CHAPTER
ONE

THERMAL HYDRAULIC CHARACTERISTICS OF POWER REACTORS

I INTRODUCTION

The energy source of a power reactor originates from the fission process within the fuel elements. Energy deposited in the fuel is transferred to the coolant by conduction, convection, and radiation.

This chapter presents the basic thermal hydraulic characteristics of power reactors. Study of these characteristics enables the student to appreciate the applications of the specialized techniques presented in the remainder of the text. The thermal hydraulic characteristics are presented as part of the description of the power cycle, core design, and fuel assembly design of these reactor types. Water-, gas-, and liquid-metal-cooled reactor types, identified in Table 1-1, include the principal nuclear power reactor designs currently employed in the world. Table 1-1 and others in Chapters 1 and 2 provide further detailed information useful for application to specific illustrative and homework examples.

II POWER CYCLES

In these plants a primary coolant is circulated through the reactor core to extract energy for ultimate conversion by a turbine process to electricity. Depending on the reactor design, the turbine may be driven directly by the primary coolant or by a secondary coolant that has received energy from the primary coolant. The number of

Table 1-1 Basic features of major power reactor types

Reactor type	Neutron spectrum	Moderator	Coolant	Fuel: Chemical form	Fuel: Approximate fissile content (all ^{235}U except LMFBR)
Water-cooled	Thermal				
PWR		H_2O	H_2O	UO_2	≈ 3% Enrichment
BWR		H_2O	H_2O	UO_2	≈ 3% Enrichment
PHWR (CANDU)		D_2O	D_2O	UO_2	Natural
SGHWR		D_2O	H_2O	UO_2	≈ 3% Enrichment
Gas-cooled	Thermal	Graphite			
Magnox			CO_2	U metal	Natural
AGR			CO_2	UO_2	≈ 3% Enrichment
HTGR			Helium	UC, ThO_2	≈ 7–20% Enrichment[a]
Liquid-metal-cooled	Fast	None	Sodium		
LMR				U/Pu metal; UO_2/PuO_2	≈ 15–20% Pu
LMFBR				UO_2/PuO_2	≈ 15–20% Pu

[a]Older operating plants have enrichments of more than 90%.

coolant systems in a plant equals the sum of one primary and one or more secondary systems. For the boiling water reactor (BWR) and the high-temperature gas reactor (HTGR) systems, which produce steam and hot helium by passage of primary coolant through the core, direct use of these primary coolants in the turbine is possible, leading to a single-coolant system. The BWR single-coolant system, based on the Rankine cycle (Fig. 1-1) is in common use. The Fort St. Vrain HTGR plant used a secondary water system in a Rankine cycle because the technology did not exist to produce a large, high-temperature, helium-driven turbine. Although the HTGR direct turbine system has not been built, it would use the Brayton cycle, as illustrated in Figure 1-2.

The pressurized water reactor (PWR) and the pressurized heavy water reactor (PHWR) are two-coolant systems. This design is necessary to maintain the primary

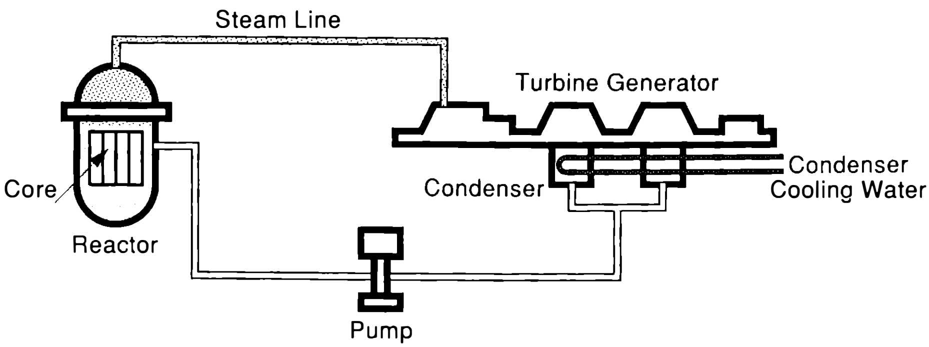

Figure 1-1 Direct, single-coolant Rankine cycle. *(Adapted courtesy of U.S. Department of Energy.)*

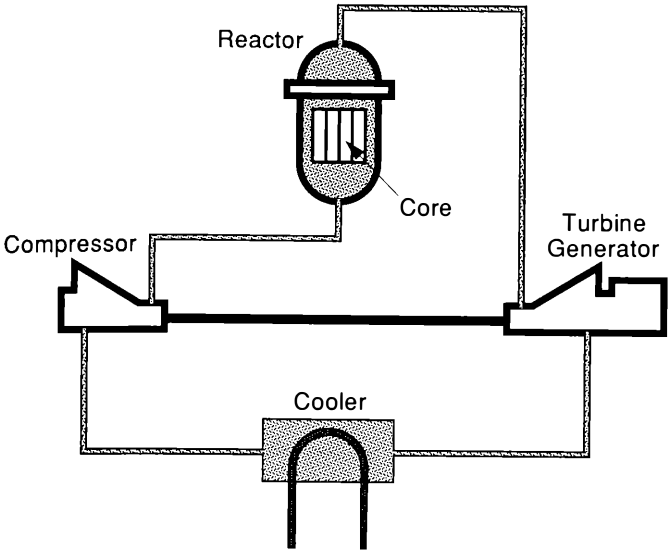

Figure 1-2 Direct, single-coolant Brayton cycle. *(Adapted courtesy of U.S. Department of Energy.)*

coolant conditions at a nominal subcooled liquid state. The turbine is driven by steam in the secondary system. Figure 1-3 illustrates the PWR two-coolant steam cycle.

The liquid metal fast breeder reactor (LMFBR) system employs three coolant systems: a primary sodium coolant system, an intermediate sodium coolant system, and a steam-water, turbine-condenser coolant system (Fig. 1-4). Three coolant systems are specified to isolate the radioactive primary sodium coolant from the steam–water circulating through the turbine, condenser, and associated conventional plant components. The liquid metal reactor (LMR) concept being developed in the United States

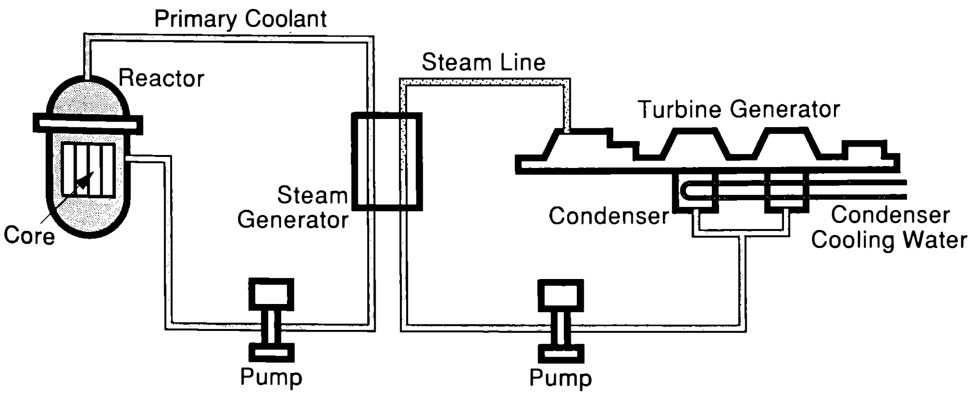

Figure 1-3 Two-coolant system steam cycle. *(Adapted courtesy of U.S. Department of Energy.)*

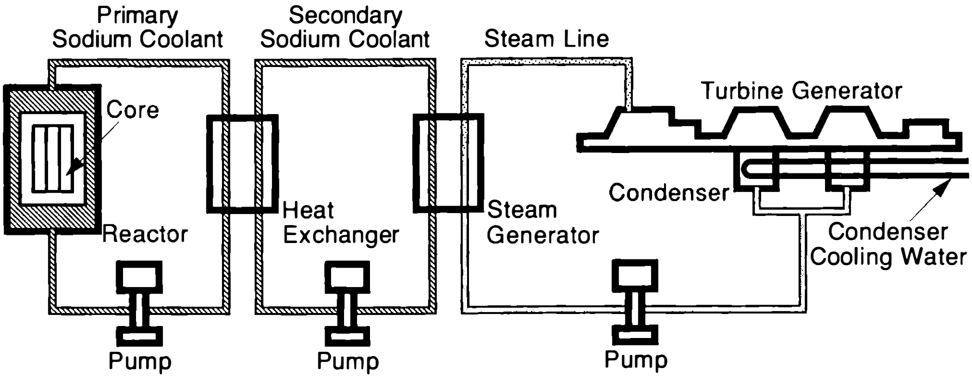

Figure 1-4 Three-coolant system steam cycle. *(Adapted courtesy of U.S. Department of Energy.)*

draws on LMFBR technology and operational experience base, but it is not designed as a breeder. Liquid-metal-cooled reactor characteristics and examples presented in this text are for the LMFBR.

The significant characteristics of the thermodynamic cycles used in these reactor types are summarized in Table 1-2. Thermodynamic analyses for typical Rankine and Brayton cycles are presented in Chapter 6.

III PRIMARY COOLANT SYSTEMS

The BWR single-loop primary coolant system is illustrated in Figure 1-5, and Figure 1-6 highlights the flow paths within the reactor vessel. The steam–water mixture first enters steam separators after exiting the core. After subsequent passage through steam dryers located in the upper portion of the reactor vessel, the steam flows directly to the turbine. The water, which is separated from the steam, flows downward in the periphery of the reactor vessel and mixes with the incoming main feed flow from the turbine. This combined flow stream is pumped into the lower plenum through jet pumps mounted around the inside periphery of the reactor vessel. The jet pumps are driven by flow from recirculation pumps located in relatively small-diameter ($\approx$ 20 inches) external recirculation loops, which draw flow from the plenum just above the jet pump discharge location.

The primary coolant system of a PWR consists of a multiloop arrangement arrayed around the reactor vessel. In a typical four-loop configuration (Fig. 1-7), each loop has a vertically oriented steam generator and coolant pump. The coolant flows through the steam generator within an array of U tubes that connect inlet and outlet plena located in the bottom of the steam generator. The system's single pressurizer is connected to the hot leg of one of the loops. The hot and cold (pump discharge) leg pipings are typically 31 and 29 inches in diameter, respectively.

The flow path through the PWR reactor vessel is illustrated in Figure 1-8. The inlet nozzles communicate with an annulus formed between the inside of the reactor

Table 1-2 Typical characteristics of the thermodynamic cycle for six reference power reactor types

Characteristic	BWR	PWR(W)	PHWR	HTGR	AGR	LMFBR
Reference design						
Manufacturer	General Electric	Westinghouse	Atomic Energy of Canada, Ltd.	General Atomic	National Nuclear Corp.	Novatome
System (reactor station)	BWR/6	(Sequoyah)	CANDU-600	(Fulton)[a]	HEYSHAM 2	(Superphenix)
Steam-cycle						
No. coolant systems	1	2	2	2	2	3
Primary coolant	H_2O	H_2O	D_2O	He	CO_2	Liq. Na
Secondary coolant	—	H_2O	H_2O	H_2O	H_2O	Liq. Na/H_2O
Energy conversion						
Gross thermal power, MW(th)	3579	3411	2180	3000	1550	3000
Net electrical power, MW(e)	1178	1148	638	1160	618	1200
Efficiency (%)	32.9	33.5	29.3	38.7	40.0	40.0
Heat transport system						
No. primary loops and pumps	2	4	2	6	8	4
No. intermediate loops	—		—	—	—	8
No. steam generators	—	4	4	6	4	8
Steam generator type	—	U tube	U tube	Helical coil	Helical coil	Helical coil
Thermal hydraulics						
Primary coolant						
Pressure (MPa)	7.17	15.5	10.0	4.90	4.30	~0.1
Inlet temp. (°C)	278	286	267	318	334	395
Ave. outlet temp. (°C)	288	324	310	741	635	545
Core flow rate (Mg/s)	13.1	17.4	7.6	1.42	3.91	16.4
Volume (L) or mass (kg)	—	3.06×10^5	1.20×10^5	(9550 kg)	5.3×10^6	(3.20×10^6 kg)
Secondary coolant						Na/H_2O
Pressure (MPa)	—	5.7	4.7	17.2	16.0	~0.1/17.7
Inlet temp. (°C)	—	224	187	188	156.0	345/235
Outlet temp. (°C)	—	273	260	513	541.0	525/487

Source: Knief [4], except AGR-HEYSHAM 2 data are from Alderson [1] and the PWR (W)-Sequoyah data from Coffey [3].
[a]Designed but not built.

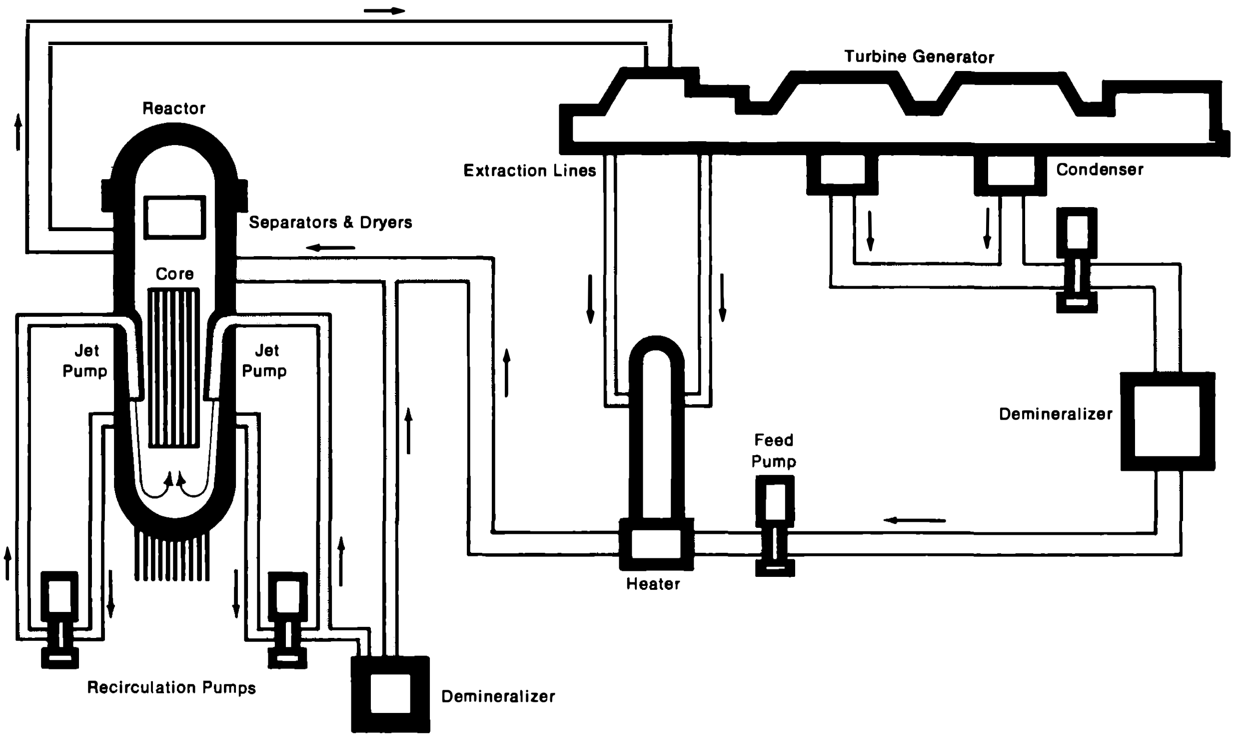

Figure 1-5 BWR single-loop primary coolant system. *(Courtesy of General Electric Company.)*

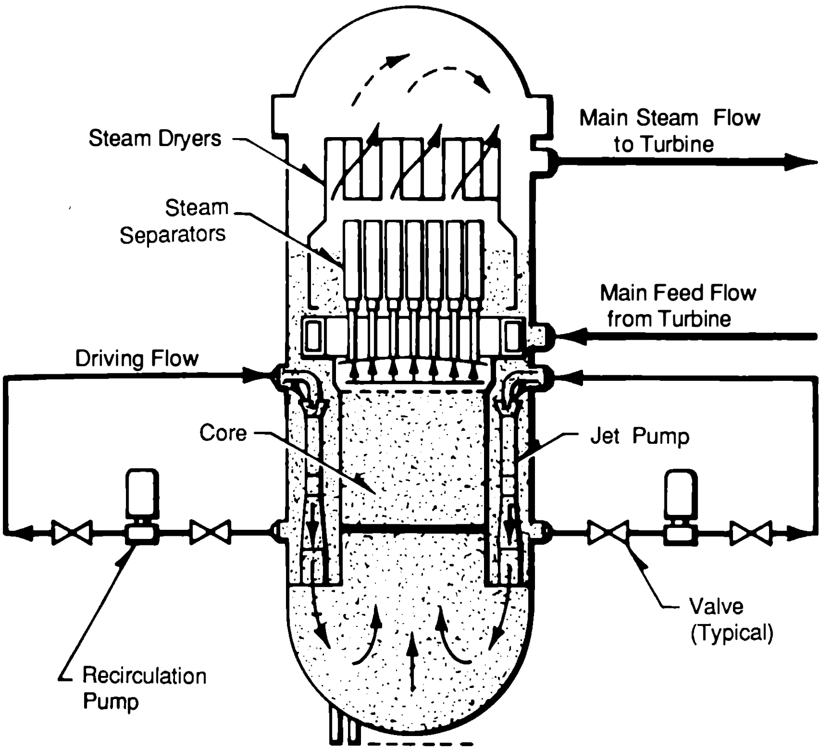

Figure 1-6 Steam and recirculation water flow paths in the BWR. *(Courtesy of General Electric Company.)*

vessel and the outside of the core support barrel. Coolant entering this annulus flows downward into the inlet plenum formed by the lower head of the reactor vessel. Here it turns upward and flows through the core into the upper plenum which communicates with the reactor vessel outlet nozzles.

The HTGR primary system is composed of several loops, each housed within a large cylinder of prestressed concrete. A compact HTGR arrangement as embodied in the modular high-temperature gas-cooled reactor (MHTGR) is illustrated in Figure 1-9. In this 588 MWe MHTGR arrangement [2] the flow is directed downward through the core by a circulator mounted above the steam generator in the cold leg. The reactor vessel and steam generator are connected by a short, horizontal cross duct, which channels two oppositely directed coolant streams. The coolant from the core exit plenum is directed laterally through the 47 inch diameter interior of the cross duct into the inlet of the steam generator. Coolant from the steam generator and circulator is directed laterally through the outer annulus (equivalent pipe diameter of approximately 46 inches) of the cross duct into the core inlet plenum.

LMFBR primary systems have been of the loop and pool types. The pool type configuration of the Superphenix reactor is shown in Figure 1-10, and its characteristics are detailed in Table 1-2. The coolant flow path is upward through the reactor

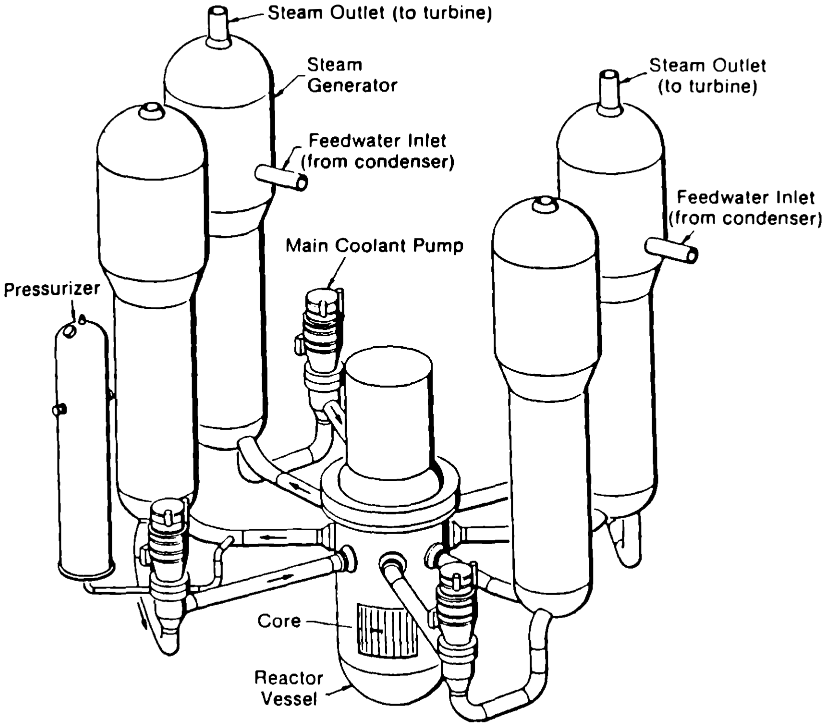

Figure 1-7 Arrangement of the primary system for a PWR. *(From WASH-1250.)*

core into the upper sodium pool of the main vessel. Coolant from this pool flows downward by gravity through the intermediate heat exchanger and discharges into a low-pressure toroidal plenum located on the periphery of the lower portion of the main vessel. Vertically oriented primary pumps draw the coolant from this low-pressure plenum and discharge it into the core inlet plenum.

IV REACTOR CORES

All these reactor cores except that of the HTGR are composed of assemblies of cylindrical fuel rods surrounded by coolant which flows along the rod length. The U.S. HTGR core consists of graphite moderator blocks that function as fuel assemblies. Within these blocks a hexagonal array of cylindrical columns is filled alternately with fuel and flowing helium coolant. The assemblies and blocks are described in detail in section V.

There are two design features that establish the principal thermal hydraulic characteristics of reactor cores: the orientation and the degree of hydraulic isolation of an

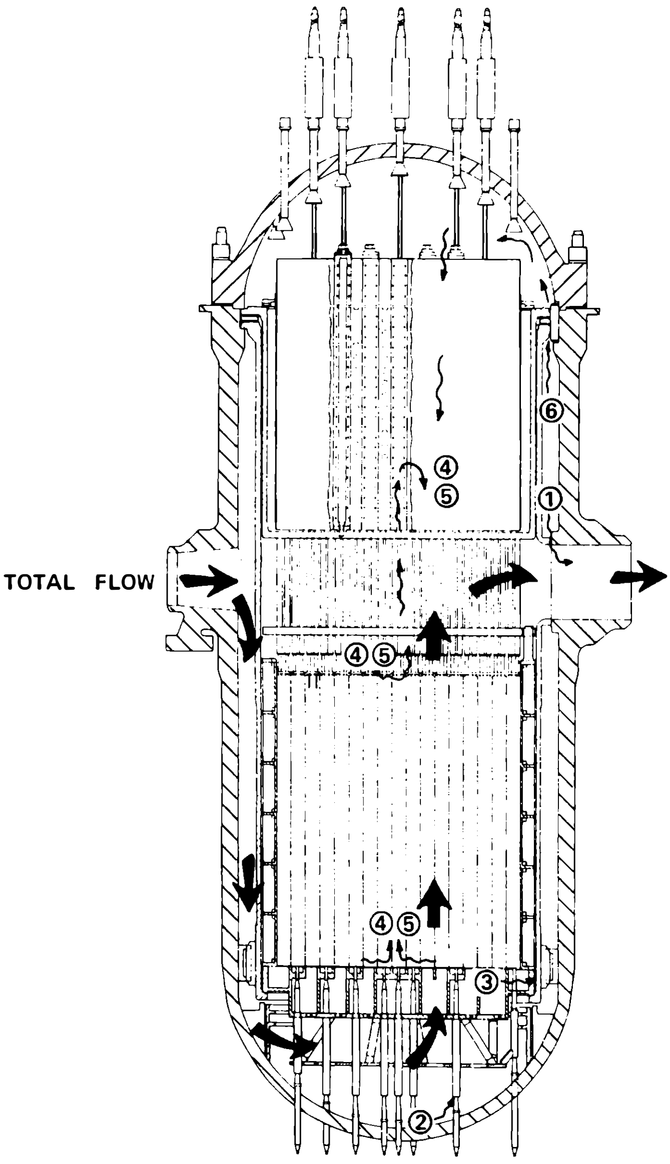

Figure 1-8 Flow path through a PWR reactor vessel. *Thick arrows*, main flow; *thin arrows*, bypass flow. *1*, through outlet nozzle clearance; *2*, through instrumented center guide tubes; *3*, through shroud-barrel annulus; *4*, through center guide tubes; *5*, through outer guide tubes; *6*, through alignment key-ways. *(Courtesy of Combustion Engineering.)*

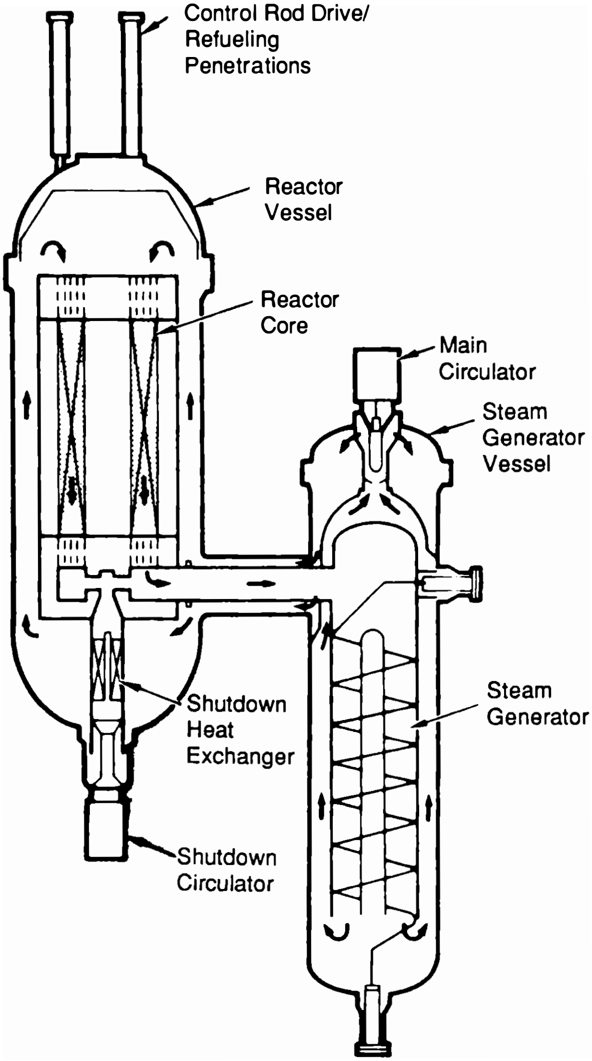

Figure 1-9 Modular HTGR primary coolant flow path. *(Courtesy of US-DOE.)*

assembly from its neighbors. It is simplest to adopt a reference case and describe the exceptions. Let us take as the reference case a vertical array of assemblies that communicate only at inlet and exit plena. This reference case describes the BWR, LMFBR, and the advanced gas reactor (AGR) systems. The HTGR is nominally configured in this manner also, although leakage between the graphite blocks which are stacked to create the proper core length, creates a substantial degree of communication between coolant passages within the core. The PHWR core consists of horizontal pressure tubes penetrating a low-pressure tank filled with heavy-water moderator. The fuel

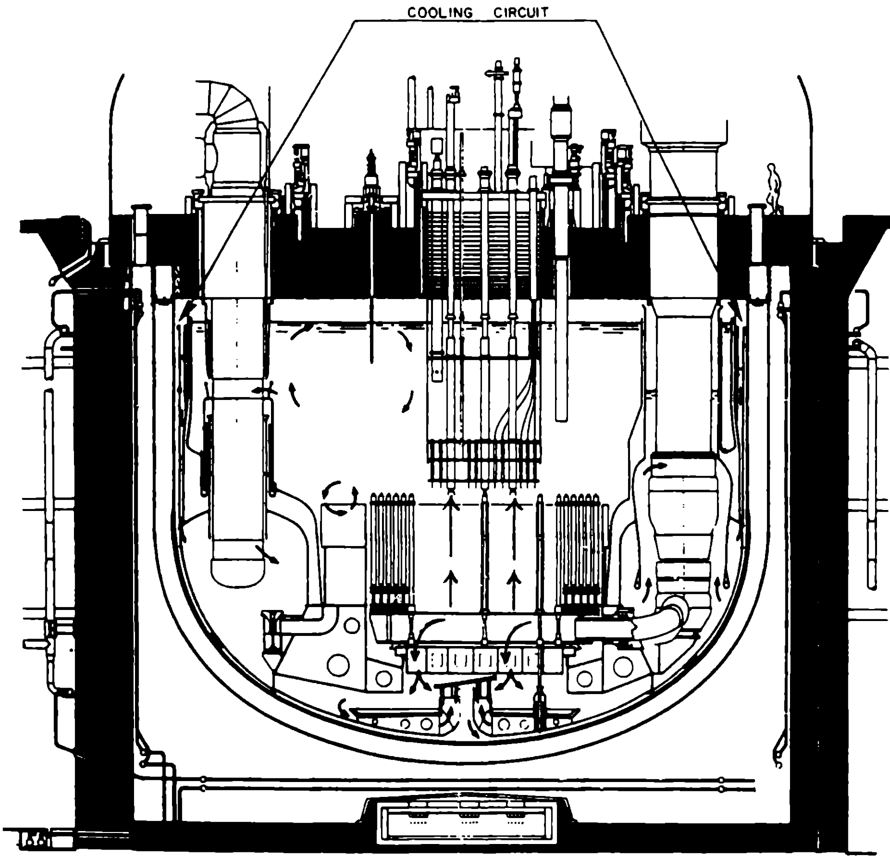

Figure 1-10 Primary system sodium flow path in the Superphenix reactor *(Courtesy of EDF.)*

assemblies housed within the pressure tubes are cooled by high-pressure heavy water, which is directed to and from the tubes by an array of inlet and outlet headers. Both the PHWR and the AGR are designed for on-line refueling.

The PWR assemblies are vertical but are not isolated hydraulically by enclosing ducts over the core length. In effect, fuel rods are grouped into assemblies only for handling and other structural purposes.

V FUEL ASSEMBLIES

The principal characteristics of power reactor fuel bundles are the array (geometric layout and rod spacing) and the method of fuel pin separation and support along their span. The light-water reactors (BWR and PWR), PHWR, AGR, and LMFBR all use fuel rods. The HTGR has graphite moderator blocks in which adjacent penetrating holes filled with fuel and flowing helium coolant exist.

Light-water reactors (LWRs), where the coolant also serves as the moderator, have small fuel-to-water volume ratios (commonly called the *metal-to-water ratio*) and consequently rather large fuel rod centerline-to-centerline spacing (commonly called the *rod pitch, P*). This moderate packing fraction permits use of a simple square array and requires a rod support scheme of moderate frontal area to yield low pressure drops. A variety of grid support schemes have evolved for this application.

Heavy-water reactors and advanced gas reactors are designed for on-line refueling and consequently consist of fuel assemblies stacked within circular pressure tubes. This circular boundary leads to an assembly design with an irregular array of rods. The on-line refueling approach has led to short fuel bundles in which the rods are supported at the assembly ends and at a center brace rather than by LWR-type grid spacers.

Liquid-metal-cooled fast-breeder reactors require no moderator and achieve high power densities by compact hexagonal fuel rod packing. With this tight rod-to-rod spacing, a lower pressure drop is obtained using spiral wire wrapping around each rod than could be obtained with a grid-type spacer. This wire wrap serves a dual function: as a spacer and as a promotor of coolant mixing within the fuel bundle. However, some LMFBR assemblies do use grid spacers.

The principal characteristics of the fuel for the six reference power reactor types are summarized in Table 1-3. The HTGR does not consist of an array of fuel rods within a coolant continuum. Rather, the HTGR blocks that contain fuel, coolant, and moderator can be thought of as inverted fuel assemblies. In these blocks, the fuel–moderator combination is the continuum that is penetrated by isolated, cylindrically shaped, coolant channels.

The LWRs (PWR and BWR), PHWR, AGR, and LMFBR utilize an array of fuel rods surrounded by coolant. For each of these arrays the useful geometric characteristics are given in Table 1-3 and typical subchannels identified. These subchannels are defined as coolant regions between fuel rods and hence are ''coolant-centered'' subchannels. Alternately, a ''rod-centered'' subchannel has been defined as that coolant region surrounding a fuel rod. This alternate definition is infrequently used.

A LWR Fuel Bundles: Square Arrays

A typical PWR fuel assembly for the LWR, including its grid-type spacer, is shown in Figure 1-11, along with the spring clips of the spacer, which contact and support the fuel rods. It is stressed that this figure represents only one of a variety of spacer designs now in use. The principal geometric parameters of the rods, their spacing, and the grid are defined in Figure 1-12, and the three types of subchannel commonly utilized are identified. Table 1-4 summarizes the number of subchannels of various-sized square arrays. Modern boiling water reactors of U.S. design utilize assemblies of 64 rods, whereas pressurized water reactor assemblies are typically composed of 225 to 289 rods. The formulas for subchannel and bundle dimensions, based on a PWR-type ductless assembly, are presented in Appendix J.

Table 1-3 Typical characteristics of the fuel for six reference power reactor types

Characteristic	BWR	PWR(W)	PHWR	HTGR	AGR	LMFBR[a]
Reference design						
Manufacturer	General Electric	Westinghouse	Atomic Energy of Canada, Ltd.	General Atomic	National Nuclear Corp.	Novatome
System (reactor station)	BWR/6	(Sequoyah)	CANDU-600	(Fulton)	HEYSHAM 2	(Superphenix)
Moderator	H_2O	H_2O	D_2O	Graphite	Graphite	—
Neutron energy	Thermal	Thermal	Thermal	Thermal	Thermal	Fast
Fuel production	Converter	Converter	Converter	Converter	Converter	Breeder
Fuel[b]						
Particles						
Geometry	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Coated microspheres	Cylindrical pellet	Annular pellet
Dimensions (mm)	$10.4D \times 10.4H$	$8.2D \times 13.5H$	$12.2D \times 16.4H$	400–800 μm D	$14.51D \times 14.51H$	$7.0\ D$
Chemical form	UO_2	UO_2	UO_2	UC/ThO_2	UO_2	PuO_2/UO_2
Fissile (wt% 1st core ave.)	1.7 ^{235}U	2.6 ^{235}U	0.711 ^{235}U	93 ^{235}U	2.2 ^{235}U	15–18 ^{239}Pu
Fertile	^{238}U	^{238}U	^{238}U	Th	^{238}U	Depleted U
Pins						
Geometry	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Cylindrical fuel stack	Pellet stack in clad tube	Pellet stack in clad tube
Dimensions (mm)	$12.27D \times 4.1$ mH	$9.5D \times 4$ mH	$13.1D \times 490L$	$15.7D \times 62L$	$14.89D \times 987H$	$8.65D \times 2.7$ mH(C) $15.8D \times 1.95$ mH(BR)
Clad material	Zircaloy-2	Zircaloy-4	Zircaloy-4	Graphite	Stainless steel	Stainless steel
Clad thickness (mm)	0.813	0.57	0.42	—	0.38	0.7
Assembly						
Geometry[c]	8 × 8 square rod array	17 × 17 square rod array	Concentric circles	Hexagonal graphite block	Concentric circles	Hexagonal rod array
Rod pitch (mm)	16.2	12.6	14.6	—	25.7	9.7 (C)/17.0 (BR)
No. rod locations	64	289	37	132 (SA)/76 (CA)[d]	37	271 (C)/91 (BR)
No. fuel rods	62	264	37	132 (SA)/76 (CA)[d]	36	271 (C)/91 (BR)
Outer dimensions (mm)	139	214	$102D \times 495L$	$360F \times 793H$	190.4 (inner)	$173F$
Channel	Yes	No	No	No	Yes	Yes
Total weight (kg)	273	—	—	—	342	—

Source: Knief [4] except AGR-HEYSHAM 2 data are from Alderson [1], and LMFBR pin and pellet diameters are from Vendryes [5].

[a]LMFBR-core (C), radial blanket (BR), axial blanket (BA).

[b]Fuel dimensions: diameter (*D*), height (*H*), length (*L*), (across the) flats (*F*), (width of) square (*S*).

[c]LWRs have utilized a range of number of rods.

[d]HTGR-standard assembly (SA), control assembly (CA).

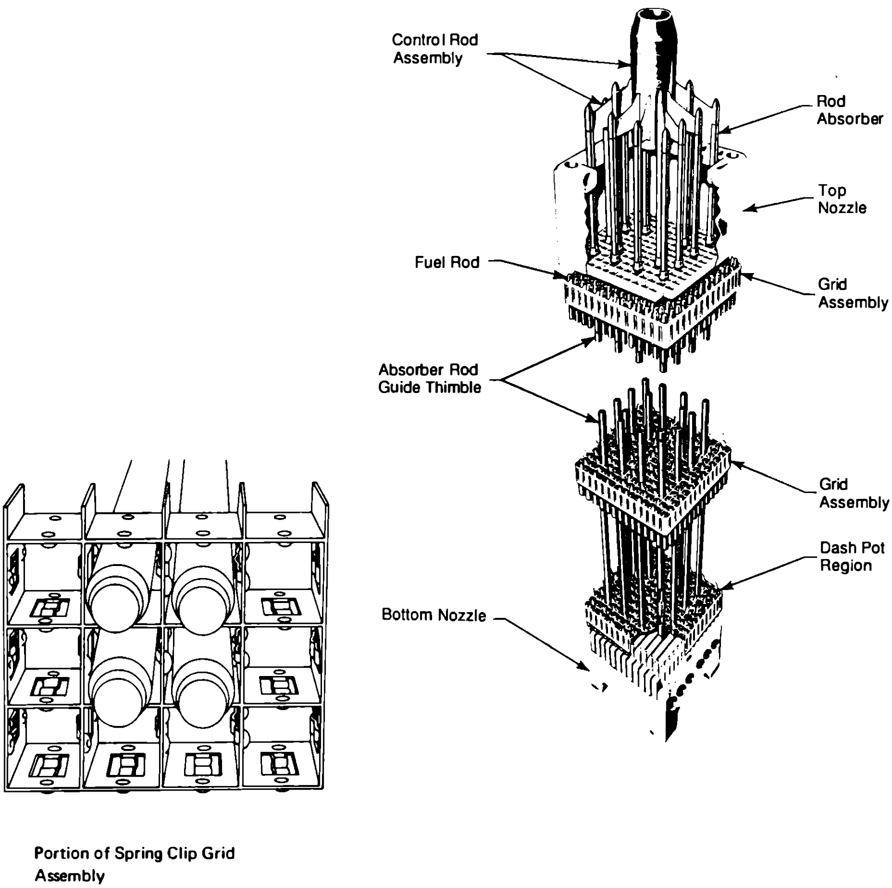

Figure 1-11 Typical spacer grid for a light-water reactor fuel assembly. *(Courtesy of Westinghouse Electric Corporation.)*

Table 1-4 Subchannels for square arrays

Rows of rods	N_p Total no. of rods	N_1 No. of interior subchannels	N_2 No. of edge subchannels	N_3 No. of corner subchannels
1	1	0	0	4
2	4	1	4	4
3	9	4	8	4
4	16	9	12	4
5	25	16	16	4
6	36	25	20	4
7	49	36	24	4
8	64	49	28	4
N_{rows}	N_{rows}^2	$(N_{rows} - 1)^2$	$4(N_{rows} - 1)$	4

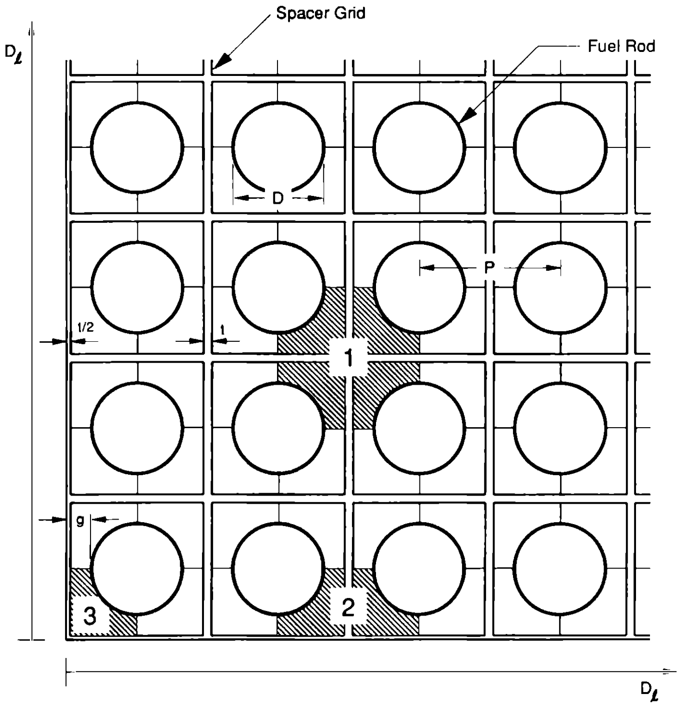

Figure 1-12 Typical fuel array for a light-water reactor. Subchannel designation: *1*, interior; *2*, edge; *3*, corner.

B PHWR and AGR Fuel Bundles: Mixed Arrays

The geometry and subchannel types for the PHWR and AGR fuel bundles are shown in Figure 1-13. Because these arrays are arranged in a circular sleeve, the geometric characteristics are specific to the number of rods in the bundle. Therefore the exact number of rods in the PHWR and the AGR bundle is shown.

C LMFBR Fuel Bundles: Hexagonal Arrays

A typical hexagonal array for a sodium-cooled reactor assembly with the rods wire-wrapped is shown in Figure 1-14. As with the light-water reactor, different numbers of rods are used to form bundles for various applications. A typical fuel assembly has about 271 rods. However, arrays of 7 to 331 rods have been designed for irradiation and out-of-pile simulation experiments of fuel, blanket, and absorber materials. The axial distance over which the wire wrap completes a helix of 360 degrees is called the lead length or axial pitch. Therefore axially averaged dimensions are based on averaging the wires over one lead length. The number of subchannels of various-sized hexagonal arrays are summarized in Table 1-5 and the dimensions for unit subchannels and the overall array in Appendix J.

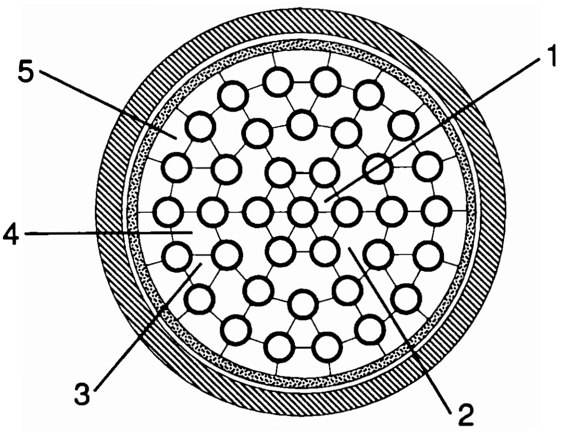

Figure 1-13 Fuel array of AGRs and PHWRs. Subchannel types: 1, interior first row (triangular); 2, interior second row (irregular); 3, interior third row (triangular); 4, interior third row (rhombus); 5, edge outer row. *Note:* Center pin is fueled in PHWR and unfueled in AGR.

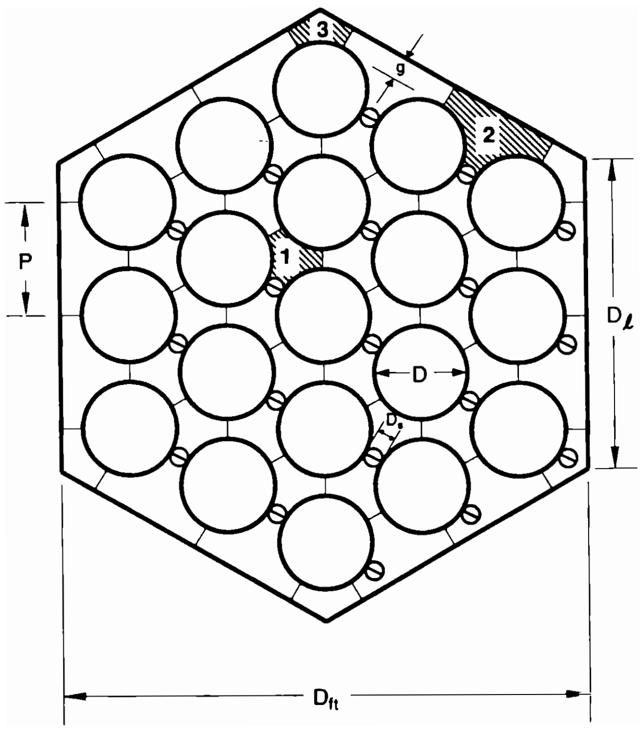

Figure 1-14 Typical fuel array for a liquid-metal-cooled fast breeder reactor. Subchannel designation: *1*, interior; *2*, edge; *3*, corner. $N = 19$ in this example. *Note:* The sectional view of the wire should strictly be elliptical.

Table 1-5 Subchannels for hexagonal arrays

Rings of rods	N_p Total no. of rods	N_{pS} No. of rods along a side	N_1 No. of interior subchannels	N_2 No. of edge subchannels	N_3 No. of corner subchannels
1	7	2	6	6	6
2	19	3	24	12	6
3	37	4	54	18	6
4	61	5	96	24	6
5	91	6	150	30	6
6	127	7	216	36	6
7	169	8	294	42	6
8	217	9	384	48	6
9	271	10	486	54	6
N_{rings}	$\sum_{n=1}^{N_{rings}} 6n$	$N_{rings} + 1$	$6N_{rings}^2$	$6N_{rings}$	6

Additional useful relations between N_p, N_{pS}, and N_1 are as follows.

$$N_{pS} = \left[1 + \sqrt{1 + \frac{4}{3}(N_p - 1)}\right] \Big/ 2$$

$$N_p = 3N_{pS}(N_{pS} - 1) + 1$$

$$N_1 = 6(N_{pS} - 1)^2$$

$$N_2 = 6(N_{pS} - 1)$$

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