fuel is required and the core is basically fuel subassemblies with heat transport fluid flowing between them. The structural material in the core forms a relatively small percentage of the total core material, eg, a typical core composition would be 25% fuel, 50% heat transport fluid and 25% structural material and cladding. Neutron losses, in a fast reactor, are rather insensitive to the amount of heat transport fluid and structural material used. For instance in the Enrico-Fermi reactor less than 0.1% of the neutrons are absorbed in the sodium and only about 1% are absorbed in structural material. So choice of core material is limited more by their neutron slowing down capabilities than by neutron absorption considerations.

Because of the absence of moderator the core is small and the power density in the core is high. To permit operation at high temperatures without high pressures, and also in order to avoid slowing down of neutrons, liquid metals appear to be the most practical heat transport fluids. The amount of fuel subdivision and the size of heat transport passages involved is illustrated in Fig. 1. The heat transport passage may well be as small as 1/8 inch in diameter or less and plugging of these passages could easily occur by material deposition. Such plugging does not seem to be a problem with liquid metal heat transport fluid, since any dissolved metal from structural components deposits preferentially on cold rather than hot surfaces. This is another factor in favour of liquid metals.

The structural material used must have corrosion resistance to liquid metals. With sodium, many materials have good corrosion resistance at the temperature involved, provided the oxygen content is low. Low-carbon iron, chromium iron, stainless steel, nickel and Inconnel and zirconium are all *compatible with sodium and* the final choice would be made on the basis of cost and mechanical properties at elevated temperatures. In this type of core the problem of mechanical strength is more important for the core-supporting components. In the Enrico-Fermi reactor core the structural materials are either zirconium or, where greater strength is required, stainless steel. The reactor vessel, which is only pressurized to 110 psig, is made from stainless steel. Thermal stresses in the vessel are prevented by surrounding the core with a stainless steel thermal shield.

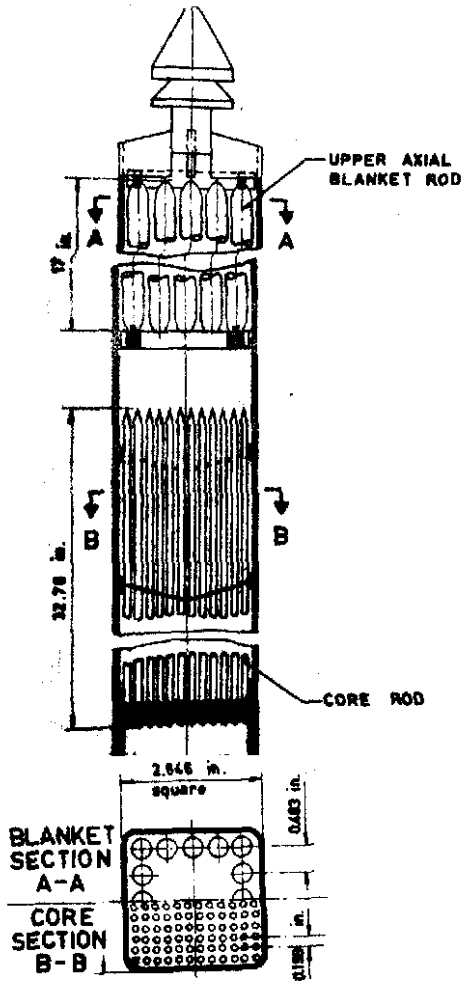

Fig. 1

(b) Homogeneous Reactors

In thermal homogeneous reactors, the reactor is essentially a large pot which is just an enlargement in the circulating system. There are no fuel elements and, consequently, no superfluous structural materials are required. If the reactor is a one region system, with a reactor core but no blanket, then choice of material is only required for the reactor vessel, which is entirely outside the neutron conservation region. 2000 psig pressurization is required and the most suitable material for the vessel would be a low-alloy steel particularly in view of the thermal stresses involved. However, the major problem involved is corrosion. If a uranyl sulphate solution in heavy water is used, the reactor vessel would have to be lined with stainless steel. Where phosphoric acid is used, as the solvent, gold or platinum lining would be required.

If the core is surrounded by a blanket which is also pressurized, the core and blanket would be separated by the core vessel. Since both regions are more or less equally pressurized, the core vessel would not be required to withstand a pressure differential of any significance and corrosion resistance and thermal neutron economy would be the major considerations. Under such circumstances an alloy of zirconium such as Zircalloy-2 would be the most suitable material. For highly corrosive fuel and blanket, such as solutions in phosphoric acid, gold or platinum cladding or lining would be required. The blanket would be contained in an outer pressure vessel the material for which would be chosen on the same basis as for a one region system.

(c) Thermal Heterogeneous Reactors

Heterogeneous reactors can be divided, structurally, into two main types, the pressure vessel type and the pressure tube type.

In the pressure vessel arrangement, illustrated in Figure 2, the reactor core and associated equipment are enclosed in a large vessel. The heat transport fluid enters the vessel, passes through the core to remove the heat produced in the fuel and then passes out of the vessel to a boiler or directly to the turbine.

If the heat transport fluid is light water, as in the pressurized or boiling light water reactors in Figures 5 and 6 of the previous lesson, light water is also the moderator. Fuel enrichment is required and if uranium oxide is used as fuel, the enrichment will be higher. The fuel channels are only required to guide the heat transport fluid over the fuel and do not have to withstand any pressurization. The tubes can, therefore, be thin and this helps to conserve neutrons. Since the operating temperatures are not excessive, the core structural material can be made of a Zirconium alloy for further neutron economy. Many reactors of this type have stainless steel structural components. The thicknesses required are then smaller but the enrichment required increases.

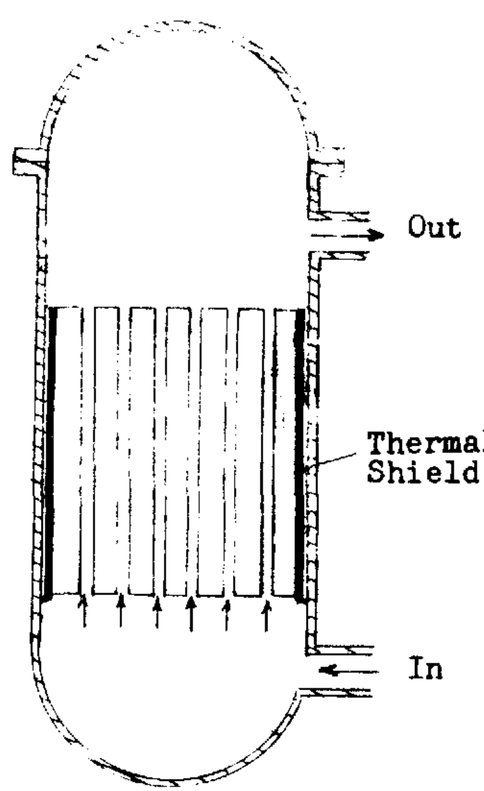

Fig. 2

If the reactor has a nuclear superheat section, like the Pathfinder reactor, the structural material in the superheat region of the core would be made of stainless steel.

In the Swedish R-3/ADAM reactor which is a pressure vessel type using heavy water, all core structural components are made of zirconium alloys. Stainless steel could be used but fuel enrichment would then be required. This would negate the main advantage of using heavy water ,ie, that of conserving neutrons and being able to use natural uranium and in the oxide form.

In graphite moderated reactors, using gas as the heat transport fluid, the graphite forms its own core structure and little other structural components are required except to support the core. Where such components are required, they would be made of magnesium or aluminum alloys. If higher temperatures are attained as in the Advanced Gas-Cooled Reactor or in the HNPF reactor, which uses sodium as the heat transfer fluid, stainless steel structural components are used for more reliable high temperature strength.

In all cases the best material for the pressure vessel is low-alloy steel. In some cases the inside wall of the vessel is lined with stainless steel to reduce corrosion. The core may also be surrounded by a thermal shield to reduce thermal stresses in the vessel. The thermal shield may be of carbon steel, stainless steel clad carbon steel, or stainless steel depending on the amount of corrosion to be expected.

In the pressure tube design only the heat transport fluid is pressurized, the moderator being separated from it. The reactor vessel, or calandria, is then merely a low pressure container for the moderator, as shown in Figure 3.

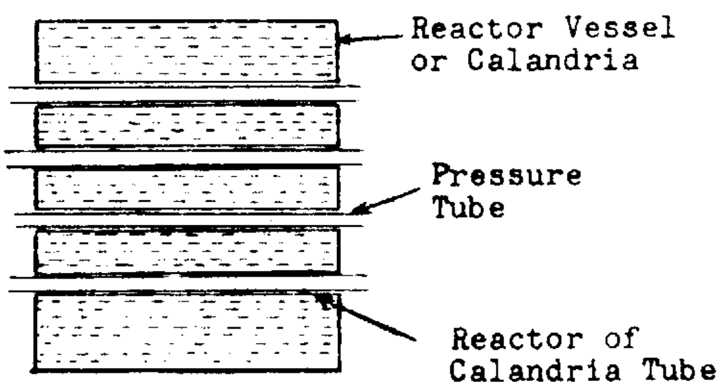

Fig. 3

The fuel is contained in channels which run horizontally or vertically through the vessel. These channels, which contain the heat transport fluid under pressure, are known as pressure tubes.

Heat is generated in the moderator by radiation absorption and neutron scattering but, because the moderator is not pressurized, it must be kept cool. The moderator can also receive heat, by convection, radiation and conduction, from the heat transport fluid and this increases the moderator cooling requirements. Transfer of heat from the pressure tubes is minimized by placing the pressure tubes inside calandria or reactor tubes. The space between them is either insulated or cooled by flow of gas. The arrangement is shown enlarged in Figure 4.

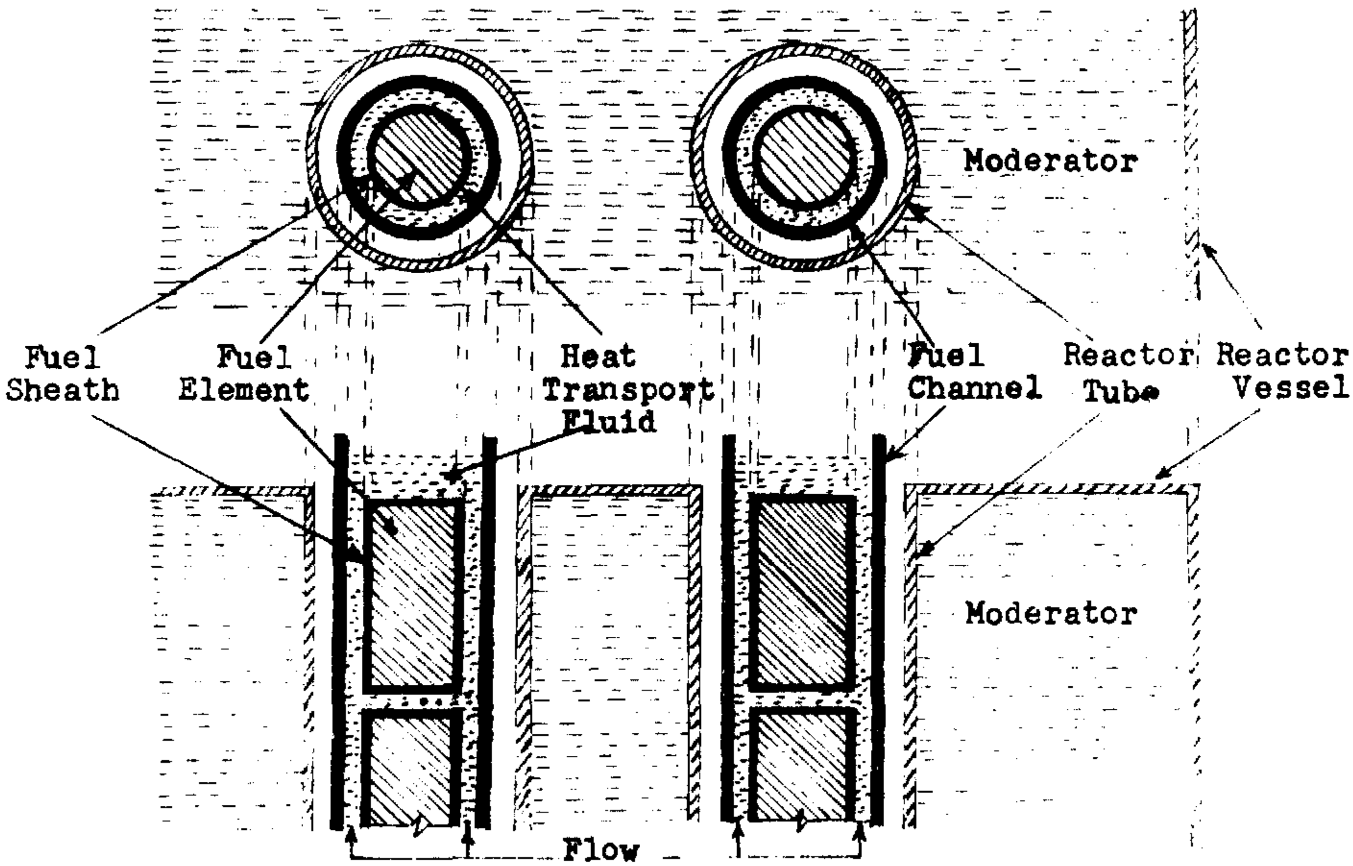

Fig. 4

The thickness of the fuel channels must now be sufficient to withstand the heat transport pressure and this introduces additional neutron absorbing material into the core. Still more such material is to be found in the reactor tubes. The choice of material for these tubes is, therefore, even more important than in the pressure vessel design. This is particularly so in the case of the reactors of this type which have been or are being designed at the present time, since they all use the natural uranium-heavy water concept in which neutron economy is of prime importance.

The reactor tube material will depend on the material used for the calandria since they are welded or rolled to the calandria wall. In a small power reactor, such as NPD, the core is surrounded by a light water reflector, which is separated from the moderator by the inner wall of a double-walled calandria. The inner wall is, therefore, part of the core and is made of aluminum alloy rather than the more expensive zirconium. Thus, the whole calandria is made of aluminum and so are the reactor tubes. The pressure tubes, being at a much higher temperature and pressurized, must be made out of zircalloy. All other core penetrations, required for reactivity control etc, are made of aluminum.

The Douglas Point and Pickering reactors are bigger and use only the outer region of the D_2O moderator as a reflector. The calandria then becomes a single-walled structure entirely outside the core. It can, therefore be made of stainless steel for added strength and corrosion resistance. The reactor tubes then have to be made of zircalloy but they would not be required to be as thick as the pressure tubes. Aluminum and stainless steel are not compatible. All core penetration must also be of zircalloy.

ASSIGNMENT

1. Why may material requirements for core structural components differ from those for structural components external to the core?

2. (a) On the basis of neutron capture cross-sections, what structural materials are suitable for a thermal reactor?

   (b) What other common material could be considered if the fuel was enriched?

   (c) Why is there a wider choice of structural material for a fast reactor?

3. State two nuclear requirements, other than low neutron capture, for reactor structural materials, and, briefly, explain their significance.

4. Explain why aluminum appears, initially, to be attractive as a structural material and why it is not, in fact, that attractive.

5. Enumerate the factors that make zirconium, or its alloys, useful as reactor materials. What disadvantage does it have?

6. (a) What material would be used for a reactor pressure vessel and why?

6. (b) Why would the same material not be used for pressure tubes?

7. What is the most likely material to be used for core structural components in a fast reactor and what factors would decide this?

8. Briefly compare the core structural material requirement for a pressure vessel and a pressure tube type of reactor.

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