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Lecture 3

Nuclear power symposium

POWER REACTOR TYPES

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NUCLEAR POWER SYMPOSIUM

LECTURE NO. 3: POWER REACTOR TYPES

by

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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.

This moderating process will be discussed in some detail in Lecture No. 4.

In the first part of this lecture, the various alternative nuclear fuels, coolants, and moderators in current use in commercial power reactors will be discussed.

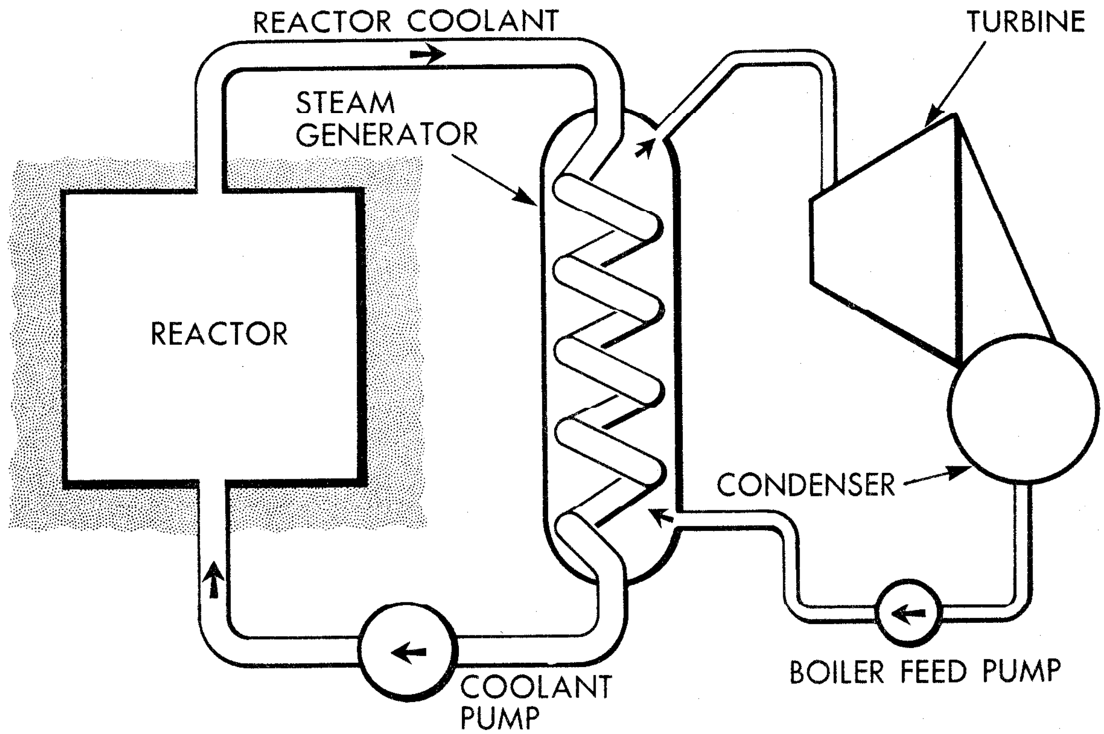

Figure 1 Basic Power Reactor Schematic Arrangement

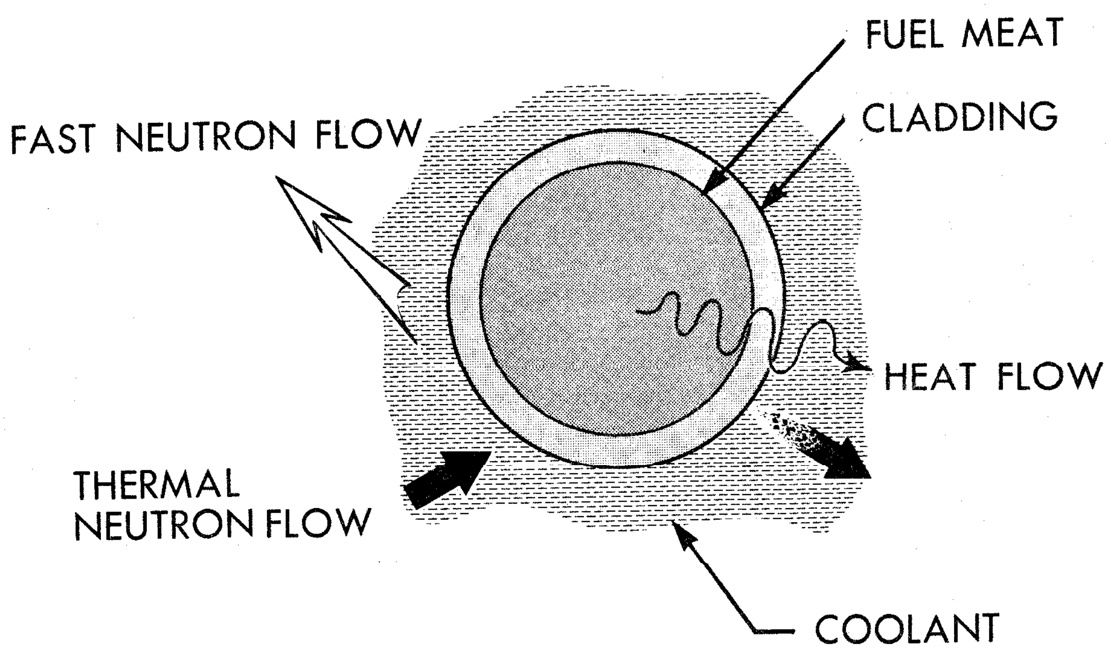

Figure 2 Basic Reactor Fuel Arrangement

2. POWER REACTOR FUELS

Uranium is the basic material used in current power reactor fuels. Uranium, as found in nature, is a mixture of various uranium isotopes. Of these, U-238 is by far the most plentiful. Another isotope, U-235, is, however, the isotope which is readily fissionable in nuclear reactors. This isotope is present in a concentration of $\sim 0.7\%$ in uranium as found in nature, which is termed natural uranium. This brings us to the first major distinction between types of power reactors. Some are capable of operating with natural uranium fuel. These are, of course, called natural uranium reactors. Others require the uranium to have a higher than normal U-235 content. These are called enriched uranium reactors. In order to operate with natural uranium fuel a reactor must be neutron economical. If it is not, enriched uranium must be employed. The basic reactor physics reasons will be covered in Lecture No. 4.

In discussing fuel, coolants and moderators in this lecture, 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 2) 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.

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.

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 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 recent development having most of the advantages of uranium carbide and, in addition, adequate resistance to corrosion by water coolants. While not yet in commercial use, it holds promise for future use in water-cooled reactors.

3. *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 3

ALTERNATIVE FUEL CLADDING MATERIALS

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

TABLE 4

DESIRABLE CLADDING PROPERTIES

1. CORROSION RESISTANCE TO COOLANT
2. MECHANICAL 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 will likely become more and more common in the future, primarily for very high temperature applications. Their primary disadvantage is, of course, a lack of ductility which makes them liable to brittle fracture.

4. 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 5

ALTERNATIVE POWER REACTOR COOLANTS

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

TABLE 6

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, viz., 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. It appears certain that helium will be chosen for all future gas-cooled reactors.

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 incompatability 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.

5. NEUTRON MODERATORS

As will be discussed in Lecture No. 4, 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.

Efficient moderators are those containing a high density of atoms having a low atomic weight, since these atoms are capable of removing a maximum amount of energy from the fission neutrons per collision. In this regard, a "bath" of liquid hydrogen would be the best possible. However, liquid hydrogen would not be practical for obvious reasons.

Before discussing practical moderators, it is firstly useful to consider desirable properties of moderators. These are listed in Table 7. Table 8 then lists the moderators currently used in commercial power reactors.

TABLE 7

DESIRABLE FEATURES OF MODERATOR

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

TABLE 8

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.

6. 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 3. 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

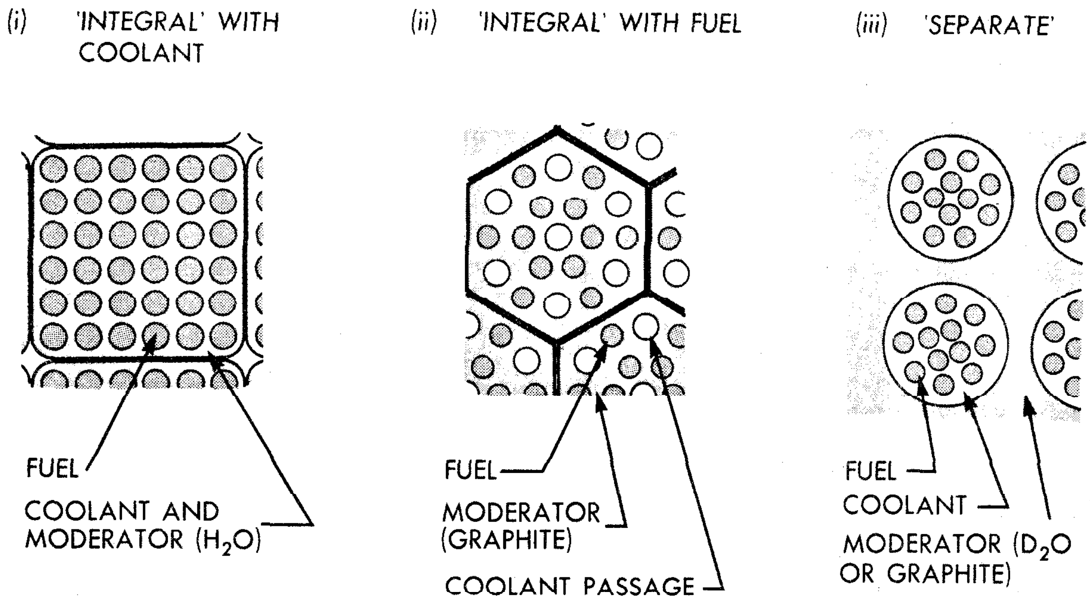

Figure 3 Moderating Arrangement

with a hydrogen-based moderator. Hence, the fuel rods can be located relatively close to each other. This arrangement is used in both PWR's and BWR's.

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.

7. 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 which I haven't mentioned. 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 a new technology. A number of the possible combinations have reached the point of commercial exploitation or will, in all likelihood, do so. I will describe these briefly in the following subsections.

7.1 "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 4 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 4, 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 $\sim 30\%$.

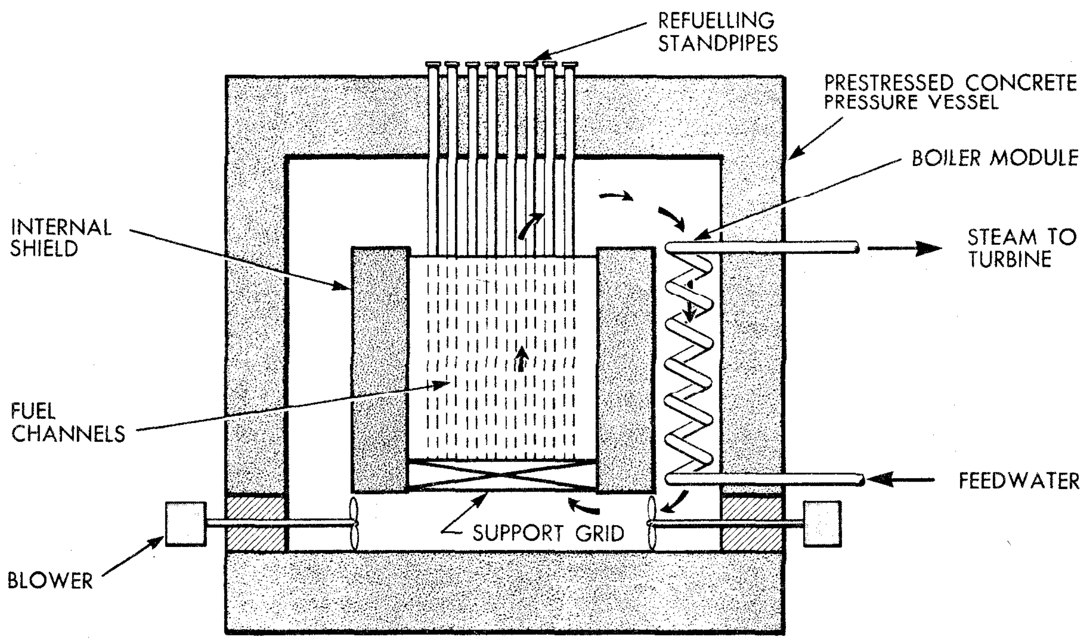

Figure 4 Schematic Arrangement - Gas Cooled Reactors

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.

7.2 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, $1025^oF/1025^oF$). 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 4 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".

7.3 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 first large prototype, the 330 MWe Ft. St. Vrain reactor in Colorado, is due to start up shortly.

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 (Lecture No. 2), 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 3.

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 4 applies to the former approach since the basic system is the same as for the Magnox and AGR concepts.

There is little doubt but that the HTGCR is a very attractive future concept. Small prototypes have demonstrated that acceptable helium leakage rates can be achieved.

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, is expected to see early commercial acceptance 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.

7.4 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 3. As is shown in Figure 5, the reactor core is located in a large steel pressure vessel. The water coolant at high pressure ($\sim$ 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 $\sim$ 750 psi, leading to a relatively low overall station efficiency ($\sim$ 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.

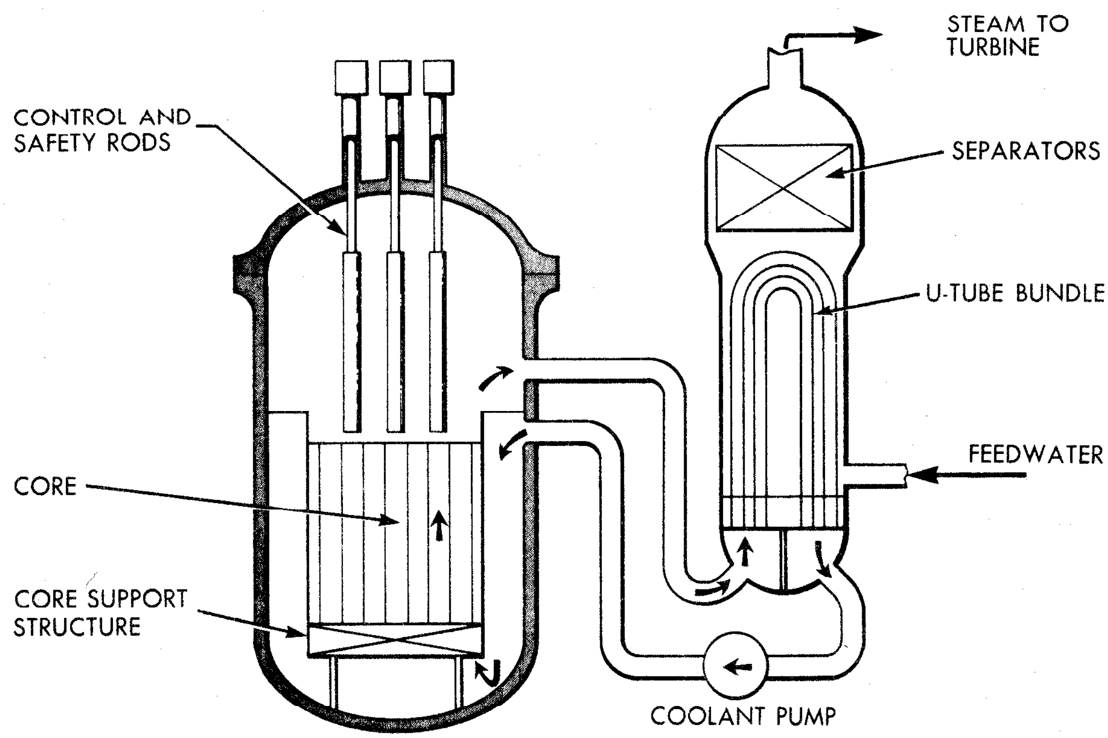

Figure 5 Schematic Arrangement PWR

7.5 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 $\sim$ 1000 psi pressure. The general arrangement is as shown in Figure 6.

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 for a variety of reasons which time does not permit me to go into. The two types have run "neck and neck" in the acceptance race for years, both in the U.S. and in many other countries.

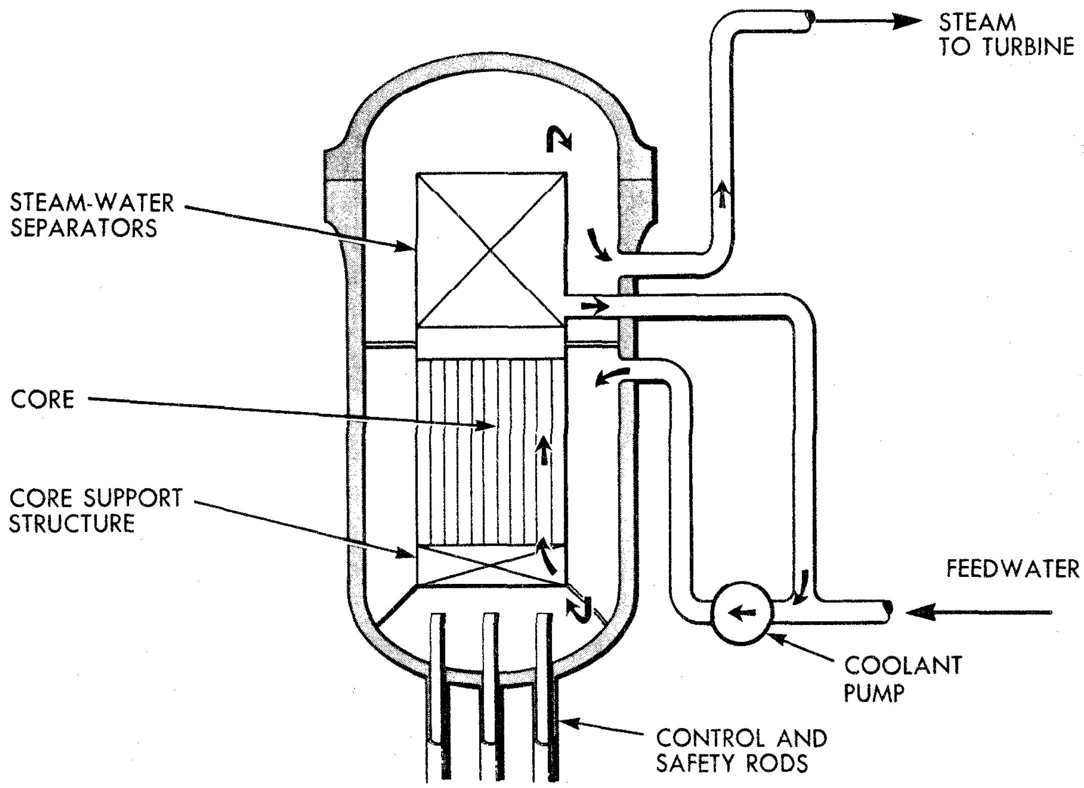

Figure 6 Schematic Arrangement BWR

7.6 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, it is a widely-held view that they will, in due course, become the dominant type.

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, as will be explained in Lecture No. 4, 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. It will therefore be seen that 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 7. Time does not permit me to explain all the "whys" so I will simply describe the system. 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 in-leakage 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°F with single reheat to 1000°F).

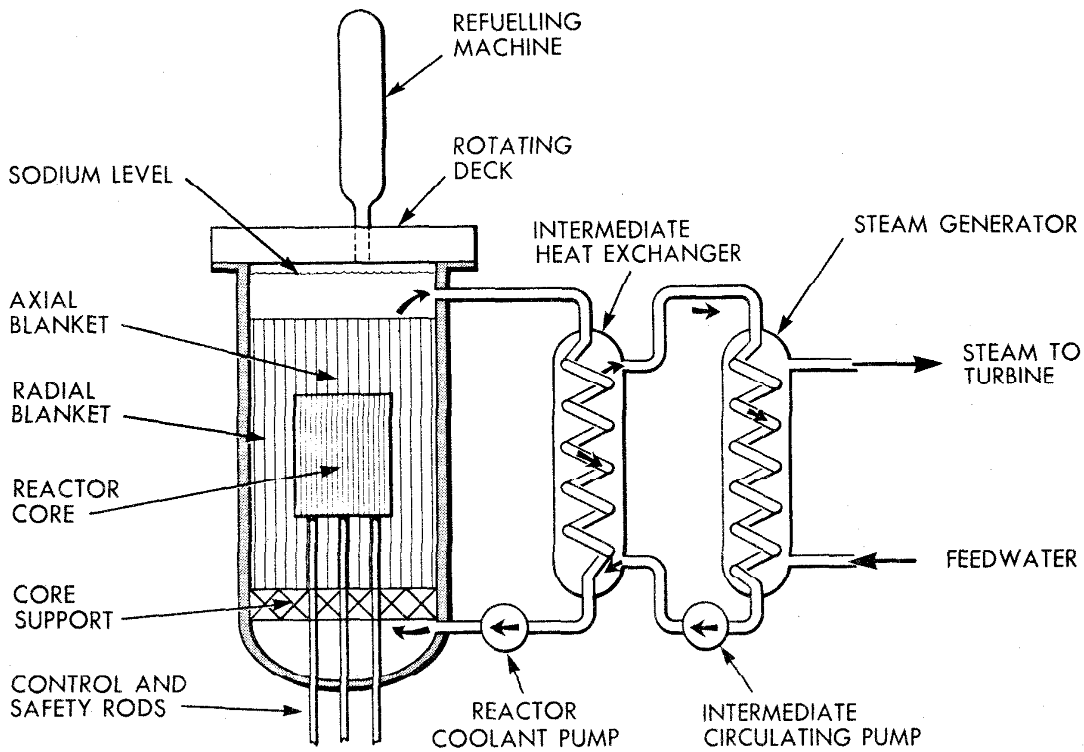

Figure 7 Schematic Arrangement LMFBR

Time does not permit me to discuss the complex economies and technical problems associated with the LMFBR. Suffice it to say that 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.

7.7 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:

(i) 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.

(ii) 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 D_2O moderator is much greater than the required volume of H_2O 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 are currently building 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.

It will be seen that with this arrangement the fuel coolant is completely separated from the moderator, permitting a free choice of coolants.

The foregoing mechanical features are shown for two types of CANDU reactors in Figures 10 and 13. The design details will be discussed later.

(iii) 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. The way in which this on-power refuelling is done is the subject of Lecture No. 5.

(iv) 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 as will be described in Lecture No. 11.

- 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. This also will be discussed in a later lecture.

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.

7.7.1 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. Design details of the reactor proper will be discussed later.

A schematic arrangement of the PHW version is shown in Figure 8. Pressurized ($\sim$ 1400 psi) heavy water coolant at $\sim 480^{\circ}$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 $\sim 560^{\circ}$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 $\sim 480^{\circ}$F, its heat being given up to produce steam at $\sim$ 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.

The foregoing describes the basic system; a much more detailed description will be provided in later lectures.

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.

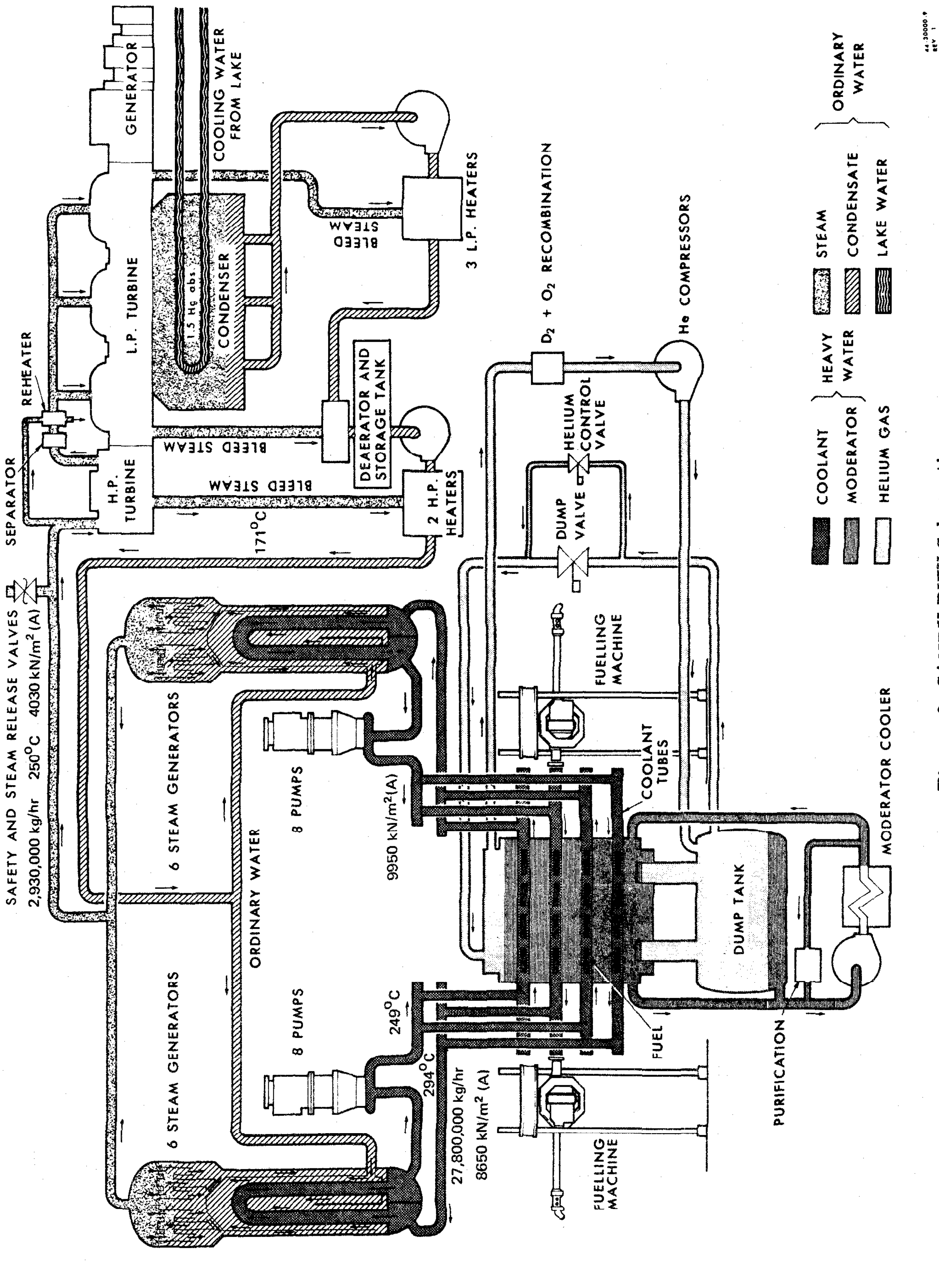

Figure 8 CANDU PHW Schematic

7.7.2 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, viz., 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 9 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 ($\sim$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. We are currently studying a similar version but 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.

7.7.3 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

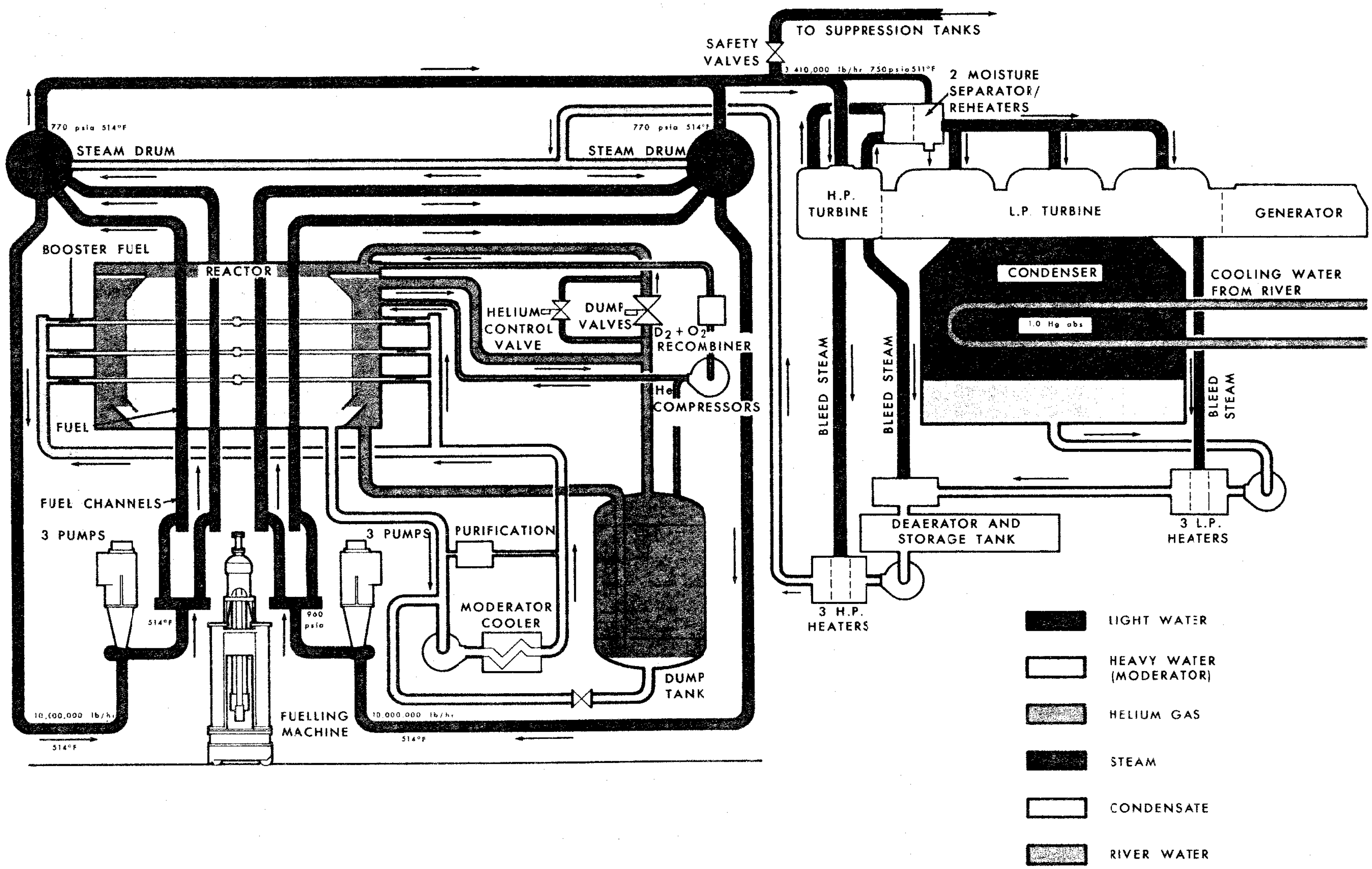

FIGURE 9 SIMPLIFIED STATION FLOW DIAGRAM -CANDU BLW

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that the coolant temperature at the reactor outlet can be $\sim 100^{o}C$ higher than in the case of heavy water cooling.

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

7.7.4 A Comparison Between CANDU Reactors and Other Types

Currently the major competitors to the CANDU system are the light water reactors (PWR's and BWR's). In the not too distant future, the main competitor may be the HTGCR.

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. 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 will now diminish 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.

The foregoing comments apply generally. How do CANDU-PHW's stack up in comparison for Canadian application? In addition to the foregoing, the following features make the CANDU-PHW particularly attractive.

(i) We can produce our own fuel within Canada since natural uranium is used. This frees us from dependence on foreign controlled supplies of enriched uranium and helps with our trade balance.

(ii) The pressure tube concept is compatible with the "size and weight" capabilities of heavy Canadian manufacturing industry. Only relatively modest investments in new plant and equipment have been required.

8. CANDU REACTOR DESIGNS

In this final section, I will describe the main design features of two CANDU reactors. The first is of the PHW type and the second is of the BLW type. I will be discussing only the reactors themselves. Other parts of the overall reactor plants will be described in later lectures.

8.1 CANDU-PHW

As a typical example of this version, I have chosen the Pickering design. The following provides a general description of the design of the reactor proper, followed by a more detailed description of the major components of the reactor.

8.1.1 General

The reactor is a heavy water moderated, pressurized heavy water cooled, natural uranium dioxide fuelled, horizontal coolant tube reactor. Figure 10 shows the general arrangement of the major components. These include the calandria with integral end shields and peripheral internal thermal shields, the dump tank with connections to the calandria, the helium cover gas system connections, and the fuel channel assemblies and connected feeder piping. The pressure tubes, in which the fuel resides, are located within 390 calandria tubes and are supported in sliding bearings in the end shields of the calandria.

The pressure tubes are separated from the calandria tubes by sealed annuli containing dry nitrogen. Heavy water which fills the calandria serves as moderator, reflector and coolant for the peripheral thermal shields. Helium fills the pipes connected to the top of the calandria and occupies space above the heavy water if the water level is below full calandria.

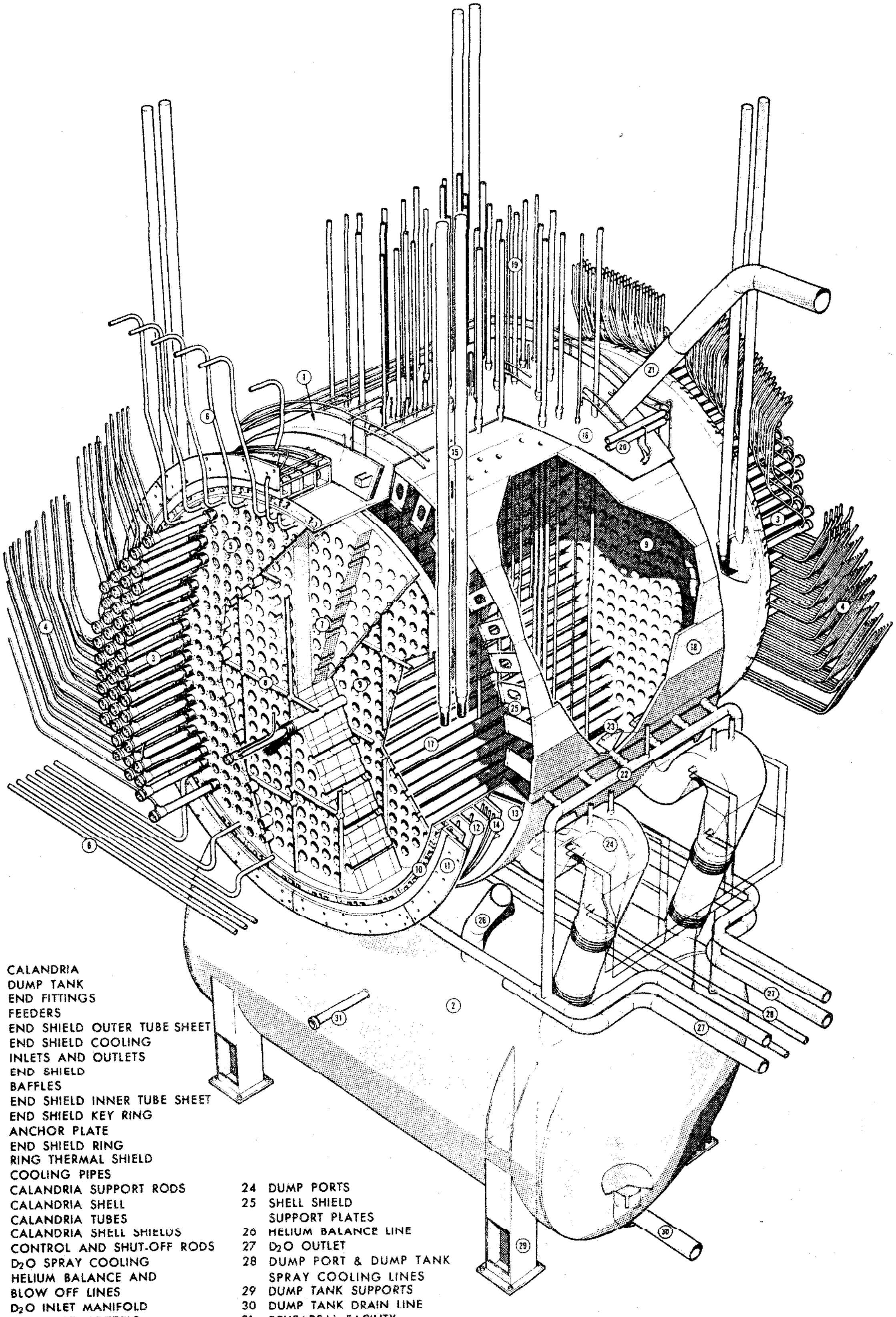

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Figure 10 Pickering Reactor Arrangement

Below the calandria and connected to it by four moderator discharge ports is the cylindrical dump tank. The goose-neck shaped discharge ports provide for a gas-liquid interface between helium in the dump tank and moderator in the calandria. During operation the helium in the dump tank is held at a pressure in excess of that in the top of the calandria by an amount equal to the height of heavy water above the gas-liquid interface. When the helium pressure above the moderator in the calandria and that in the dump tank is made equal by inter-connection, the moderator is "dumped" by gravity into the dump tank shutting down the reactor.

Shielding from direct radiation from the reactor is provided by heavy concrete (ilmenite aggregate) forming the calandria vault and by the steel and water end shields of the calandria. The large opening in the south wall of the calandria vault, which is provided to permit entry of the major reactor components, is subsequently filled by heavy concrete. The internal thermal shields in the calandria reduce the intensity of radiation reaching the walls of the calandria vault. Heat produced in the concrete is removed by one layer of cooling coils embedded in the concrete. Cooling water in a closed circuit is circulated through the coils.

Fuel for the reactor is in the form of bundles, 19.5 inches long. Each bundle consists of 28 hermetically sealed elements containing compacted and sintered pellets of UO_2. The elements are attached mechanically at their end to form a cylinder 4.03 inches in diameter with a small space being maintained between each element by spacers attached to the element cladding.

Loading of new fuel into the reactor and removing spent fuel is carried out "on power" by two co-ordinated fuelling machines controlled from the station control centre. This will be described in a later lecture.

8.1.2 <u>Calandria</u>

The calandria is a horizontal single-walled austenitic stainless steel cylindrical vessel which provides containment for the heavy water moderator and reflector. It has internal peripheral thermal shell shields of 4-1/2 inch thick austenitic stainless steel slabs which are positioned close to the cylinder wall of the vessel. At each end and integral with the calandria shell are combination thermal-biological shields. These end shields provide support for the calandria shell and for the calandria tubes which are rolled into the inner tubesheets of each end shield.

The 390 Zircaloy-2 calandria tubes are spaced on an 11-1/4 inch square lattice. At each end the vessel is stepped down in diameter to provide an internal corner cutout. The complete calandria is supported at the ends by eight support rods. Facilities to dump the moderator are provided through four rectangular dump ports, which form syphon-shaped ducts connected to the dump tank. These ducts act as water traps, and are located near the bottom of the vessel. A helium balance line, 16 inches in diameter, connects to the top of the vessel through one of two 18-inch diameter pressure relief ducts. Each 18-inch duct has a branch with a rupture disc at its end to act as a pressure-relief, in the unlikely event of an overpressure condition in the calandria shell, resulting from a burst pressure tube and calandria tube.

All the reactivity control mechanisms penetrate the reactor from the top of the calandria. Typical details of the calandria are shown in Figure 10.

The calandria shell and dump ports are fabricated from austenitic stainless steel. The details of construction and the design stresses are generally in accordance with the requirements of Section III of the ASME Boiler and Pressure Vessel Code for a Class A vessel. All shell main welds are of the full-penetration type and have been subjected to radiographic and/or ultrasonic inspection.

Rolled joints are used to join the calandria tubes to the calandria tube-sheets. The joint uses a "landed" sleeve insert in compression to give a strong leak-tight joint with a relatively thin calandria tube. The calandria tube thickness has been kept to a minimum for the sake of neutron economy.

The step at each end of the calandria provides an annular section of the shell which can deflect to allow for the differential thermal expansion of the Zircaloy-2 calandria tubes and the stainless steel shell of the vessel. The dimensions of the step were selected to achieve the optimum reduction in heavy water in the low-flux regions of the reactor, and to maintain an adequate minimum radial clearance from the calandria tubes at the ends of the calandria shell.

The arrangement of a discharge or dump port is shown in Figure 10. The interface between the moderator in the calandria and the helium in the dump tank occurs in the dump ports.

The dump ports are rectangular ducts where they fit onto the calandria main shell in its lower quadrants. Before entering the dump tank they change to circular sections to allow for the incorporation of an expansion joint. The circular portion is 30 inches in diameter, while the rectangular portion starts as 24 inch x 40 inch and then contracts to 18 inch x 40 inch before changing to the circular shape.

The two moderator inlet manifolds, which are located on either side of the calandria just below the middle, supply two sets of six upturned nozzles feeding cool moderator into the reflector region between the reactor core and the shell shield slabs. The shape and direction of the nozzles prevent direct impingement of the incoming flow on the calandria tubes. The mixing action of the incoming flows causes the moderator to flow downward between the calandria tubes resulting in nearly uniform temperatures throughout.

Four moderator outlets are located at the bottom of the calandria.

Both during reactor operation and during shutdown periods, the shell shields and all internal exposed metal of the reactor, including pressure relief nozzles, dump ports, calandria tubes, and control rods are subject to heating due to radiation. To prevent overheating of parts not in continuous contact with the moderator, the calandria is fitted with 25 spray nozzle clusters at its top. These provide a drenching spray throughout the entire interior of the calandria. The sprays operate continuously so as to cool continuously any part not covered by moderator, except for the calandria shell.

The calandria shell is adequately protected by the shell shields from overheating at power levels which are permitted when the moderator level is below full calandria.

8.1.3 Calandria End Shields

The two end shields are located at either end of the calandria shell and are integral with it. Each end shield consists of four layers of steel slabs, totalling 2 feet 11-1/2 inches in thickness, plus the inner and outer austenitic stainless steel tubesheets, of 5 inch combined thickness, plus two 2-1/2 inch thick layers of cooling water adjacent to the tubesheets. The circumferential plate is of austenitic stainless steel 2 inches thick. The overall diameter of an end shield, including the circumferential plate, is 22 feet 9 inches.

The end shields are penetrated by 390 horizontal passages for reactor fuel channel end fittings and are fitted with austenitic stainless steel lattice tubes which surround, support and guide the end fittings and are welded into the tubesheets at either end.

The end shield assemblies form a part of the calandria vault enclosure and provide shielding to reduce the radiation reaching the fuelling machine vaults to a level which permits occupancy during shutdown. They are an integral part of the calandria structure and the whole weight of fuel, moderator, calandria and end shields is carried by four pairs of support rods, two pairs attached to each end shield. Each end shield assembly is located centrally within an end shield ring which is grouted into the calandria vault wall.

Each end shield assembly contains ten slabs of steel, making a core 22 feet 5 inches in diameter and 2 feet 11-1/2 inches thick. The material used for the slabs is carbon steel. Two upper 12-inch semi-circular sections are each in one piece and carry the weight of the calandria end shield assembly to the support rods. The various shielding slabs are sandwiched together without welding, and are held together as an assembly by keys and bolts. The circumferential plates are shrunk onto the machined shielding slabs and welded to the tubesheets. The circumferential plates are 2 inches thick and, like the tubesheets and lattice tubes, are type 304L austenitic stainless steel. The inner tubesheet is 2-3/4 inches thick and the outer tube-sheet is 2-1/4 inches thick. The 390 holes in the end shield slabs around the stepped lattice tubes are 8-9/16 inches in diameter toward the inner end and 9-3/16 inches in diameter toward the outer end and provide 3/8 inch wide annular cooling passages which interconnect the water spaces at either end. Baffles within each water space provide a six-channel multi-pass cooling flow arrangement with cooling water entering at six points at the bottom of the shield and leaving at the top. The cooling passages are generously sized to preclude the possibility of internal fouling. The end shield assemblies are weldments, weighing approximately 245 tons apiece.

The nuclear heat generated in the slabs and the heat transferred from the end fittings and tubesheets amounts to approximately 1600 kW per end shield. To keep the operating temperature of the steel in the end shields at approximately 150°F, the velocity and rate of flow of the cooling water within the end shields has been selected to keep temperature differences small; hence, the outlet temperature of approximately 146°F.

8.1.4 Calandria and End Shield Support

The calandria with its integral end shields, which are located at the two ends of the calandria, is supported by four pairs of 5-5/8 inch diameter by 28-1/2 feet long carbon steel rods, screwed into carbon steel inserts, which in turn are screwed into the upper halves of the central slabs of the end shields. Keys between the slabs transfer the load to the two supported slabs in each end shield assembly.

Since the calandria shell and end shields form an integral assembly, alignment between the calandria end shields is not a problem. Because the support rods are normally quite cool, water cooling is not necessary, and relative movement between the end shields and end shield rings will be small.

The support rods are designed so that the stress level results in a small (approximately 0.020 inch) vertical movement of the calandria between its full and dumped condition. The rods are supported from assemblies located on top of the calandria vault structure.

Tie rods and keys between the end shield ring and the end shields align and restrain movement of the whole calandria. The rods at the east end restrain axial movement, so that the calandria is free to expand axially at the west end. Keys at the top and bottom restrain lateral movement of the calandria at both ends, but allow radial expansion.

8.1.5 End Shield Rings

The two carbon steel end shield rings are grouted into circular openings in the calandria vault walls. Each ring comprises a cylindrical shell, on the outside of which five annular flanges are spaced and welded circumferentially. The addition of stiffener bars attached to each flange provides a rigid structure.

The end shield rings serve three main purposes. They provide (a) increased radiation shielding in high flux regions, (b) structures to which the end shields are keyed, thus restraining the calandria assembly in the required position, and (c) accurate openings to contain the end shields and accommodate radial and axial expansion of the calandria.

Provision is made to prevent neutron streaming through the annular gap between the end shields and rings. Piping is installed within the ring structures to remove heat generated by the immergent heat current, caused by radiation from the calandria and heat transmitted from the end shields, end fittings and feeder pipes.

8.1.6 Dump Tank

The dump tank, shown in Figure 10, is a horizontal cylindrical austenitic stainless steel vessel with dished heads. It is 38 feet 4 inches long and 18 feet 3 inches in diameter. It is located in the calandria vault directly below the calandria and its longitudinal axis is at 90° to that of the calandria. It is connected to the calandria by four dump ports attached to its upper two quadrants, at either end of the tank, through expansion joints. The expansion joints allow for vertical and lateral movement of the calandria relative to the dump tank.

The dump tank is supported from the floor by four flexible legs to accommodate thermal movements. The calandria is fixed at the east end, and in order to minimize relative movement between the calandria and the dump tank, the two legs on the east side will only deflect axially. The other two legs are free to deflect in any direction.

The dump tank has connections for the supply of spray cooling, with duplicated feed pipes, and for transfer of heavy water and helium to the moderator circuit and helium system. A sump located at one end of the tank, at the bottom, ends in the D_2O drain connection. This sump allows for the necessary rate of water removal from the tank without helium entrainment during pump-up.

8.1.7 Fuel Channel Assemblies

The primary function of the 390 fuel channel assemblies is to house the reactor fuel and to direct the flow of primary coolant past it to remove the nuclear heat. Each coolant assembly consists of a zirconium alloy pressure tube to which is attached at each end a ferritic stainless steel end fitting. The zirconium alloy pressure tube provides a low neutron capture containment structure for the primary coolant within the reactor core, while the end fittings provide entry and exit connections both to the primary system and to the reactor fuelling system.

Figure 11 provides an illustration of a fuel channel. The pressure tubes have the following parameters:

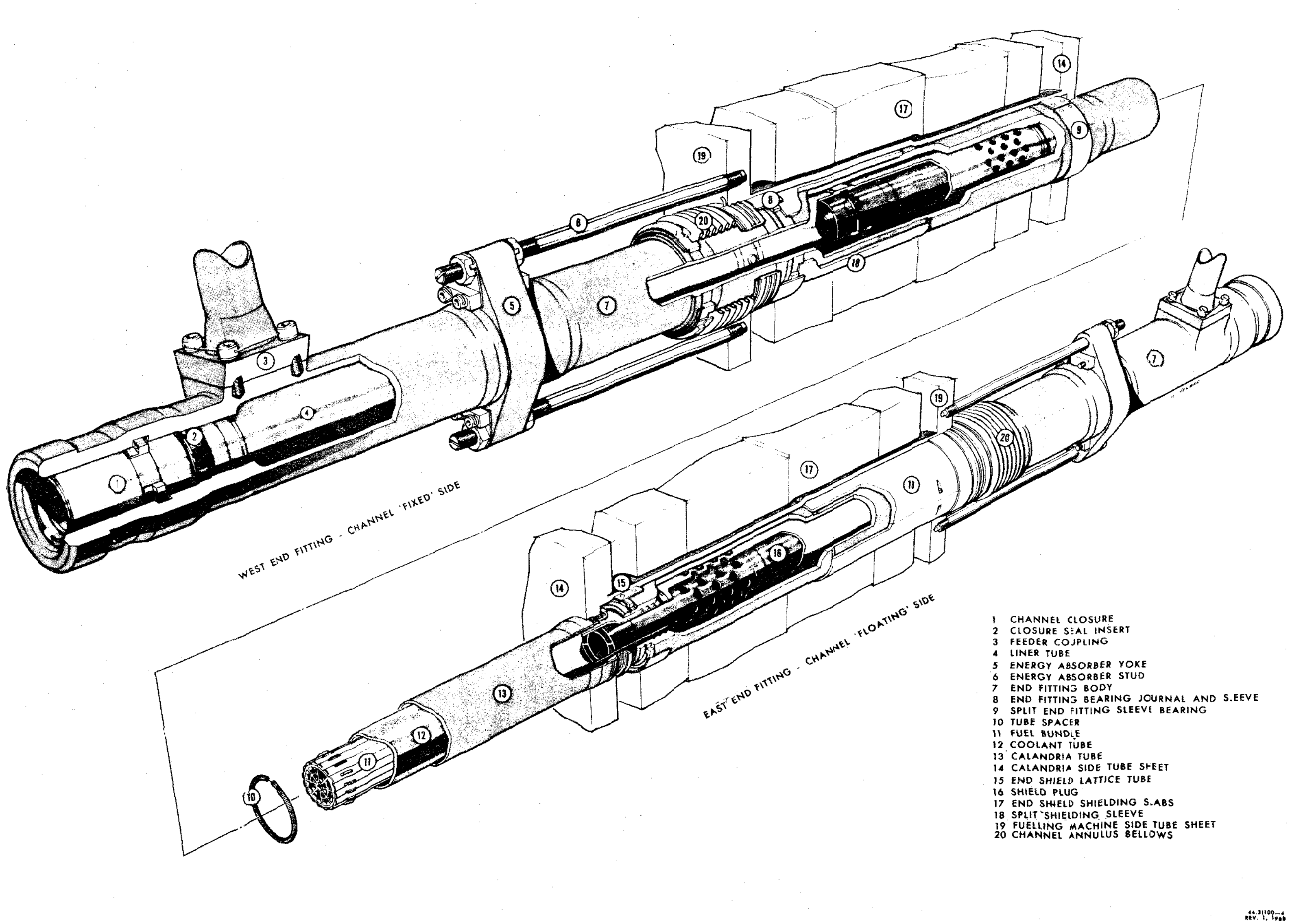


Figure 11 Pickering Fuel Channel

	Unit 1 & 2	Unit 3 & 4
Internal diameter (minimum)	4.07 in.	4.07 in.
Minimum wall thickness	0.1965 in.	0.160 in.
Length, approx. (trimmed for installation)	20 ft. 8 in.	20 ft. 8 in.
Material	Cold drawn Zircaloy-2 autoclaved at 750°F	Zirconium 2.5% Niobium cold drawn, stress relieved at 750°F

Zirconium 2½% Niobium is preferable to Zircaloy for coolant tubes because of higher strength and superior creep properties even at higher stresses. It was not used for Units 1 and 2 because there was insufficient manufacturing experience and inadequate data on corrosion properties at the time the order was placed for the tube material.

The inlet and outlet end fittings are identical and are fabricated from ferritic type 410 stainless steel extrusions. The fittings are approximately 6-1/2 inches external diameter by 8 feet 4 inches long. The pressure tubes are rolled into the end fittings with a three-groove joint.

The end fittings are designed to provide the following:

(a) Transition joints between the pressure tubes and the primary circuit piping.

(b) Support for the pressure tubes and their contents.

(c) Suitable configuration to make a pressure tight connection with the fuelling machines and to allow insertion and removal of fuel during operation of the primary coolant system.

(d) Shielding for the penetrations through the reactor end shield to permit access to the fuelling machine vaults and the face of the end shields, at shutdown, for servicing.

(e) Sealing for the annulus between the coolant and calandria tubes to maintain a protective atmosphere within.

The features of the end fittings which satisfy the above are as follows.

A feeder connection flange on each end fitting provides for attachment to a primary coolant feeder pipe with a metal gasket. This joint is accessible for remaking from the fuelling machine area, if required. Internally, the end fittings contain a liner tube extending from near the outboard end to a point adjacent to, but not in contact with, the end of the pressure tube. The liner tube forms the inner wall of an annular coolant channel joined to the feeder connection. Radial holes in the liner tube permit the coolant to enter or leave the fuel channel beyond the end of the string of fuel.

A stop prevents the end fitting from blowing out of the lattice in the event of a tube fracture or failure of the expanded joint.

Annulus sealing is provided by an Inconel bellows attached to the end fitting and to the end shield tube sheet. The bellows also resists rotation of the end fitting by feeder pipe moments, and thereby keeps torsional stresses in the pressure tubes very low.

A type 410 stainless steel shield plug 39 inches long resides in the liner tube. It is located axially by retractable jaws which seat in a groove in the liner tube. The forward or inner end of the shield plug, which overlaps the coolant entry or exit radial holes in the liner tube, contains a fuel support plate. The flow through the channels furthest from the reactor centre is trimmed by using smaller diameter feeders.

A removable channel closure is located at the outboard end of each end fitting. These closures are held in place by retractable jaws. The closure is fitted with a seal disc which provides containment of the primary system coolant. The design and support of the seal disc is such that the primary system pressure increases the unit loading at the seal surface, thus improving the seal. The sealing contact is soft nickel plate on the face of the seal disc, bearing against a replaceable hardened seat in the end fitting.

The end fitting bodies are mounted in the lattice tubes of the end shields. The passage between each end fitting and the lattice tube is stepped to prevent radiation streaming. Each end fitting is supported at the inner and outer end of the end shield lattice tube on a non-lubricated metal to metal bearing. These bearings provide alignment and positioning for the end fitting and permit end movement. All fuel channel assemblies are held stationary with respect to the end shield by adjustable positioners at the "fixed" (west) end. The positioners can withstand the axial thrust of a blown seal plug or a ruptured pressure tube. At the east or "floating" end, energy absorbers are designed to catch and hold the end fitting in the end shield in the event of a failure of the pressure tube, its expanded joint, or an end fitting.

8.1.8 Calandria Vault

The calandria vault, shown in Figure 12, is of rectangular shape with inside dimensions of 19 feet 6 inches wide, 35 feet 2 inches long and 54 feet 10 inches high. It provides an enclosure, the radiation shielding and support for the calandria vessel and dump tank. The entire structure is of heavy concrete (north and south walls 4 feet 6 inches thick, east and west walls 3 feet 9-1/2 inches thick, and roof 10 feet 6 inches thick) with a nominal density of 210 lb/ft^3 using the ilmenite ore aggregate. In order to allow independent vertical movement (from thermal expansion and shrinkage), the vault is built completely separate from all adjacent structures. Contact with the surrounding ordinary structural concrete is limited to points at the edge of the boiler room floor. These contact areas are located at the top corners of the vault and provide lateral support in the east-west direction (19 feet 6 inch dimension) during unbalanced emergency pressure loading and earthquake conditions.

Embedded into the east and west walls of the vault, i.e., between the reactor and the east and west fuelling machine vaults, are the end shield rings which receive and locate the end shields.

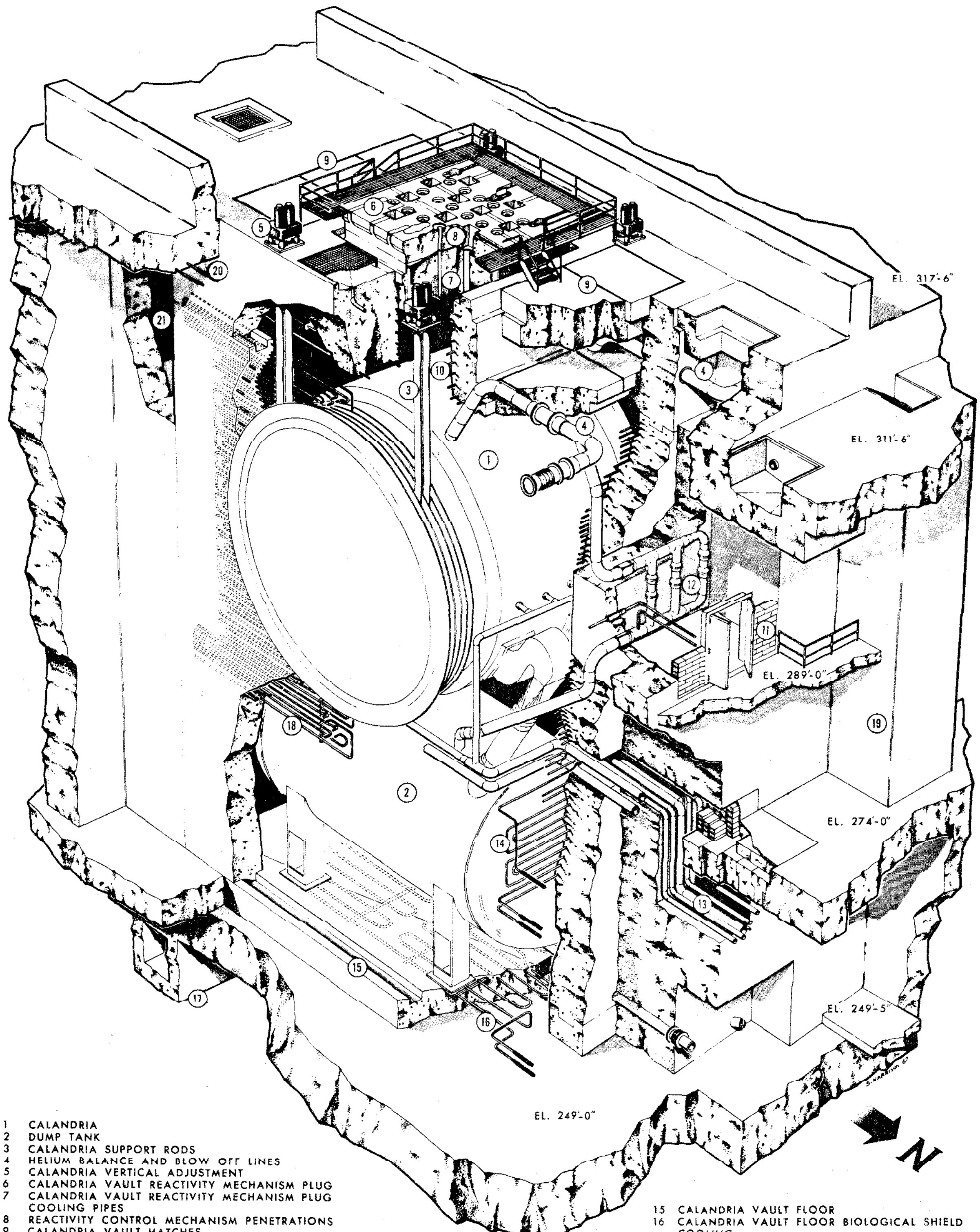
Two 18-inch calandria overpressure blowoff lines pass through carbon steel sleeves embedded into the north wall of the vault and leading into the top of a vertical pipe shaft. One line then leads to the upper northeast corner of the west fuelling machine vault and the other to the upper northwest corner of the east fuelling machine vault. Sealing and locking of the embedded sleeves into the heavy concrete is achieved by using suitably positioned steel flanges seal welded to the sleeve outside diameter and embedded into the concrete to form a labyrinth type seal, backed up with an epoxy grout filled pocket placed between the concrete and the sleeve. Access to the vertical shaft is via a hatch beam at the boiler room floor level.

Sealing of the annular space between the embedded sleeve inside diameter and the blowoff pipe outside diameter is with a metal bellows seal suitably welded into place.

Adjacent to the north wall of the vault is an ordinary structural concrete wall 11 feet 9-1/2 inches thick into which is cast:

(1) A valve chest (floor elevation 289 feet 6 inches) to contain the helium balance valves;

(2) a pipe labyrinth (floor elevation 262 feet 8 inches) at outside face and rising to elevation 272 feet 2-1/2 inches at inside face of vault; and



1 CALANDRIA
2 DUMP TANK
3 CALANDRIA SUPPORT RODS
4 HELIUM BALANCE AND BLOW OFF LINES
5 CALANDRIA VERTICAL ADJUSTMENT
6 CALANDRIA VAULT REACTIVITY MECHANISM PLUG
7 CALANDRIA VAULT REACTIVITY MECHANISM PLUG COOLING PIPES
8 REACTIVITY CONTROL MECHANISM PENETRATIONS
9 CALANDRIA VAULT *HATCHES*
10 CALANDRIA VAULT ROOF BIOLOGICAL SHIELD COOLING
11 HEAVY CONCRETE BLOCK WALL
12 HELIUM VALVE CHAMBER
13 CALANDRIA VAULT PIPING
14 NORTH WALL BIOLOGICAL SHIELD COOLING
15 CALANDRIA VAULT FLOOR
16 CALANDRIA VAULT FLOOR BIOLOGICAL SHIELD *COOLING*
17 SPENT FUEL TRANSFER DUCT
18 EAST WALL BIOLOGICAL SHIELD COOLING
19 PIPE CHASE
20 FUELLING MACHINE VAULT COOLING
21 CALANDRIA VAULT BOILER ROOM INTER SPACE

Figure 12 *Pickering Calandria Vault*

(3) a vertical pipe shaft joining boiler room floor (elevation 317 feet 6 inches) to the moderator room floor (elevation 249 feet).

A 16-inch diameter helium pipe from the top of the dump tank passes through an embedded sleeve in the north heavy concrete wall of the calandria vault into the vertical pipe shaft, thence through a sleeve embedded in the ordinary concrete wall and into the helium valve chest where it is welded into the helium balance valve assembly. Again, the vault atmosphere is contained by a metal bellows seal welded between the 16-inch pipe and the sleeve embedded and sealed into the heavy concrete wall. In order to complete the helium balance line circuit, a 16-inch pipe is connected between the helium balance valves and that portion of the east side blowoff line passing through the vertical pipe shaft. Connecting the helium line to the blowoff line avoids the necessity of having an extra penetration and seal to the vault.

Except for the dump tank drain, other piping, such as moderator circuits, spray lines and drain lines, passes from the vault to the moderator room via the pipe labyrinth; all pipes are suitably sealed with metal bellows and organic seals in order to contain the vault atmosphere.

The dump tank drain passes through an embedded sleeve at the bottom of the north wall. Shielding of all penetrations into the north wall of the vault is provided by a minimum of 4 feet 6 inches of ordinary concrete.

To allow component access into the vault the entire bottom half of the vault south wall is temporarily omitted, giving a clear entry of 19 feet 6 inches wide by 31 feet 10 inches high during construction. This opening is closed by poured "in situ" shielding which consists of unreinforced heavy concrete blocks. Ion chambers to sense reactor flux are positioned in a suitable manner through this shielding.

Above the shielding and embedded into the south wall is a blow-in-blow-out panel having an area of 12-1/4 ft^2, which connects the calandria vault interior with the boiler room. This panel is designed in such a way that in the event of any loss-of-coolant accident in the reactor building the vault external pressure differential is limited to 1/2 psi. This panel also limits the vault internal pressure differential to the design figure of 1/2 psi in the event of an accidental vacuum building connection to the reactor building.

The calandria vault roof incorporates two steel lined hatches and hatch beams.

The outermost hatch beams provide emergency access to the vault.

The reactivity mechanisms are supported by and pass through a heavy concrete and steel plug located at the centre of the vault roof. The bottom of this plug is cooled by a network of pipe coils in the same manner as the rest of the calandria vault internal surfaces. The top and bottom of this plug consists of steel plate, which permits accurate positioning of the plug and, consequently, the reactivity mechanisms.

8.2 CANDU-BLW

As a typical example of this version, I have chosen the Gentilly design. The following provides a general description of the reactor proper, followed by a more detailed description of the major components of the reactor.

8.2.1 General

The reactor is heavy water moderated, boiling light water (ordinary water) cooled and is fuelled with natural uranium dioxide. The arrangement of the major reactor components is shown in Figure 13.

The vertical pressure tubes contain the fuel: 308 of these tubes traverse the calandria which contains the heavy water moderator. The pressure tubes operate at essentially reactor coolant temperature and are thermally insulated from the relatively cool moderator ($\sim$ 140^{o}F) by a gas annulus between each pressure tube and its surrounding calandria tube. These calandria tubes are an integral part of the calandria.

The calandria contains three radially disposed zones. The central zone comprises the reactor core and contains the pressure tubes and surrounding calandria tubes plus the heavy water moderator. The central zone is surrounded by the second zone which contains only heavy water. This zone provides reflection of neutrons escaping radially from the core. No physical boundary separates these first two zones. The third zone surrounds the second zone and is separated from it by a radial baffle plate. This third zone is the dump annulus. It is connected hydraulically to the inner two zones by a radial dump port located at the bottom of the baffle. During operation, helium gas pressure in the dump annulus prevents heavy water in the inner two zones from flowing into the dump annulus. Rapid equalization of this pressure with that in the helium gas space above the heavy water

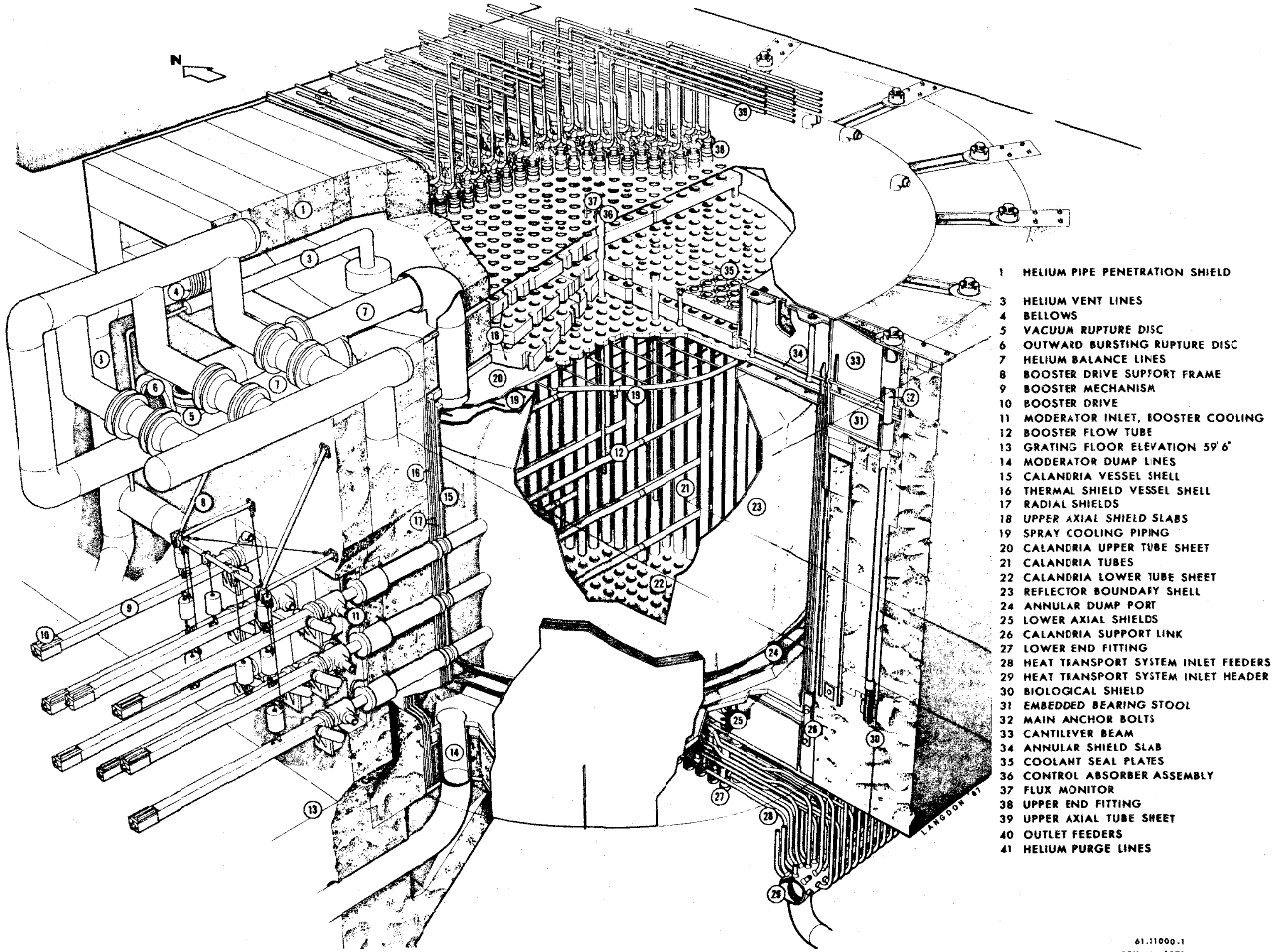


Figure 13 Gentilly Reactor Assembly

surface in the inner two zones permits the heavy water to flow rapidly into the dump annulus and then into a dump tank, thereby shutting down the reactor.

The calandria is surrounded by shielding to protect operating personnel from radiation emanating from the reactor. The inner part of this shielding is termed the radial thermal shielding. It consists of mild steel plates cooled by light water. This thermal shielding is contained within a tank, termed the thermal shield vessel. The outer part of the reactor shielding, termed the biological shielding, is constructed mostly of ordinary concrete.

The thermal shielding attenuates the intense radiations emanating from the reactor core to a level where the induced heating rate in the concrete biological shielding can be dissipated without incurring excessive temperatures in the concrete. The reactor biological shielding provides further attenuation of these radiations to permit operator access to regions beyond the shielding during reactor shutdowns. The axial regions of the thermal shielding are of sufficient thickness to provide both thermal and biological shielding.

There are 308 fuel channels (a fuel channel consists of a pressure tube and associated end fittings) in the reactor core. These are divided equally between two separate heat transport circuits.

The fuel for the reactor is in the form of bundles of individual fuel elements. Each bundle is 19.5 inches long and contains 18 fuel elements arranged in inner and outer rings of 6 and 12 elements respectively about an unfuelled central position. This central position is occupied by a tubular tie-rod which holds together the complete fuel channel charge of ten bundles. The individual fuel elements consist of Zircaloy-4 tubular sheaths ~ 0.78 inches outside diameter containing compacted and sintered natural UO_2 fuel pellets.

Fuel changing for the reactor is "on power". It is accomplished by a single fuelling machine which couples to a lower fuel channel end fitting and replaces the complete charge of fuel in the fuel channel.

8.2.2 Calandria

The calandria is a vertical, cylindrical, austenitic stainless steel vessel which contains the heavy water moderator and radial reflector and also incorporates an annular space into which part of the moderator can be dumped to provide fast reactor shutdown. The calandria is contained within and is structurally supported by the thermal shield vessel.

Three hundred and eight calandria tubes penetrate the central (reactor core) region of the calandria from top to bottom. These tubes are located on an 11 inch square lattice. The calandria tubes are joined to the calandria shell via the extension tubes. This joint is of the sandwich rolled type. The calandria tube wall thickness (nominally 0.040 inch) is minimized for reasons of neutron economy.

The calandria contains an internal radial baffle which separates the dump annulus region from the central core and radial reflector regions. The upper and lower ends of this baffle are tapered in inwards to provide an economically optimum radial reflector shape. A gap is provided between the bottom of the baffle and the lower tubesheet. This forms the entrance to the radial dump port which acts as a water trap. Helium gas pressure acts on the free heavy water surface in the dump port to support the operating height of heavy water in the calandria. Rapid equalization of this gas pressure with the pressure in the gas space above the free moderator surface in the reactor core permits moderator to flow rapidly into the dump annulus, providing fast reactor shutdown.

The top of the radial baffle is not joined to the upper calandria tubesheet. A shallow annular space is provided above the dump annulus, separated by a horizontal baffle, to permit the helium cover gas to flow between the gas space above the moderator surface in the reactor core and two 18-inch vent pipes which connect to this annular space. Two 18-inch diameter vents are connected to the top of the dump annulus. All four vent pipes pass upward through the upper axial thermal shield and are connected to the external helium system. Two rupture disc housings are "teed" into each of the two top gas space vent pipes. One of these rupture discs provides pressure relief in the event of overpressure in the calandria, and the other rupture disc provides for calandria protection in the event of reactor building pressurization.

Reactivity control mechanisms penetrate the calandria both vertically and horizontally. The control absorbers, the injection shutdown nozzles, and the in-core flux monitor tubes enter vertically through the top tubesheet on inter-lattice positions. The booster rods penetrate the calandria horizontally.

The moderator circulation flow enters the calandria via two routes. The first is via the booster rods. This flow provides cooling of the booster rod fuel elements. The second route is via a spray nozzle system. Most of this spray flow is directed against the under-surface of the upper tubesheet and then flows down over the outside of the calandria tubes to provide cooling of the tubes when the moderator is dumped. A relatively small flow is directed to the horizontal baffle separating the dump annulus from the shallow annulus at the top of the vessel. This flow is further directed to other parts of the baffle which separates the dump annulus from the radial reflector, thereby providing overall cooling of the baffles following moderator dump to remove heat generated in the baffles by gamma radiation which persists after reactor shutdown. All remaining calandria component cooling is provided by the bulk moderator and the thermal shield coolant.

The moderator circulation flow leaves the calandria via a collector ring which is integrated with the bottom plate of the dump port. The water enters this collector ring via holes through the bottom plate of the dump port. Two pipes lead from the collector ring to the external moderator system via penetrations through the lower thermal shielding.

Four 20-inch diameter pipes lead from the bottom of the dump annulus to the external dump tank. The dump annulus has sufficient capacity to provide the required initial rapid reduction in moderator level on dump but does not have sufficient capacity to cover all possible long-term reactivity effects. This additional capacity is provided by the external dump tank. This final "dumped" moderator level in the calandria is 125 cm (1/4 operating level).

Small diameter helium pipes connect to the upper gas space and the dump annulus in the calandria. These, together with the large vent lines, carry purge flows of helium which pass through the calandria gas spaces to remove radiolytically formed oxygen and deuterium gases. These gases enter the helium from exposed heavy water surfaces and could, unless removed, increase in concentration until the flame propagation level is reached. The external helium system catalytic units recombine these gases to form heavy water.

Other than the calandria tubes and in-core reactivity control mechanism components which are fabricated of Zircaloy-2, the calandria is completely fabricated of type 304L austenitic stainless steel.

The following table summarizes the major dimensions and metal thicknesses of the calandria:

Nominal Dimensions and Metal Thickness of Calandria

Outside diameter of shell	30 ft. 0 in.
Outside length of vessel	17 ft. 6-1/2 in.
Outside diameter of reflector boundary baffle	23 ft. 5-1/2 in.
Shell thickness	1 in.
Reflector boundary baffle thickness	3/4 in.
Tubesheet thickness	3-1/2 in.
Dump port area	74 sq. ft. min.
Calandria tube outside diameter	4.73 in. nominal
Calandria tube wall thickness	0.040 in. nominal
Lattice pitch (square)	11 in.
Approximate weight (less moderator and fuel channels)	167 tons

8.2.3 Thermal Shielding and Thermal Shield Vessel

The basic thermal shielding medium is carbon steel in the form of slabs. Radiation-induced heating in these slabs is removed by circulated coolant water. Light (ordinary) water is employed. The shield coolant augments the efficiency of the thermal shielding by providing some moderation of fast neutrons leaking from the reactor core.

The thermal shield slabs and coolant water are contained in the thermal shield vessel as shown in Figure 13. This vessel is a vertically oriented right cylinder of carbon steel. The thermal shield slabs completely surround the calandria. The calandria is effectively immersed within the thermal shield vessel.

Additional shielding is provided within the thermal shield vessel in the axial direction. This provides sufficient biological shielding to permit personnel access to the areas above and below the vessel following reactor shutdown. This additional shielding consists of extra carbon steel slabs in the central portion, which extends to slightly beyond the reactor core radius, and high density (300 lb/cubic foot) concrete in the remaining (annular) portion. This concrete is completely "canned" in carbon steel boxes to prevent leaching of the concrete by the shield coolant water. The boxes are vented to atmosphere.

Each axial thermal shield region is penetrated by 308 calandria extension tubes. As the name implies, these tubes effectively form extensions to the calandria tubes. They contain and laterally support the fuel channel end fittings. These extension tubes are roll-expanded and welded at one end to a calandria tubesheet and at the other end to a thermal shield vessel tubesheet. The tubes pass through clearance holes in the axial thermal shield slabs. The inner portion of these extension tubes is type 304L stainless steel welded to an outer portion of carbon steel.

Tubes, similar to the extension tubes, penetrate the upper axial shield region on inter-lattice sites. These provide access to the core for the control absorbers and in-core flux monitors.

The coolant flow through the thermal shielding is as follows. The coolant enters the bottom of the lower axial shield region, passes upwards through the clearance gaps between the calandria extension tubes and shield slabs and then outward under the lower calandria tubesheet to the radial thermal shield region. The coolant flows upwards through the coolant gaps in the radial shield regions and inward over the upper calandria tubesheet. The flow then passes upward through the gaps between the calandria extension tubes and shield slabs and then outward under the upper thermal shield vessel tubesheet to the outlet piping. A system of baffles in the various coolant water passages provides proper distribution of the coolant flow.

8.2.4 Fuel Channels

The fuel channel assembly is illustrated in Figure 14. The primary function of the 308 fuel channels is to contain the reactor fuel and coolant within the reactor core. The design differs from that employed in CANDU-PHW's in that the complete fuel channel is shop assembled to facilitate installation and subsequent replacement. Each fuel channel is installed in the lattice positions from the bottom end of the reactor and is supported by a bolted connection to the lower thermal shield.

Each fuel channel consists of a heat-treated Zirconium-2.5% Niobium alloy pressure tube attached at each end by means of "sandwich" type rolled joints to AISI type 403 (modified) stainless steel end fittings. The pressure tube extends through the reactor core while the end fittings extend through the axial thermal shields to make connection with the coolant feeder pipes. The lower end fitting contains a removable closure plug which provides a coolant seal at the bottom end

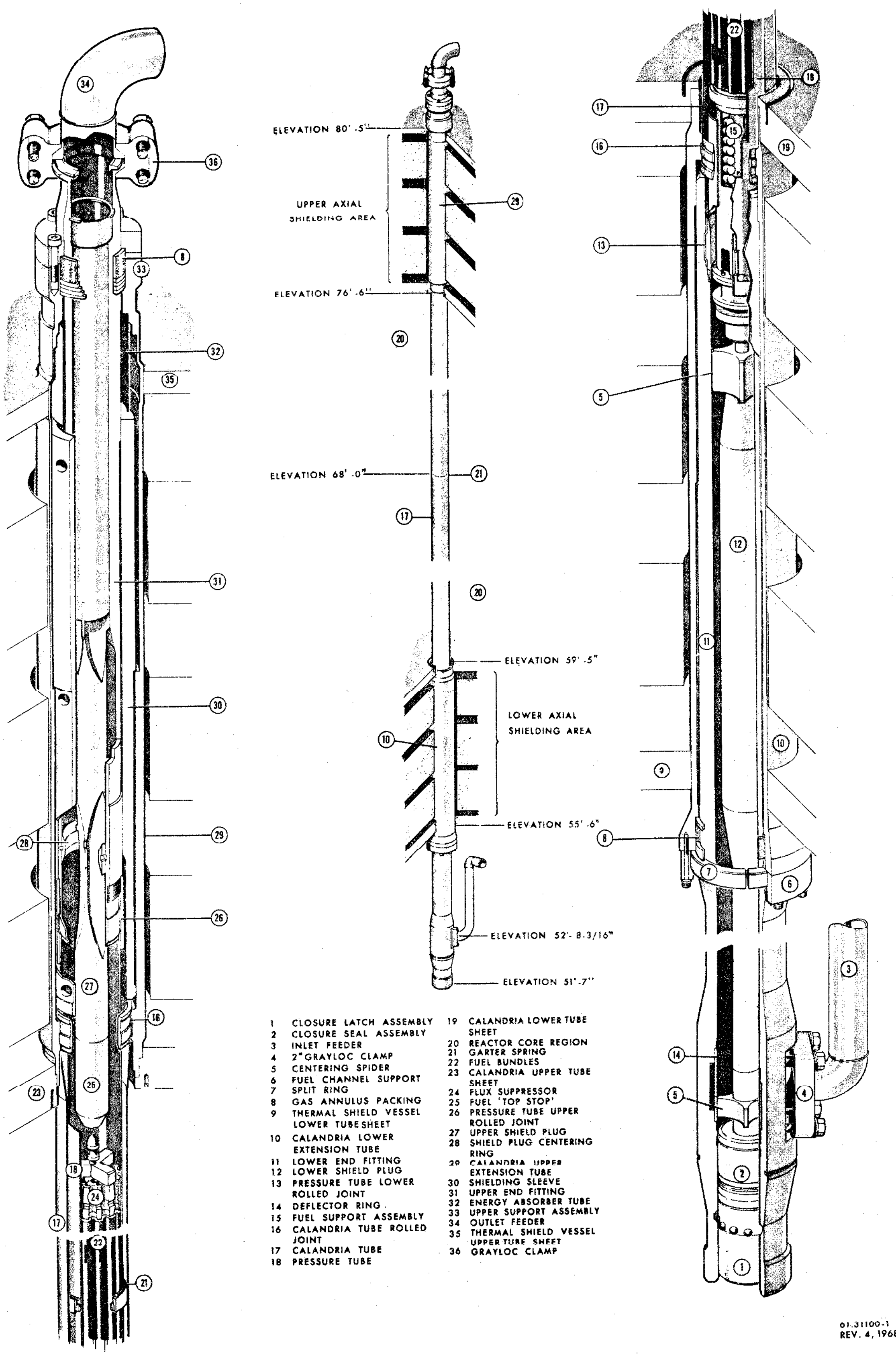


Figure 14 Gentilly Fuel Channel Assembly

and also permits access into the fuel channel for on-power fuel changing. The top end of the fuel channel connects directly to the outlet feeder pipe. The coolant enters the fuel channel through a side entrance in the lower end fitting slightly above the closure plug and exits axially through the upper end fitting. The feeder pipes are connected to the end fittings by means of special flange-type Grayloc* connections. The fuel channels are designed and constructed as Class A vessels in accordance with the provisions of Section III of the ASME Boiler and Pressure Vessel Code.

Heat-treated Zirconium-2.5% Niobium is used for the pressure tubes because this material possesses substantially higher yield and ultimate tensile strengths than the cold-worked Zircaloy-2 material used in earlier reactors. This permits a thinner-walled pressure tube which substantially improves neutron economy and, hence, fuel burnup.

The major pressure tube parameters are as below:

Inside diameter - nominal	4.077 inches
- minimum	4.064 inches
Wall thickness - nominal	0.095 inch
- minimum	0.090 inch
Length between end fittings	18 ft. 5-1/8 in.
Design stress	26,000 psi
Design temperature	523°F

The Gentilly rolled joints are of the "sandwich" type, i.e., the pressure tube is sandwiched between the end fitting and a separate threaded ring.

The lower end of the pressure tube is flared, prior to rolling, to a larger diameter over a length of 2-1/2 inches to permit the insertion of the inner ring of the lower rolled joint. The inside diameter of this ring is the same as that of the non-flared portion of the pressure tube. This permits passage of the fuel through the joint region during refuelling.

The upper rolled joint is not subject to the same limitation on inside diameter since fuel passage is not required. However, since the channel is inserted into the reactor from below, the joint outside diameter is limited in size in order to pass through the calandria tube. For this reason, the separate ring is placed on the outside and the end fitting on the inside of the joint. Inconel 718 has been chosen as the ring material.

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* A trade name

No field rolling of the joints is required, since the channels are assembled in the manufacturer's shop and are shipped to site as completed units.

The end fittings are forgings of AISI type 403 (modified) stainless steel.

The lower end fitting is 6-3/4 inches maximum outside diameter by 87-3/4 inches long. The upper end of the fitting forms a part of the rolled joint to the pressure tube as discussed previously. The lower end incorporates an internal recessed groove into which the retaining balls of the ball latch closure plug seat and an external shoulder on which the snout jaws of the fuelling machine clamp. The coolant entrance port is machined to provide a seat for a Grayloc* seal ring. A Grayloc* hub is welded to the feeder pipe and clamped on to the end fitting by a bolted connecting flange. Tapped holes are provided in the end fitting wall for the bolting. The coolant entrance port opens into an annular "lantern ring" cavity which permits the coolant to be distributed around the full periphery of the fuel bundles during fuel changing. Lateral guidance for the fuel is provided by a perforated ring which is expanded into position on the inside of the lantern ring cavity.

The lower end fitting contains the end closure plug, the shielding plug and the support section of the fuel assembly, in this sequence, starting from the bottom end.

The upper end fitting is approximately 4-3/8 inches outside diameter by 51 inches long. The lower end of the end fitting forms a part of the rolled joint to the pressure tubes as discussed previously. The upper end forms one mating hub of the Grayloc* outlet feeder connection. The maximum outside diameter of the upper end fitting is limited in size to pass through the calandria tube, permitting the fuel channel to be installed in the reactor from the underside.

A shielding plug is provided in the lower half of the upper end fitting. The bore of the upper end fitting is stepped such that coolant flow is annular in the lower half of the end fitting and central in the upper half. This arrangement is necessary for shielding purposes.

The end closure plug consists of a seal subassembly and a latch subassembly. The seal subassembly, termed a "dome seal", contains a titanium seal ring which is forced radially outwards to contact the bore

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* A trade name

of the end fitting, providing a high pressure coolant seal. Springs contained in the seal subassembly apply an initial sealing load via a "dome" shaped member. This is supplemented by a considerable pressure assist due to the spring action of the dome as internal pressure is increased.

The latch subassembly contains twelve 5/8-inch diameter balls which are forced radially outwards into a groove in the end fitting. These balls are held in position by a spring-loaded locking sleeve.

To remove the closure, the fuelling machine first releases the load on the dome seal, and then unlocks the balls, allowing them to retract into the latch casing. The sequence is reversed for re-insertion of the closure.

8.2.5 Reactor Biological Shield

The reactor biological shield is shown in Figure 13. In plan, it is square in outer shape with a face-to-face dimension of approximately 44 feet 6 inches. In elevation, it is rectangular in outer shape with a height of approximately 24 feet 6 inches. In inner shape it is cylindrical with a diameter essentially that of the thermal shield vessel it encloses, approximately 31 feet 6 inches. It is constructed of ordinary concrete in two radial layers. The inner layer is a cylindrical ring and contains a diametral step on its outer surface. The outer layer has an internal diametral step conforming to that of the inner layer. The gap between the two layers is filled with a weak, joint filling material.

The step between the layers provides for the transfer of loads from the inner shield layer to the outer shield layer. Loads are transferred from the outer layer to the east and west walls which transfer them to the reactor building foundation. The outer shield layer and these walls are monolithic. Conventional reinforcement is used in the biological shield.

The inner layer of the biological shield is separated from the outer layer to permit independent movement from thermal expansion and shrinkage effects. All significant radiation-induced heating will occur in the inner layer which is adjacent to the reactor. A matrix of cooling water pipes is embedded in the concrete near the inner surface of the inner layer. These pipes will remove radiation-induced heating in the concrete to limit the maximum temperature in the inner layer to 150°F.

Heat dissipation to the air in the reactor building will limit the temperature in the outer layer to 90°F. This will prevent significant shrinkage and thermal expansion cracking in the outer layer considering, as previously mentioned, it is monolithic with the east and west supporting walls.