Design Requirements and Engineering Considerations

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Summary:

The basic requirements of fuel, moderator and coolant dictate key design decisions which define the various reactor types.

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1 Introduction

All presently developed nuclear power reactors act as sources of thermal energy, producing electricity through the conventional "heat engine" process. This is shown diagrammatically in Figure 1. In all current central generating station applications, steam is the final working fluid with more or less conventional steam turbines being employed to drive the electrical generators.

The thermal energy is generated within the nuclear fuel which resides within the nuclear reactor. This thermal energy is transferred from the fuel by a fluid medium called the reactor coolant. This fluid medium may be boiling water, in which case the steam may be used directly in the turbine (the reactor is then called a direct cycle reactor) or it may act as an intermediate heat transport medium, giving up its heat to raise steam in external heat exchangers called boilers or steam generators (the reactor is then called an.indirect cycle reactor).

The various types of power reactors in use today differ regarding the nuclear fuel and the reactor coolants used and also in one further important regard, the type of medium used to slow down or moderate the high energy neutrons produced by the fission process.

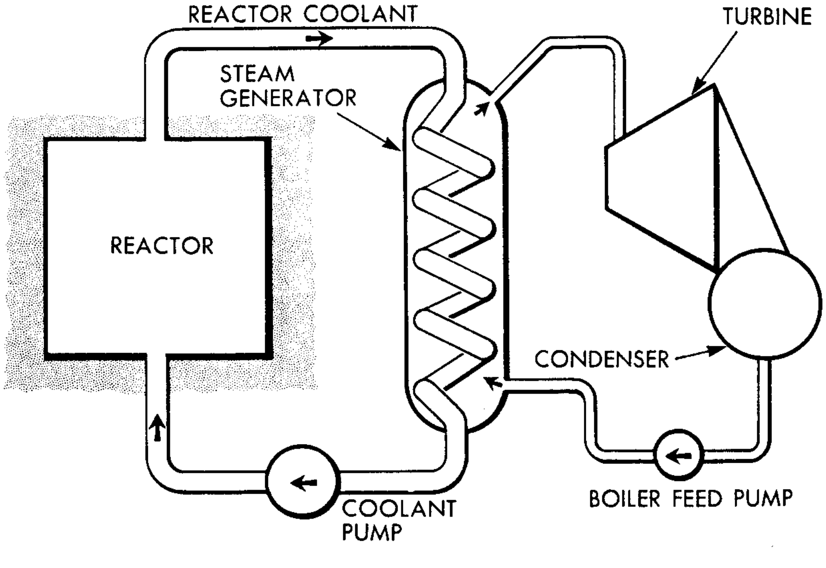

Figure 1 Basic power reactor schematic arrangement

We first look at the life cycle of neutrons in the typical nuclear reactor and then consider the various alternative nuclear fuels, coolants, and moderators in current use in commercial power reactors.

2 Basic Neutron Cycle

Figure 2 depicts the basic neutron cycle wherein a slow neutron is absorbed by a fissile nucleus, causing fission and the emitting of 2 or 3 fast neutrons. The probability of these fast neutrons interacting with other fissile nuclei is low relative to the probability of fission with slow neutrons; hence, the fission neutrons must be slowed down or moderated. This is done by collision with the surrounding media. During the course of this interaction, some neutrons are lost by absorption that do not lead to fission (parasitic absorption).

If one thermal (slow) neutron ultimately leads to at least one thermal neutron in the next generation, then a chain reaction is achieved. For this to be the case, the process must exhibit an "economy of neutrons". We need to:

- enhance the probability of neutron moderation
- reduce the probability of neutron absorption
- enhance the probability of fissioning.

This occurs subject to the following constraints:

- safety: the reaction needs to be controllable
- cost: overall cost should be minimized
- process: the reactor system must perform the desired function (ie, generate X MWe) given the limitations such as heat sink capacity, etc

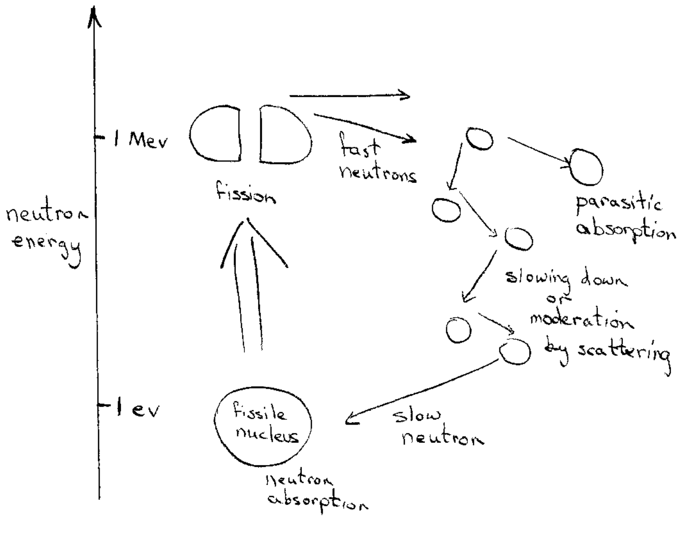

Figure 2 The basic neutron cycle

3 Possible Fuels

The probability of neutron capture leading to fission (called the fission cross section) is larger for slow neutrons than for fast neutrons. Hence, most practical reactors are "thermal" reactors, that is, they utilize the higher thermal cross sections. Possible fuels include ^{233}U (a fissile material that can be formed from ^{232}Th by neutron bombardment) and ^{239}Pu (also fissile and produced from ^{238}U by neutron bombardment). With one notable exception, all other fissile fuels require a high energy neutron to fission and the cross section is low. The only naturally occurring fuel of significant quantities is ^{235}U, hence most reactors use this fuel.

Naturally occurring uranium is composed of 0.7% ^{235}U. The rest is ^{238}U. This percentage is too low to sustain a chain reaction when combined with most practical moderators. Hence, to achieve criticality, either, the probability of fission must be enhanced or the moderator effectiveness must be enhanced. One group of reactor types (PWR, BWR, HTGR) enrich the fuel (a costly task) and use a cheap moderator (ordinary water or graphite). Alternatively, natural uranium (relatively cheap) is used with an excellent but expensive moderator (heavy water). This is the CANDU approach. In a later section, we shall see why heavy water is such a good moderator.

Enriching the fuel leads to a reactor system with a lower capital cost but higher operating cost than using natural uranium and heavy water. The overall cost over the life if the plant is about the same for either case.

Fast fissions do occur with ^{238}U and can contribute up to 3% to the fission process. But more importantly, some of the ^{238}U is converted to ^{239}Pu which subsequently fissions. In CANDU reactors and other reactors fuelled by natural uranium, roughly 50% of the power is generated through ^{238}U. This is less true for reactors with enriched fuel simply because there is relatively less ^{238}U present in the fuel.

4 Heat Transfer Considerations

All other things being equal, heat transfer is proportional to surface area. Therefore, best geometries for fuel are those with high area / volume ratios, such as flat plates. However, because a finite thickness of sheath is required, this is not optimum for low parasitic absorption. This is illustrated in figure 3.

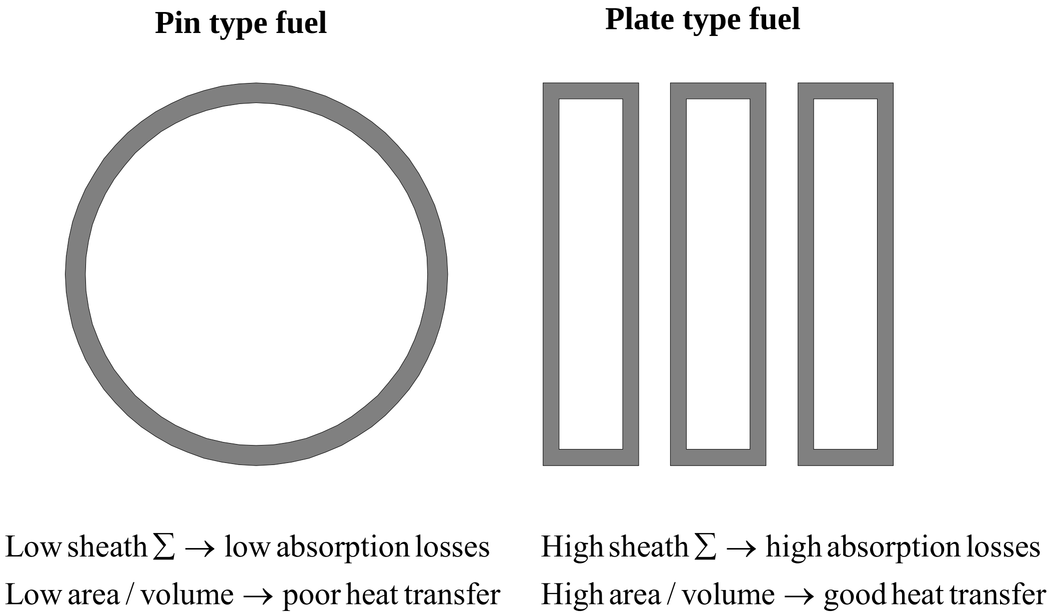

Figure 3 Tradeoff between heat transfer and neutron capture

In addition, to cope with internal pressure generated by fission product gases and swelling at high powers, the circular geometry is better. Tubes are also more economical to manufacture.

Given that many geometries can be made to operate practically and safely, the choice boils down to one of cost.

5 Uranium Fuel Forms

In discussing fuel, coolants and moderators, you will note that neutron economy is repeatedly mentioned as an important parameter. This is true even for enriched uranium reactors because the amount of enrichment, and hence the cost of the fuel, is very sensitive to the neutron economy of the reactor. This is particularly so because the enriching of uranium is very costly since it involves an isotope separation process rather than a chemical separation process. No matter which process is chosen, it must utilize the very slight difference in physical properties between the U-238 and U-235 atoms; hence, the process is inherently costly.

In all commercial power reactors, the fuel is used in solid form. Various geometries are employed such as solid rods, plates, spheres, or annular rings. Solid round rods (see Figure 4) are used predominantly, primarily because of manufacturing costs. A basic parameter governing fuel design is the external surface area to volume ratio. Good heat transfer to the coolant medium is promoted by high values of this ratio whereas low fuel manufacturing costs and, generally, good neutron economy are promoted by low values of this ratio. This presents a "classical" problem in optimization during the reactor design process, as discussed previously.

In certain power reactors, the fuel material is in the form of uranium metal. Other forms are also used as listed in table 1. Before discussing the merits of the alternative forms, it is useful to consider the desirable properties of fuel material. These are listed in table 2.

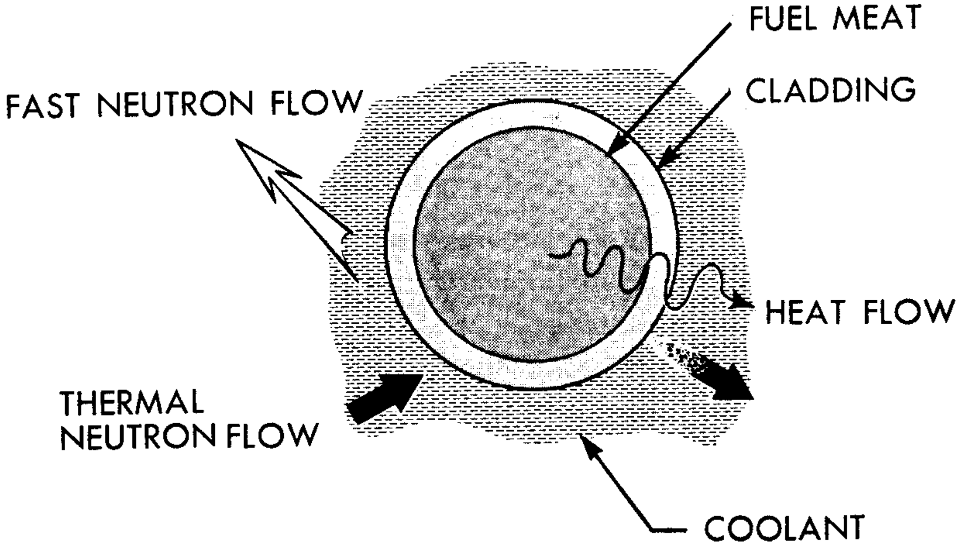

Figure 4 Basic reactor fuel arrangement

Table 1 Forms of uranium in power reactor fuel

1. URANIUM METAL
2. URANIUM/OTHER METAL. ALLOY
3. CERAMIC URANIUM DIOXIDE
4. URANIUM CARBIDE
5. URANIUM SILICIDE

Table 2 Desirable fuel material properties

1. LOW COST - CONSTITUENTS AND FABRICATION
2. GOOD NEUTRON ECONOMY
3. GOOD CORROSION RESISTANCE TO COOLANT
4. PHYSICAL STABILITY UNDER EFFECTS OF IRRADIATION, TEMPERATURE, PRESSURE

Uranium metal is generally lowest in manufacturing cost and highest in neutron economy, the latter because of its high density and the absence of the other neutron absorbing elements. On the debit side of the ledger, it has poor corrosion resistance to most coolants which is of importance in the event of fuel cladding (to be discussed later) failures. Its geometric stability in reactor use is poor, primarily because of the swelling effects of fission products whose specific volume is, of course, greater than the parent uranium. Small quantities of alloying agents have been found useful but do not fully solve the problem. The problem is aggravated by a metallurgical phase change at relatively moderate temperatures which causes further geometric distortion. This limits the operating power density achievable with the fuel.

Larger quantities of alloying agents such as zirconium can be used which effectively cure the geometric stability problem and the coolant corrosion problem. Unfortunately both the cost and neutron economy suffer. This fuel is used for certain specialized applications where the latter factors are not of overriding importance. Uranium - aluminum alloys are attractive for low power density, pressure and temperature situations such as research reactors.

Uranium dioxide is the form in which the uranium fuel is used in the vast majority of today's power reactors. It is somewhat more expensive to manufacture and less neutron economical than uranium metal because of its lower density but possesses excellent corrosion resistance to most coolants and a high degree of geometric stability. Being a ceramic, it is capable of high operating temperatures.

Uranium carbide is attractive as a future fuel for certain types of reactors. It is relatively inexpensive to manufacture (comparable to UO_2) and has somewhat better neutron economy than UO_2 (because of its higher density, but not as good as uranium metal. It has good corrosion resistance to many coolants but unfortunately not to water. Its dimensional stability is good and it can operate at high temperatures.

Uranium silicide is a more recent development having most of the advantages of uranium carbide and, in addition, adequate resistance to corrosion by water coolants.

The above properties of the various uranium fuel forms are summarized in the following table:

Table 3 Uranium fuel form summary

U Fuel Form	Cost	Neutron Economy	Corrosion	Physical Stability
U Metal	Lowest (dense + no parasites)	OK	Poor	Poor (swells due tc FP), limits power density
U Alloy	Higher	Lower	OK	OK
UO_2	Higher	Lower	Excellent	Excellent, high T possible
UC	Lower than UO_2	UO_2<UC<U Metal	Good except against water	Good, high T possible
US	~ UC	~ UC	Good even with water	~ UC

6 Fuel Claddings

In the fission process, new isotopes of a wide variety of elements are produced. These are called fission products. Many of these remain radioactive for significant durations of time after they are generated and, hence, constitute a potential radiation hazard to plant operators and the public at large. It is therefore clearly desirable to keep these fission products "bottled up" within the fuel where they are generated.

This is the primary function of the fuel cladding. This cladding takes the form of an impervious "skin" or "shell" which encloses the fuel material proper. Most cladding materials in current use are metals although ceramic-type materials have had limited use in certain applications. Table 3 lists the commonly used power reactor cladding materials. Before discussing the merits and demerits of each it is useful to consider the desirable properties of cladding materials. These are summarized in table 4.

Table 4 Alternative fuel cladding materials

1. ALUMINUM
2. MAGNESIUM (MAGNOX)
3. STAINLESSSTEEL
4. ZIRCONIUM
5. CERAMICS

Table 5 Desirable cladding properties

1. CORROSION RESISTANCE TO COOLANT
2. MECHAN ICAL DURABILITY
3. HIGH OPERATING TEMPERATURE CAPABILITY
4. GOOD NEUTRON ECONOMY
5. LOW COST - BASE MATERIAL & FABRICATION
6. IMPERMEABILITY TO FISSION PRODUCTS

Aluminum and its alloys possess many attractive properties such as low cost, easy fabrication, high ductility (important in preventing cladding failures), good neutron economy, and impermeability to fission products. Their major disadvantages for power reactor use are poor mechanical properties at high temperatures and poor high temperature corrosion resistance with most coolants. Since the latter are temperature dependent, aluminum alloys are widely used in research reactor fuels where cladding operating temperatures are low but are not currently used in power reactors.

Magnesium alloys are similar to aluminum alloys in most regards. An alloy called "Magnox" has, however, better high temperature properties and adequate corrosion resistance to permit its use in some CO_2 cooled power reactors.

Stainless steel is a very attractive material in all major regards except for its poor neutron economy. It has been and still is used in a number of enriched uranium reactors where its poor neutron economy is somewhat less important.

Zirconium, in various low-alloy forms, is by far the most common cladding material in current use. Despite its relatively high base material cost, it combines to a large degree all of the other desirable cladding properties for use with most coolants.

The use of ceramics and ceramic-type materials have potential for very high temperature applications. Their primary disadvantage is, of course, a lack of ductility which makes them liable to brittle fracture.

The above properties of the various fuel cladding are summarized in the following table:

Table 6 Fuel cladding summary

Cladding Type	Corrosion Resistance	Mechanical Durability	High T Capability	Neutron Economy	Cost	FP Containment
Al	Good except at high T	Low	Low	Good	Low	Good
Mg	~Al, OK for CO2	~ Al	> Al	~ Al	> Al	~ Al
Stainless Steel	Good	Good	Good	Poor	Good	Good
Zr	OK	OK	OK	Excellent	High	Good
Ceramic	Good	Brittle	Excellent	OK	OK	OK

7 Reactor Coolants

As discussed earlier, the purpose of the reactor coolant is to transport heat generated in the reactor fuel either to the turbine (direct cycle reactor) or to intermediate heat exchangers (indirect cycle reactor). The coolants may be liquids, two-phase liquid/vapour mixtures or gases. table 5 lists the coolants commonly used in current power reactors. Table 6 lists the desirable properties of reactor coolants.

Table 7 Alternatuve power reactor coolants

1. CO_2 GAS
2. HELIUM
3. ORDINARY WATER
4. HEAVY WATER
5. ORGANIC FLUID
6. LIQUID METAL

Table 8 Desirable features of reactor coolants

1. HIGH HEAT CAPACITY
2. GOOD HEAT TRANSFER PROPERTIES
3. LOW NEUTRON ABSORPTION
4. LOW NEUTRON ACTIVATION
5. LOW OPERATING PRESSURE REQUIREMENT AT HIGH OPERATING TEMPERATURES
6. NON-CORROSIVE TO FUEL CLADDING AND COOLANT SYSTEM
7. LOW COST

Of the gases, two are in common use: CO_2 and helium. CO_2 has the advantages of low cost, low neutron activation (important in minimizing radiation fields from the coolant system), high allowable operating temperatures, good neutron economy and, for gases, relatively good heat transfer properties at moderate coolant pressures. At very high temperatures, it tends to be corrosive to neutron economical fuel cladding materials and also to the graphite moderator used in most gas-cooled reactors. Its chief drawback, as for all gases, is its poor heat transfer properties relative to liquids. As a result, coolant pumping power requirements tend to be very high, particularly if high reactor power densities are to be achieved (desirable to minimize reactor capital costs).

The other candidate gas, helium, possesses all of the good features of CO_2 and, in addition, is non-corrosive (if pure). Its chief disadvantages are higher costs, particularly operating costs, because helium is very "searching", leading to high system leakage rates unless extreme measures are taken to build and maintain a leak-proof system. This has, however, been successfully done in a number of cases.

Of the candidate liquid coolants, ordinary water is by far the most commonly used. It is inexpensive, has excellent heat transfer properties, and is adequately non-corrosive to zirconium alloys used for fuel cladding and reactor structural components and ferritic or austenitic steel coolant system materials. its disadvantages include only moderate neutron economy and its relatively high vapour pressure at coolant temperatures of interest. It is activated by neutrons in the reactor core but this activity dies away rapidly, permitting reasonable shutdown maintenance access to the coolant system. A further disadvantage is that water transports system corrosion products, permitting them to be activated in the reactor core. These activated corrosion products then create shutdown radiation fields in the coolant system.

The water coolant may be used as a liquid in an indirect cycle system or may be permitted to boil, producing steam in a direct cycle system. Heavy water may also be used as a coolant. Its outstanding advantage is much better neutron economy relative to ordinary water. Its primary disadvantage is its high cost. Otherwise its properties are similar to ordinary water.

Certain organic fluids (primarily hydrogenated polyphenyls) may also be used. They are moderate in cost, have a lower vapour pressure than water, are essentially non-corrosive, and are not significantly subject to neutron activation. Also they do not transport significant quantities of corrosion products which can become activated in the reactor core. Their chief disadvantages include higher neutron absorption than heavy water (but lower than ordinary water), inflammability, and they suffer radio-chemical damage in the reactor core which leads to a requirement for extensive purification facilities and significant coolant make-up costs. On balance, however, they may well see wider application in the future.

Certain liquid metals can be used as coolants. Of these, only sodium and a sodium/potassium eutectic called NaK have achieved significant use. Their advantages include excellent heat transfer properties and very low vapour pressures at high temperatures. Fuel cladding and coolant system materials require careful selection to avoid "corrosion". Their chief disadvantages include incomparability with water (the turbine working fluid), relatively high neutron absorption, a relatively high melting point (leading to coolant system trace heating requirements) and high coolant activation with sustained radiation fields after reactor shutdown.

These disadvantages have effectively precluded the use of liquid metal coolants in commercial power reactors to date with one exception and this is the fast breeder reactor which will be discussed later. In this reactor, the neutrons are "used" at relatively high energy levels where the neutron absorption of the liquid metal is much less, overcoming one of the foregoing disadvantages. In addition, the economics of fast breeder reactors depend on very high core power densities where the excellent heat transfer capability of liquid metals becomes a major advantage. Furthermore, it is desirable in this type of reactor that the coolant not moderate the neutrons excessively. Liquid metals are superior to other liquids in this regard because they do not contain "light" atoms which are inherently effective moderators.

Table 9 Coolant summary

Coolant Type	Cost	Neutron Economy	Corrosive	Heat Capacity	HT Coeff	Activation	Vapour Pressure	Other
CO_2 Gas	< He	Good	OK except at high T	Low	Low	Low	High	
He	Higher	Good	Good if pure	Low	Low	Low	High	Leaks
H_2O	Very low	Moderate	OK but transports corrosion products	High	Excellent	Yes but $T_{1/2}$ short	High	
D_2O	High	Excellent	Ok but transports corrosion products	High	Excellent	Like H_2O but with tritium	High	
Organic	Moderate	H_2O < organic < D_2O	Excellent	High	Excellent	None	Low	*See note
Liquid Metal (eg NaK)	High	Not great	Must be careful to select materials	High	Excellent	High with long $T_{1/2}$	Very low	**See note

* Suffers radio-chemical damage

** Incompatible with water in the turbine. High Melting point, low cross section at high energy. Good for fast reactors and breeders.

8 Neutron Moderators

The most current power reactors are of the thermal type, i. e. , where the energy of the neutrons causing fission is in the thermal range. Since the neutrons produced by the fission process have very high energies, it is necessary that they be slowed down, or "thermalized". The medium employed for this is termed the moderator. It is deployed as a continuous medium surrounding the fuel "cells". The fuel cells form a geometric pattern, termed the reactor "lattice". The optimum spacing between these fuel cells is a function of several variables including the mass of fuel per cell, the mean free path of the neutrons in being thermalized, the degree to which the moderator wastefully absorbs neutrons, the cost of the moderating medium, etc.

The best moderator is something that is the same size as a neutron, ie, the hydrogen atom, $^1H_1$. However, hydrogen does absorb neutrons as well. The deuterium atom, $^2H_1$, at twice the mass of hydrogen, is almost as good a slowing down agent but, since it already has an extra neutron in the nucleus, it has a very low absorption cross section. So, overall, it deuterium is a far better moderator than hydrogen. By using deuterium in the form of heavy water, natural uranium can be used as a fuel. If ordinary water is used, the fuel must be enriched in ^{235}U.

A good moderator has a high scattering cross section, a low absorption cross section and slows down the neutron in the least number of collisions (high lethergy, ξ). Table 7 summarizes this. The "figure of merit" is defined as $\xi\Sigma_s / \Sigma_a$.

Before discussing practical moderators, it is firstly useful to consider desirable properties of moderators. These are listed in table 8. Table 9 then lists the moderators currently used in commercial power reactors.

Table 10 Slowing down parameters of typical moderators [Source: DUD76, table 8-1]

Moderator	A	α	ξ	$\rho[g/cm^3]$	Number of collisions from 2 MeV to 1 eV	$\xi\Sigma_s[cm^{-1}]$	$\xi\Sigma_s/\Sigma_a$
H	1	0	1	gas	14	—	—
D	2	.111	.725	gas	20	—	—
H_2O	—	—	.920	1.0	16	1.35	71
D_2O	—	—	.509	1.1	29	0.176	5670
He	4	.360	.425	gas	43	1.6×10^{-5}	83
Be	9	.640	.209	1.85	69	0.158	143
C	12	.716	.158	1.60	91	0.060	192
^{238}U	238	.983	.008	19.1	1730	0.003	.0092

Table 11 Desirable features of moderators

1. HIGH MODERATING EFFICIENCY
2. LOW NEUTRON ABSORPTION
3. FREEDOM FROM DAMAGE - IRRADIATION, CORROSION
4. LOW COST - RAW MATERIAL, MANUFACTURE, INSTALLATION

Table 12 Alternative power reactor moderators

1. GRAPHITE
2. ORDINARY WATER
3. HEAVY WATER

Graphite has been widely used as a moderator for power reactors. The carbon atom is relatively "light", graphite is relatively inexpensive, and carbon is a relatively weak absorber of neutrons. Nevertheless, the carbon atom is sufficiently large, leading to relatively long neutron mean free paths for thermalization, that graphite moderated reactors tend to be large. Furthermore, the relatively large amount of graphite required leads to significant neutron wastage through absorption.

Ordinary water is a much more efficient moderator in terms of the neutron mean free path for thermalization because of its hydrogen atoms. It is also very inexpensive. Unfortunately, however, hydrogen also has a significant "appetite" for absorbing thermal neutrons which hurts neutron economy.

Heavy water is almost as good as ordinary water in terms of neutron mean free path since the deuterium atoms (which replace the hydrogen atoms in ordinary water) are relatively "light". Its outstanding advantage, relative to ordinary water, is that it has a very small "appetite" for absorbing neutrons. Hence, it promotes a high level of neutron economy. Its major disadvantage is its high cost.

Table 13 Moderator summary

Moderator Type	**Cost**	**Neutron Economy**	**Moderator efficiency,** $\frac{\xi\Sigma_s}{\Sigma_a}$	**Irradiation stability**	**Activation**	**Mean Free Path***
Graphite	OK	H_2O < graphite < D_2O	192	Excellent	Irrelevant	Long
H_2O	Very low	Moderate	71	Excellent	Good	Small
D_2O	High	Excellent	5670	Excellent	Good	Medium

* Mean free path determines the size of the core

9 Moderating Arrangements

How do the fuel, the coolant, and the moderator "fit" together to form practical power reactors? The currently established alternatives are shown in Figure 5. If ordinary water is used as both coolant and moderator, it is practical to arrange the fuel "rods" in cluster assemblies as shown. The clusters abut against each other. The space between the individual fuel rods is occupied by ordinary water which acts as both moderator and coolant. A relatively small volume of water is required because of the very short neutron mean free path with a hydrogen-based moderator. Hence, the fuel rods can be located relatively close to each other. This arrangement is used in both PWRs and BWRs.

If graphite (a solid) is used as the moderator, it is possible to arrange the graphite and fuel into abutting composite assemblies.

Coolant passages are arranged through the fuel rods (annular form) or through the graphite. The former approach is used in one Russian reactor type where the coolant is water and steam (for superheating). The latter is used in HTGCR's where the coolant is helium and the fuel is uranium carbide, permitting extremely high fuel operating temperatures.

A third arrangement is where the fuel is in the form of assemblies completely separated from the moderator. This arrangement is used in heavy water moderated and most graphite moderated reactors.

The choice between these alternatives is influenced by many factors, both of a neutron physics nature and a practical engineering nature, and is very dependent on the particular choice of fuel, coolant and moderator.

Time does not permit a detailed discussion of all of these, although many of the factors have been touched on in a qualitative way in the preceding sections. Most of the rest, also in a qualitative way, will be touched on in the next section which deals with specific power reactor types.

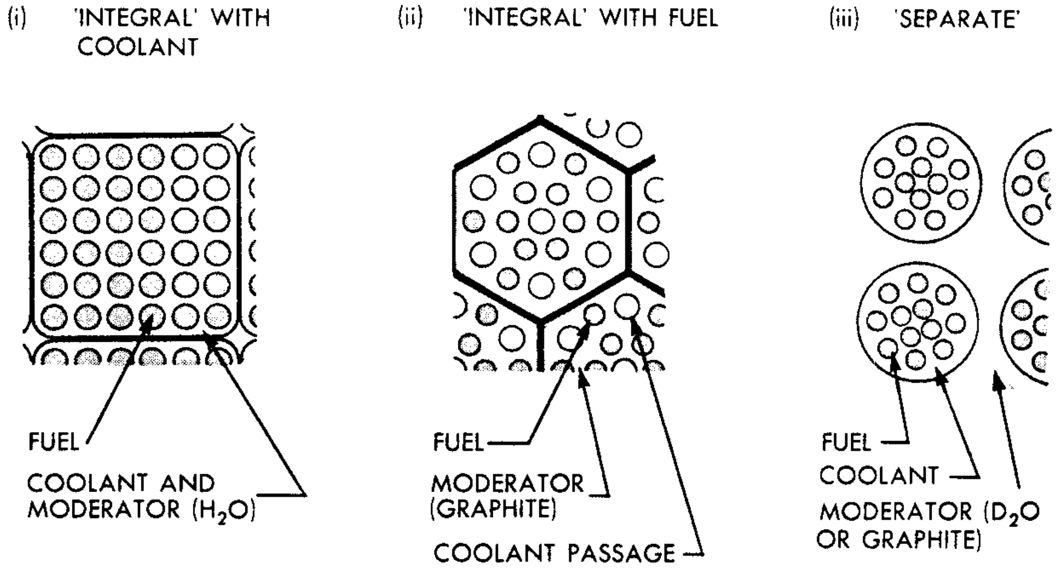

Figure 5 Moderating arrangements

10 HTS Design Requirements and Engineering Considerations

This section introduces the heat transport system and associated systems by a discussion of design requirements and engineering considerations which guide the design of systems to transfer fission heat to the coolant for the production of steam.

The fissioning process results in heat generation in the nuclear fuel and surrounding media. This thermal energy can be utilized to produce electricity or process steam by the use of a heat transport medium, the coolant. Here we will discuss some of the thermalhydraulic features which characterize the CANDU system, but the story is similar for PWRs..

The main objectives of the heat transport system are to provide heat transfer at high thermal efficiency and to allow the maximum amount of energy to be extracted from the fuel without surpassing safe limits. The requirements for such a system can be summarized as follows:

a) Due to the decay heat produced by the fuel even when the reactor is shut-down, continuous coolant flow must be provided. This leads to the requirement for pumps, pump flywheels, standby cooling, thermosyphoning, etc.
b) Costs should be minimized with due regard for the other requirements. This usually leads to trade offs between, for example, heavy water (D_2O) costs, pumping power costs, equipment and piping size and costs, layout and engineering constraints.
c) Layout should minimize man-rem exposure and maximize maintainability and accessibility within the constraints of other considerations.
d) Provision must be made for pressure and inventory control of the heat transfer system. Excessively high pressure could damage the fluid boundaries (pipes, etc.). Low pressure could lead to high coolant voiding and possible fuel damage and to pump damage from cavitation. Low inventory jeopardizes coolant circulation and pressure control.
e) The system must be sufficiently reliable since downtime leads to high replacement energy costs, high man-rem exposure and repair costs.
f) The design should provide high process efficiency.
g) The system should exhibit ease of constructibility to reduce initial costs and time of construction, and to enhance maintainability.
h) The system should meet and, preferably surpass all safety and licensing requirements.

Various coolants can be used in the CANDU design to achieve the above objectives and requirements. Any nuclear station design employs a tradeoff in design features to best achieve the lowest cost power within the safety limits. The U.S. nuclear industry, for instance, because of the availability of enriched uranium from existing UF_6 diffusion plants, chose to use enriched uranium and H_2O coolant in order to achieve the necessary neutron economy.

From a neutron economy viewpoint, the medium surrounding the fuel, ie., the coolant and the moderator, must not absorb neutrons and must moderate the neutron energy by a minimum of collision interactions. D_2O is by far the best moderator/coolant from this viewpoint. The cost, however, is high at approximately \$300/kg in 1980 dollars.
Using H_2O as the coolant, as in the CANDU-BLW, Gentilly-1, gives poorer neutron economy than the

CANDU-PHW and requires booster rods for startup until the positive void coefficient of reactivity adds a sufficient positive reactivity to maintain criticality. Because of this and because of reactivity control difficulties associated with the large void coefficient of reactivity, no new commercial CANDU-BLW's are planned. Organic coolant, Monsanto OS-84, requires slightly enriched fuel (1.2 to 2.4 wt%). This option was found feasible but, due to the success of the CANDU-PHW, no commercial OCR's are planned.

Another nuclear consideration is that the coolant should have a low induced radioactivity. Both H_2O and D_2O produce N-16 and 0-19 which emit γ's in the 6-7 MeV range. This leads to reduced accessibility and maintainability while on power. the short half life (<1 minute) allows shutdown accessibility. Tritium, H^3 or T, has a 12 year half life and represents a major dose commitment for the station. Since tritium is a β emitter, the problem is one of leakage, leading to possible absorption/ingestion by humans. Organic coolant has very little induced reactivity and aids in ease of operations, accessibility, etc.

The coolants should also be stable in a radiation environment. At the high system pressure of the heat transport systems of H_2O and D_2O, radiolysis is not a problem. However, since hydrogen and deuterium have a tendency to diffuse through the pipework, the heat transport system becomes concentrated in oxygen and enhances corrosion. Supplying an excess of hydrogen or deuterium prevents this occurrence by driving the chemical equilibrium balance towards the associated state.

Organic coolant is more susceptible to radiolysis and requires degassing and makeup.

The choice of coolant also depends on other factors, such as pumping power, heat capacity, heat transfer coefficients, flowrates, pressure drop, boiling point, freezing point, corrosion, flammability, thermal stability, and cost.

Water (both D_2O and H_2O) is an attractive heat transport fluid since it offers a good balance of the above considerations. The specific heat, density and thermal conductivities are high compared to alternatives such as N_2, CO_2 and OS-84 (organic). Since pumping power is given by:

Pumping power = pressure drop x volumetric flow rate,

water requires less pumping power for a given heat removal.

For the Bruce reactors (which generate about 750 MWe), approximately 24 MW's of pumping power are required for each reactor. Of this 24 MW, roughly 90% (or 21.5 MW) ends up in the primary heat transport system as heat due to friction. At an overall station efficiency of 30%, the net unit load for pumping power is 24 - 21.5 MW (bearing and windage losses) plus 21.5 x .7 = 15 MW (rejected energy) for a total of 18.5 MW. This represents over 2% of the electrical power generated. Since MW saved here by reducing pumping power is gained as electrical output, considerable emphasis is placed on lowering pumping power.

Limiting flowrates for water depend on many factors such as temperature, the presence of boiling, water chemistry, geometry and flow regime. Fretting considerations have led to a 10 m/sec limit on fuel channel velocity in single phase water. Erosion/corrosion considerations have led to 4.3 to 6.1 m/s (14 to 20 ft/s) in the steam generator tubes and 16.8 m/s (55 ft/s) in heat transport piping. These limits may change as more is learned about the limiting phenomena.

The fuel distribution in the coolant is such to maximize the surface to volume ratio of the fuel so that the highest heat transfer surface can be exposed to the coolant for maximum heat transfer without drying out the fuel surface. However, if carried to extremes the fuel volume in the core will be lower than optimum and parasitic neutron absorption due to the sheath will increase. Present designs employ 37 or 28 elements in a fuel bundle.

The use of boiling in the coolant permits higher heat transfer due to the high heat transfer coefficient of post-nucleate boiling.

Ideally, the coolant temperature should be as high as possible for maximum overall thermal efficiency. Thus a high boiling point, low vapour pressure liquid is desirable so that the heat transport system can be at the lowest possible pressure. This reduces the thickness of the pressure boundary and thus is important for reducing the parasitic burnup in the core. Organic coolant is far superior to water from this point of view.

For the case of organic coolant, the secondary side H_2O pressure is higher than the primary side OS-84 pressure. Thus boiler tube leaks will cause a water leak into the primary coolant system.

Freezing point concerns for H_2O and D_2O are minor. For OS-84 provision must be made to prevent freezing while shutdown and cold. Continuous coolant makeup reduces this problem.

Corrosion of the heat transport system materials must be minimized because of possible deterioration, flow restrictions and contamination with active isotopes.

The CANDU-PHW heat transport system has water coolant, low cobalt carbon steel piping, stainless steel end fittings, zircalloy pressure tubes and Monel or Incoly steam generator tubes. A pH of 10.2 to 10.8 is maintained by lithium hydroxide. Hydrogen gas is added to keep the dissolved oxygen content low to help minimize corrosion. The intent is to produce and maintain a continuous and adherent film of magnetite on all the carbon steel surfaces. Corrosion with organic coolant is a lesser problem, controlled by degassing, by using N_2 cover gas, and by a dechlorinator system.

No flammability or thermal stability problems exist with water (except for the possible Zr-water reaction producing H_2 during a LOCA giving the potential for H_2 explosion) but organic coolant is combustible, although it will not sustain combustion on its own. Organic coolant is also not as thermally stable as water.

The current cost of D_2O ($300/kg - 1995 dollars) is high, making it the more expensive coolant. This contributes to a high capital cost for the CANDU-PHW but a low operating cost due to the efficient use of natural U.