UNENE Graduate Course Reactor Thermal-Hydraulics Design and Analysis

McMaster University
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Power Reactor Types

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Power Reactor Types

- Magnox Reactors
- AGR – Advanced Gas Cooled Reactors
- HTGR – High Temperature Gas Cooled Reactors
- PWR – Pressurized Water Reactors
- AP1000 – Advanced PWR
- EPR-1000 – European Advanced Power Reactor
- BWR – Boiling Water Reactors
- LMFBR – Liquid Metal Fast Breeder Reactors
- SGHWR – Steam Generating Heavy Water Reactor
- CANDU-BLW – Boiling Light Water Reactor
- CANDU-OCR – Organic Coolant Reactor
- CANDU 6 – PHWR (Pressurized Heavy Water Reactor)
- CANDU 9
- ACR-700 – Advanced CANDU Reactor
- ACR-1000 – Advanced CANDU Reactor

Power Reactor Types

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	Cylindrical pellet
Dimensions (mm)	10.4*D* × 10.4*H*	8.2*D* × 13.5*H*	12.2*D* × 16.4*H*	400–800 μm *D*	14.51*D* × 14.51*H*	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)	12.27*D* × 4.1 m*H*	9.5*D* × 4 m*H*	13.1*D* × 490*L*	15.7*D* × 62*L*	14.89*D* × 987*H*	8.65*D* × 2.7 m*H*(C) 15.8*D* × 1.95 m*H*(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	102*D* × 495*L*	360*F* × 793*H*	190.4 (inner)	173*F*
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).

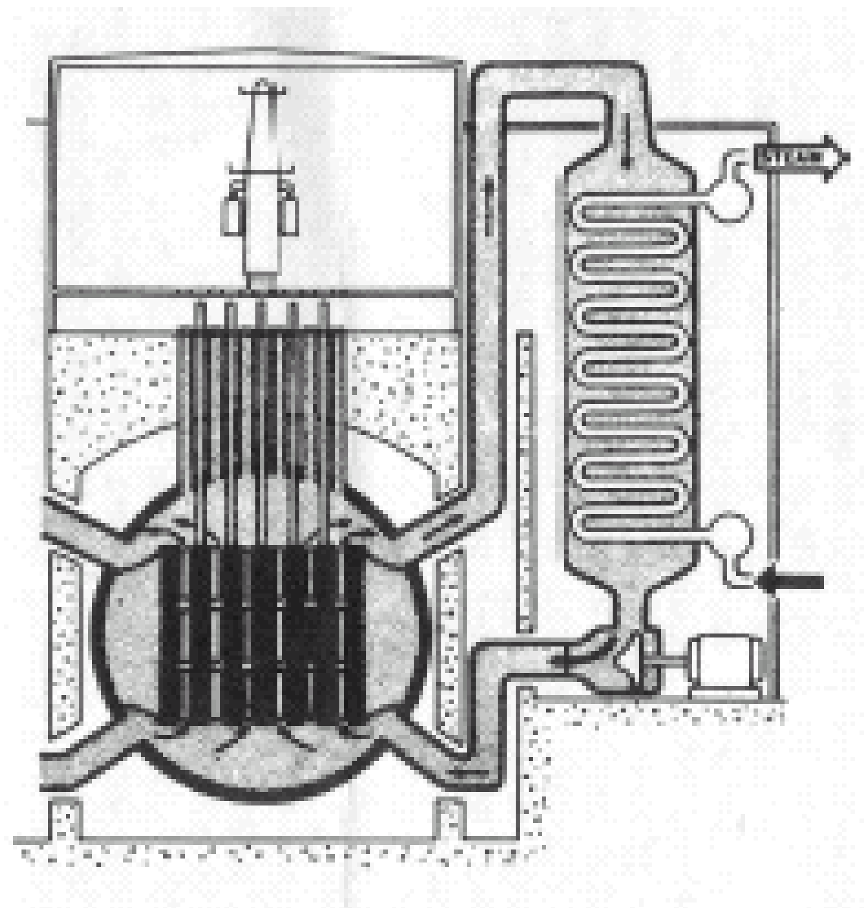
[b]Fuel dimensions: diameter (*D*), height (*H*), length (*L*), (across the) flats (*F*), (width of) square (*S*).

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

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

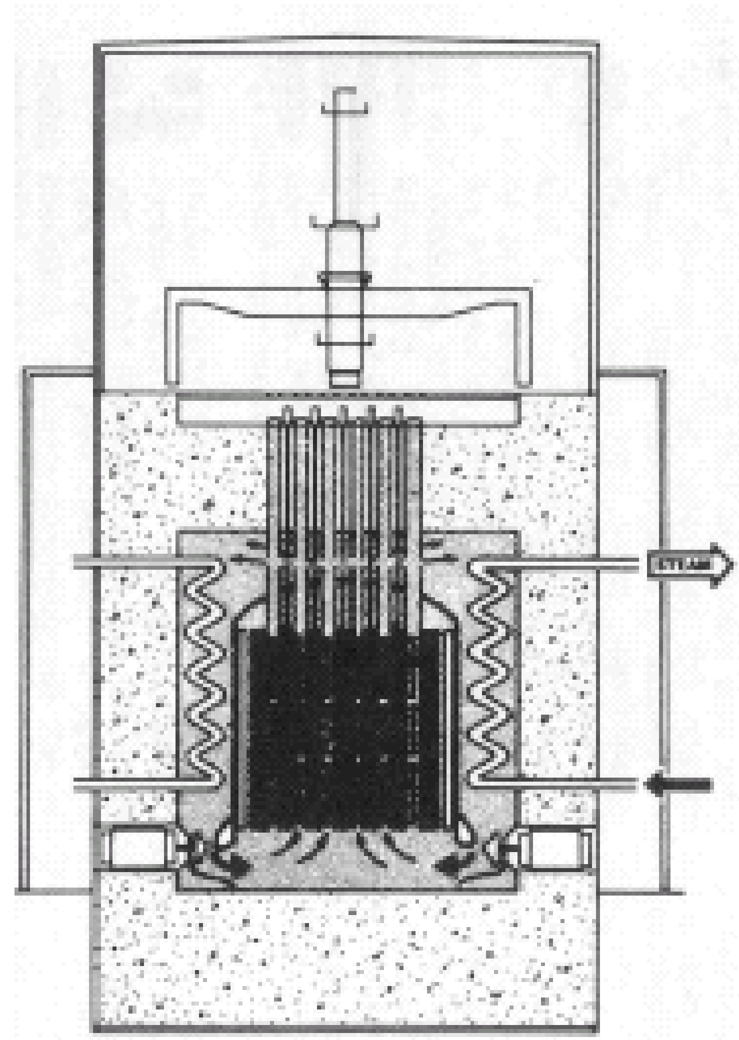
MAGNOX Reactor (UK)

- Graphite moderated
- CO_2 cooled
- Natural uranium metal
- Magnesium clad
- Steel reactor pressure vessel or pre-stressed concrete vessel
- No containment
- Thermal efficiency 30%
- On-power re-fuelling
- High capital cost
- Modest achievable fuel utilization
- Single fuel elements



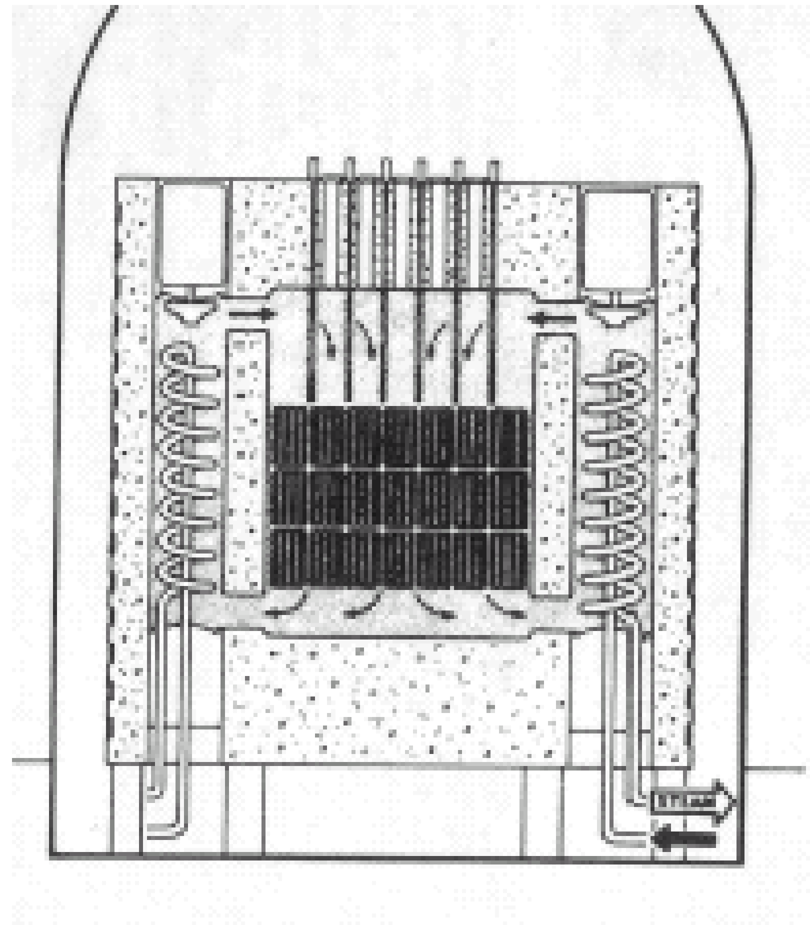
AGR Reactor (UK)

- Graphite moderator
- CO_2 cooled
- UO_2 fuel 2-3% enriched
- Steel cladding
- Clusters of smaller fuel elements – more compact core
- Higher power levels
- Higher thermal efficiency



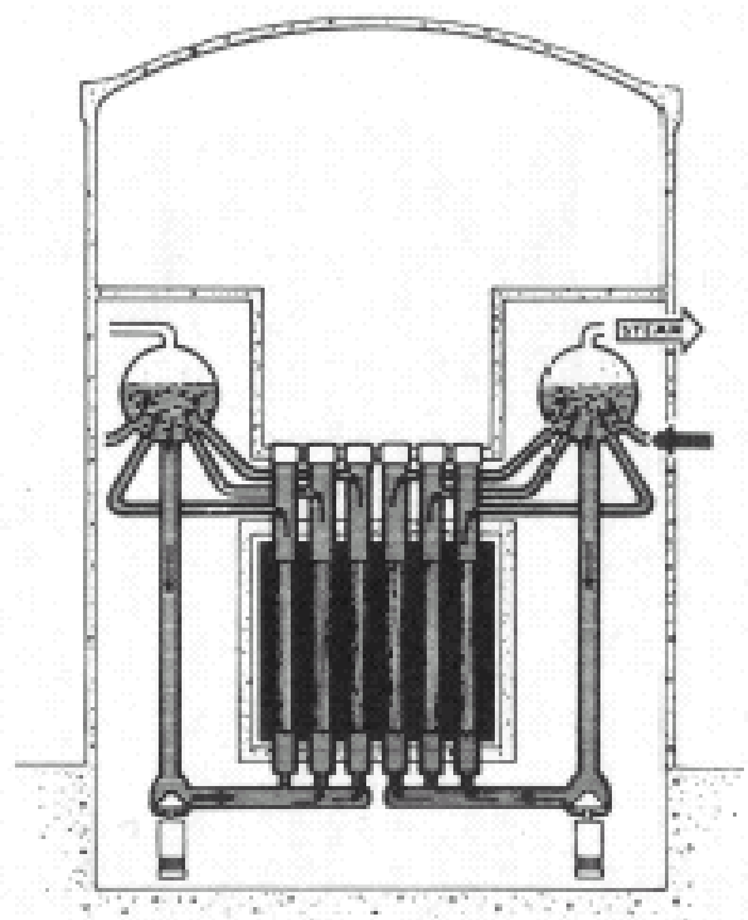
HTGCR Reactor (US, Germany, UK)

- Graphite moderator
- Helium gas cooled
- High coolant temperatures
- Carbide fuel 93% U^{235} and thorium
- Fuel in small spheres coated with pyrolitic graphite
- High thermal efficiency



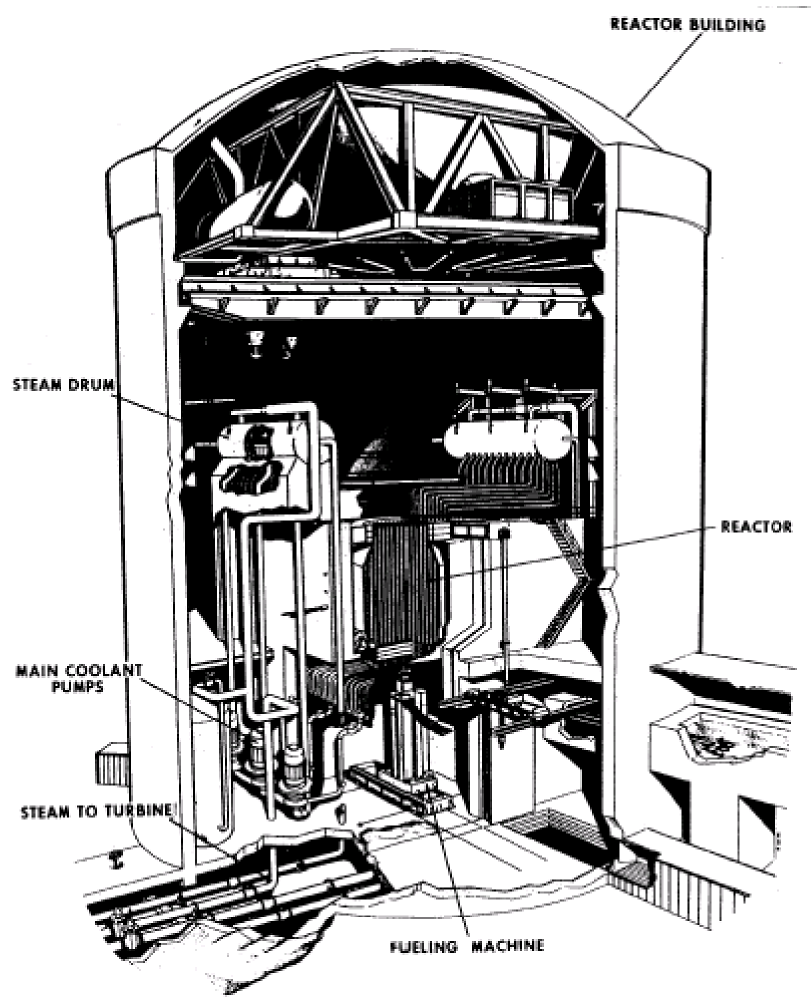
SGHWR Reactor (UK, Japan, Italy)

- Similar to the CANDU-BLW
- Vertical pressure tubes
- Heavy water moderator in calandria
- Recirculating pumps used to return water from steam drums to lower end of pressure tubes
- Low enriched uranium fuel
- On-power refuelling
- Containment included

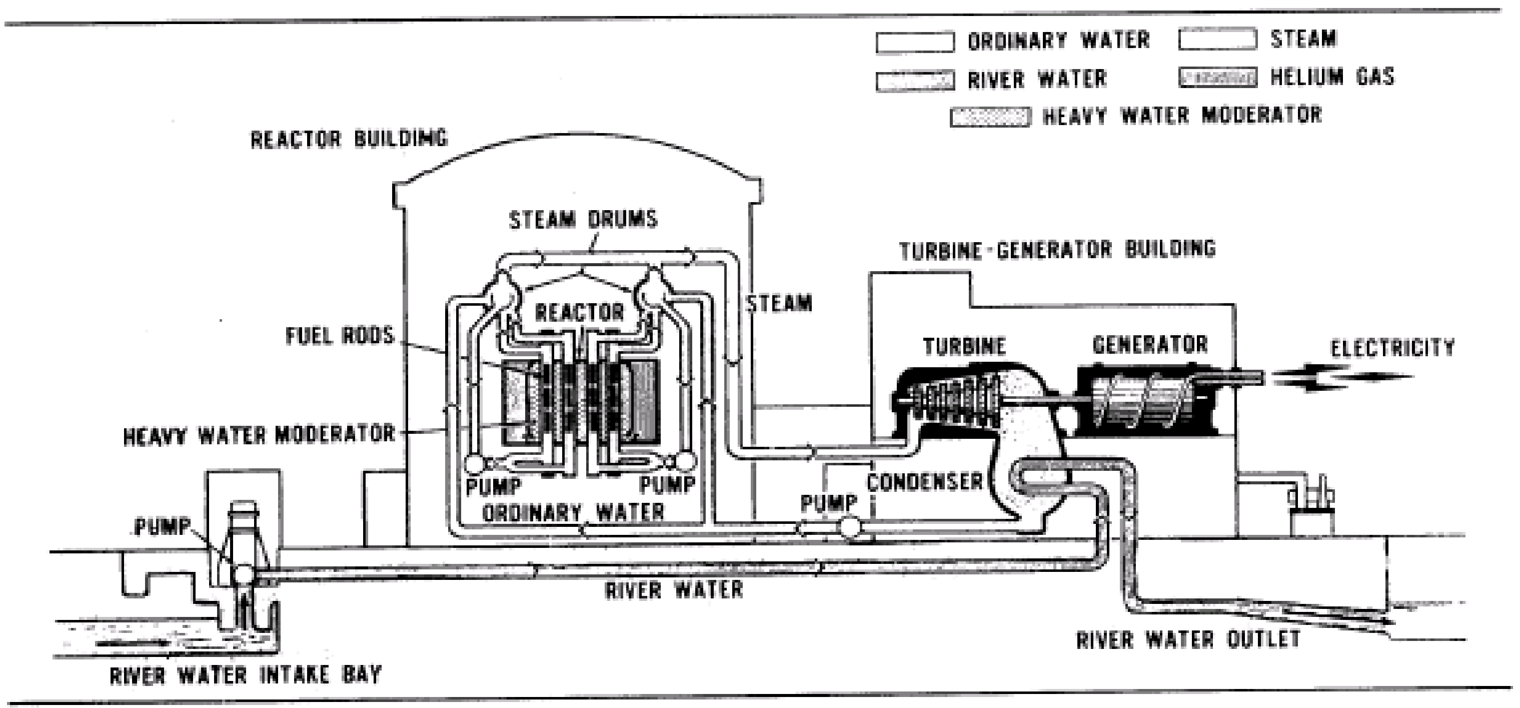


CANDU-BLW

- Natural uranium fuel
- Bottom refuelling on power
- Light water coolant
- Core exit quality up to 20%
- Concept used in Gentilly-1
- Enriched uranium considered
- Positive power coefficient



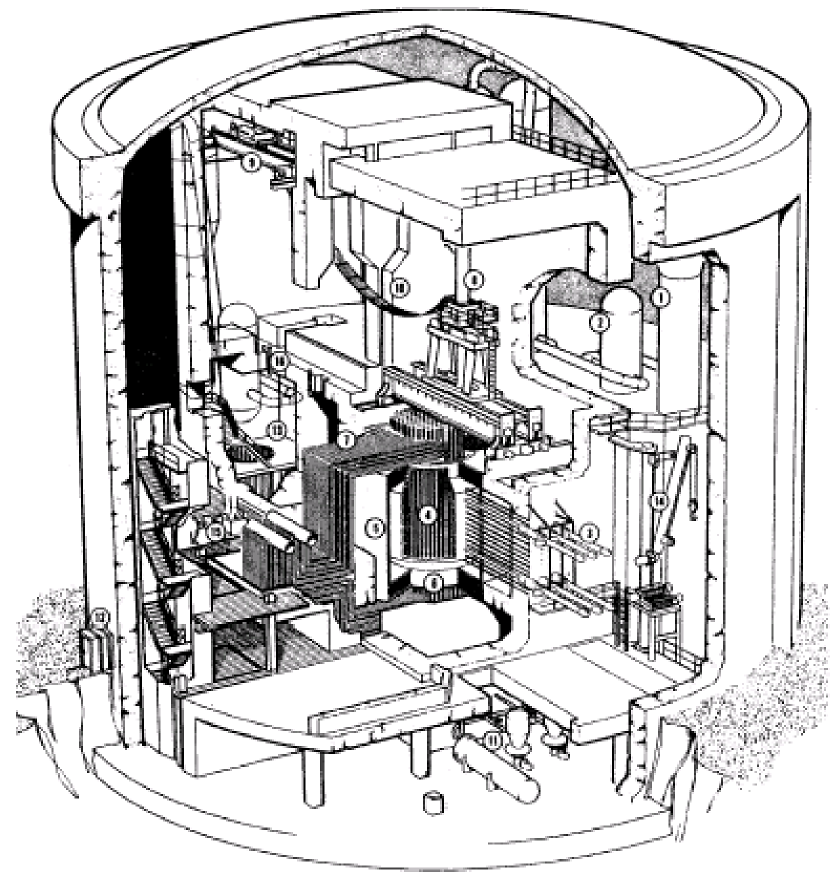
CANDU-BLW



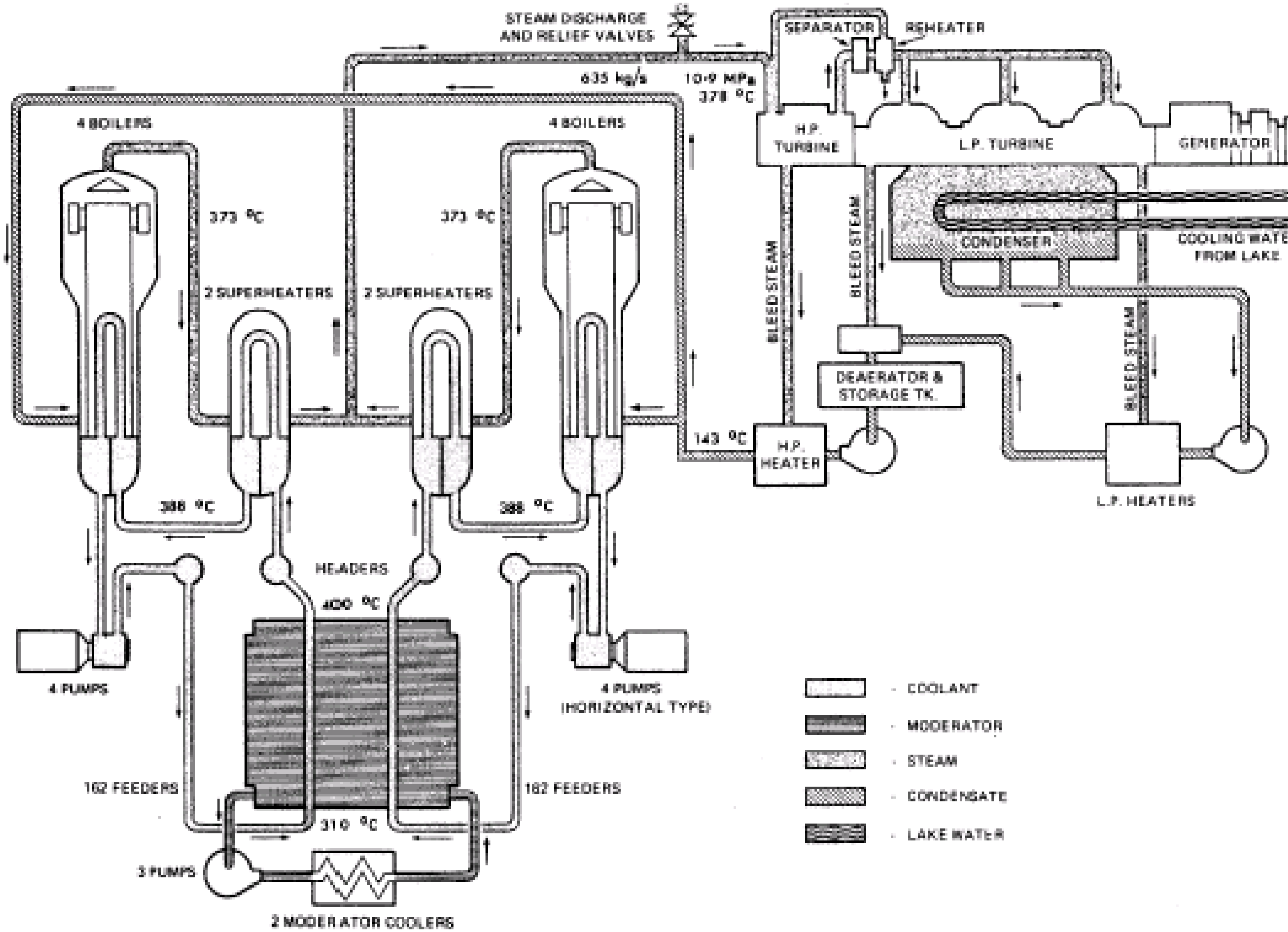
ORDINARY WATER
STEAM
RIVER WATER
HELIUM GAS
HEAVY WATER MODERATOR
REACTOR BUILDING
STEAM DRUMS
TURBINE-GENERATOR BUILDING
REACTOR
STEAM
FUEL RODS
TURBINE
GENERATOR
ELECTRICITY
HEAVY WATER MODERATOR
PUMP
PUMP
CONDENSER
ORDINARY WATER
PUMP
PUMP
RIVER WATER
RIVER WATER OUTLET
RIVER WATER INTAKE BAY

CANDU-OCR

- Organic cooled
- WR-1 reactor operated at Whiteshell Lab 20 years
- Once-through boilers
- Vertical pressure tubes
- Fueling from the the top
- Gradual decomposition of the coolant with irradiation
- Zr-2.5Nb clad natural uranium carbide fuel
- Outlet coolant temperature of about 400 C
- Thermal efficiency 34%
- Low radiation field, low stored energy, low coolant pressure, no ballooning, no dryout



CANDU-OCR


STEAM DISCHARGE
AND RELIEF VALVES
SEPARATOR
REHEATER
635 kg/s
10·9 MPa
378 °C
4 BOILERS
4 BOILERS
H.P.
TURBINE
L.P. TURBINE
GENERATOR
373 °C
373 °C
BLEED STEAM
BLEED STEAM
CONDENSER
COOLING WATER
FROM LAKE
2 SUPERHEATERS
2 SUPERHEATERS
DEAERATOR &
STORAGE TK.
BLEED STEAM
143 °C
H.P.
HEATER
L.P. HEATERS
388 °C
388 °C
HEADERS
400 °C
4 PUMPS
4 PUMPS
(HORIZONTAL TYPE)
- COOLANT
- MODERATOR
- STEAM
- CONDENSATE
- LAKE WATER
162 FEEDERS
162 FEEDERS
310 °C
3 PUMPS
2 MODERATOR COOLERS

PWR Reactor

- Light water cooled and moderated
- Enriched UO2 fuel (~3%)
- Square fuel assemblies
- Large steel pressure vessel
- Large excess reactivity associated with refueling
- Neutron poisons used to balance excess reactivity (removable and burnable)
- High fuel burnup
- Control rods in the core
- Flow in fuel assemblies not restricted in radial direction

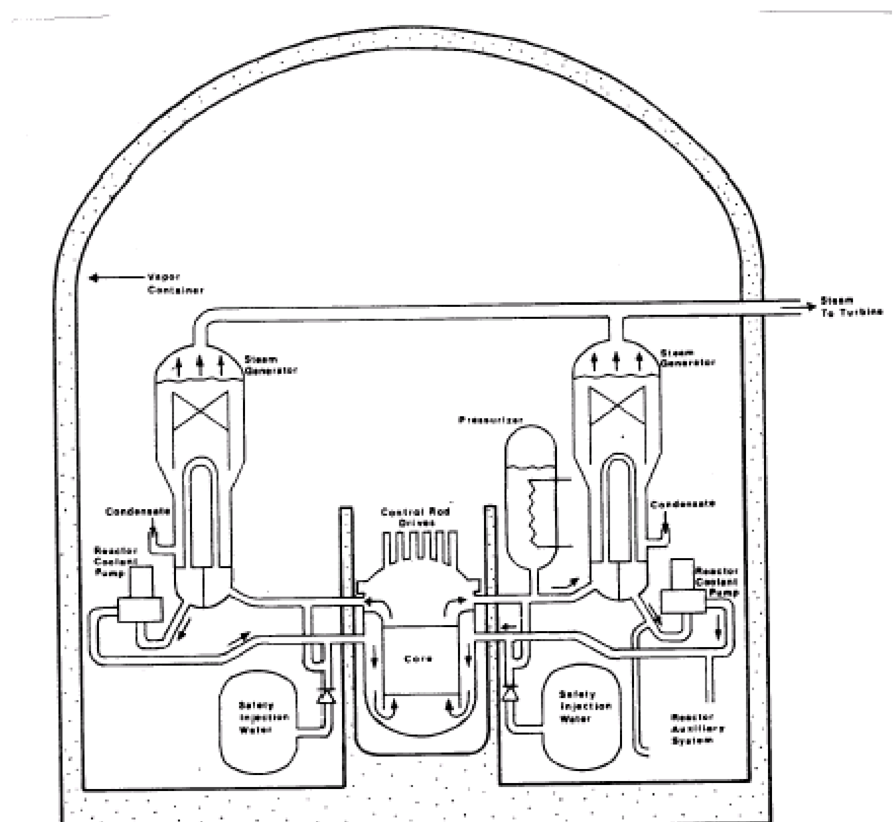
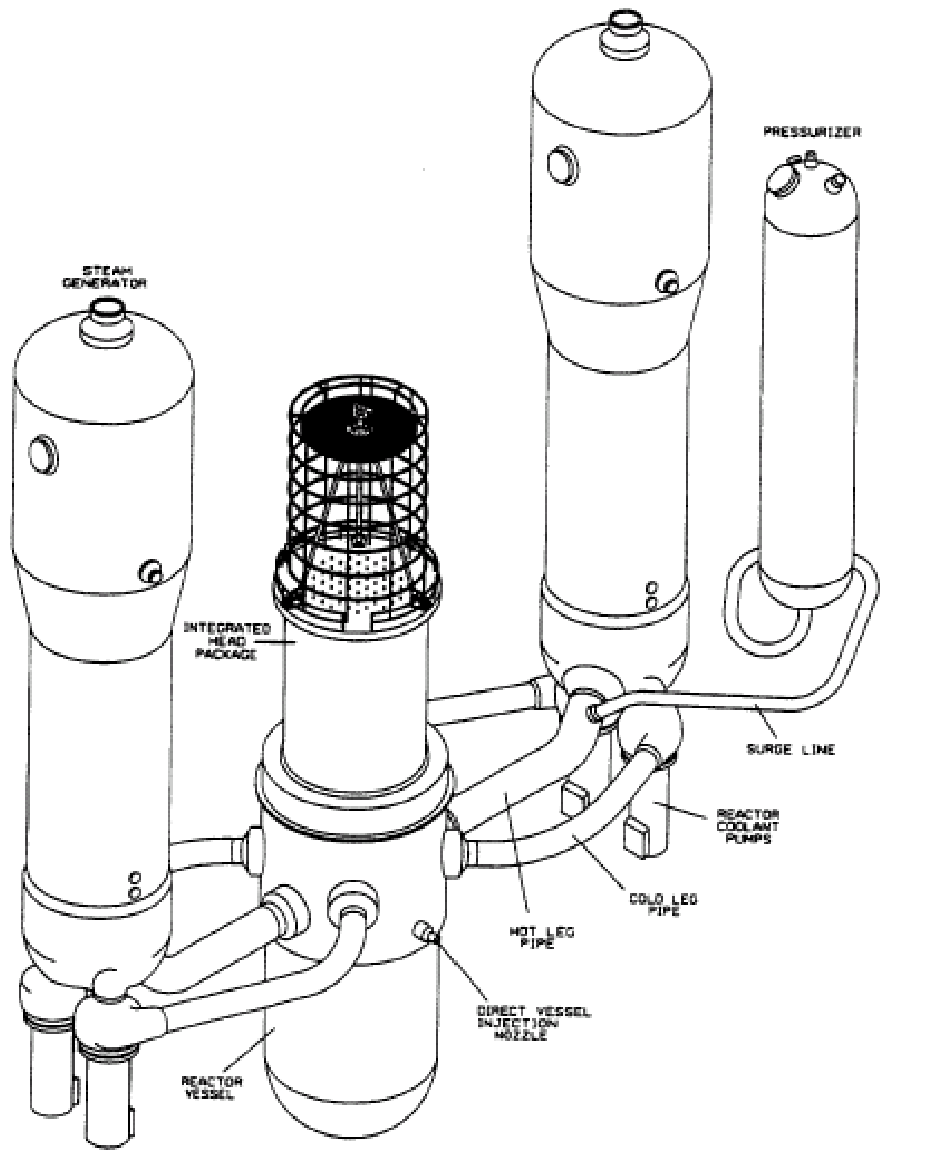
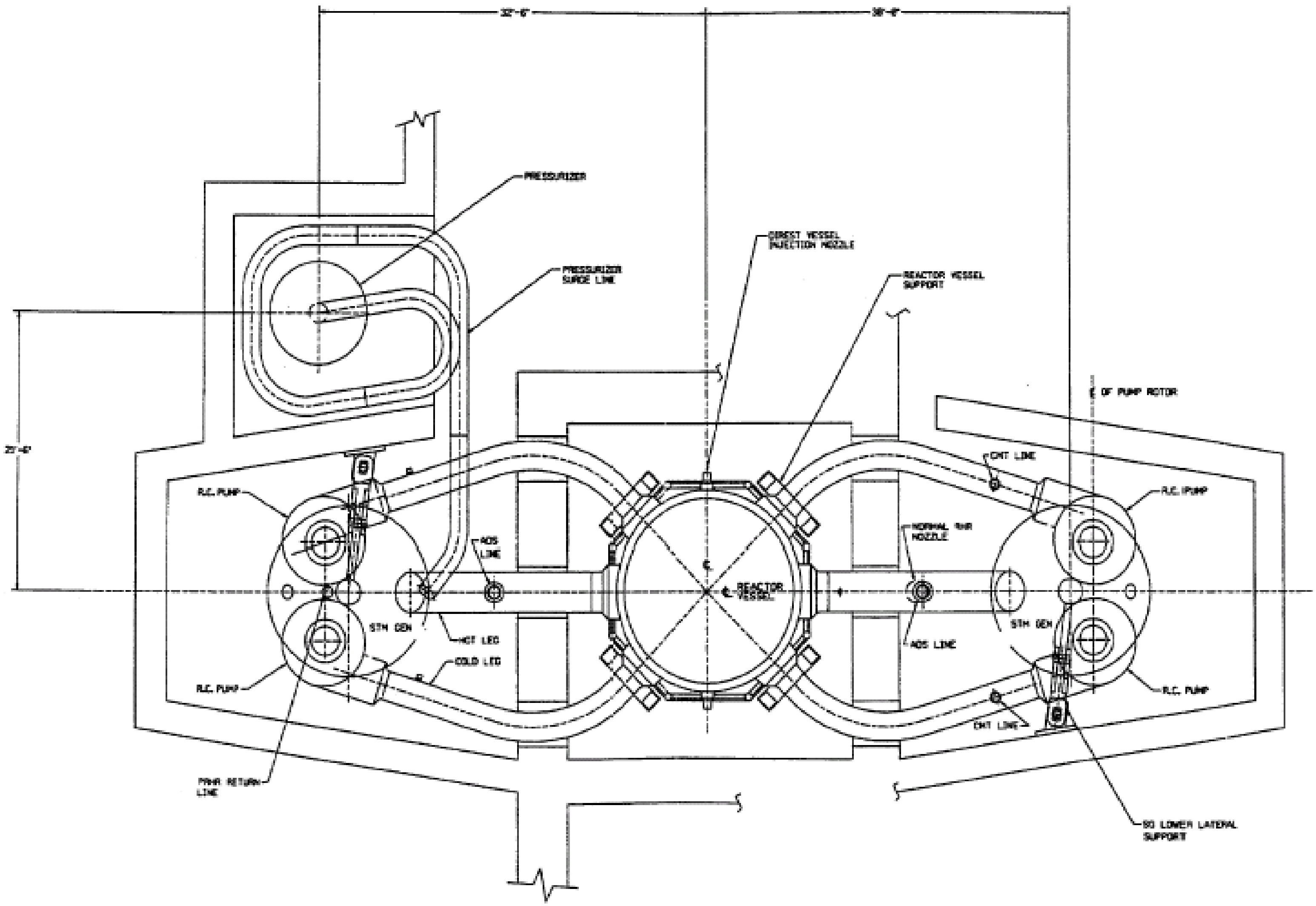


Fig. 1.1(a). Pressurized water reactor system — vessel concept.

PWR Reactor - RCS

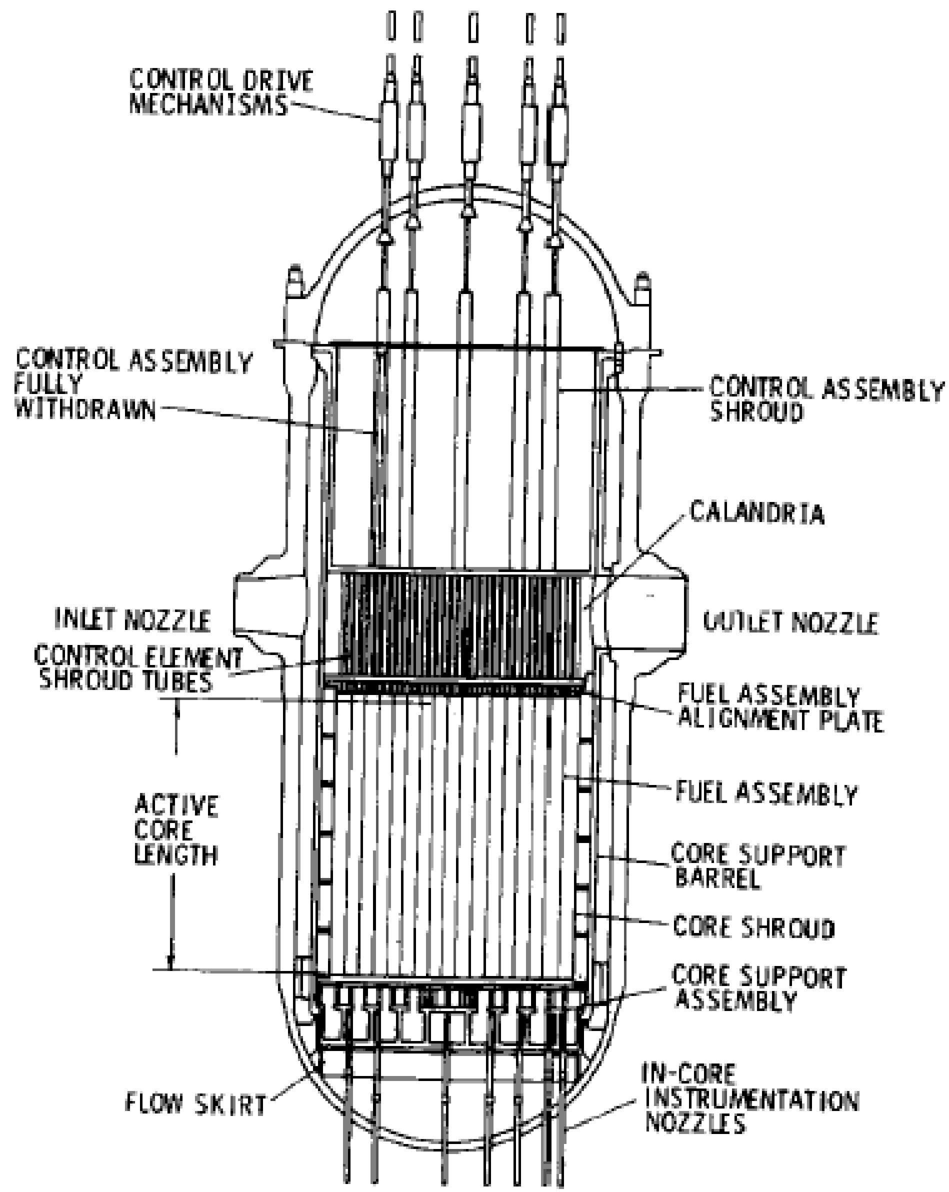


PWR Reactor – RCS Top View

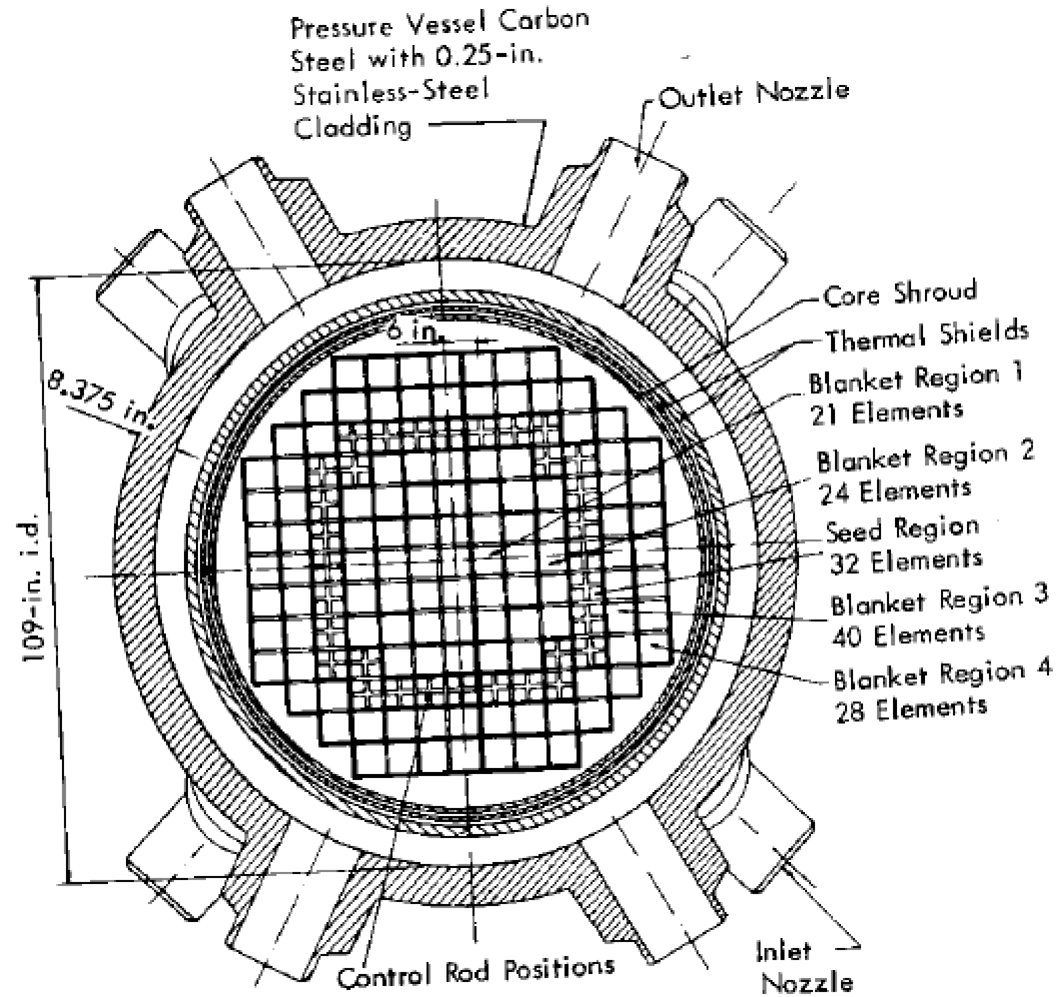


PWR Reactor Vessel and Internal Structures

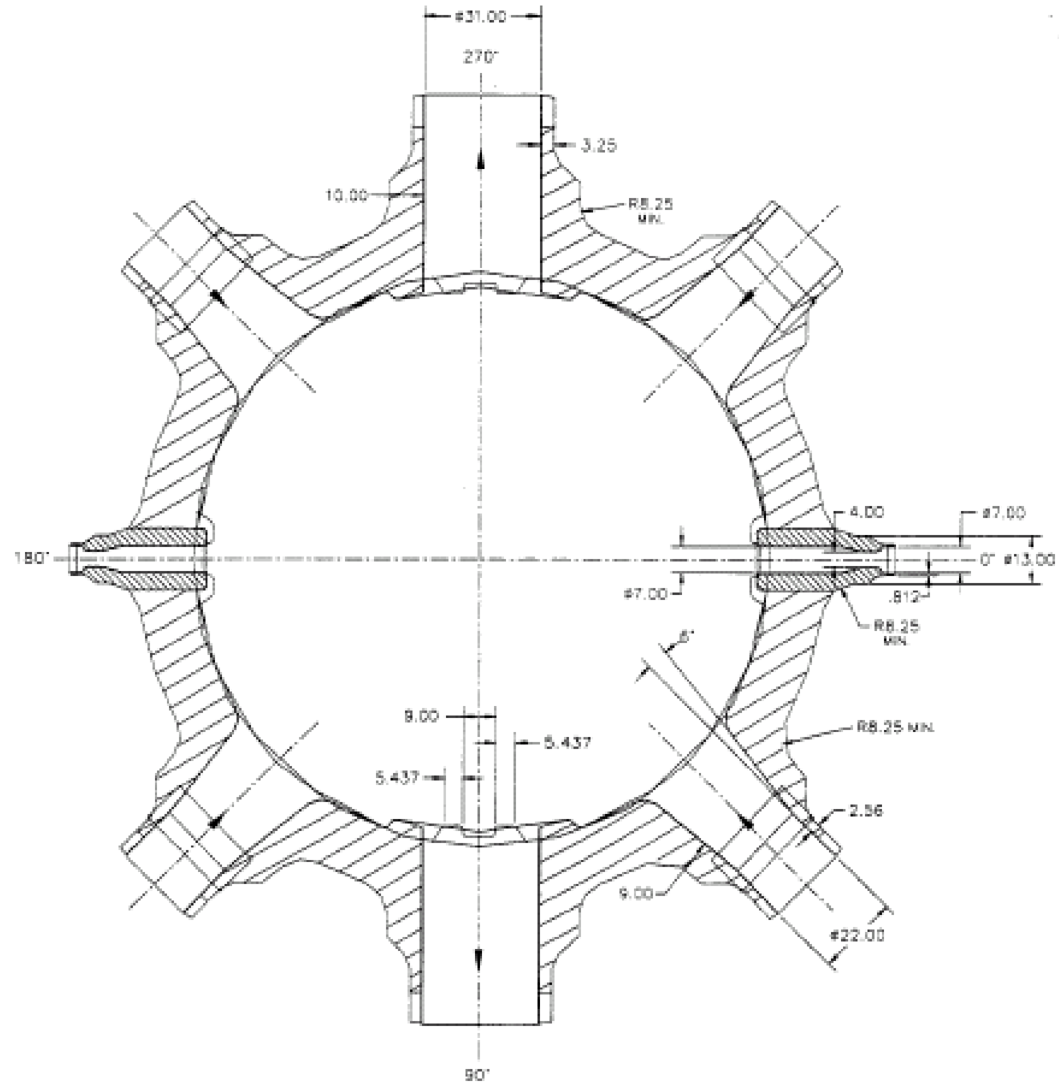
POWER GENERATION



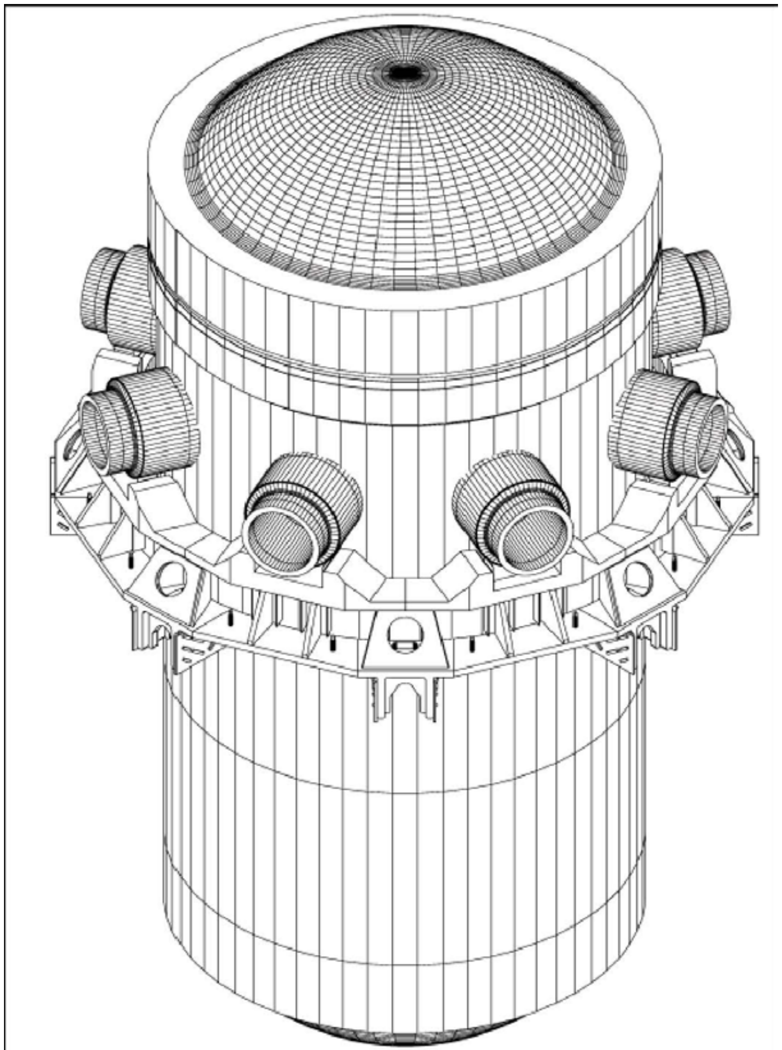
PWR Reactor – Core Cross Section

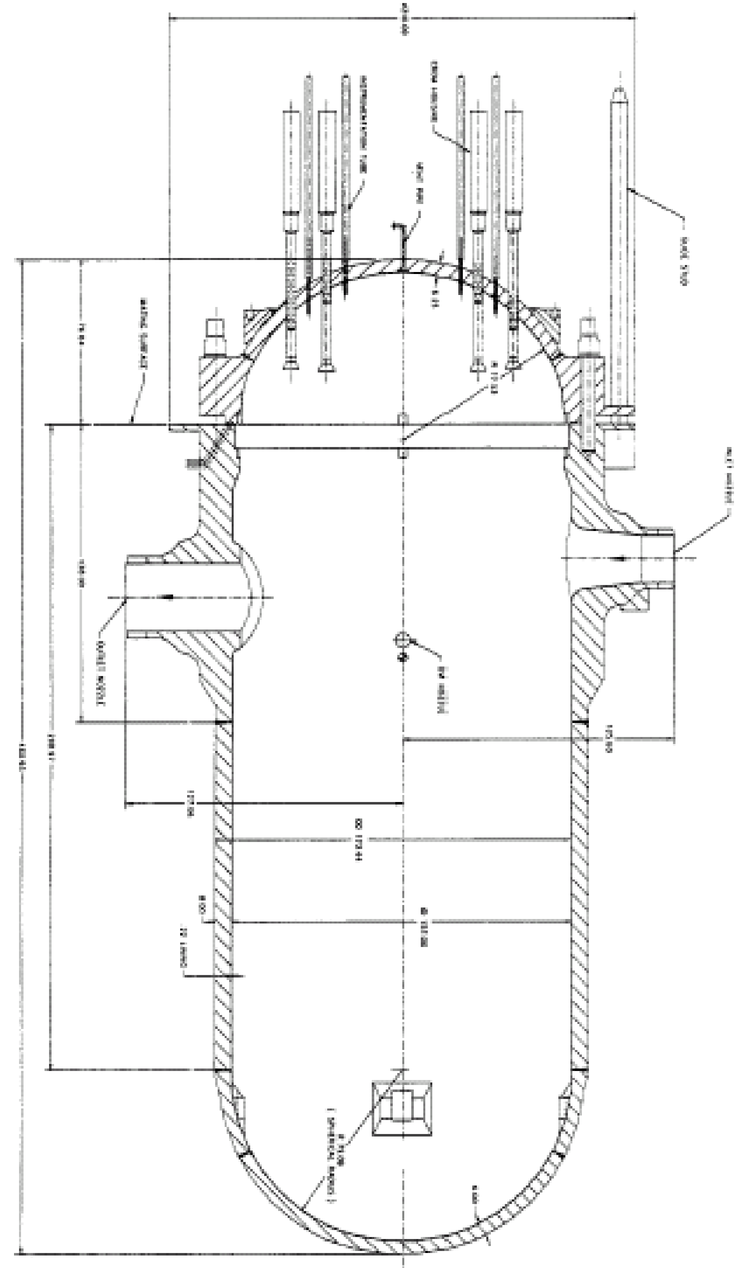


PWR Reactor – Vessel Cross Section

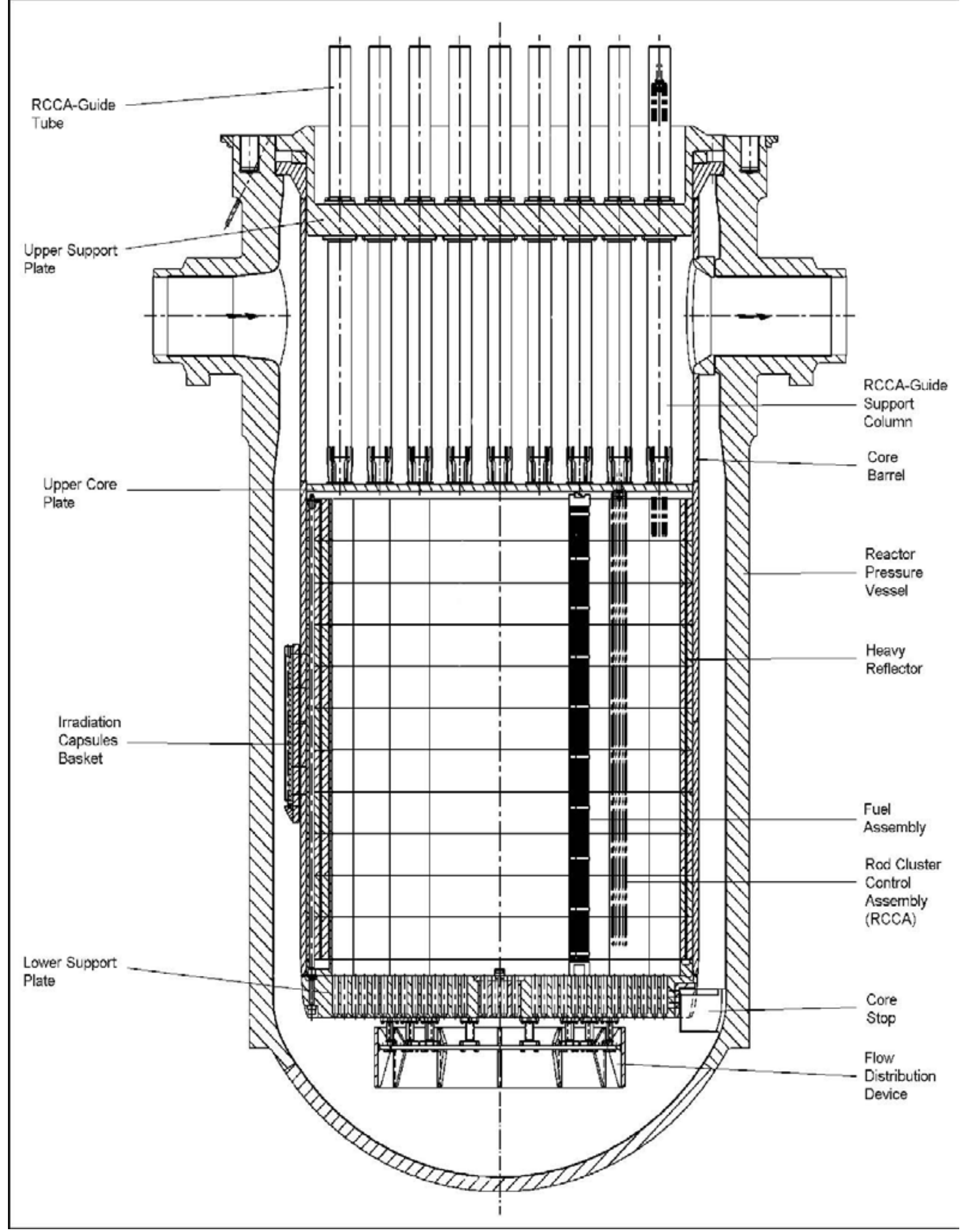


PWR Reactor Vessel Longitudinal Section



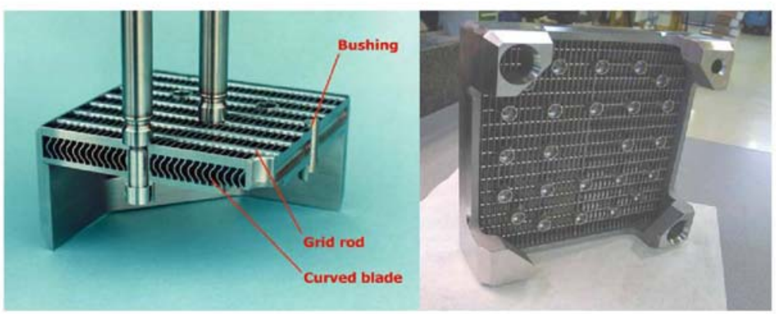


PWR Reactor Vessel

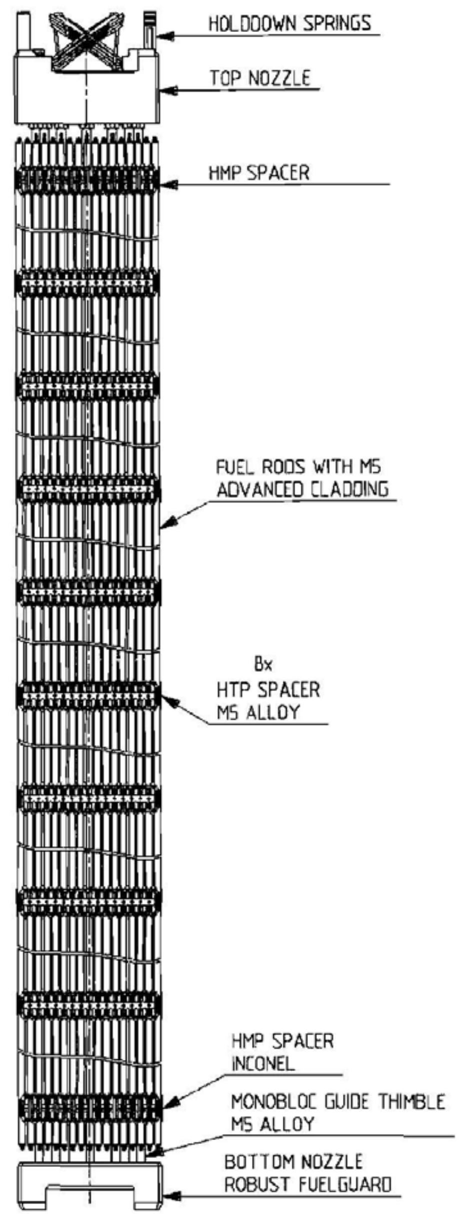


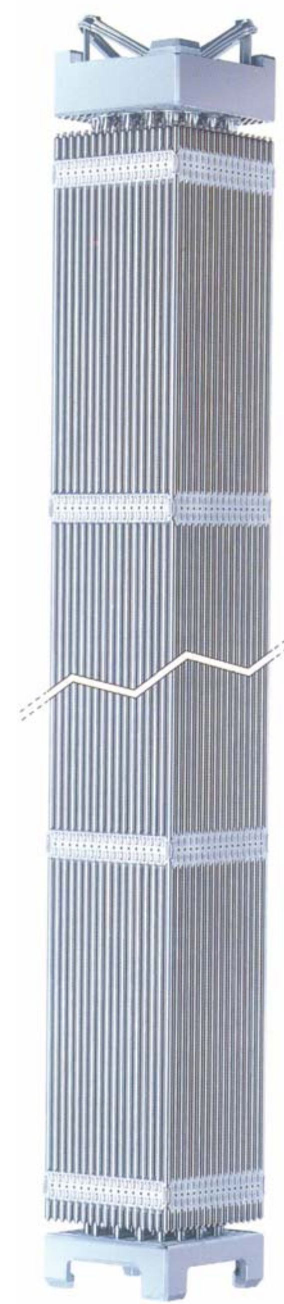
PWR Reactor Fuel Assembly

Top Nozzle

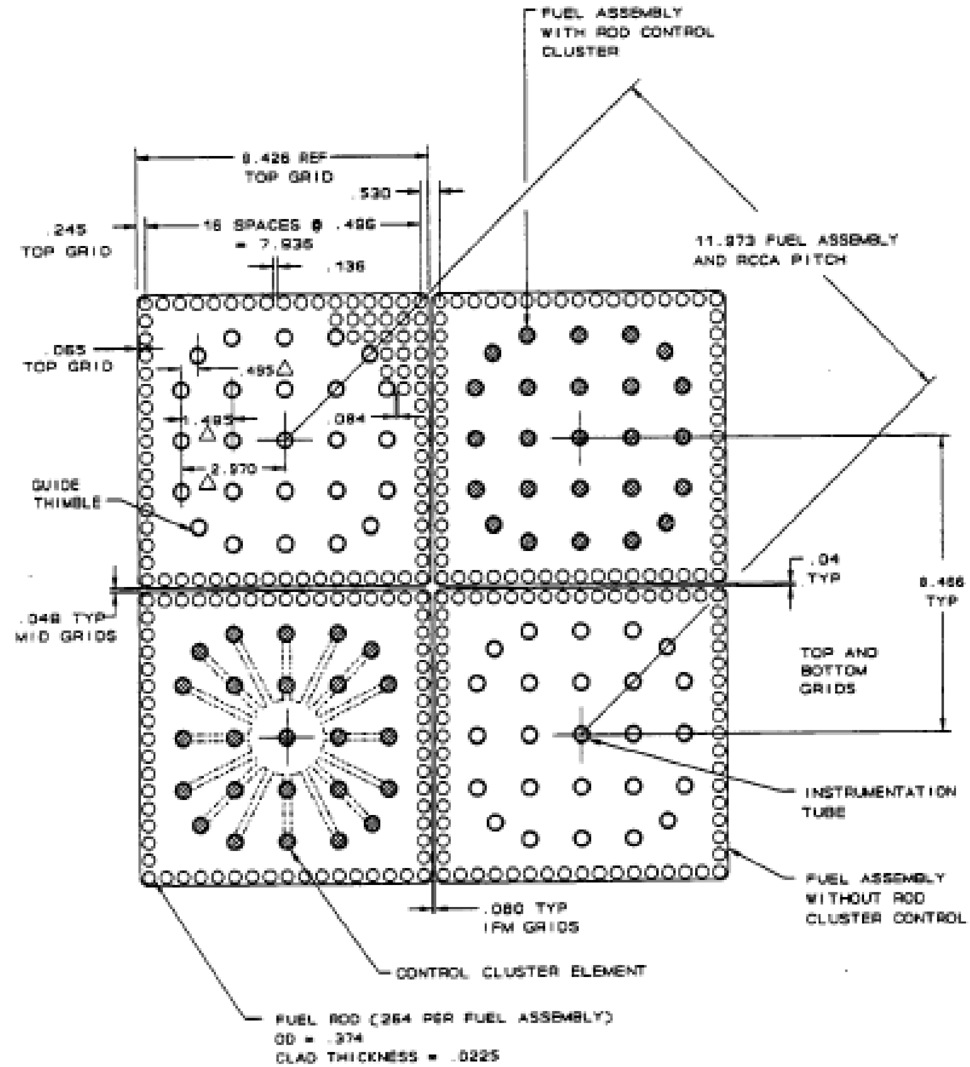


Robust FUELGUARD™ Bottom Nozzle

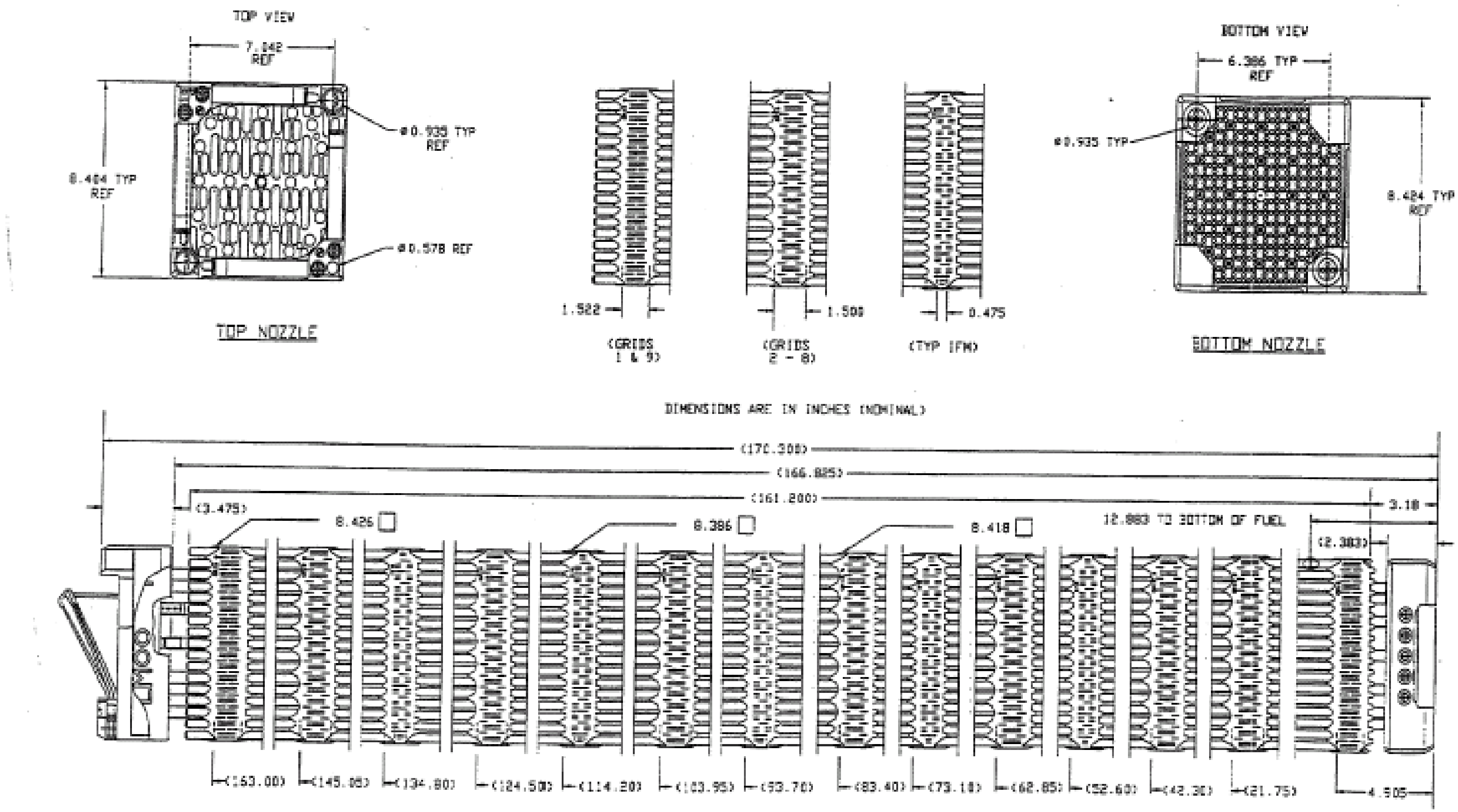




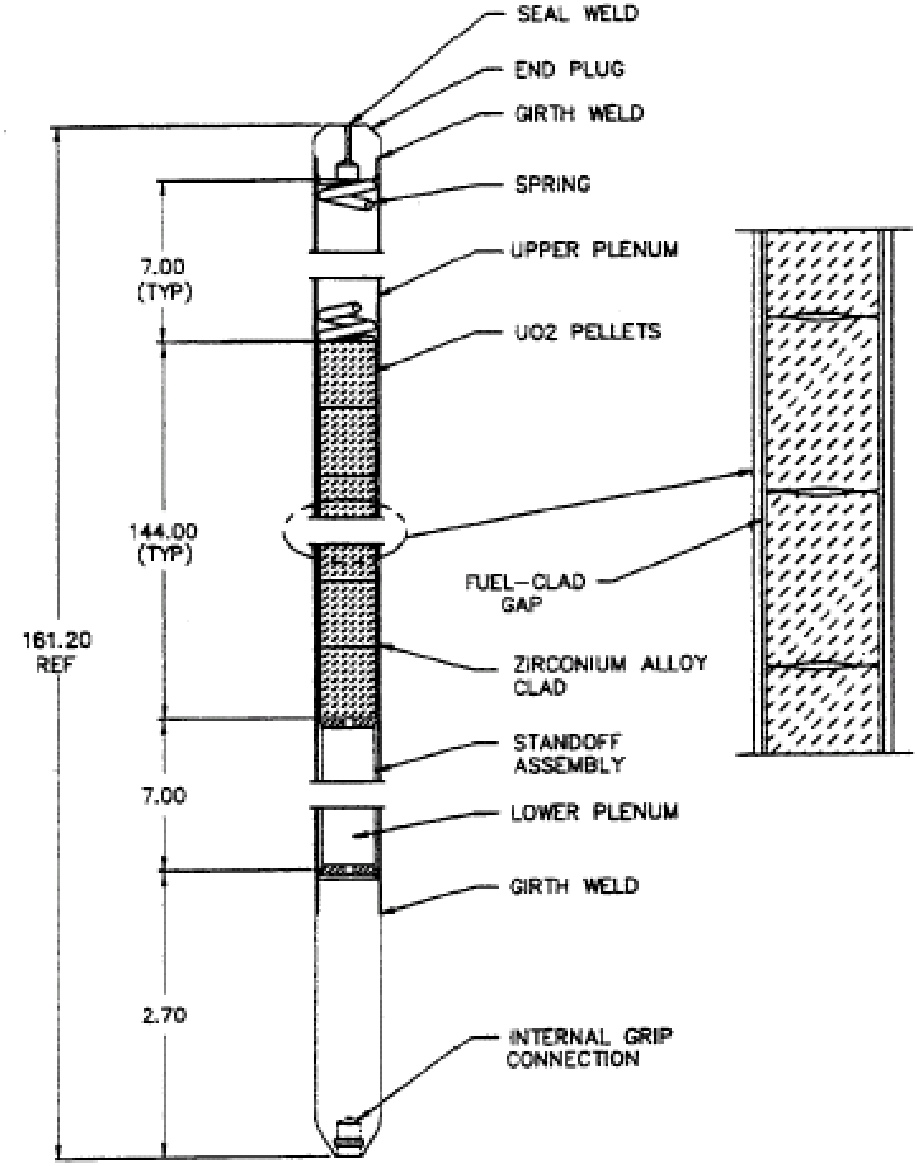
PWR Reactor Fuel Assembly Cross Section



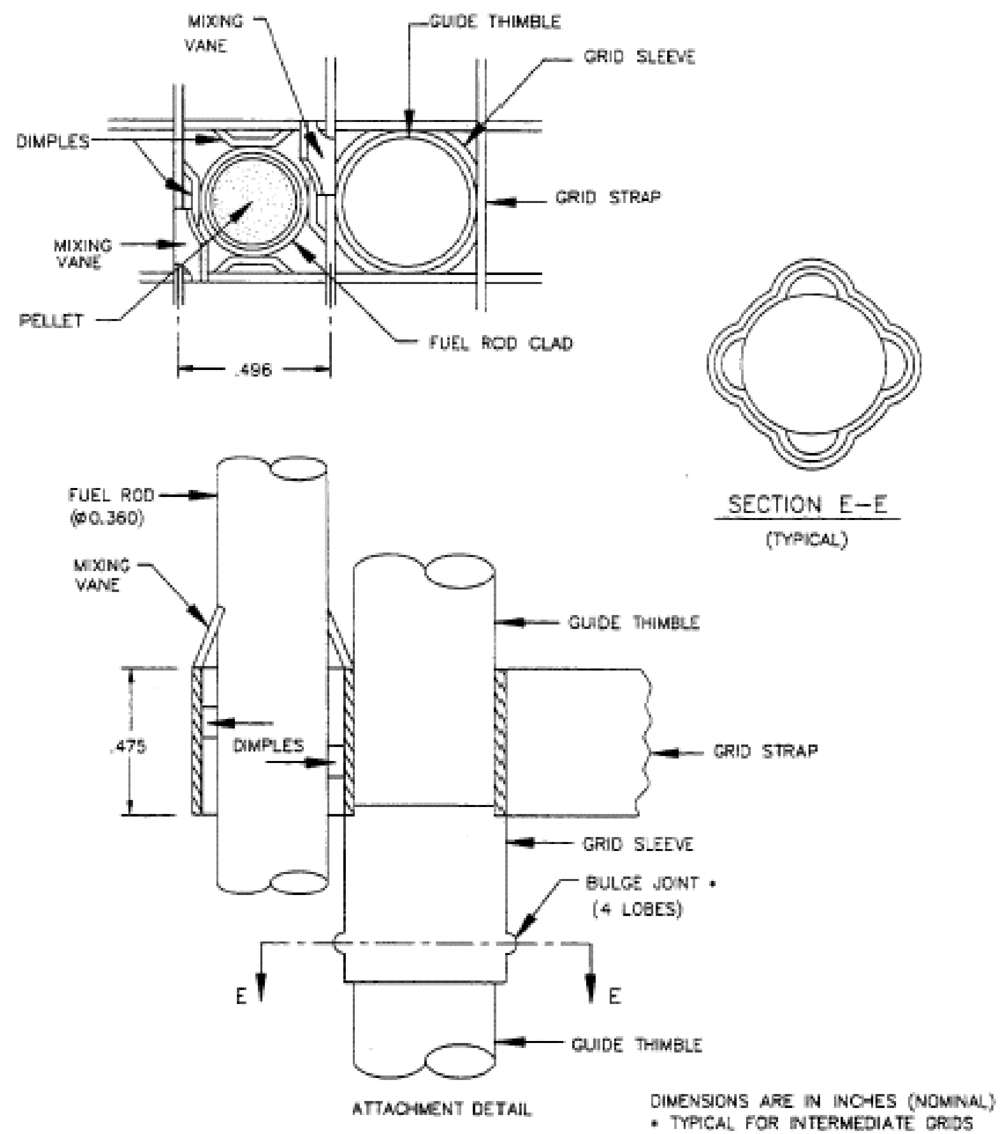
PWR Reactor – Fuel Assembly



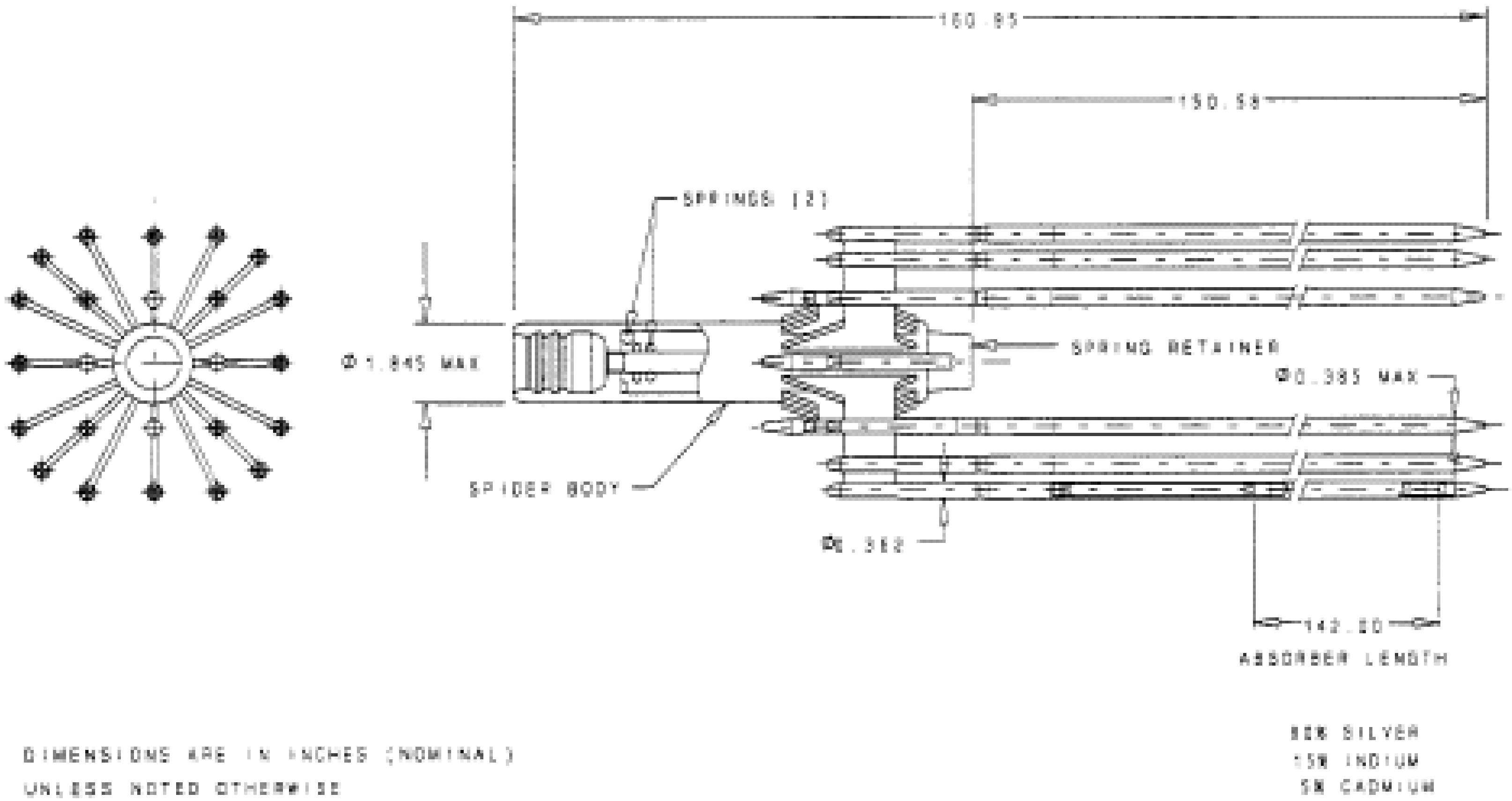
PWR Reactor Fuel Rod



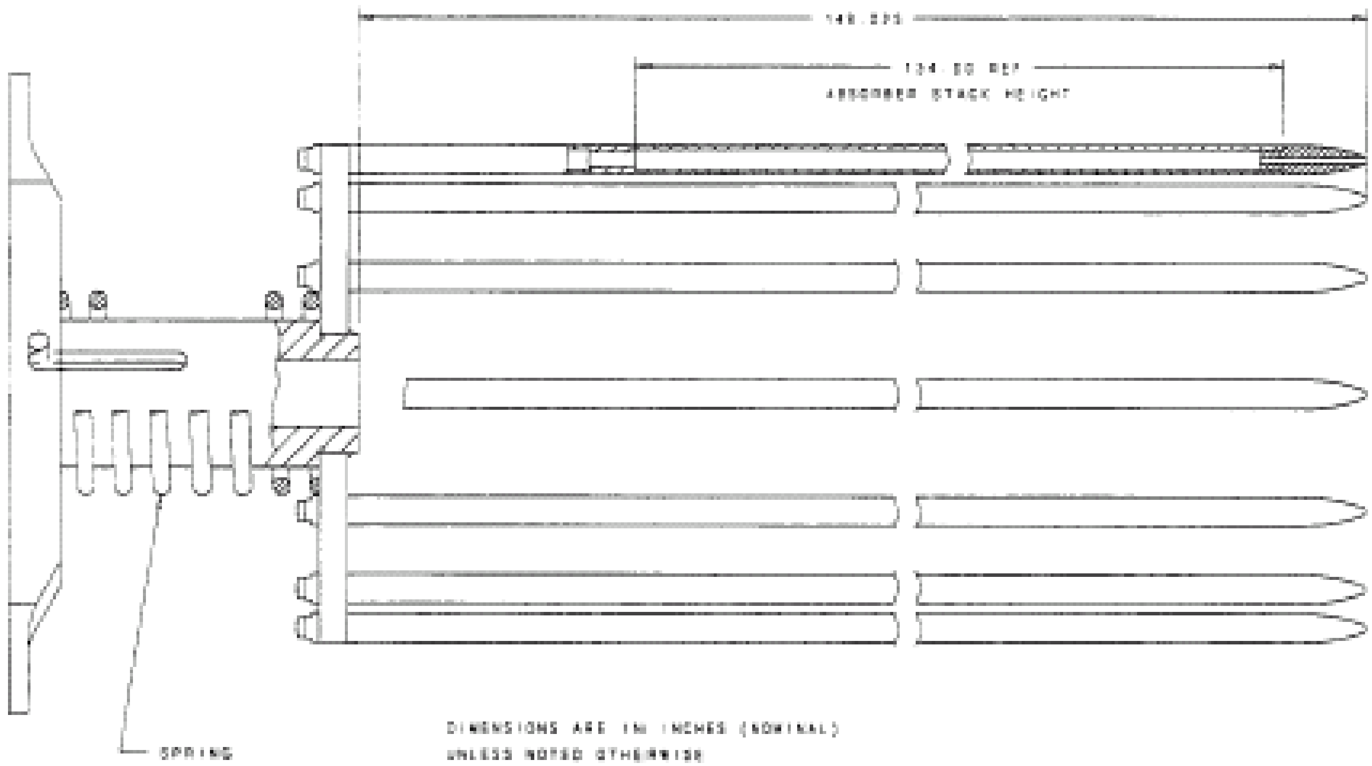
PWR Reactor Fuel Rod Attachments



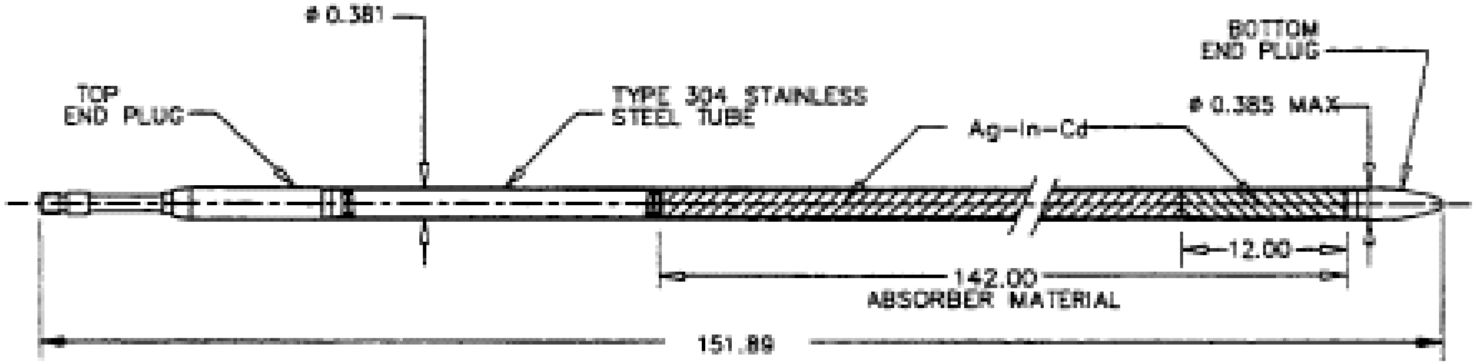
PWR Reactor – Control Cluster Assembly



PWR Reactor – Burnable Absorber Assembly

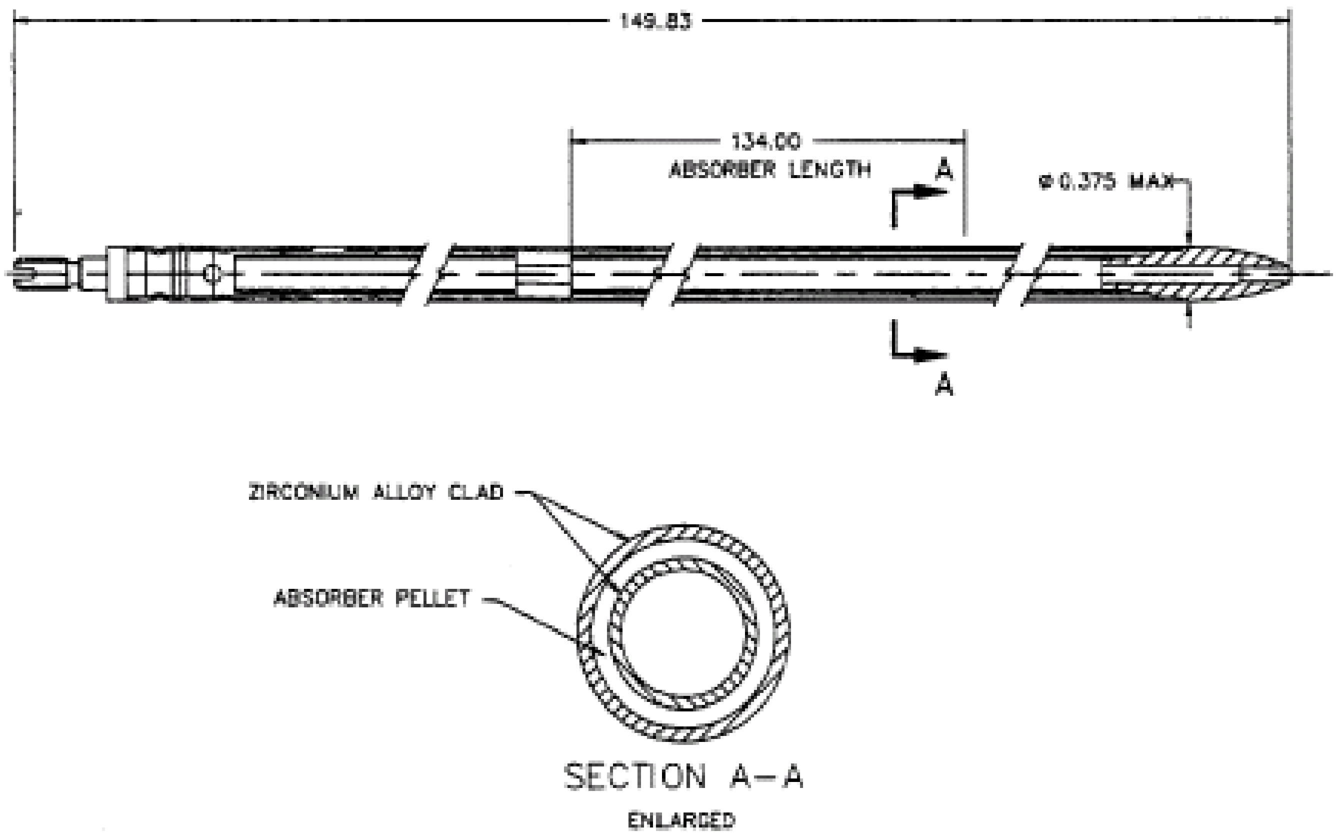


PWR Reactor – Solid Absorber Rod

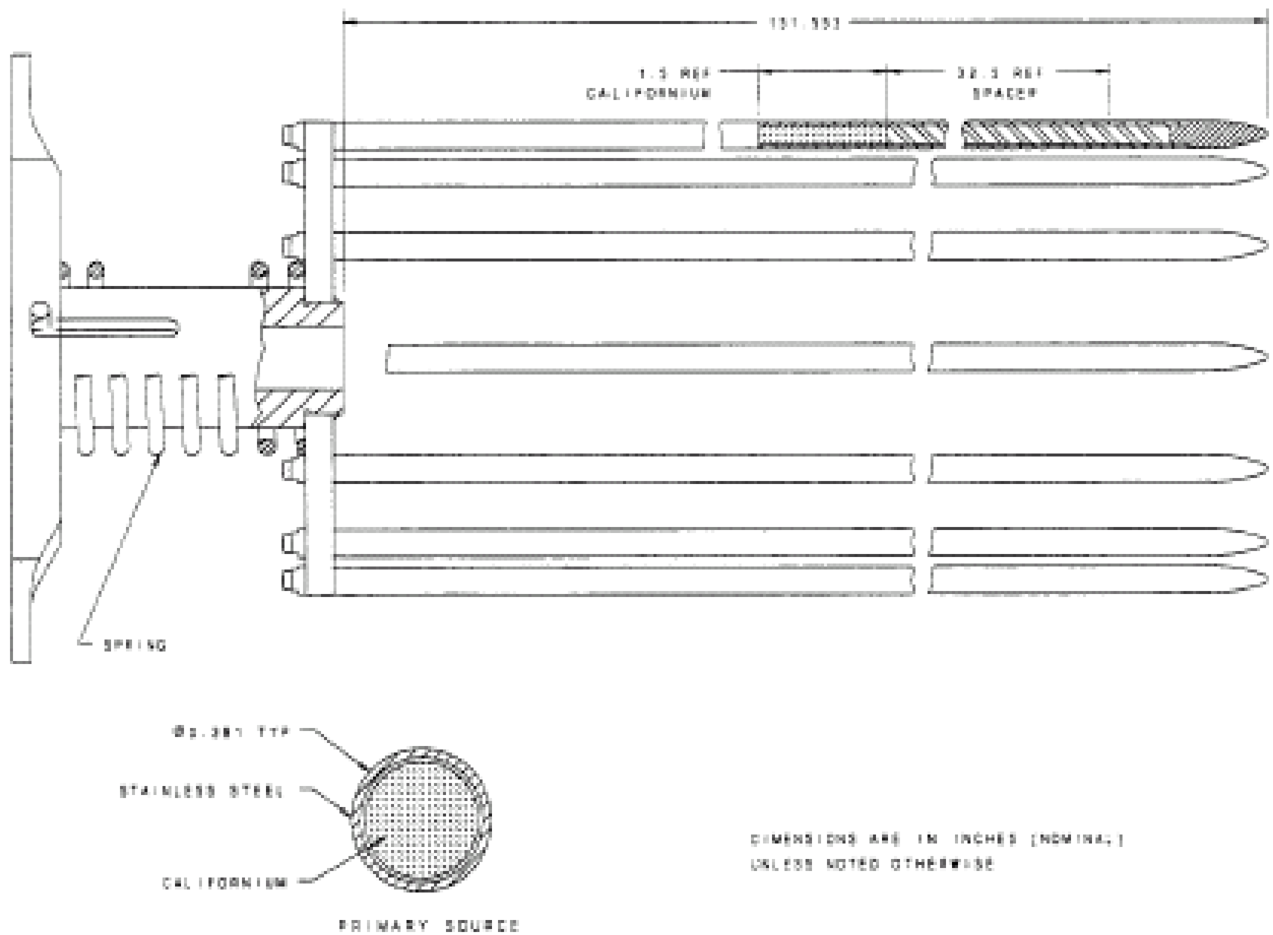


DIMENSIONS ARE IN INCHES (NOMINAL)
UNLESS OTHERWISE NOTED

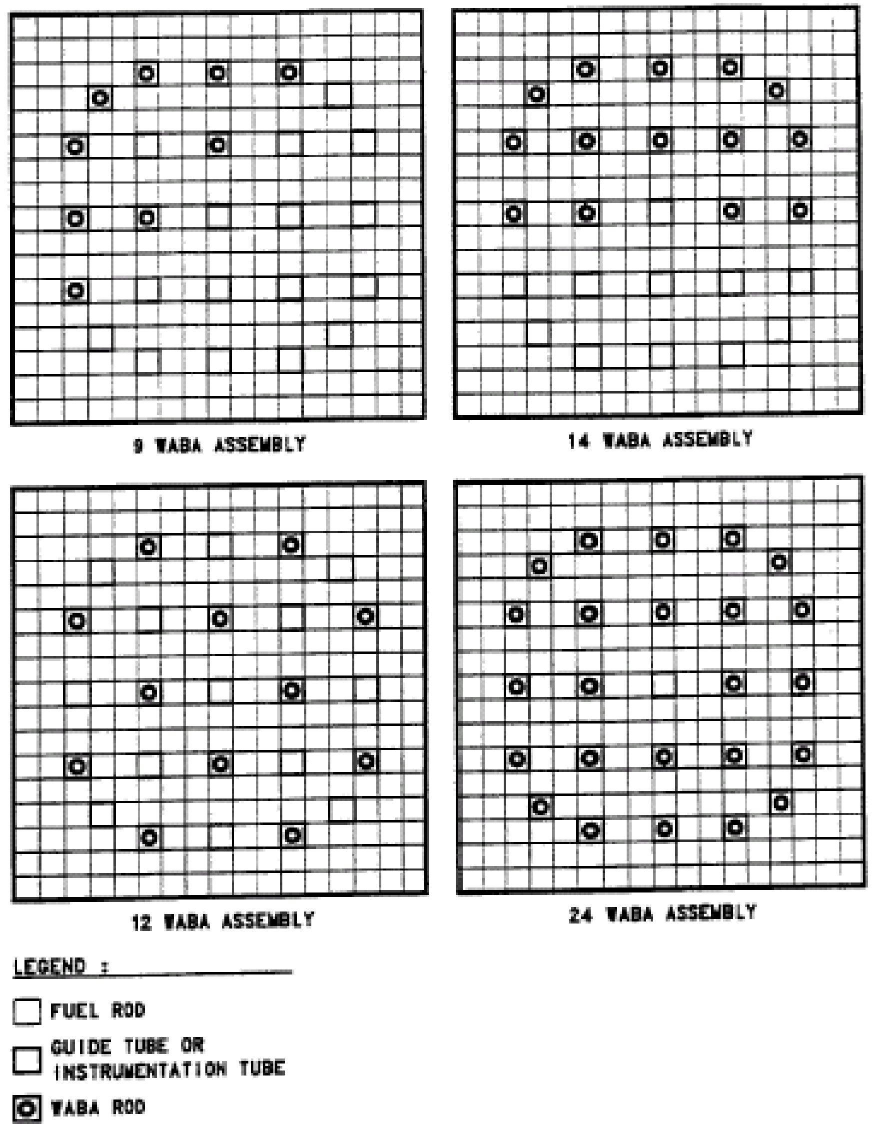
PWR Reactor – Annular Absorber Rod



PWR Reactor – Primary Source Assembly



PWR Reactor – Burnable Poison Distribution



PWR Reactor – Burnable Poison Distribution

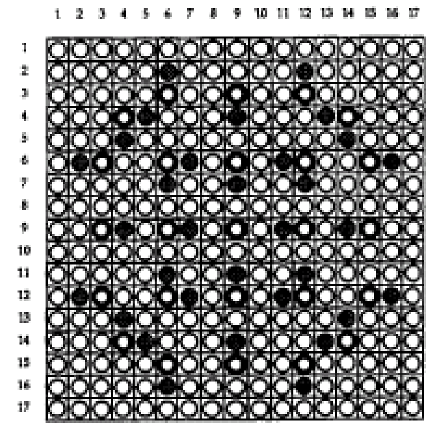
180°

	N	M	L	K	J	H	G	F	E	D	C	B	A	
1				9W	32I 6S	14W	64I	14W	32I	9W				
2			9W		24W 104I		12W 1P		24W 104I		9W			
3		9W	104I	24W		24W		24W		24W	104I	9W		
4	9W		24W		24W	128I	24W	128I	24W		24W		9W	
5	32I	24W 104I		24W		24W		24W		24W		24W 104I	32I	
6	14W		24W	128I	24W		24W		24W	128I	24W		14W	
7 90°	64I	12W		24W		24W		24W		24W		12W	64I	270°
8	14W		24W	128I	24W		24W		24W	128I	24W		14W	
9	32I	24W 104I		24W		24W		24W		24W		24W 104I	32I	
10	9W		24W		24W	128I	24W	128I	24W		24W		9W	
11		9W	104I	24W		24W		24W		24W	104I	9W		
12			9W		24W 104I		12W 1P		24W 104I		9W			
13				9W	32I	14W	64I	14W	32I 6S	9W				

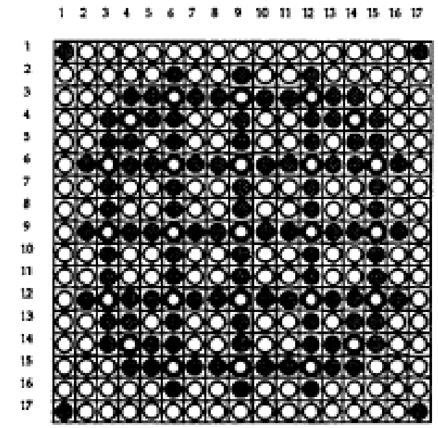
0°

	TYPE	TOTAL
##W	NUMBER OF WABA RODLETS	1456
##I	NUMBER OF IFBA RODS	2784
#S	NUMBER OF SECONDARY SOURCE RODLETS	12
#P	NUMBER OF PRIMARY SOURCE RODLETS	2

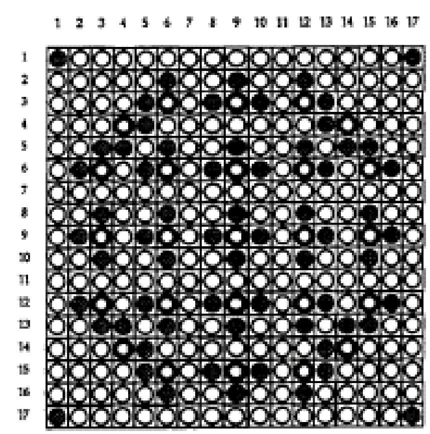
PWR Reactor – Burnable Poison Distribution



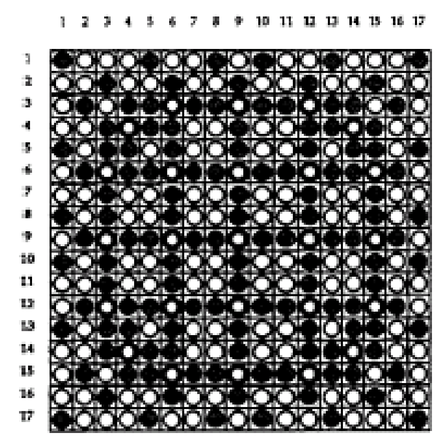
32 IFBAs / Assembly



104 IFBAs / Assembly

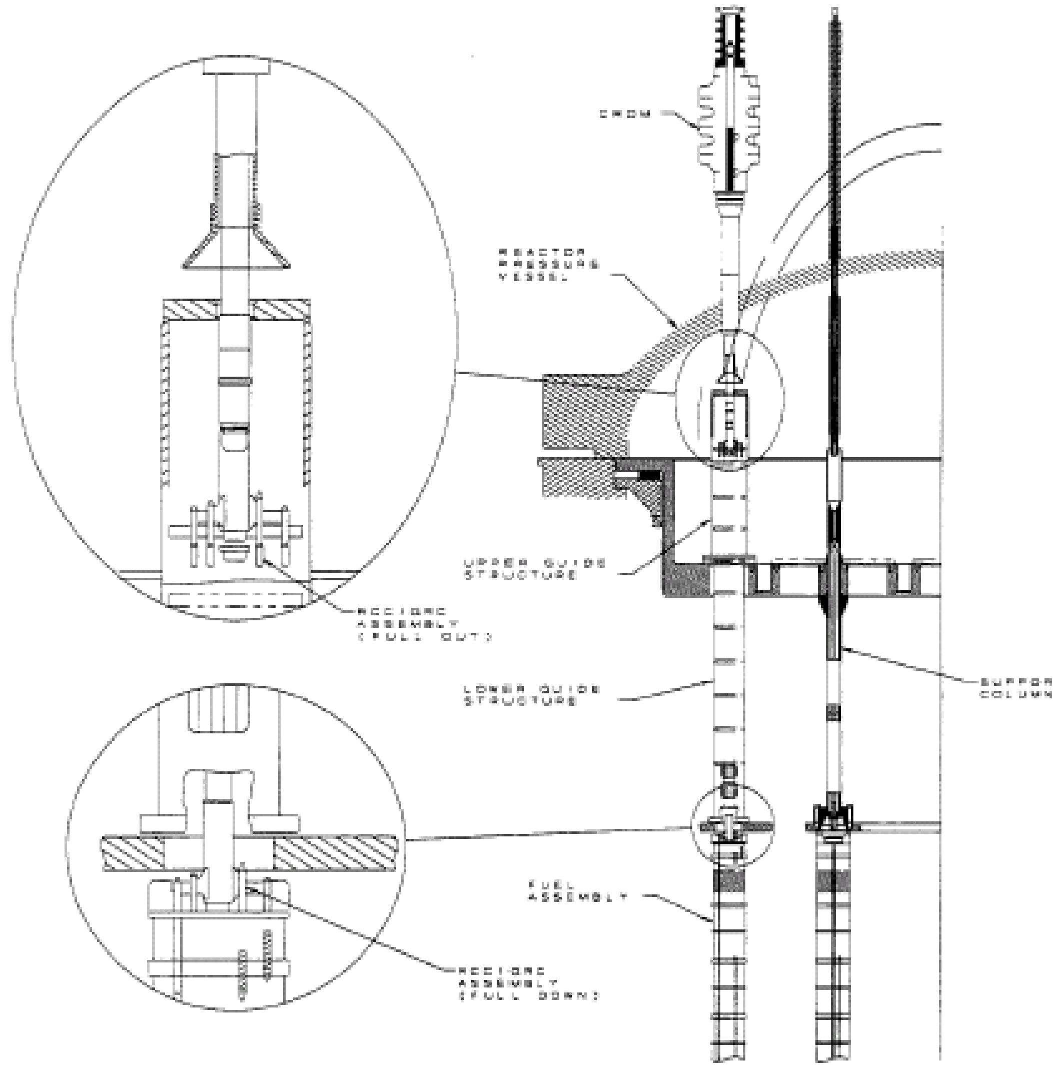


64 IFBAs / Assembly

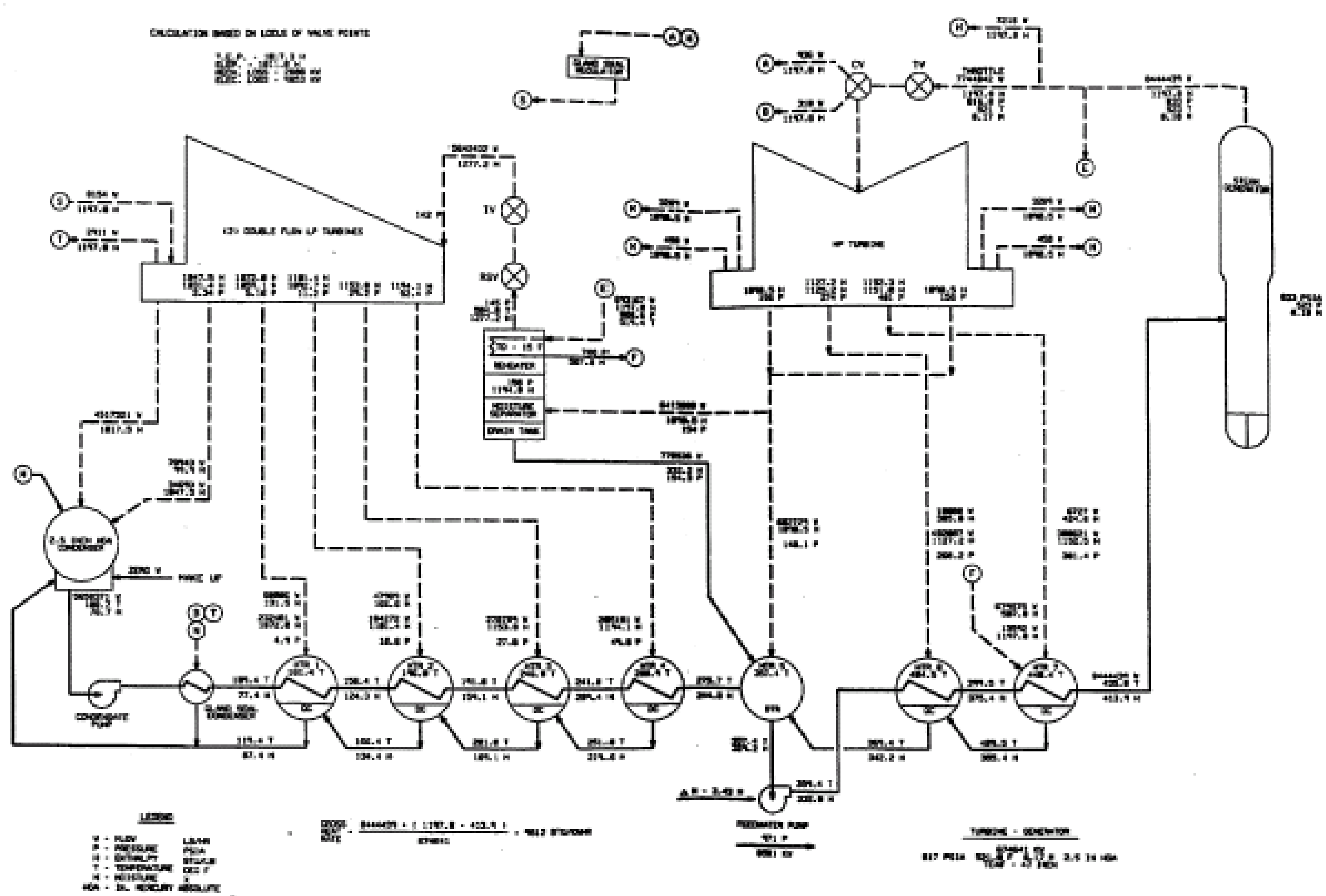


128 IFBAs / Assembly

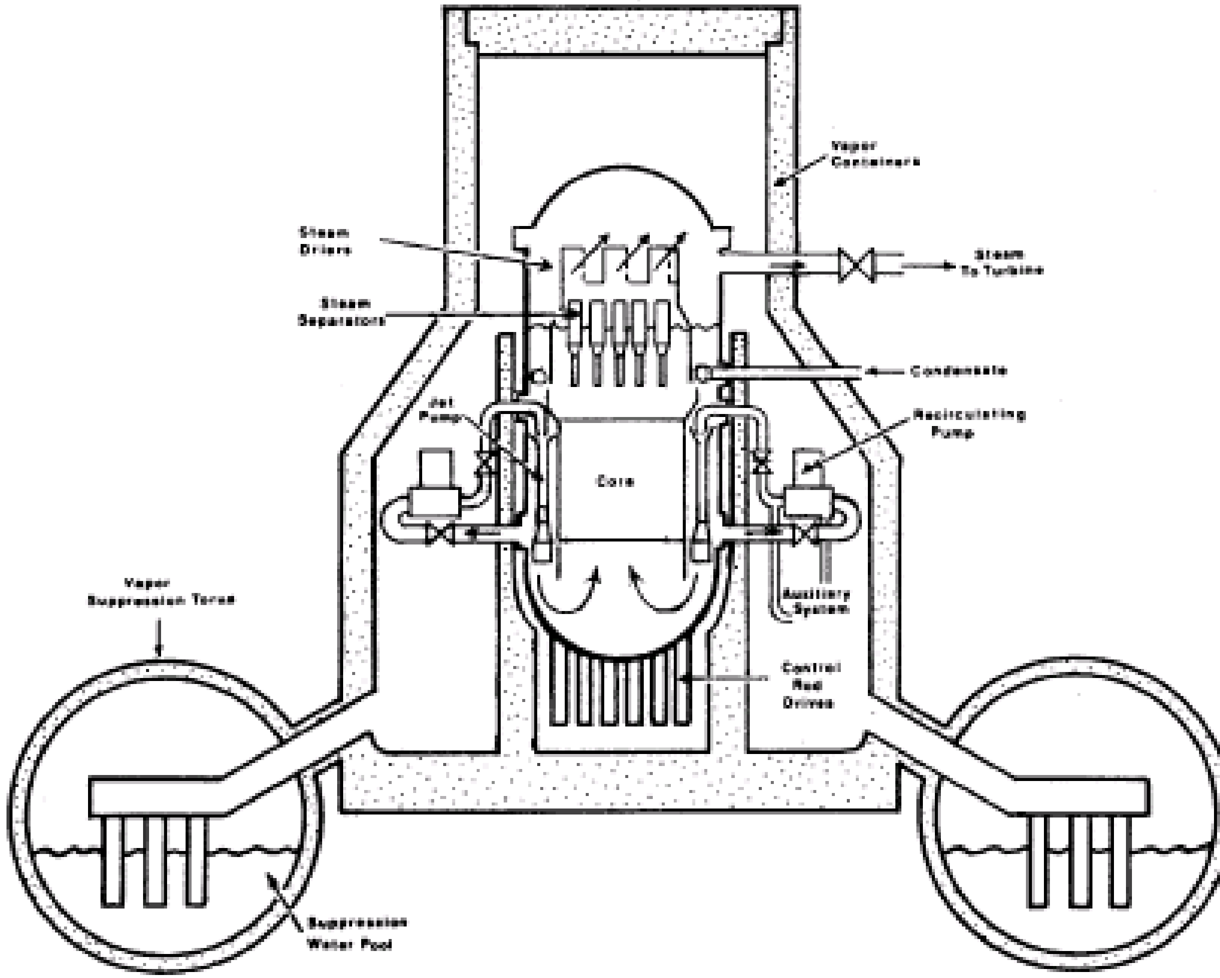
PWR Reactor Control Rod Assembly and Drive Rod

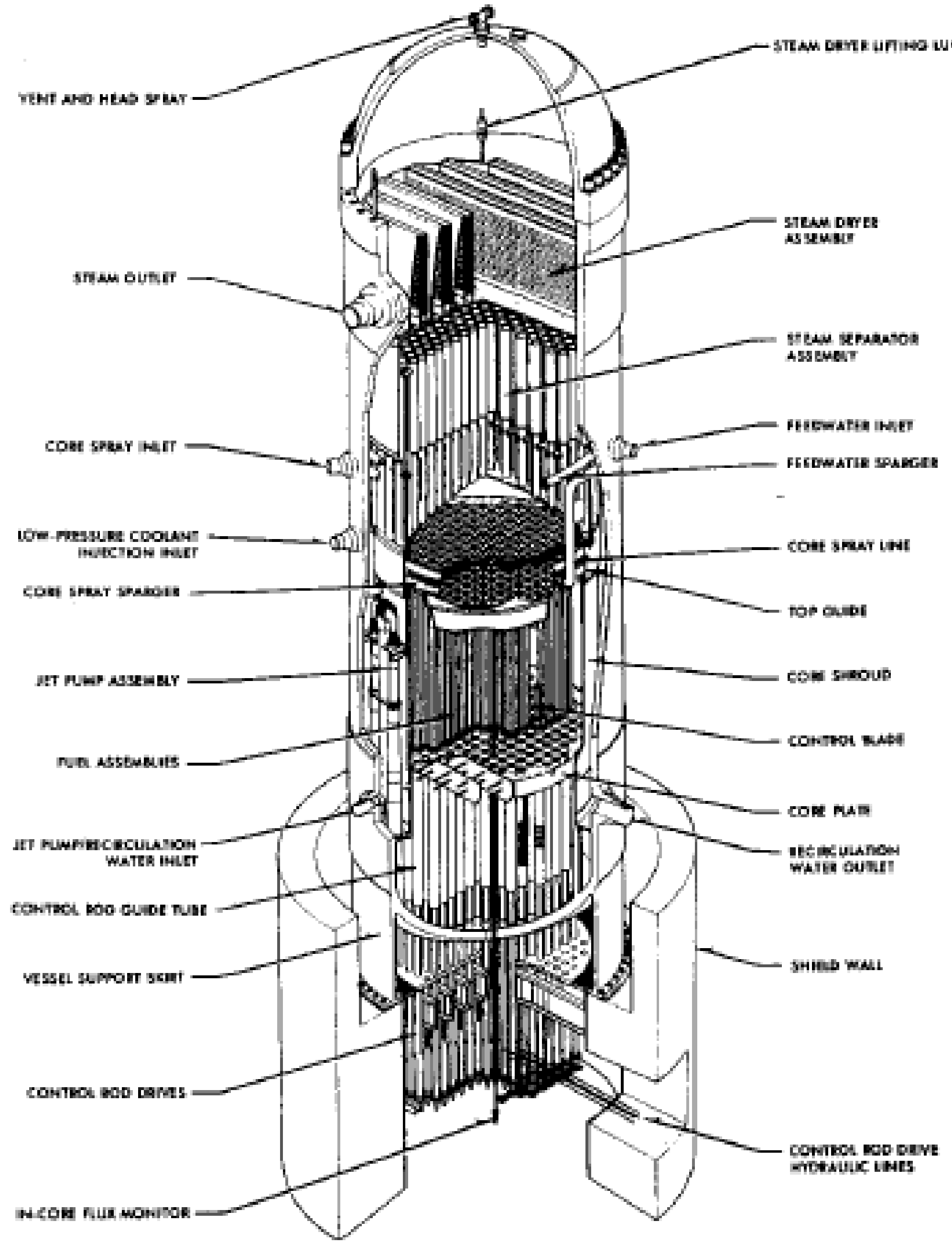


PWR Reactor – BOP Schematic



BWR Reactor


Vapor Containers
Steam Driers
Steam Separators
Steam To Turbine
Condensate
Jet Pump
Recirculating Pump
Core
Auxiliary System
Control Rod Drives
Vapor Suppression Torus
Suppression Water Pool

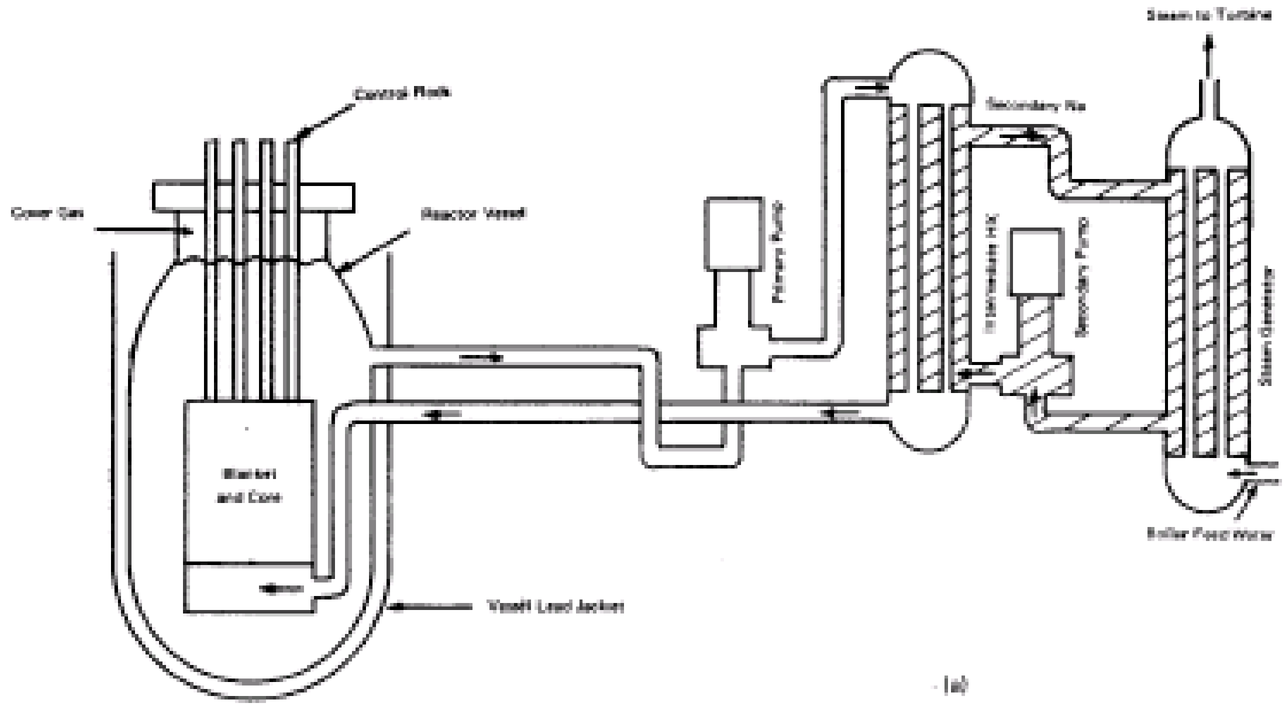


VENT AND HEAD SPRAY
STEAM DRYER LIFTING LUG
STEAM DRYER ASSEMBLY
STEAM OUTLET
STEAM SEPARATOR ASSEMBLY
FEEDWATER INLET
CORE SPRAY INLET
FEEDWATER SPARGER
LOW-PRESSURE COOLANT INJECTION INLET
CORE SPRAY LINE
CORE SPRAY SPARGER
TOP GUIDE
JET PUMP ASSEMBLY
CORE SHROUD
CONTROL BLADE
FUEL ASSEMBLIES
CORE PLATE
JET PUMP/RECIRCULATION WATER INLET
RECIRCULATION WATER OUTLET
CONTROL ROD GUIDE TUBE
VESSEL SUPPORT SKIRT
SHIELD WALL
CONTROL ROD DRIVES
CONTROL ROD DRIVE HYDRAULIC LINES
IN-CORE FLUX MONITOR

BWR Reactor

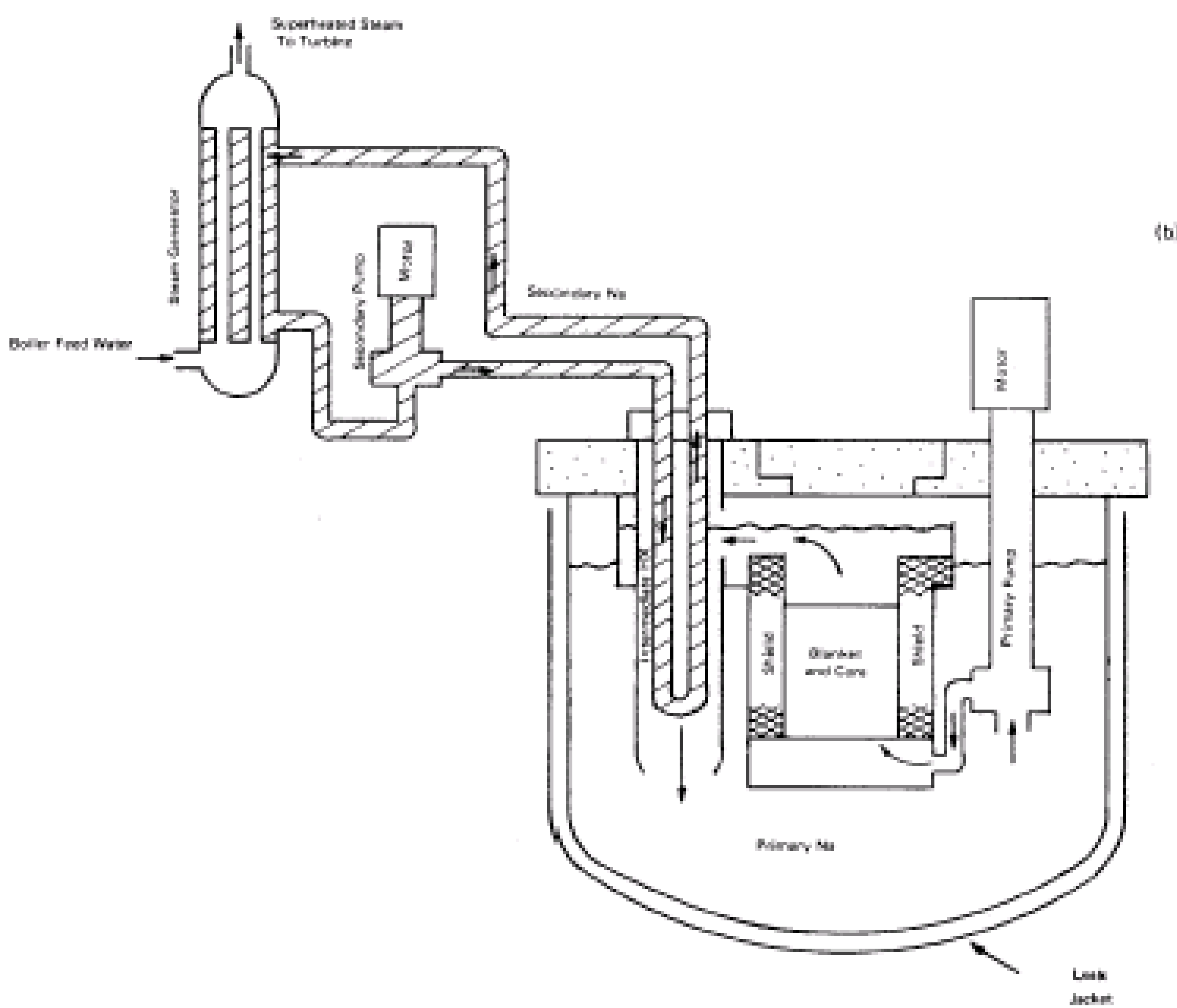
- Water enters the core near saturation temperature, so the heat is used to generate steam
- Jet pumps used to recalculate the water separated from the steam in the upper part of the reactor
- External pumps also used to recalculate part of the water
- Recalculating pumps use variable-speed drives, to vary the flow, ad steam volume in the core
- Power variation between 70-100% achievable without control rod movement
- Bottom insertion of control rods helps flatten the power profile axially
- Containment structure much smaller compared to PWRs.

LMFBR Reactor



(a)

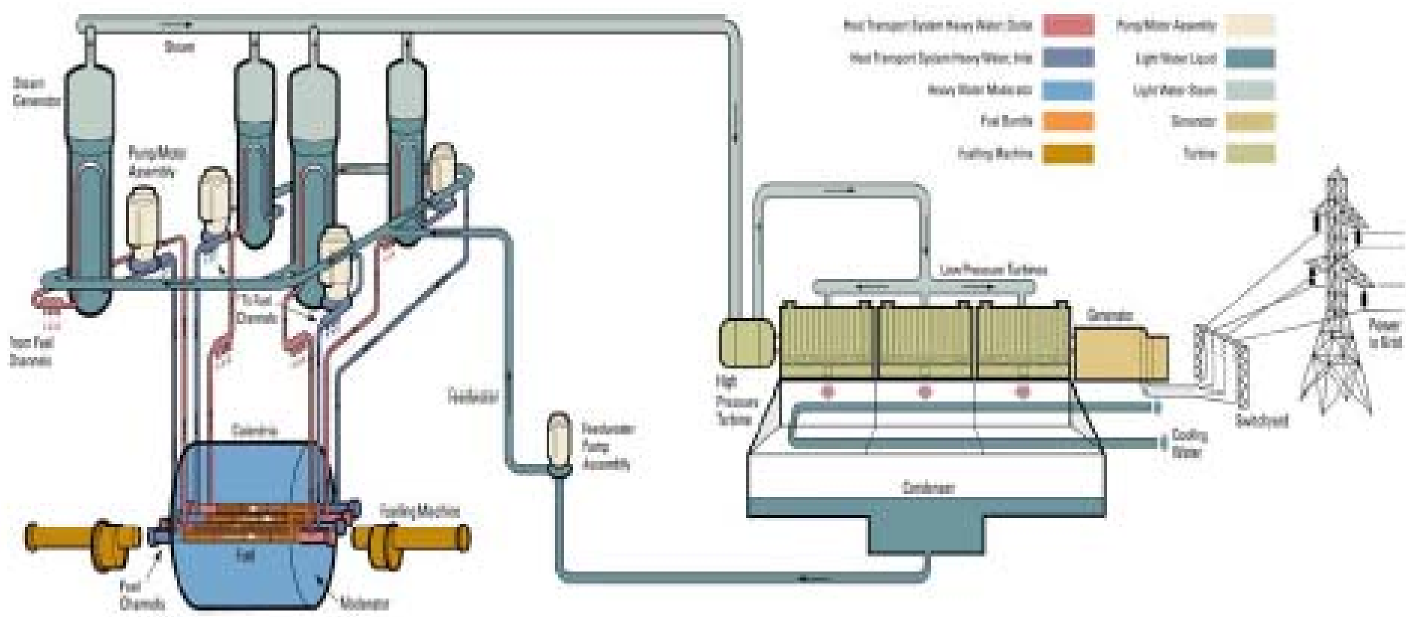
LMFBR Reactor



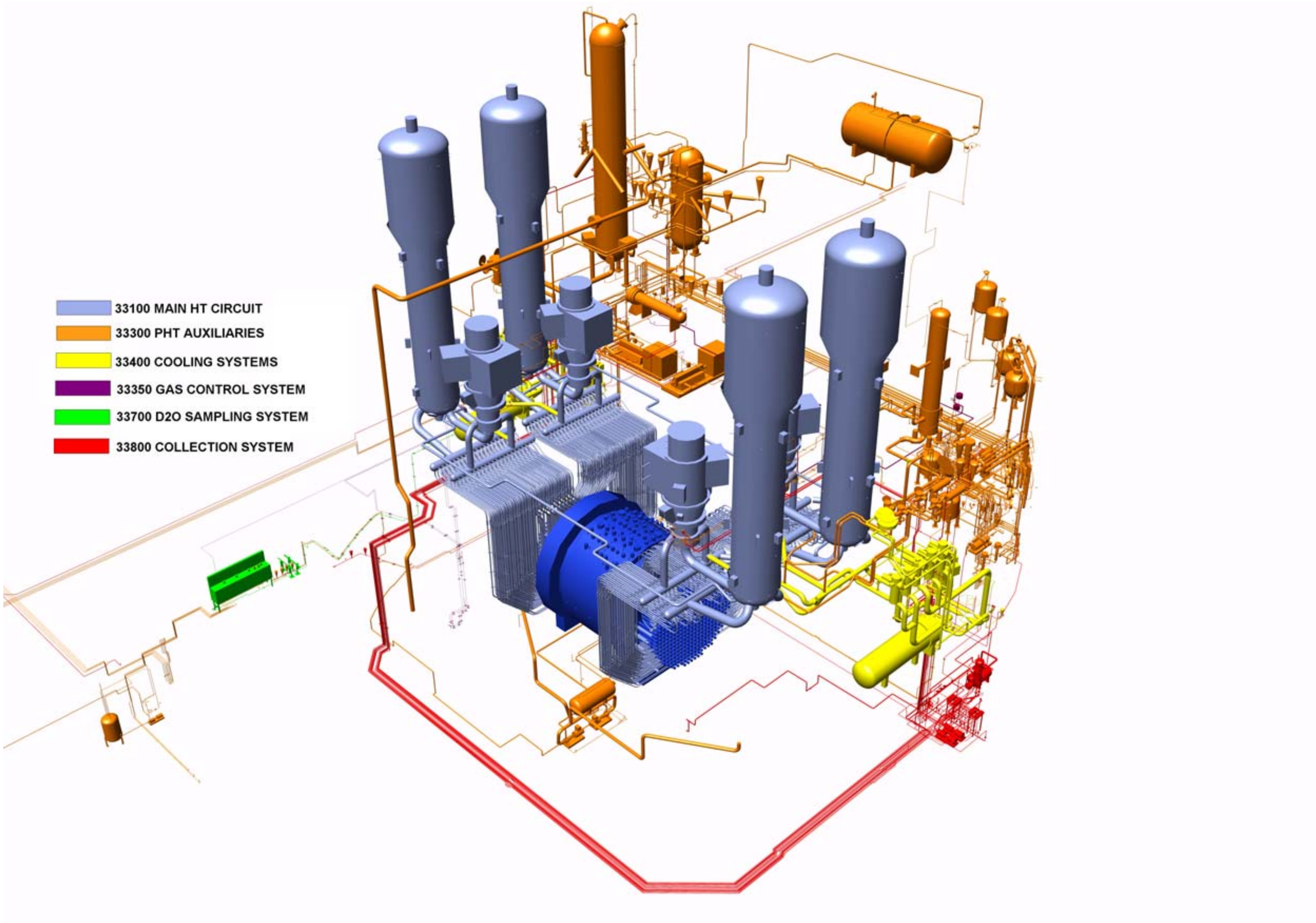
LMFBR Reactor

- Fission caused by fast neutrons (no termalization required)
- Absorption in U-238 results in conversion to Pu-239 (breeding)
- High fast neutron economy required for effective ‘breeding’
- Reactor core consists of closely packed array of highly enriched mixed oxide rods (U-235 and Pu-239)
- Core surrounded by a blanket of U-238 for breeding
- Core and blanket cooled by liquid sodium (high atomic mass for reducing moderation effect)
- Heat exchangers with sodium on both sides (secondary sodium side)
- Secondary sodium loop intended to ensure complete isolation from water contamination

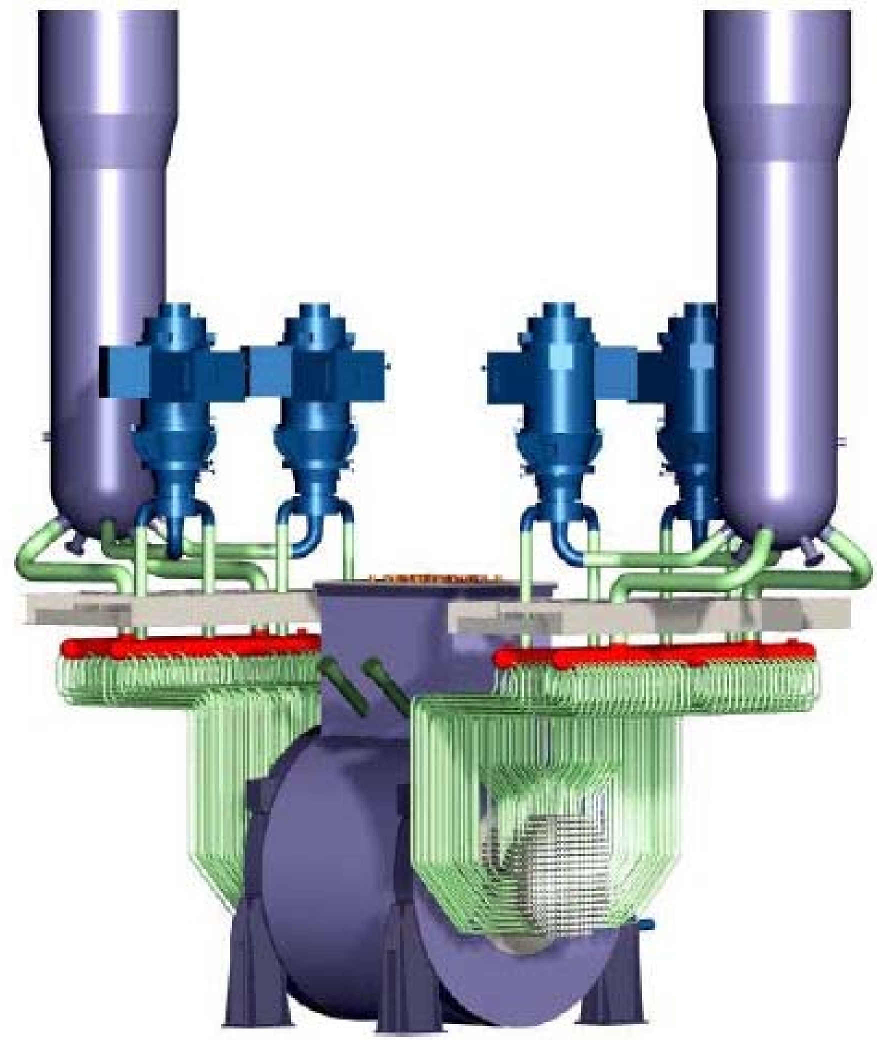
CANDU 6 Reactor



CANDU 6 Reactor



ACR-700 Advanced CANDU Reactor

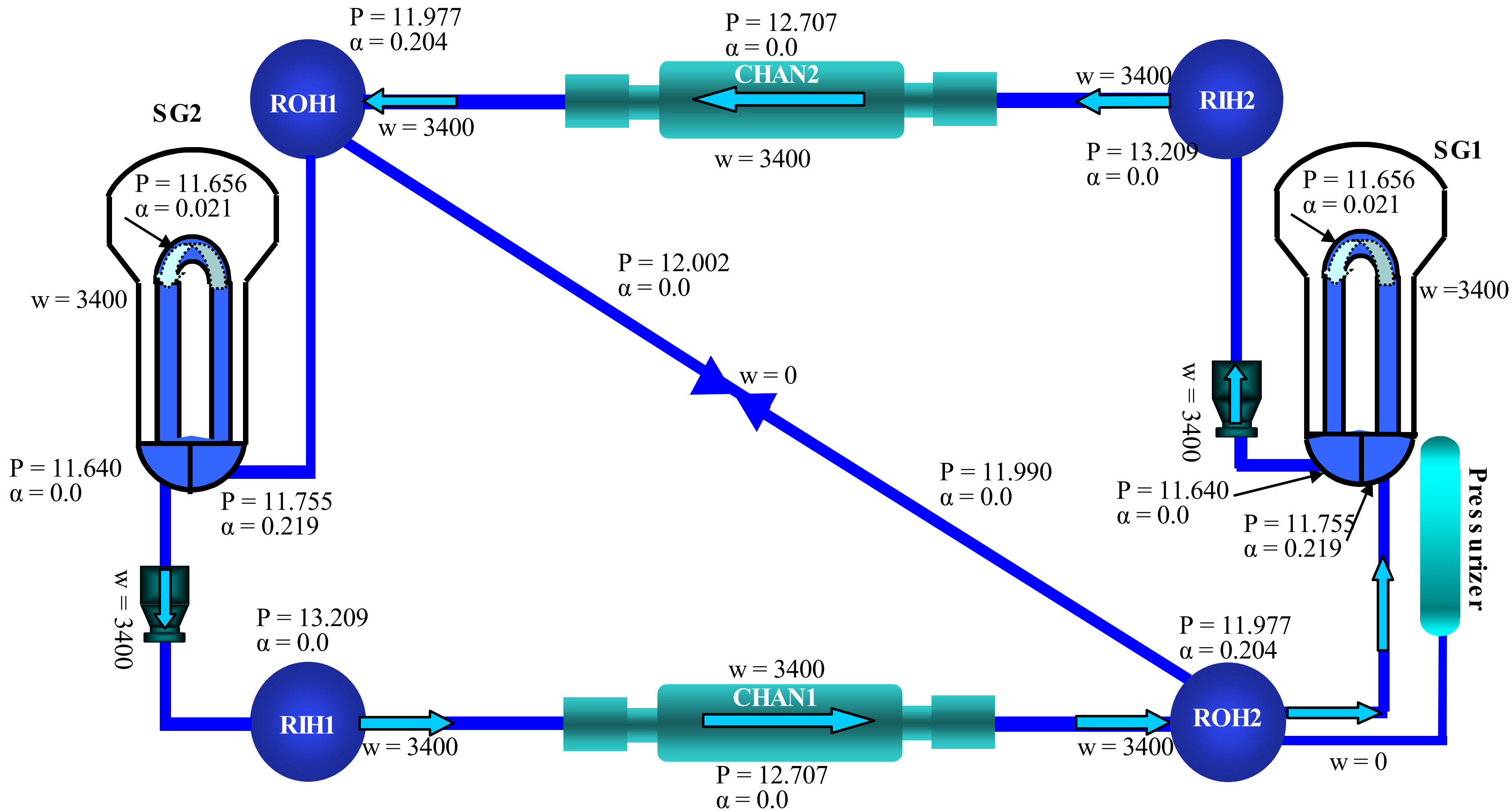


ACR-700 Heat Transport System Layout

ACR-700 Advanced CANDU Reactor

- Light water cooled, heavy water moderated reactor
- Slightly enriched uranium (2.1%)
- Single ‘figure-of-eight’ loop (no CVR issue, no power pulse)
- Large interconnect linking outlet headers to for better ECC performance
- ECC injection only into inlet headers

ACR-700 Advanced CANDU Reactor



ACR-700 Advanced CANDU Reactor

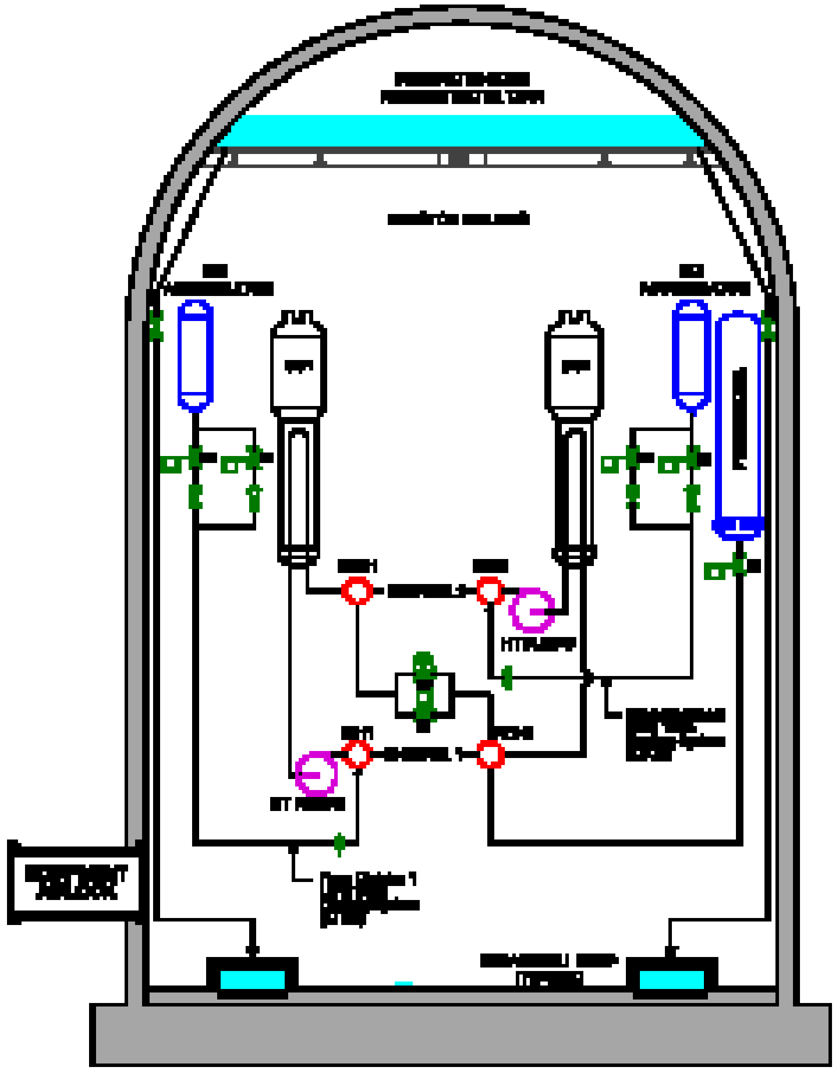
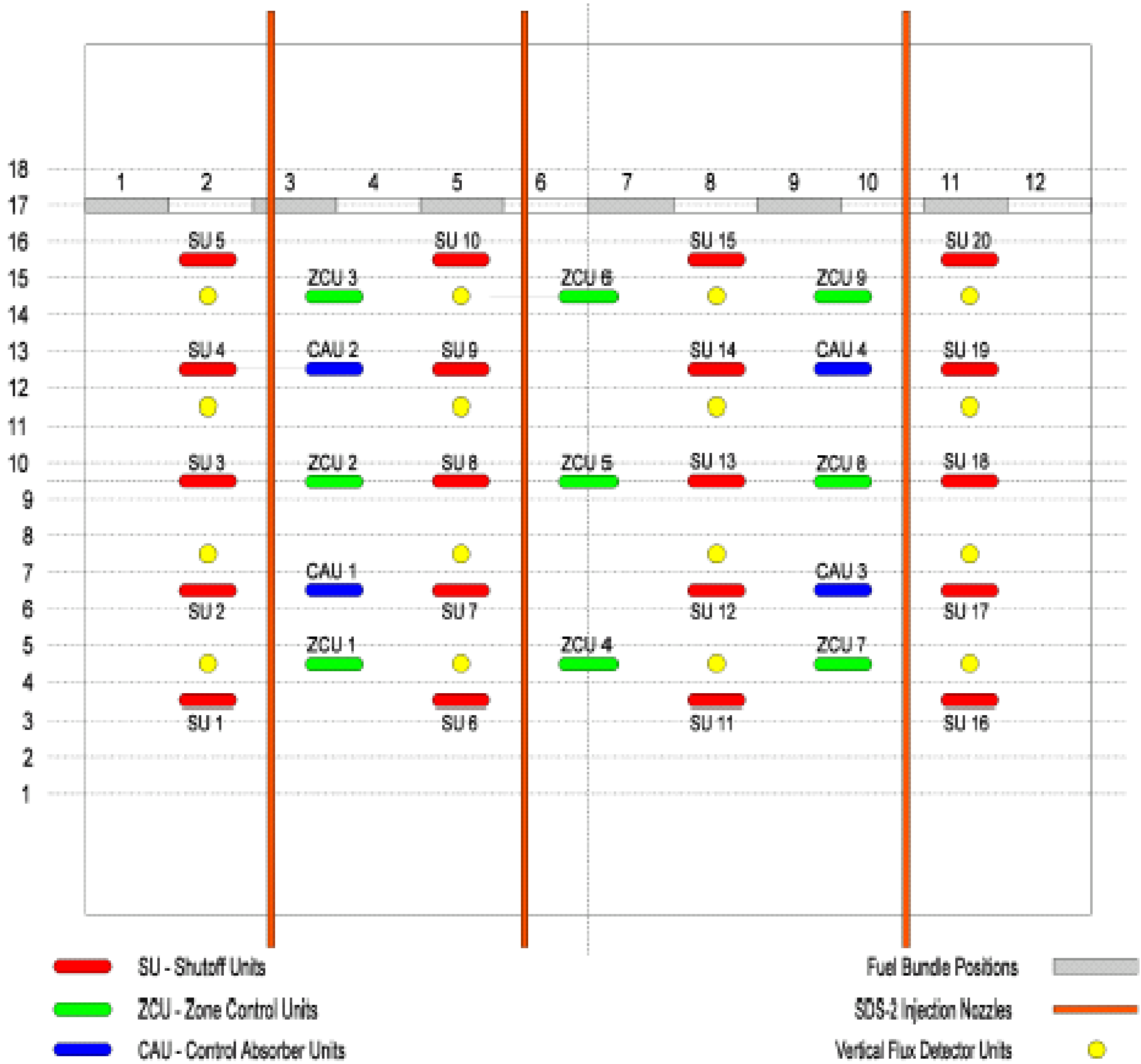
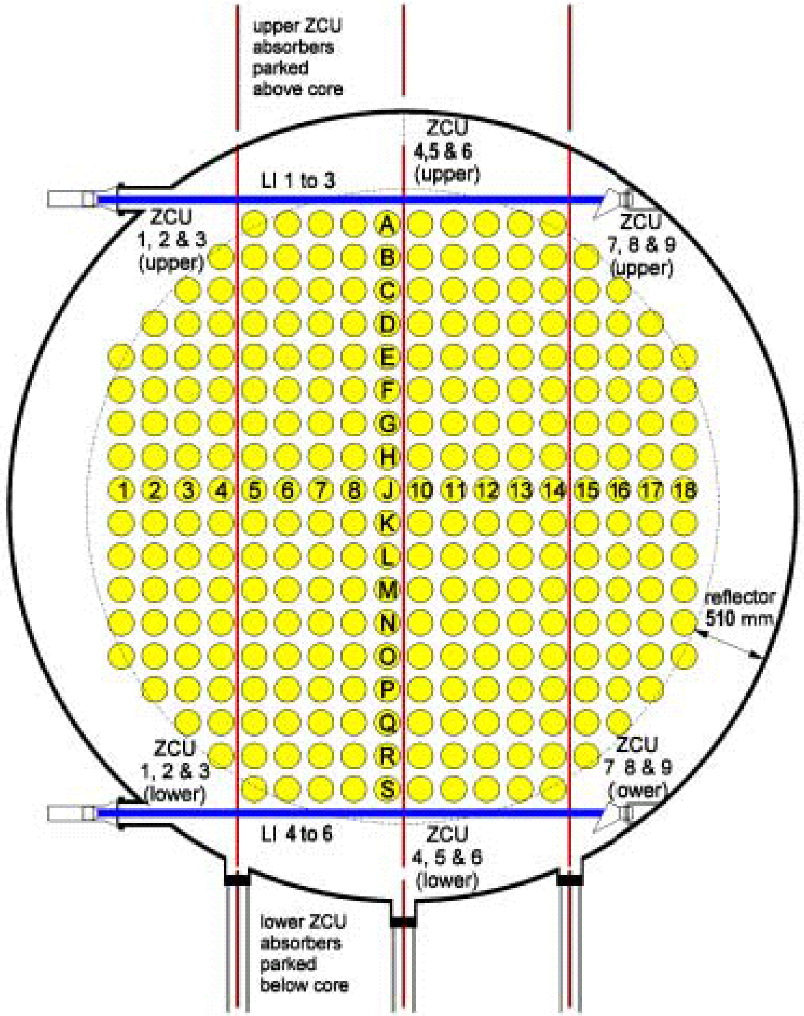


Figure 6.4.1-1 Emergency Coolant Injection System

ACR-700 Advanced CANDU Reactor– Core Design



ACR-700 Advanced CANDU Reactor – SDS2 Design



ACR-700 Reactor Core
284 Fuel Channels
220 mm Lattice Pitch

ACR-700 Advanced CANDU Reactor

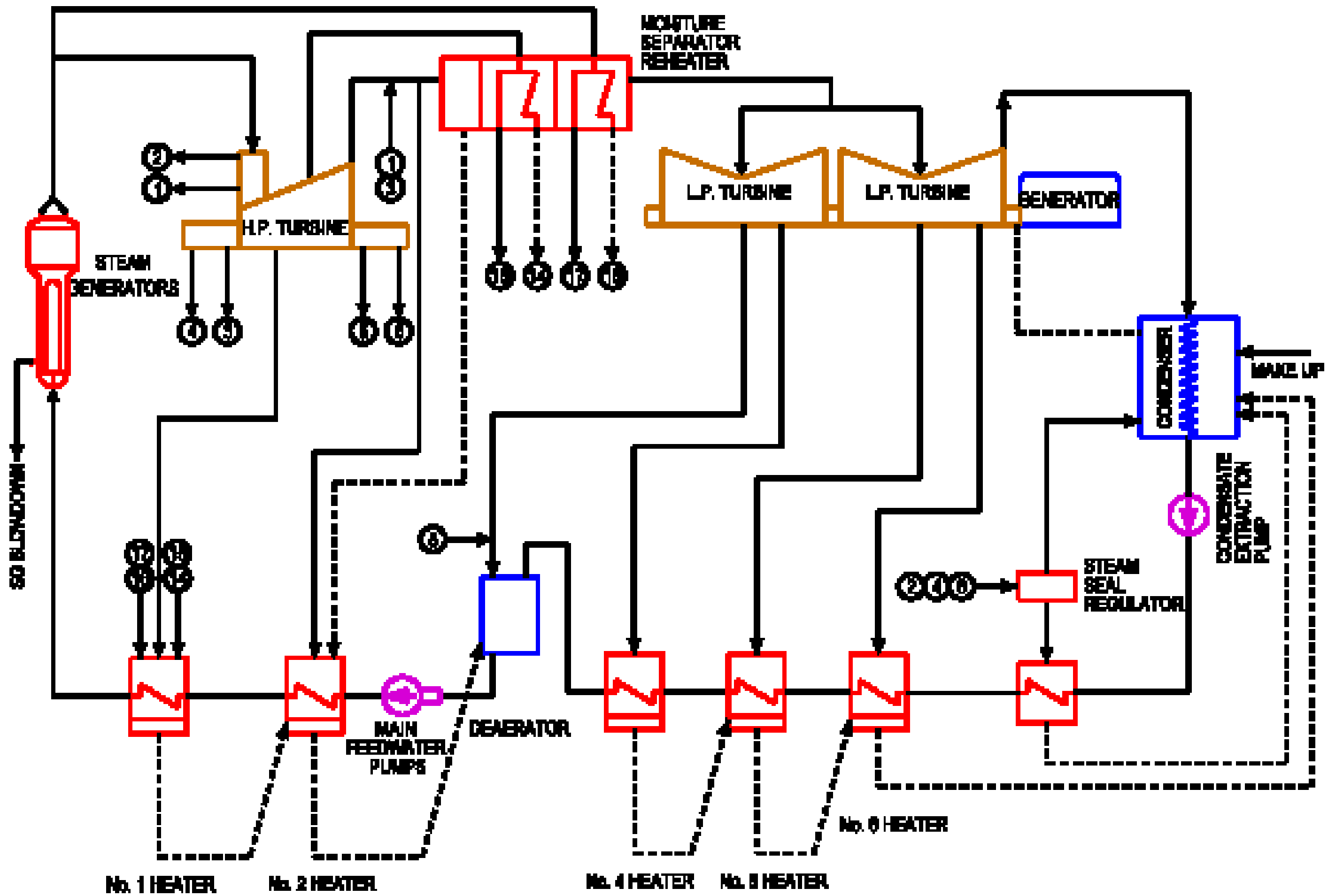


Figure 10.1-1 Turbine-Generator and Auxiliaries Flow Diagram

Questions?