11 Power Reactor Types

It is not much of an exaggeration to state that in the early days of power reactor development there were champions for every possible combination of the fuels, coolants, moderators, and moderator arrangements discussed in the preceding sections and a few more besides. Many of these have fallen by the wayside, either because of basic, inherent shortcomings or, in some cases, because their champions could not rally adequate support. This is, of course, natural with an emerging technology. A number of the possible combinations have reached the point of commercial exploitation. These are described briefly in the following subsections.

11.1 "Magnox" Reactors

These are graphite moderated, CO_2 gas cooled reactors fuelled with natural uranium metal clad with a magnesium alloy called Magnox. They have derived their generic name from this latter feature. Figure 6 shows a schematic arrangement of one version of this reactor type.

This type of reactor was pioneered by the British and French and was a natural outgrowth of earlier air-cooled, graphite-moderated research and plutonium production reactors. A significant number were built in Britain and France with a few exported to other countries. Early versions used steel reactor pressure vessels with external heat exchangers (boilers) and gas circulating blowers. Later versions, as per Figure 6, employed prestressed concrete pressure vessels incorporating the reactor core, heat exchangers and coolant circulation blowers. This was primarily a cost reduction measure, although safety advantages in terms of risk of coolant system rupture were also claimed (likely valid).

Primarily because of coolant temperature limitations imposed by the uranium metal fuel and the Magnox cladding, only relatively modest turbine steam conditions are achievable, limiting the station overall efficiency to ~ 30%.

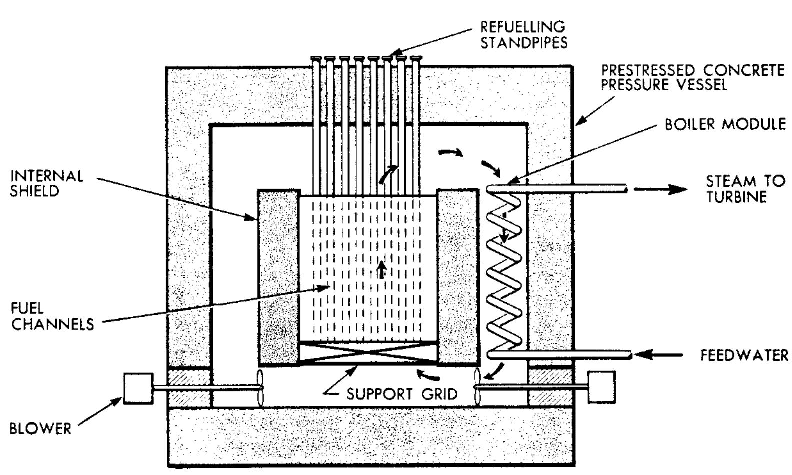

Figure 6 Schematic arrangement - Gas Cooled Reactors

As is typical of all natural uranium power reactors, the Magnox reactors are fuelled on-load. This is because large quantities of excess reactivity, in the form of additional U-235, is not "built into" the new fuel.
The in-service availability of the Magnox reactors has proven to be relatively good. On-load refuelling helps in this regard. Nevertheless, their relatively high capital cost and relatively modest achievable fuel utilization has led to the discontinuation of construction of further reactors of this type.

11.2 AGR

The AGR (advanced gas cooled reactor) has been developed in the U. K. as a successor to their Magnox line of reactors. Several are now under construction. They differ from the latest Magnox reactors primarily in the fuel used. The fuel is UO_2 clad in stainless steel. This permits rather higher fuel temperatures and, hence, coolant temperatures to be achieved, leading to conventional fossil fuel steam conditions (2400 psi, 1025 ^{o}F/1025 ^{o}F). The fuel is in the form of a cluster of small diameter rods, permitting relatively high power levels to be achieved. This reduces the size of the reactor core relative to the Magnox reactors where the fuel is in the form of large single elements. However, because of these fuel changes, the AGR requires some fuel enrichment.

Figure 6 also applies to the AGR reactor type.

The British currently appear to have decided that the AGR is not fully competitive with some other types of power reactors. Hence, this design, like the Magnox type, appears to be "dead-ended".

11.3 HTGCR

This type represents the next evolutionary step in the Magnox-AGR line of gas-cooled, graphite-moderated reactors. It is being developed by Gulf General Atomic in the U.S. and by the West Germans and British.

The HTGCR differs from the AGR in two major respects. The first is the use of helium as the coolant in place of CO_2. This permits even higher coolant temperatures without inducing a chemical reaction with the graphite moderator. The second relates to the fuel. The fuel uses fully enriched (93%) U-235 mixed with thorium. Thorium absorbs neutrons and is converted, after a radioactive decay chain, to U-233 which is fissile. As a result, the reactivity of the fuel remains high even after very long irradiation, the U-233 replacing the U-235 as the latter is burned up. Their fuel is in the form of mixed carbides. It is manufactured in very small spheres which are coated with pyrolytic graphite, the latter providing the cladding. These spheres are compacted into holes in large graphite assemblies, forming an integral fuel and moderator assembly as per Figure 5.

The very high achievable coolant temperatures lead to high steam cycle efficiencies, or alternatively, make possible the ultimate use of gas turbines directly driven by the coolant. Figure 6 applies to the former approach since the basic system is the same as for the Magnox and AGR concepts.

The fuel probably represents the major development problem yet to be completely solved in terms of achieving attractive long-term fuelling costs. This reactor type, because of its high thermal efficiency, would see some preference in areas where waste heat rejection presents a particular problem. The development of the direct cycle gas turbine version would be particularly attractive in this regard.

11.4 PWR

The PWR (pressurized water reactor) has, to date, been the world's most widely accepted power reactor type. It got its start in the development of the PWR propulsion reactors for the U. S. nuclear submarines.

In this type of reactor, ordinary water is used both as the coolant and the moderator. The fuel is in the form of clusters of enriched UO_2 rods clad in zirconium alloy or, in some cases, austenitic stainless steel. These clusters are square in shape, i.e., the rods form a square array in each cluster assembly, with the clusters, in turn, being closely packed in a square array forming the reactor core, see Figure 5. As is shown in Figure 7, the reactor core is located in a large steel pressure vessel. The water coolant at high pressure (~ 2000 psi) is circulated by external pumps into the reactor vessel, flows upwards through the fuel clusters, out of the vessel to heat exchangers, and from the heat exchangers back to the pumps. On the secondary side of the heat exchangers, water is boiled forming saturated steam which drives the turbine. This steam is generated at ~ 750 psi, leading to a relatively low overall station efficiency (~ 30%).

In order to refuel the reactor, it must be shut down, cooled out and depressurized. The top of the pressure vessel is then removed and the fuel assemblies changed. This refuelling is normally done annually. In order to operate for long periods without refuelling, the new fuel is relatively highly enriched in U-235.

While the fuel is new, the excess reactivity in the core is compensated for by a neutron poison dissolved in the coolant/moderator water. As the fuel burns up, the poison is gradually removed by ion exchange columns.

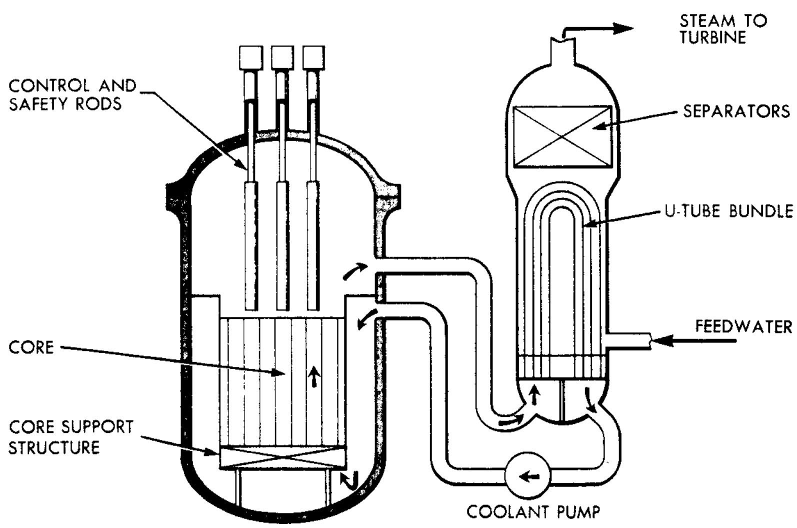

Figure 7 Schematic arrangement - PWR

11.5 BWR

The BWR (boiling water reactor) is second only to the PWR in terms of world-wide acceptance. It is similar in many respects to the PWR, the basic difference being that the light water coolant is permitted to boil in the reactor core. The steam thus produced is separated from the coolant water by centrifugal separators located in the reactor vessel above the core and fed directly to the turbine at ~1000 psi pressure. The general arrangement is as shown in Figure 8.

With this arrangement, the turbine plant is "active" because of activity induced in the reactor coolant (primarily N-16). As a result, the turbine plant is more or less inaccessible during operation; fortunately, however, this activity dies out quickly following shutdown, permitting normal direct access maintenance.

While the BWR appears simpler than the PWR, it has not been able to secure a clear economic advantage over the latter. The two types have run "neck and neck" in the acceptance race for years, both in the U.S. and in many other countries.

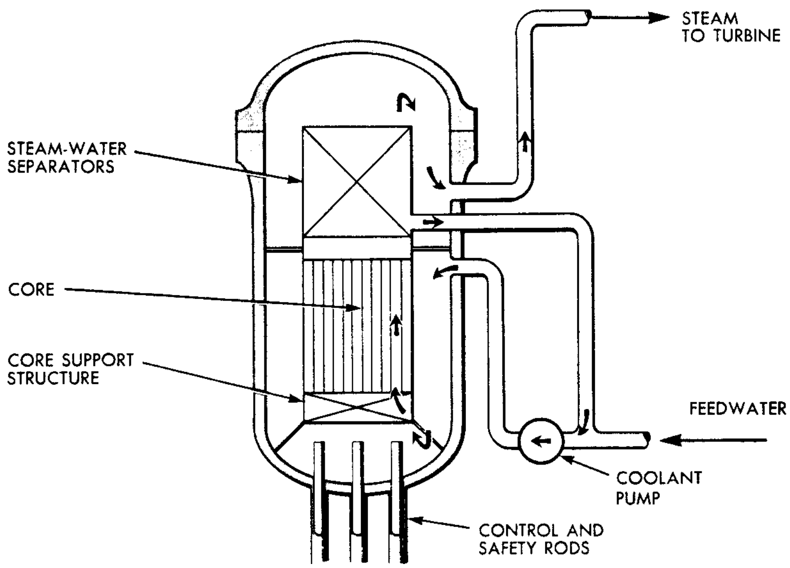

Figure 8 Schematic arrangement - BWR

11.6 LMFBR

Before discussing the last major current commercial type of power reactor, I would like to briefly describe the liquid metal cooled fast breeder reactor (LMFBR). While no reactors of this type are currently in commercial operation.

Firstly, a few "basics". All of the previously described reactors are of the thermal type, i.e., the fissions in the fuel are primarily induced by thermal neutrons. It is, however, possible to sustain a chain reaction with high energy, i.e., fission, neutrons, provided the fuel is highly enriched with fissile material such as U-235 or Pu-239. Furthermore, an average of rather more than two neutrons are born from each fission. One of these neutrons is required to induce the next fission, leaving a surplus of rather more than one neutron which can be absorbed by a "fertile" material such as U-238, producing fissile Pu-239. We can produce fissile material as rapidly as we use it up. This is called "breeding". In fact, it is possible to produce more fissile material than is used because the average number of neutrons produced per fission is >2. The excess is referred to as the "breeding gain". Clearly this can only be done if the neutron economy is high, i. e. , relatively few neutrons are wasted.

This possibility of breeding is very attractive as a means of extending the power available from uranium since, as you will remember, less than 1% of natural uranium is fissile. If a substantial part of the other ~99% can be converted to fissile Pu-239 as a byproduct of reactor operation, then the world's uranium reserves can be stretched enormously. The fast breeder reactor is one way of doing this; hence, the widespread interest in this concept.

The basic arrangement of a liquid metal cooled fast breeder reactor is shown in Figure 9. The reactor core consists of a closely packed array of highly enriched (U-235 or PU-239) oxide rods clad in a high temperature resistant metal. This core is surrounded on all sides by a "breeder blanket" of fertile U-238 (also in clad oxide form) rods. The excess fission neutrons produced in the core "leak" out of the core and are absorbed in the blanket rods. Both the core and blanket are cooled by a flow of liquid sodium. This sodium is, in turn, cooled in heat exchangers and returned to the reactor by more or less conventional centrifugal pumps. The heat exchangers are cooled by a second flow of sodium which, in turn, is cooled in a second set of heat exchangers which produce steam for the turbine. The purpose of this intermediate sodium loop is to provide completely positive isolation between the sodium cooling the reactor and the turbine cycle steam and water, thereby ensuring that an inleakage of water cannot contaminate the reactor coolant.

Despite this intermediate loop, the reactor operating temperature is sufficiently high to permit steam to be produced at modern fossil fuelled plant conditions (~-2400 psig and 1000 ºF with single reheat to 1000 ºF).

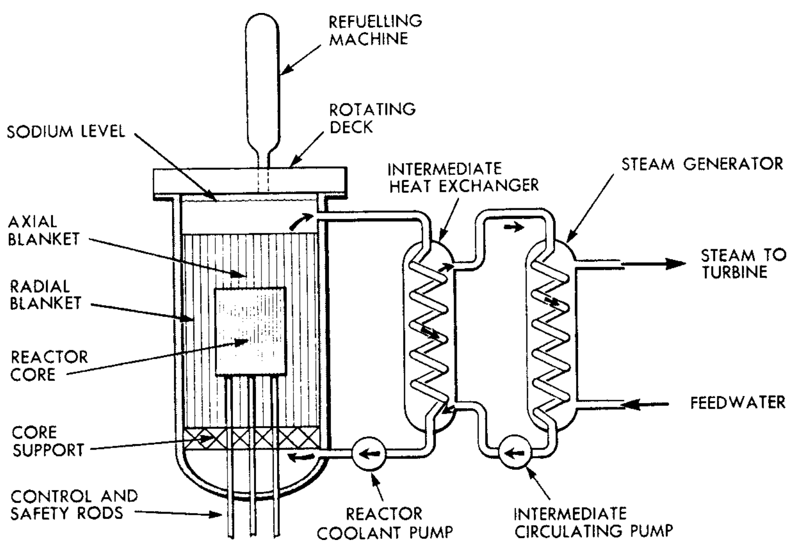

Figure 9 Schematic arrangement - LMFBR

Because of the complex economies and technical problems associated with the LMFBR, while many people feel this is the "reactor of the future", it is probable that the future in this case will be quite a few years in coming.

11.7 CANDU

This, as you know, is the generic name for the Canadian heavy water moderated, natural uranium type power reactor. You will notice that there is no coolant specified in this definition. This is because a variety of coolants can be used.

All CANDU reactors possess certain basic characteristics and features as follows:

11.7.1 Neutron Economy

This is the keystone of the concept. If natural uranium fuel is to be used economically, high burnups must be achieved, i. e., the megawatts extracted per kilogram of uranium must be high. This led to the choice of heavy water as the moderating medium since heavy water is by far the most neutron economic moderator available.

11.7.2 Pressure Tubes

While it is possible to use heavy water in a PWR type of pressure vessel reactor as both the coolant and moderator, the size of pressure vessel required is rather larger than for a PWR because the required volume of D20 moderator is much greater than the required volume of H20 moderator. The early studies of CANDU reactors were based on the pressure vessel approach and, in fact, NPD started out to be a pressure vessel type. It was, however, recognized that the size of pressure vessel manufacturable in Canada at that time would be quite limited, placing a definite limit on the power output achievable when the first commercial units were built. At the same time, the development of zirconium alloy (a neutron economical material) had proceeded to the point where it became possible to employ this material for pressure tubes. Before proceeding to describe the pressure tube approach, I should say that the pressure vessel approach was followed by Sweden and Germany for some years and is still being followed by Kraftwerk-Union for a plant they built in Argentina.

The pressure tube reactor concept can be described as follows. The reactor consists of an array of pressure tubes, generally arranged on a square lattice, which pass through, from end to end, a large cylindrical tank. The reactor fuel, in the form of cylindrical clusters of individual fuel rods, resides inside the pressure tubes. The coolant is pumped through the pressure tubes to cool the fuel. The fact that this coolant is generally at high pressure gives rise to the term "pressure tube".

The heavy water moderator is held in the large cylindrical tank which surrounds the pressure tubes. This large cylindrical tank is called the calandria. Because the coolant, and hence the pressure tubes, must operate at high temperature in a power reactor and because it is desirable to operate the moderator at low temperature to avoid the necessity of pressurizing the calandria, the pressure tubes must be insulated from the moderator. This is done by introducing a second tube which surrounds the pressure tube but is separated from it by a stagnant gas space. This second tube is called the calandria tube. This calandria tube is sealed at both ends to the calandria end plates or tubesheets, thereby completing the moderator containment.

With this arrangement the fuel coolant is completely separated from the moderator, permitting a free choice of coolants.

11.7.3 On-Power Fuelling

If natural uranium fuel is to be employed and high burnups achieved, neutrons must not be wasted needlessly. This is best achieved by introducing new fuel and removing old, burned-up fuel in a "continuous" manner since the excess reactivity possessed by the new fuel can be used to compensate for the loss of reactivity on the part of the old fuel, thereby extending its useful life.

The pressure tube approach lends itself to on-power refuelling since the fuel residing in individual pressure tubes can be changed without affecting other pressure tubes or the fuel in them.

11.7.4 Separate Moderator

As was mentioned earlier, the pressure tube approach used in CANDU reactors permits the heavy water moderator to be kept quite separate from the fuel coolant. This, in turn, permits the moderator to be operated at a low temperature, which has several advantages:

- the calandria can operate at atmospheric pressure, avoiding the need for a heavy, high pressure vessel
- the cold moderator can act as a valuable heat sink under certain accident conditions.
- since the moderator is cold it cannot add energy to the reactor containment under accident conditions. This reduces the total quantity of energy which the containment system must handle.

In the foregoing, I have described certain general features common to all CANDU reactors. I will now discuss the various types of CANDU reactors developed to date.

11.8 CANDU-PHW

This is the pressurized heavy water (PHW) cooled version. It was the first type developed and is by far the most widely used. While not inherently necessary, this version has to date always employed a horizontal reactor core orientation. Vertical versions have been studied a number of times but no clear incentive to switch to this orientation has been identified.

A schematic arrangement of the PHW version is shown in Figure 10. Pressurized (~ 1400 psi) heavy water coolant at~ 480°F is supplied to each fuel channel (an assembly consisting of the zirconium alloy pressure tube with an alloy steel fitting attached at each end) via an individual pipe, called a feeder pipe. As the coolant passes through the fuel channel it picks up heat from the fuel and leaves the channel at ~560°F. It is then conveyed to the outlet header via the outlet feeder pipe. From the outlet header, the coolant flows through the boiler heat exchangers where it is cooled back to ~ 480°F, its heat being given up to produce steam at ~ 600 psi which is fed to the turbine. The coolant then enters the circulating pumps which deliver it to the reactor inlet header and, thence, to the inlet feeder pipes.

A separate auxiliary circuit is employed to circulate the heavy water moderator through external heat exchangers. These reject to the station cooling water the heat generated in the moderator by the slowing down of the neutrons, by the effects of γ radiation, and also the heat leaking into the moderator across the insulation gaps between the calandria tubes and pressure tubes.

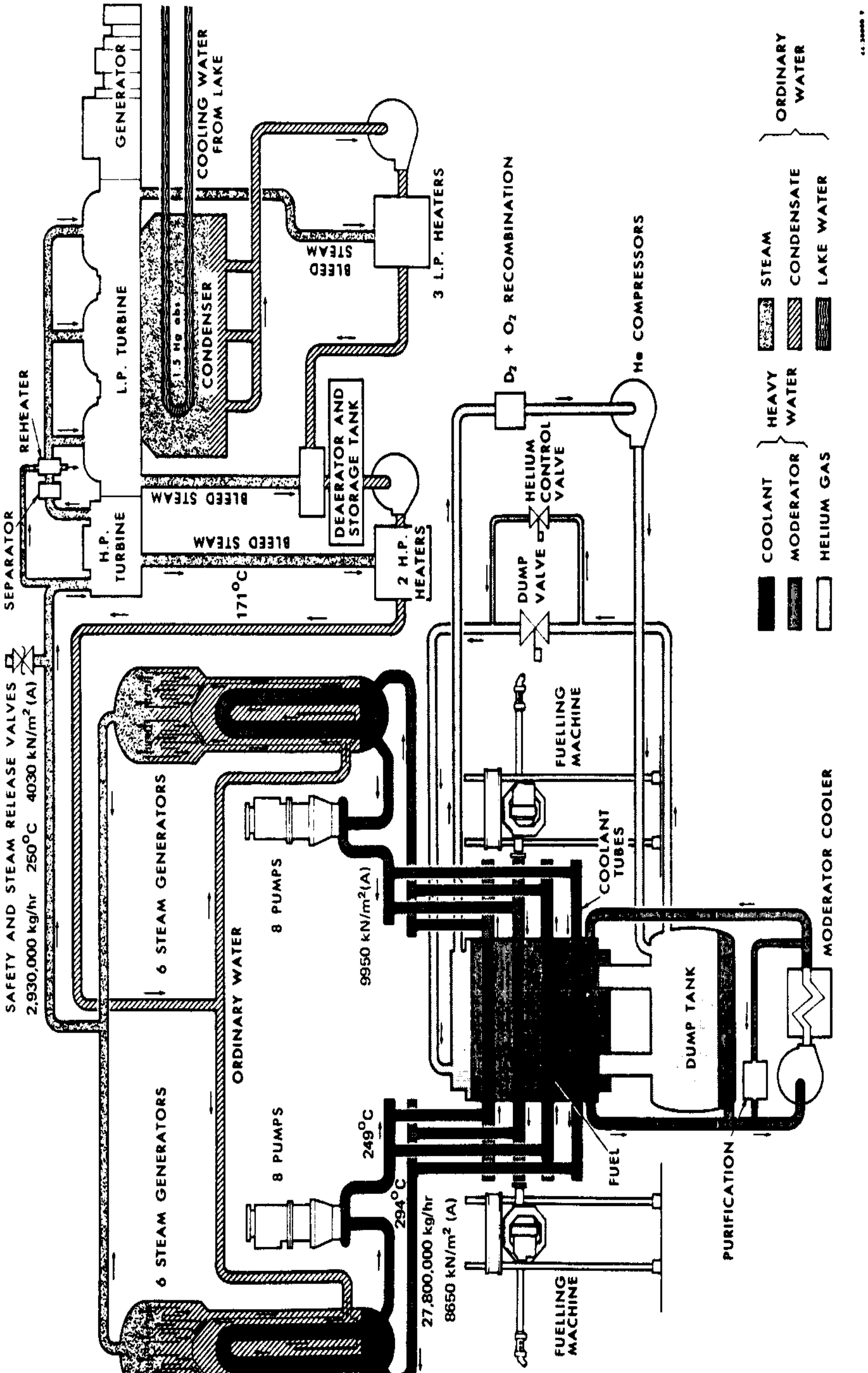

Figure 10 CANDU PWR schematic

11.9 CANDU-BLW

This was the second version of the basic CANDU concept to reach the prototype reactor stage (the 250 MWe Gentilly plant). Its major difference lies in the choice of coolant: boiling light (ordinary) water, hence BLW. Its reactor coolant and turbine systems are fundamentally the same as those of the BWR described earlier, i.e. , a direct cycle is employed.

For this version, a vertical orientation was chosen. There were a number of detailed considerations relating to the boiling coolant which led to this choice. It is likely that future CANDU-BLW reactors will retain this orientation. Design details of the reactor proper will be described later.

Figure 11 provides a schematic illustration of the concept. Ordinary water is pumped to the bottom of each fuel channel via an individual feeder pipe. As the water passes upwards and absorbs heat from the fuel, a fraction (~ 18%) is evaporated to steam. The resulting steam/ water mixture then flows to a conventional steam drum where the steam and water are separated. The steam then flows to the turbine and the water, mixed with incoming feedwater in the drum, flows down to the circulating pumps, completing the cycle.

The moderator cooling system is basically the same as for the PHW version.

The British have developed a similar version which they call the SGHWR (steam generating heavy water reactor). A 100 MWe prototype has been built and is in operation. It differs from our Gentilly prototype in that it uses slightly enriched fuel. This permits rather less heavy water moderator to be used, reducing capital costs. The fuelling costs are, however, somewhat higher. Another possible variation is one in which the enrichment is provided by plutonium which is produced as a by-product in the fuel used in our PHW reactors. This plutonium, as plutonium oxide, would be mixed with natural UO_2 in the fuel.

11.10 CANDU-OCR

A third version of the basic CANDU concept is one which would use an organic fluid as the coolant. It would be similar to the PHW concept except that the boilers would likely be of the "once-through" type with some steam superheating provided. This is made possible by the fact that the coolant temperature at the reactor outlet can be ~ 100 ºC higher than in the case of heavy water cooling.

The WR-1 experimental reactor at our Whiteshell establishment employed this concept except that the heat is "wasted", i. e. , no turbine was provided. The reactor operated with coolant conditions which are the same as would be employed in a commercial power plant.

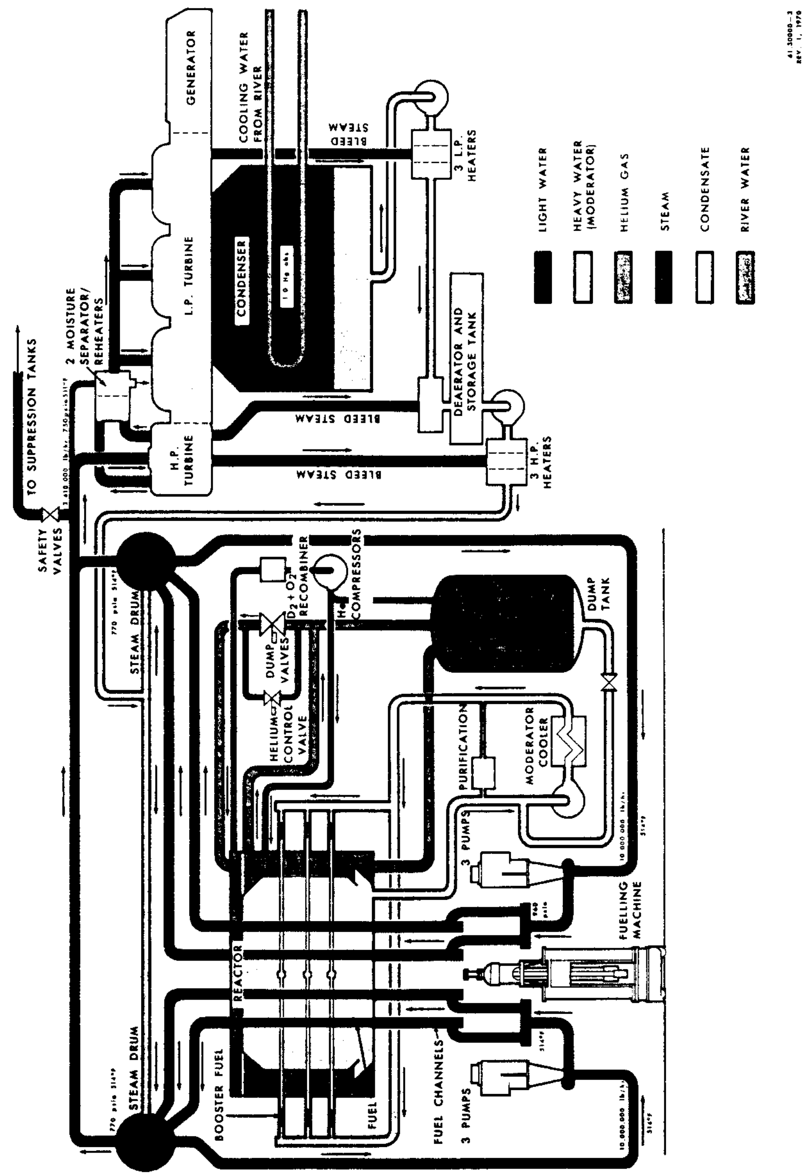

Figure 11 Simplified station flow diagram - CANDU BWR

11.11 A Comparison Between CANDU Reactors and Other Types

Currently the major competitors to the CANDU system are the light water reactors (PWRs and BWRs).

With regard to the competitive position between current commercial reactors, CANDU-PHW on one hand and the light water reactors on the other, neither type has a clear lead in all cases. This arises because of differences in basic characteristics.

From the standpoint of fuelling costs, the CANDU-PHW is the clear winner. This is, of course, because it can use natural uranium fuel whereas the light water reactors require enriched fuel. The enriched fuel is more expensive in several regards. Firstly, there is the cost of producing the enriched UO_2. This appears both as a "consumption" cost and as an added interest cost on the fuel while in manufacture, while resident in the reactor and while awaiting subsequent chemical reprocessing. Secondly, there is a manufacturing cost penalty because of the precautions necessary to avoid a criticality accident. Thirdly, there is a much more severe penalty should the fuel fail before achieving its full burnup life. Such failure is fundamentally more likely with enriched fuel because its "economic" life (burnup) needs to be approximately double that of natural fuel.

From the standpoint of capital costs, the picture is not as clear. The generally held view is that the capital cost of a light water reactor will be considerably lower. This is at least partly attributable to the difference in the way that heavy water and enriched fuel costs are accounted for in common utility practice. The former is treated as a normal plant depreciating capital asset whereas, in fact, it does not really depreciate. The latter is not considered as a capital asset. The fact is, of course, that a large amount of somebody's money is tied up in the enriched fuel. This is not, however, always utility money although the utility ultimately pays for it in terms of interest charges as pointed out earlier.

There is another significant difference which, while real, is not inherently the result of differences between the concepts. Relatively little advantage has been taken to date in the replication of design between CANDU plants. This is because relatively few have been built compared to PWRs. As a result, the CANDU reactors have been burdened with higher engineering costs and in costs arising from longer construction schedules because of relative inexperience. This difference is now diminished because we have built a strong technological base which will permit the replication of most design features from plant to plant.

There is only one way in which a utility can really answer the question as to which type is best for it and this is to go through a full comparative evaluation program based on its own requirements and financing position. Certainly, capital costs quoted in technical journals, newspapers, etc., are meaningless because they are, of necessity, quoted "out of context".

From a purely technical standpoint, one cannot say that one type of reactor has a clear advantage over the other, whether this be in terms of safety, or availability, or ease of operation, or what have you. For example, the use of heavy water at elevated temperatures and pressures for the coolant in the CANDU-PHW imposes strict requirements on coolant system leak-tightness and on systems for recovering leakage. Leakage is, however, not greatly more tolerable in the light water cooled reactors, primarily because of radioactive materials in the water. A, perhaps, compensating feature in another direction is that the on-load refuelling capability of the CANDU-PHW means that fuel defects are much more tolerable since the defective fuel can be readily removed. In the case of the light water reactors, the removal of defective fuel requires a plant shutdown of several weeks' duration.

One last point on the subject of comparisons. The CANDU-PHW is a "water reactor" as are the PWR's and BWR's. They therefore share many of the same advantages and problems. There is no question but that we, in developing the CANDU-PHW, have benefited greatly from much of the R & D work done for the light water reactors. Examples include UO_2 fuel, zirconium alloys for fuel cladding and reactor components, boiler heat exchangers, and main coolant pumps.

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Revision history:

Revision 0.0, September 28, 1998, initial creation
Revision 1.0, March 14, 2001, switch from Word Perfect to Word, added some tables to summarize the text, no new content.
Source document archive location:
D:\TEACH\THAI-TM2\text\CHAP2.doc
Contact person: Wm. J. Garland

Notes: