NE301
Fundamentals of Nuclear Engineering

Reactor Types
Part 1

Fall 2022

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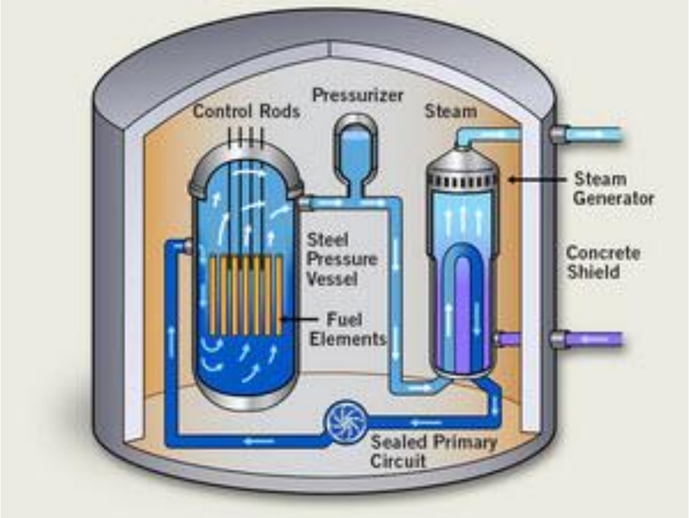
Reactor Types

Reactor Type	Fuel	Moderator	Coolant	Number
Pressurized Water Reactor (PWR)	Enriched UO_2	Water	Water	291
Boiling Water Reactor (BWR)	Enriched UO_2	Water	Water	78
Pressurized Heavy Water Reactor “CANDU” (PHWR)	Natural UO_2	Heavy water	Heavy water	49
Gas-cooled reactor (GCR)	Natural U (metal), Enriched UO_2	Graphite	Carbon dioxide	14
Light Water Graphite Reactor (LWGR)	Enriched UO_2	Graphite	Water	15
Fast breeder reactor (FBR)	PuO_2 and UO_2	None	Liquid sodium	3

Source: https://www.euronuclear.org/info/encyclopedia/n/npp-reactor-types.htm
Numbers current from 28 Nov 2016 (link no longer active)

PWR

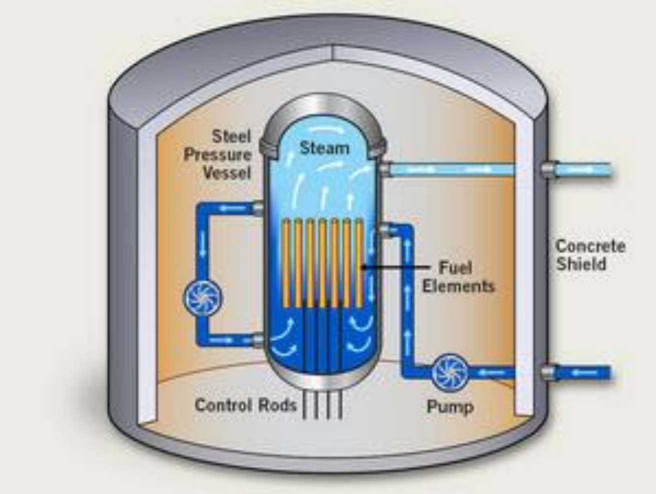
Pressurized water reactors (PWRs) are the most common type of reactor worldwide (2/3). PWRs use ordinary (or "light") water as both coolant and moderator. The coolant is pressurized to stop it from flashing into steam keep it liquid during operation. Powerful pumps circulate the water through pipes, transferring heat that boils water in a separate, secondary loop. The resulting steam drives the electricity-producing turbine generators.



Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

BWR

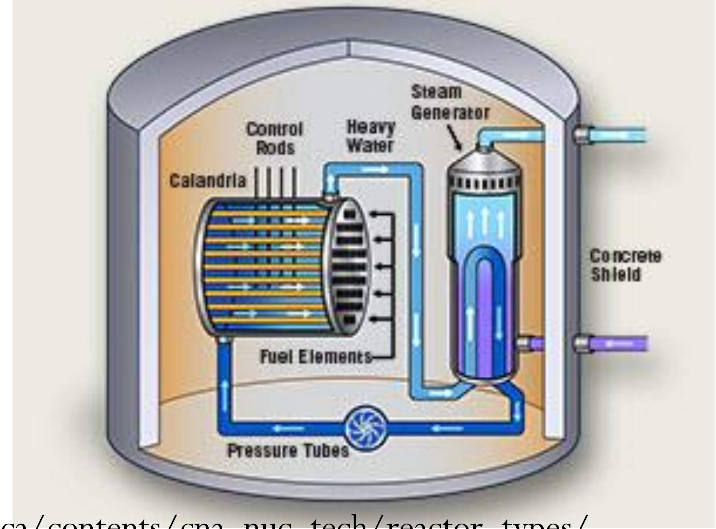
Boiling water reactors (BWRs) make up 20% of reactor output globally. In a BWR, light water acts as both coolant and moderator. The coolant is kept at a lower pressure than in a PWR, allowing it to boil. The steam is passed directly to the turbine generators to produce electricity. While the absence of a steam generator simplifies the design, radioactivity can contaminate the turbine.



Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

Pressurized Heavy Water Reactors

Also known as CANDU reactors, pressurized heavy water reactors (PHWRs) represent about 7% of the reactor output in the world and are used at all Canadian nuclear power generation stations. They use heavy water as both coolant and moderator, and use natural uranium as fuel. As in a PWR, the coolant is used to boil ordinary water in a separate loop. CANDU reactors can be refueled without shutting the reaction down.



Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

Gas-Cooled Reactors

Gas-cooled reactors (GCRs) are in use only in the United Kingdom. There are two types, the Magnox (named from the magnesium alloy used to clad the fuel elements) and the advanced gas-cooled reactor (AGR). Both types use carbon dioxide as the coolant and graphite as the moderator. The Magnox uses natural uranium as fuel, while the AGR uses enriched uranium. Like CANDU reactors, these designs can be refueled while operating.

Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

Light Water Graphite Reactors

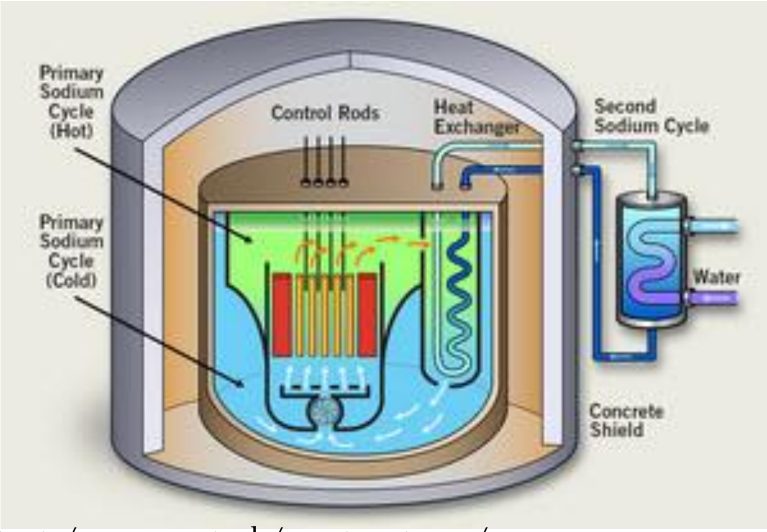
Light water graphite reactors (LWGRs) are used in Russia, with ordinary water as the coolant and graphite as the moderator. As with BWRs, the coolant boils as it passes through the reactor and the resulting steam is passed directly to turbine generators. Early LWGR designs were often built and operated without the safety characteristics and features required elsewhere.

The well known 1986 accident at Chernobyl (Ukraine) happened to a reactor of this type.

Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

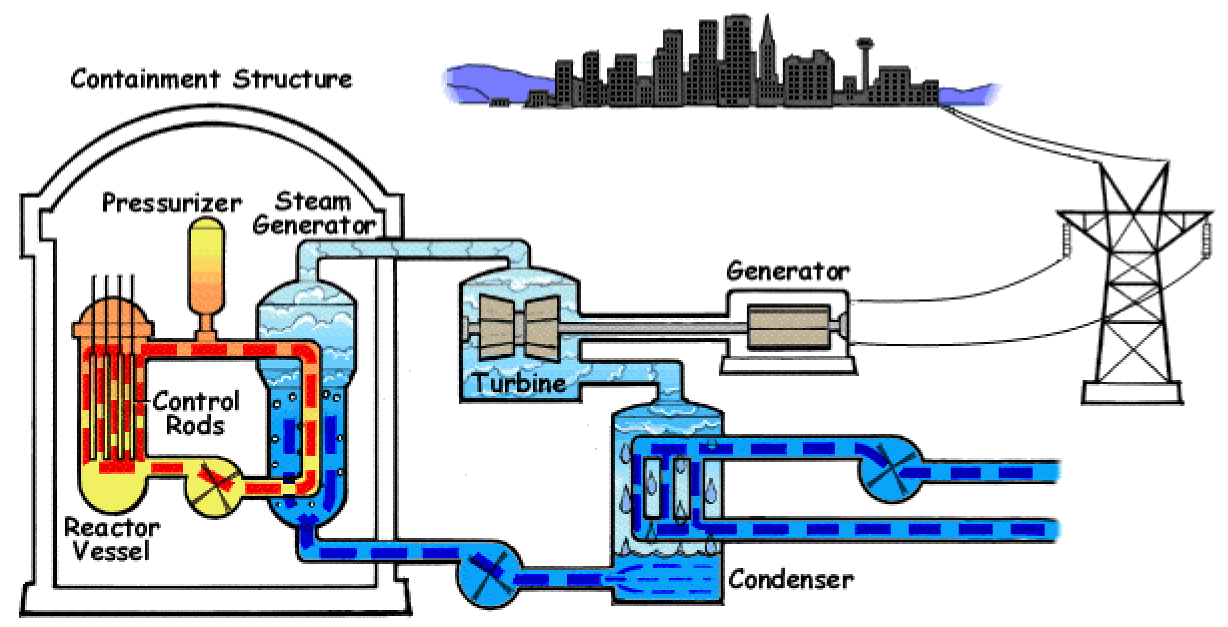
Fast Breeder Reactors

Because slow neutrons are more likely to split uranium atoms, most reactor types are designed to make use of them. In contrast, fast breeder reactors (FBRs) use fast neutrons to convert materials such as uranium-238 and thorium-232 into fissile materials, which then fuel the reactor. This process, combined with recycling, has the potential to increase available nuclear fuel resources in the very long term. FBRs operate mainly in Russia.



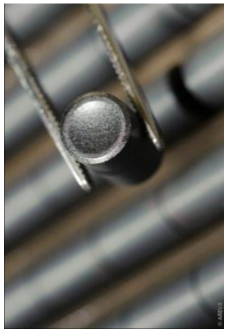
Source: http://teachnuclear.ca/contents/cna_nuc_tech/reactor_types/

PWR Description

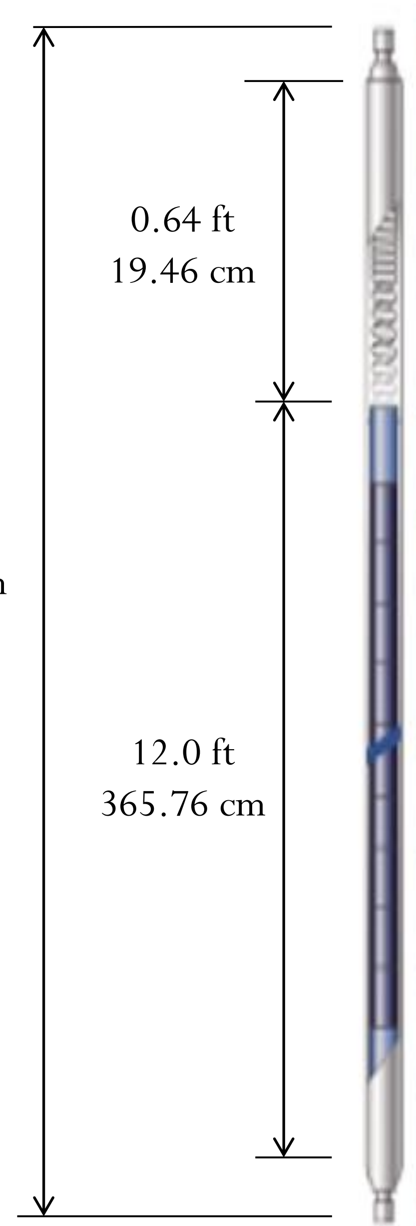


Source: http://www.nrc.gov/images/reading-rm/basic-ref/students/student-pwr.gif

PWR Fuel Rods



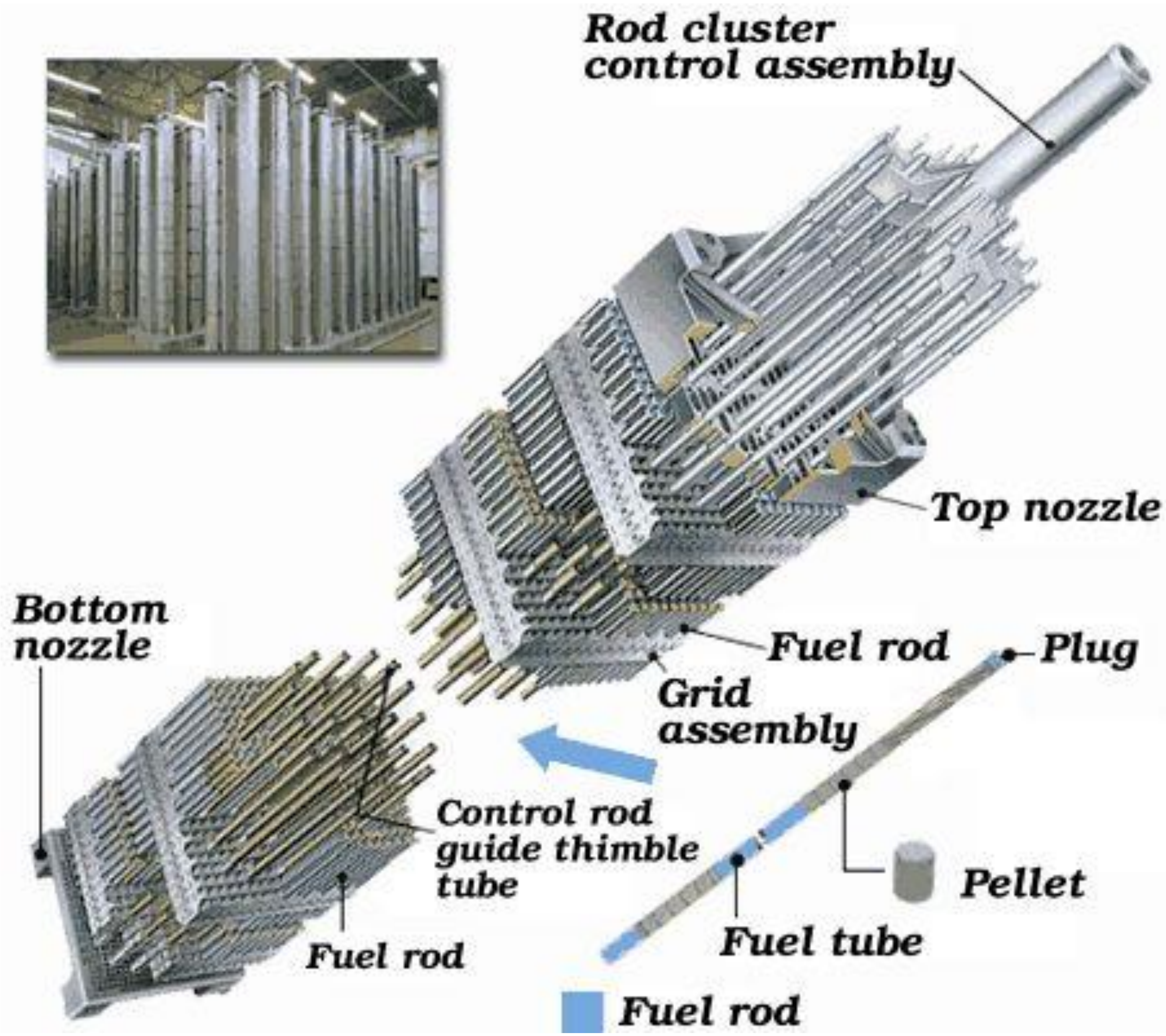
PWR Fuel Pellet
(0.82 cm OD)

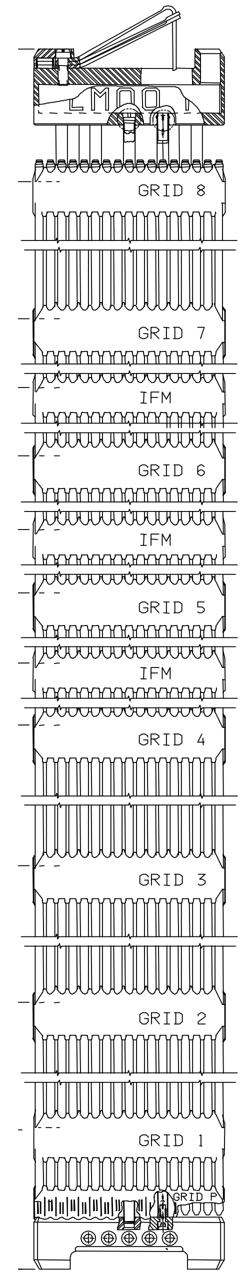


- UO_2 Pellets
- multiple initial U-235 enrichments
  (2.1, 2.6, 3.1 w/o heavy metal)
- Density ~ 10.2 g/cc

All dimensions in presentation are typical of Watts Bar (non-proprietary)

Fuel Assembly



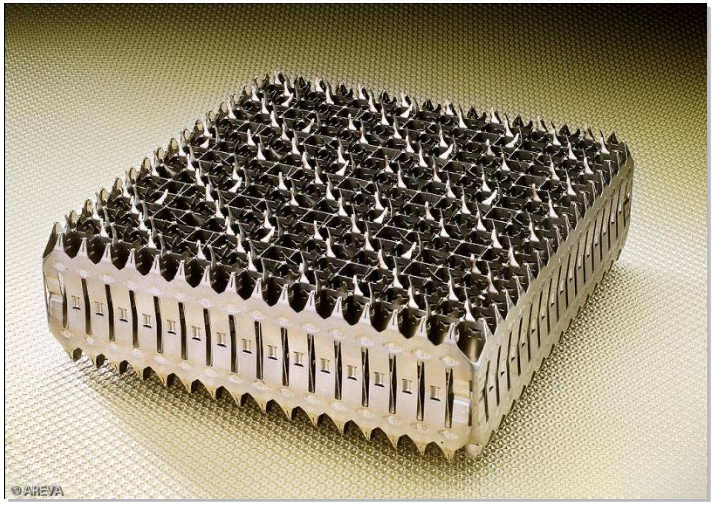


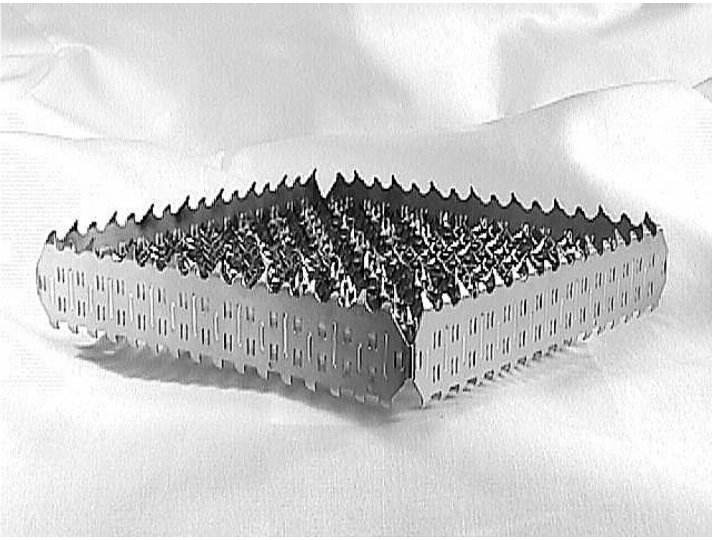
Fuel Assembly

Some idea of relative size!

Source: Internet

Spacer Grids



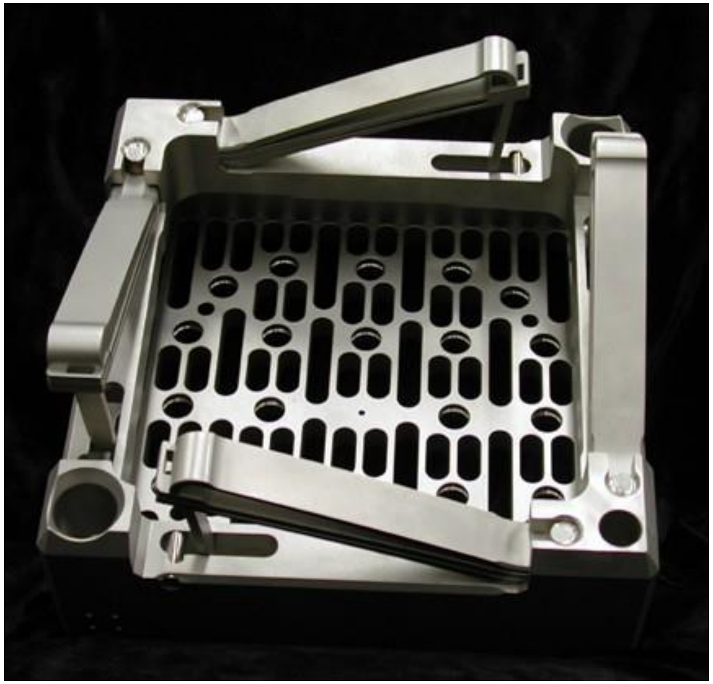


8 (or more) grids per assembly

Grid Materials:

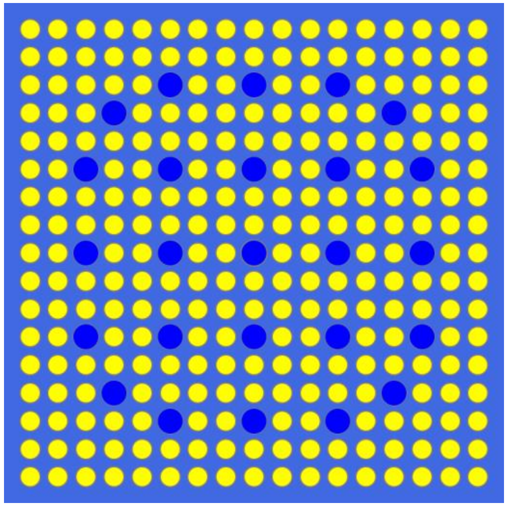
- Inconel (top and bottom)
- Zirconium (middle)
- Combination for structure + springs

Top and Bottom Nozzle

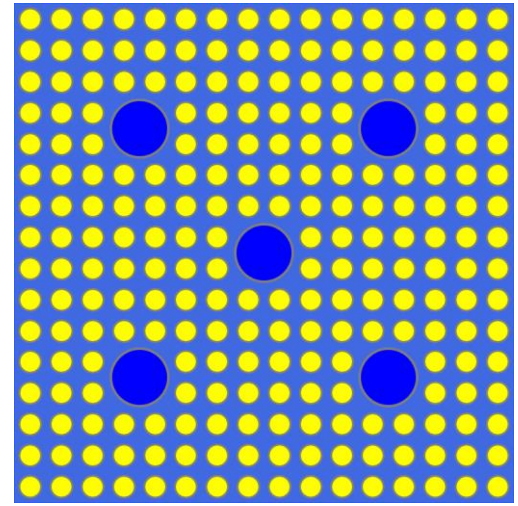


Materials: Stainless steel

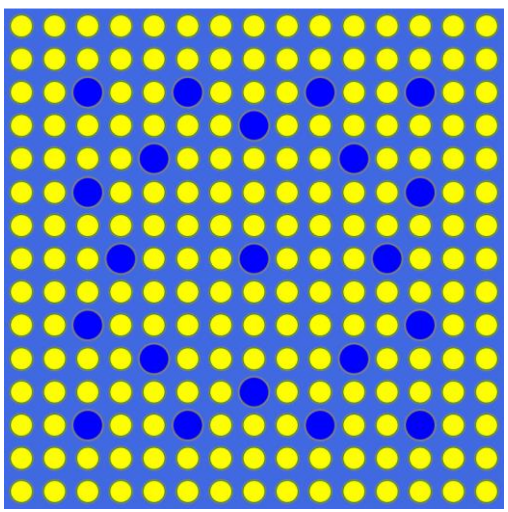
Different Lattice Designs



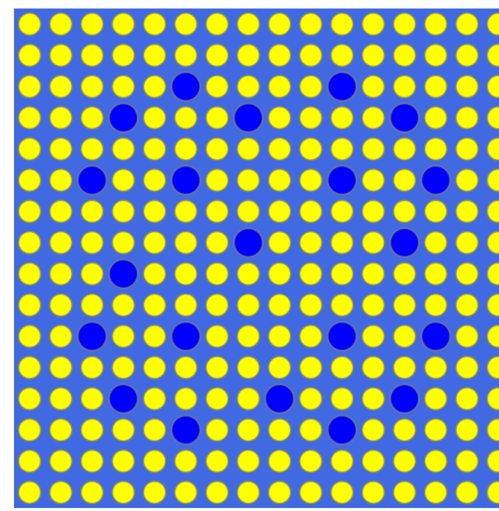
Standard
Westinghouse 17x17



CE 16x16 with
large water rods



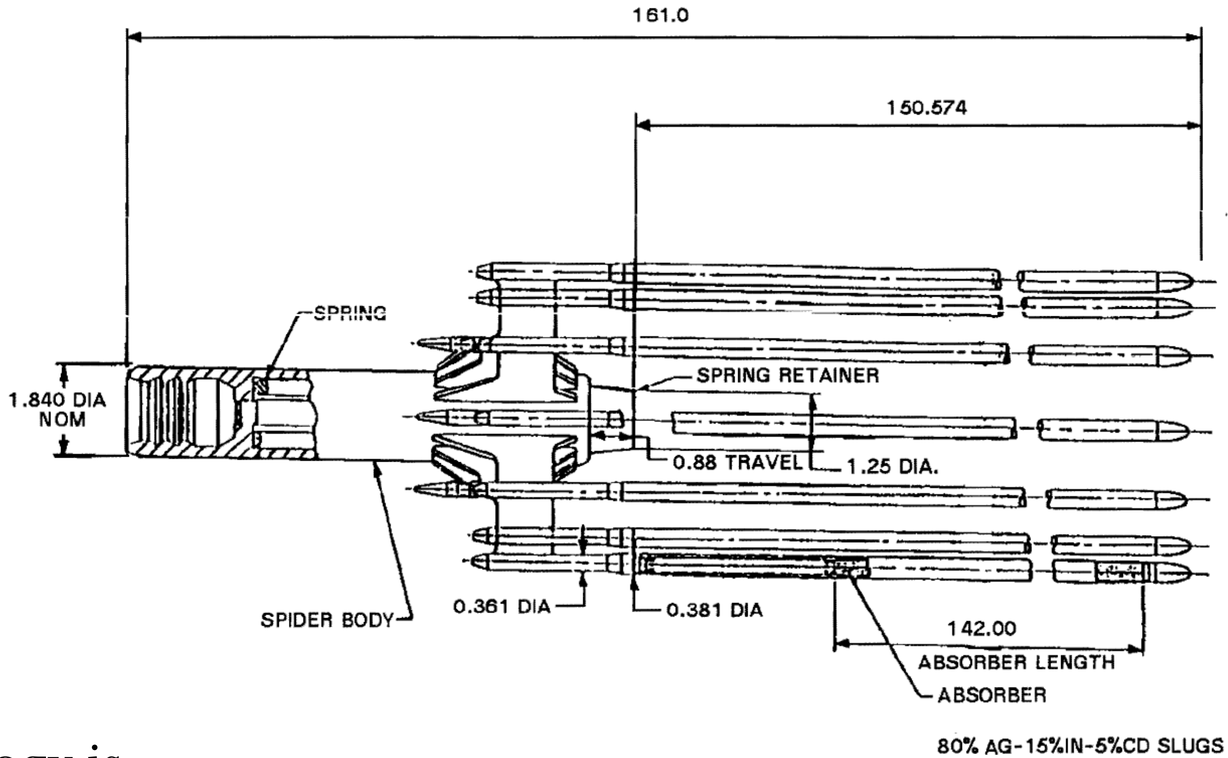
15x15



16x16 with
offset center

PWR lattices typically have
uniform enrichments

Control Rods

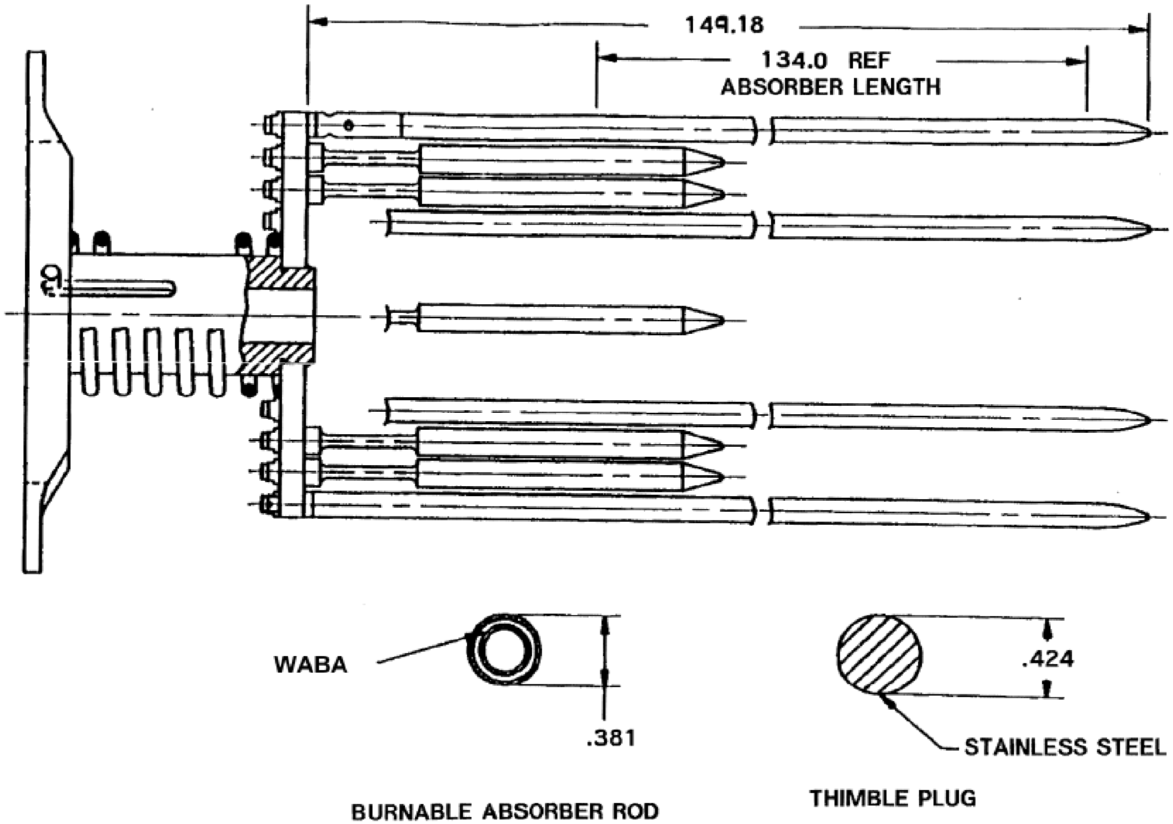


The correct terminology is:
Rod Cluster Control Assemblies (RCCA)

Source: Internet

Control Rods move during operations

Discrete Burnable Absorber Assemblies



BA's can have different configurations of absorber rods
(8, 12, 16, 20, 24)

BA's are usually Pyrex or WABA

Source: Internet

BA's do not move during operation

Fuel Loading Pattern

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1					3	3	3	3	3	3	3				
2			3	3	3	1	3	1	3	1	3	3	3		
3		3	3	2	1	2	1	2	1	2	1	2	3	3	
4		3	2	2	2	1	2	1	2	1	2	2	2	3	
5	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
6	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3
7	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
8	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3
9	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
10	3	1	2	1	2	1	2	1	2	1	2	1	2	1	3
11	3	3	1	2	1	2	1	2	1	2	1	2	1	3	3
12		3	2	2	2	1	2	1	2	1	2	2	2	3	
13		3	3	2	1	2	1	2	1	2	1	2	3	3	
14			3	3	3	1	3	1	3	1	3	3	3		
15					3	3	3	3	3	3	3				

Reg 1	2.10%
Reg 2	2.60%
Reg 3	3.10%

Watts Bar Unit 1 Cycle 1

- 3 enrichment zones
- No IFBA
- WABA

Source: CASL

Burnable Absorber Loading Pattern

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1						8		12		8					
2					16		24		23s		16				
3			12	24		16		20		16		24	12		
4			24		20		20		20		20		24		
5		16		20		20		20		20		20		16	
6	8		16		20		24		24		20		16		8
7		24		20		24		20		24		20		24	
8	12		19s		20		20	+	20		20		19s		12
9		24		20		24		20		24		20		24	
10	8		16		20		24		24		20		16		8
11		16		20		20		20		20		20		16	
12			24		20		20		20		20		24		
13			12	24		16		20		16		24	12		
14					16		24		23s		16				
15						8		12		8					

Watts Bar Unit 1 Cycle 1

- 5 Pyrex Assembly Types
- +4 neutron sources

Note: large number of BA's because all the fuel is fresh

BA's cannot exist in the same location as control rods

Source: CASL

RCCA Bank Positions

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1															
2				SA		B		C		B		SA			
3					SD		SB		SB		SC				
4		SA		D				D				D		SA	
5			SC		A						A		SD		
6		B				C		A		C				B	
7			SB		SP								SB		
8		C		D		A		D		A		D		C	
9			SB										SB		
10		B				C		A		C				B	
11			SD		A						A		SC		
12		SA		D				D				D		SA	
13					SC		SB		SB		SD				
14				SA		B		C		B		SA			
15															

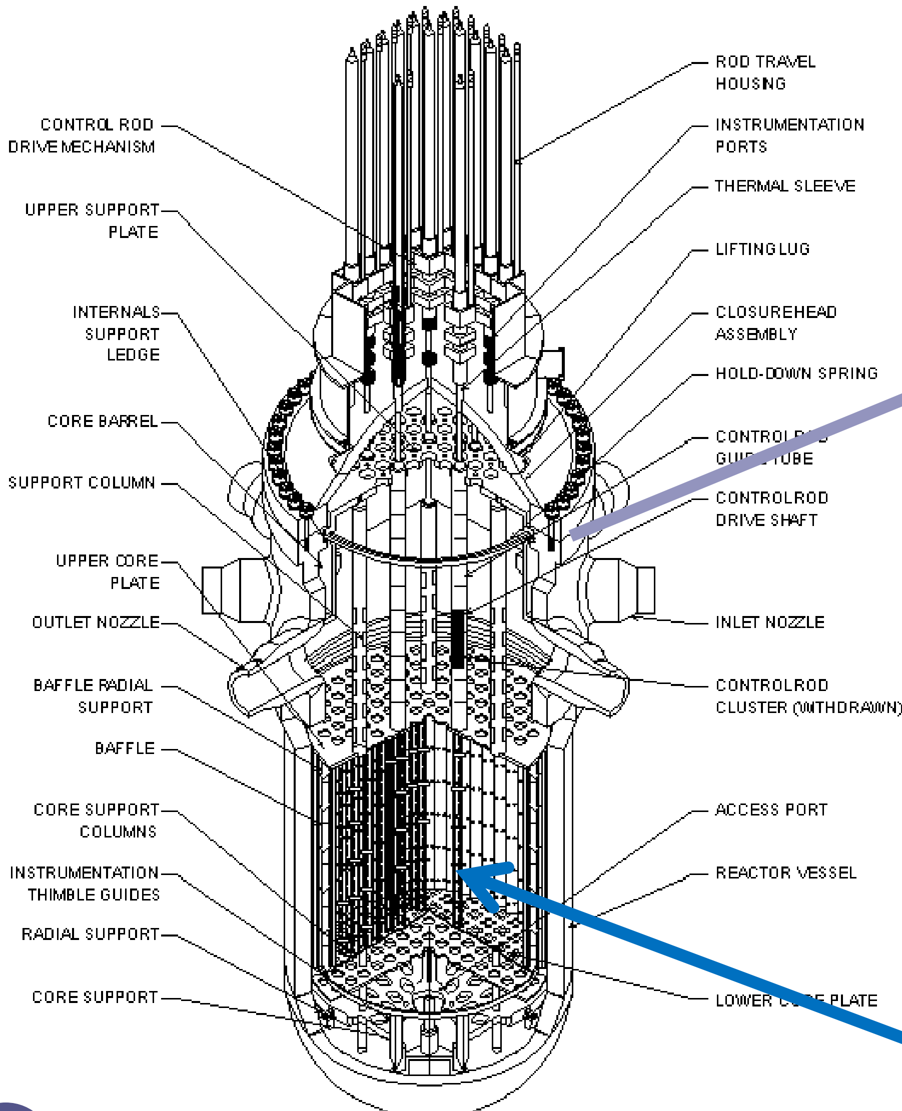
Watts Bar Unit 1 Cycle 1

- Operational Banks A-D
- Shutdown Banks
- Banks are symmetric

During normal operation, all rods are withdrawn and criticality maintained with soluble boron

Source: CASL

PWR Vessel

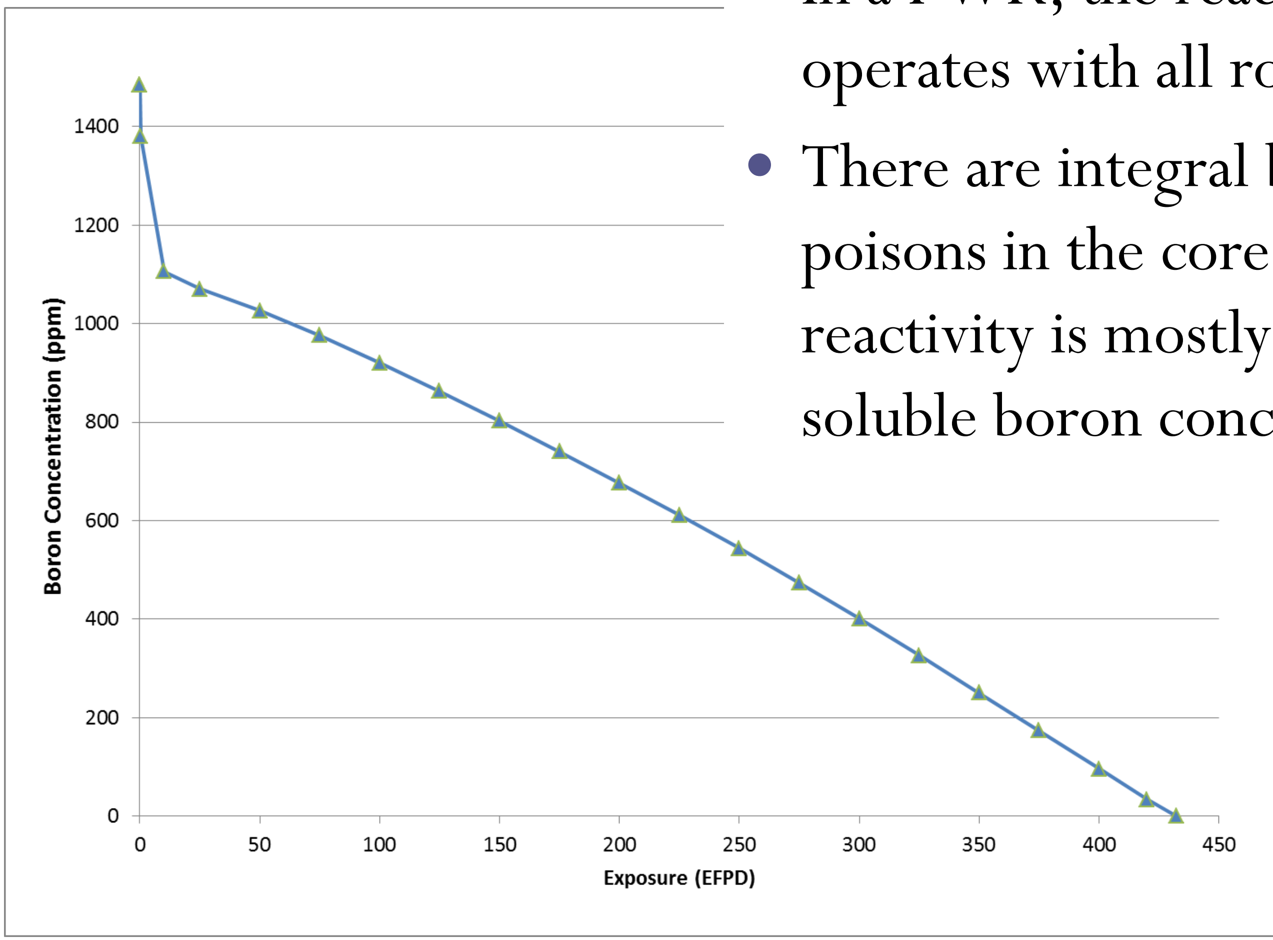


TVA Watts Bar

Reactor Core

Source: CASL

PWR Excess Reactivity



- In a PWR, the reactor generally operates with all rods out (ARO)
- There are integral burnable poisons in the core, but excess reactivity is mostly controlled with soluble boron concentrations

End-of-life is achieved when boron concentration is near zero

Questions?

Finished with PWR description

A book with a description of Westinghouse PWR reactors is on the website

New PWR Reactors

Westinghouse AP1000

- The AP1000 is the newest Westinghouse reactor design
- Design approved by NRC in 2011
- In the United States,
  - 2 units currently under construction at Vogtle (Southern Co.)
  - 2 units started construction, but have been cancelled at VC Summer (SCANA)
- In China
  - 2 units operating at Sanman Nuclear Power Plant in Zhejiang
  - 2 units operating at Haiyang Nuclear Power Plant in Shandong
  - All units became operational in 2018

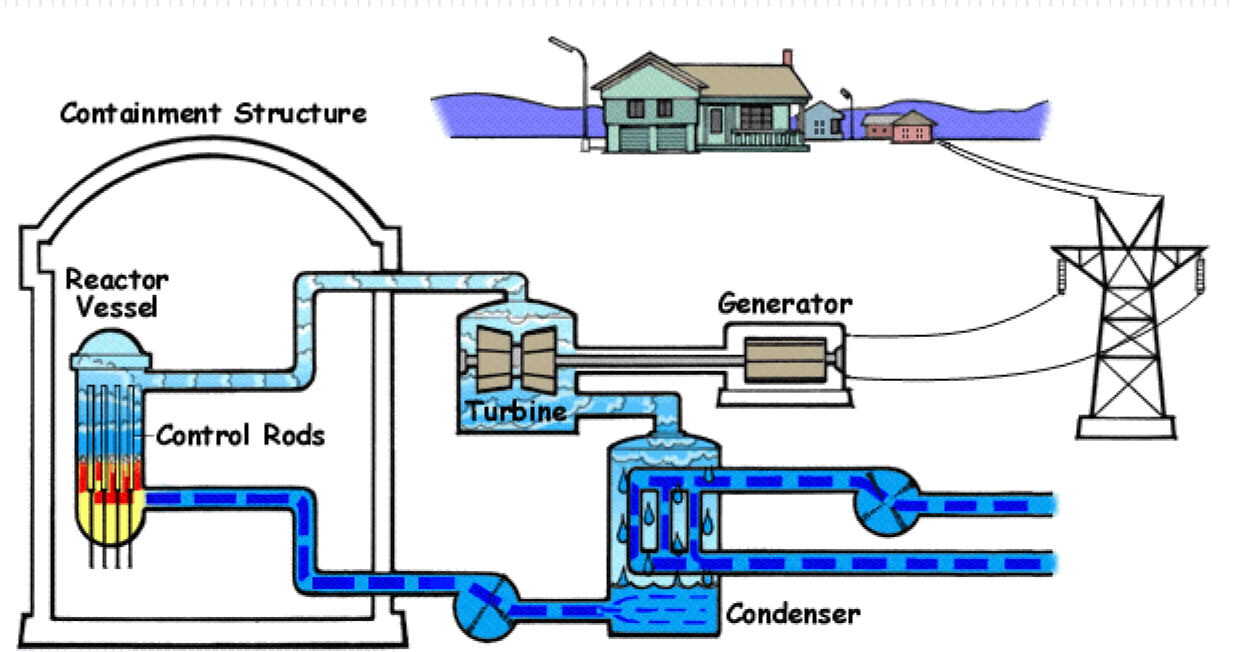
Framatome EPR

- Latest PWR design from Framatome (previously Areva)
- 3 units completed
  - Taishan 1 (China) started in December 2018.
  - Taishan 2 (China) started in September 2019
  - Olkiluoto 3 (Finland) first electricity production March 2022
- 3 unit currently under construction
  - Flamanville 3 (France) expected 2023?
  - Hinkley Point C (United Kingdom, 2 units)

Watts Bar Units 1 and 2

- Construction Permit issued in 1973
- Watts Bar Unit 1 (WBN1) received a full power operating license in early 1996, and is presently the last power reactor to be licensed in the U.S.
- TVA suspended construction of Watts Bar Unit 2 in 1985.
- In 2007, TVA informed NRC of its plan to resume construction of Watts Bar Unit 2.
- On October 22, 2015, the NRC issued a full power Facility Operating License for Watts Bar Unit 2 to TVA.
- Started up in early 2016!
- Newest plant in fleet took 40+ years to build

BWR Description



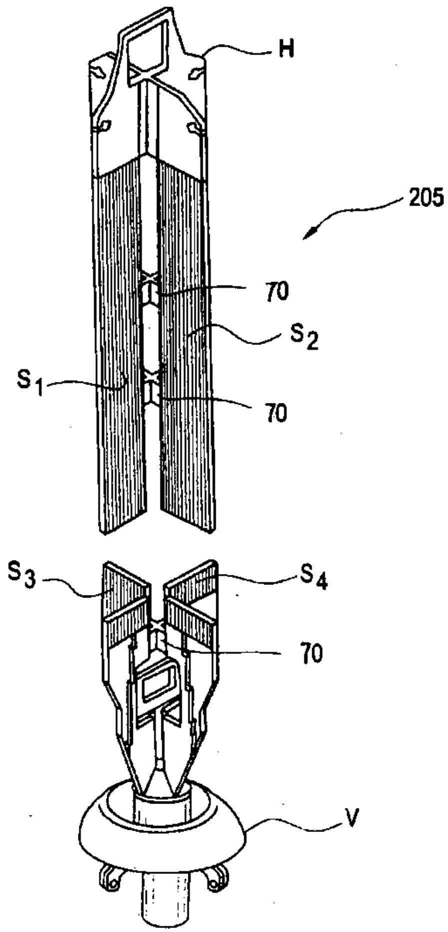
Source: http://www.nrc.gov/images/reading-rm/basic-ref/students/student-bwr.gif

BWR Assemblies

- BWR assemblies have a channel box around them to isolate void
- BWR assemblies have evolved from 8x8 fuel pins to 9x9 to 10x10
- BWR assembly designs can change because the control blade is outside the box

BWR Control Blades

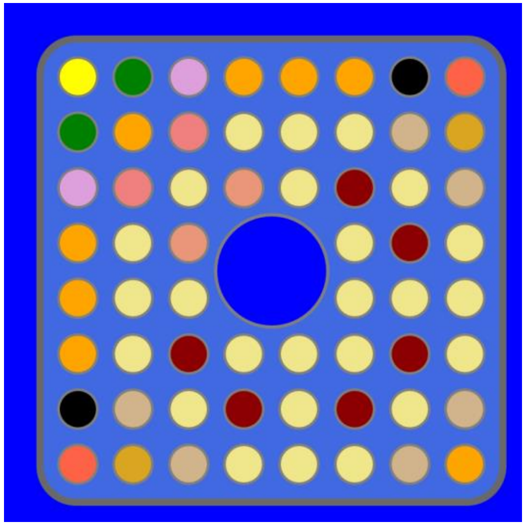
FIG. 5

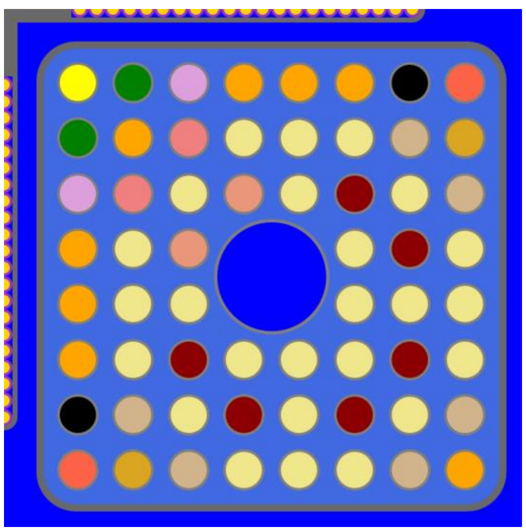


B_4C Powder in Blades

Source: Internet

BWR Lattice Designs



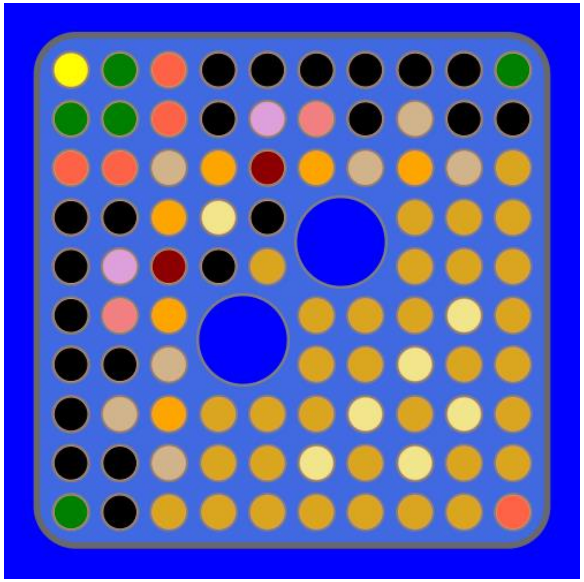


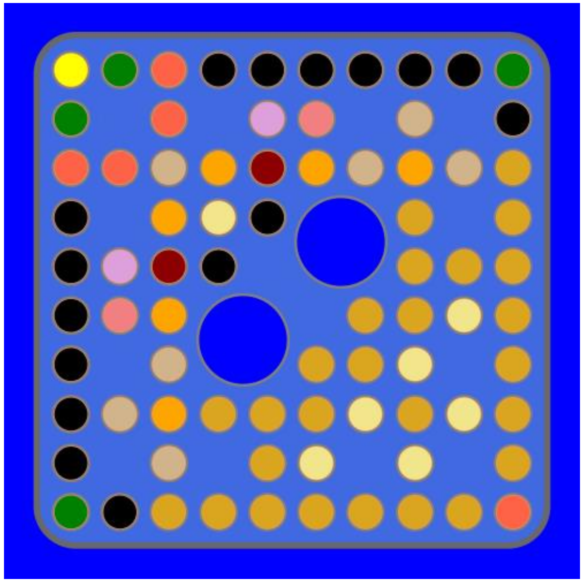
Control blade inserted into NW corner

- GE 9x9 Design with and without a control blade shown
- Channel box surrounds the assembly
- Older 7x7 and 8x8 designs exist with no water rods
- Newer designs are 10x10 design with two large water rods
- Framatome has a design with a large water “box” in center
- Westinghouse has a design with a “water cross”

- In general, BWR assemblies have many more unique fuel rods (with different U235 enrichments and gadolinia enrichments) than PWR assemblies

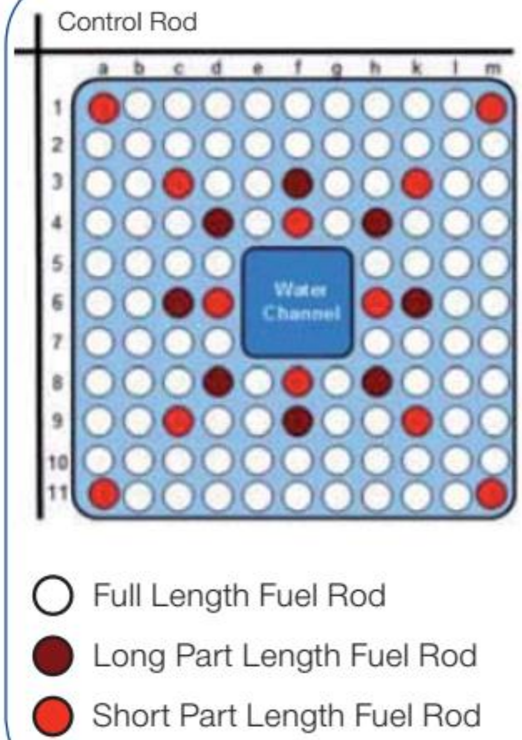
BWR Lattice Designs (10x10)





- Figures show "modern" GE 10x10 Fuel Designs
- Designs have two large water rods
- Figure on right shows "part length rods" at the top of the core, which are used to reduce two-phase pressure drop

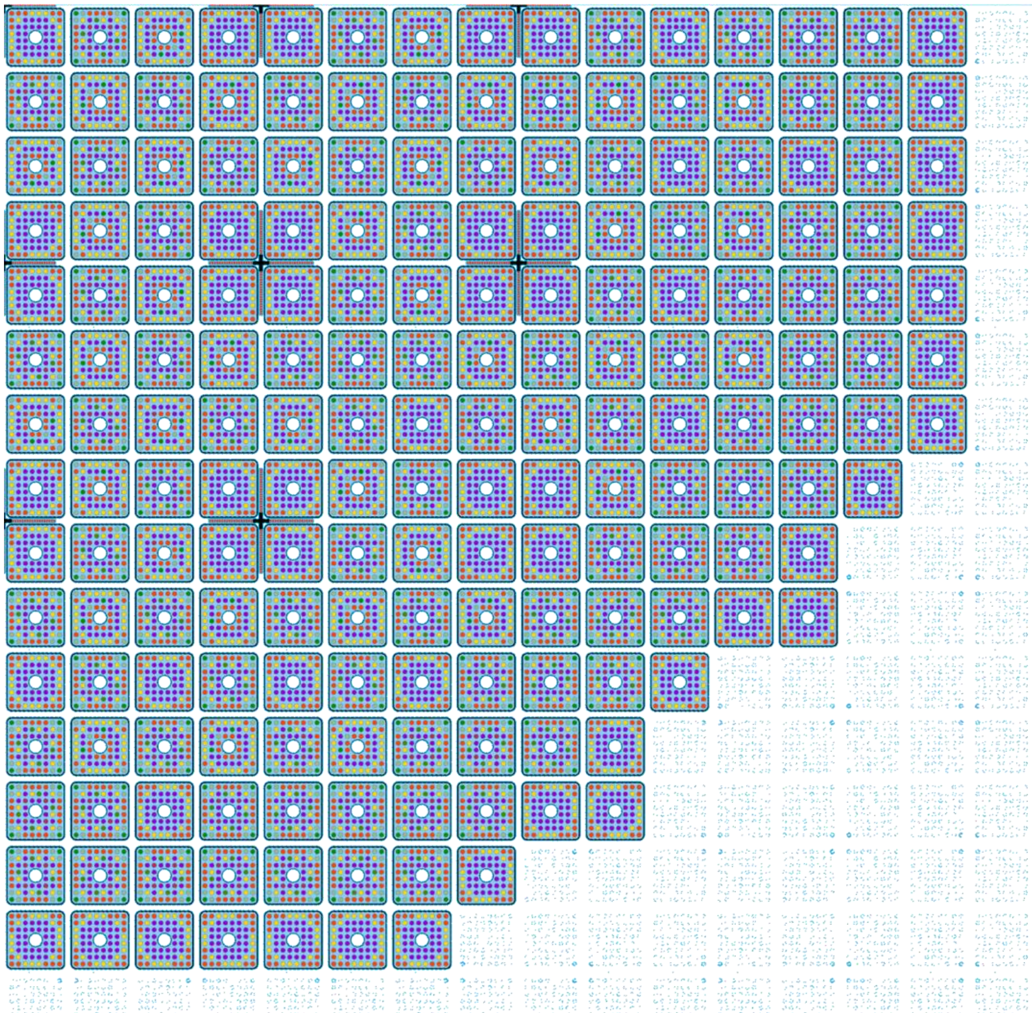
BWR Lattice Designs (Atrium)



ATRIUM™ 11 Fuel Assembly

- Framatome (formerly Areva) uses the "Atrium" design
- Atrium has a new 11x11 design that is currently being introduced
- Older Atrium designs were 10x10 and 9x9
- Atrium uses a "water box" instead of two large water rods

BWR Core

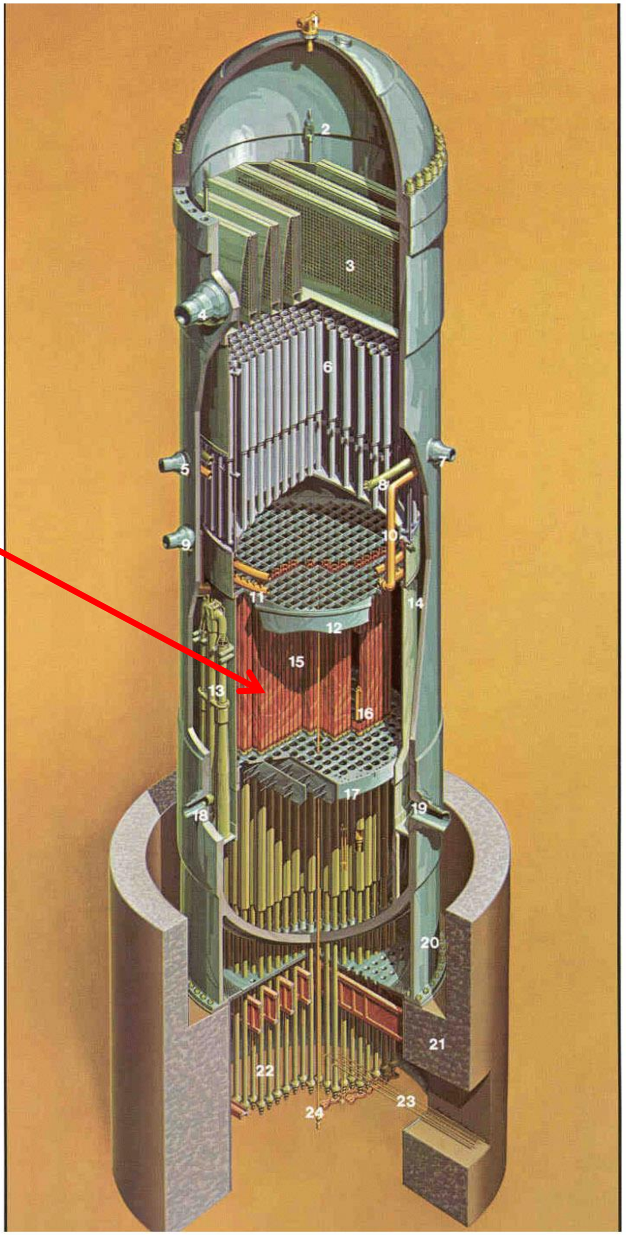


- Picture of a ¼ core
- BWR assemblies are smaller than PWR assemblies
  (15.24 cm vs. 21.54 cm)
- For a fixed power, there are more assemblies in a BWR than a PWR
- Note the control blade positions in the diagram

BWR Vessel

Core

Steam separator and dryer are at the top of the core, hence the control blades enter from the bottom



BWR/6
REACTOR ASSEMBLY

1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

GENERAL ELECTRIC

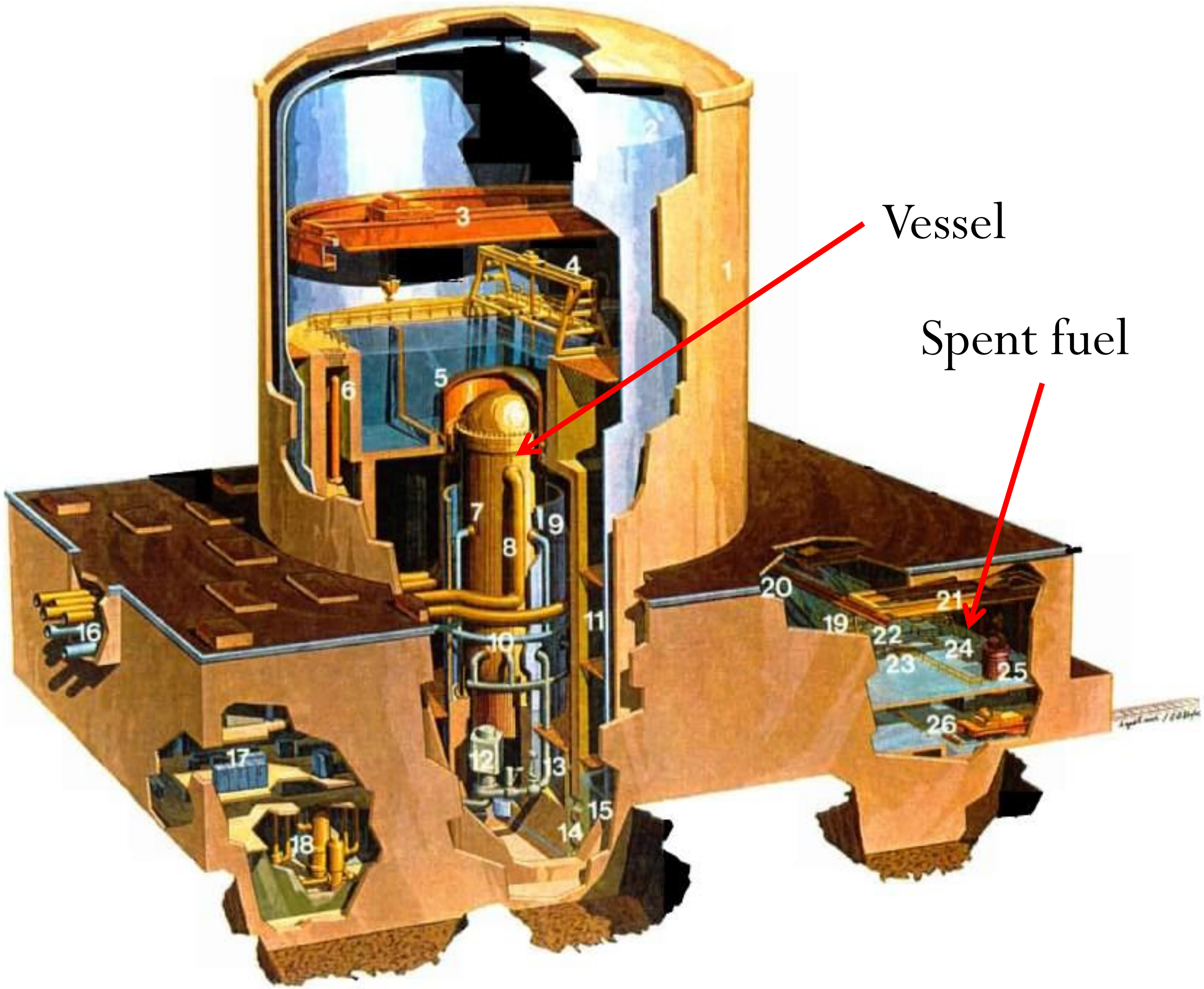
Source: Internet

Mark III Containment

Reactor Building
- Shield Building
- Free-Standing Steel Containment
- Polar Crane
- Refueling Platform
- Upper Pool
- Reactor Water Cleanup
- Reactor Vessel
- Steam Line
- Shield Wall
- Feedwater Line
- Drywell
- Recirculation Loop
- Weir Wall
- Horizontal Vent
- Suppression Pool

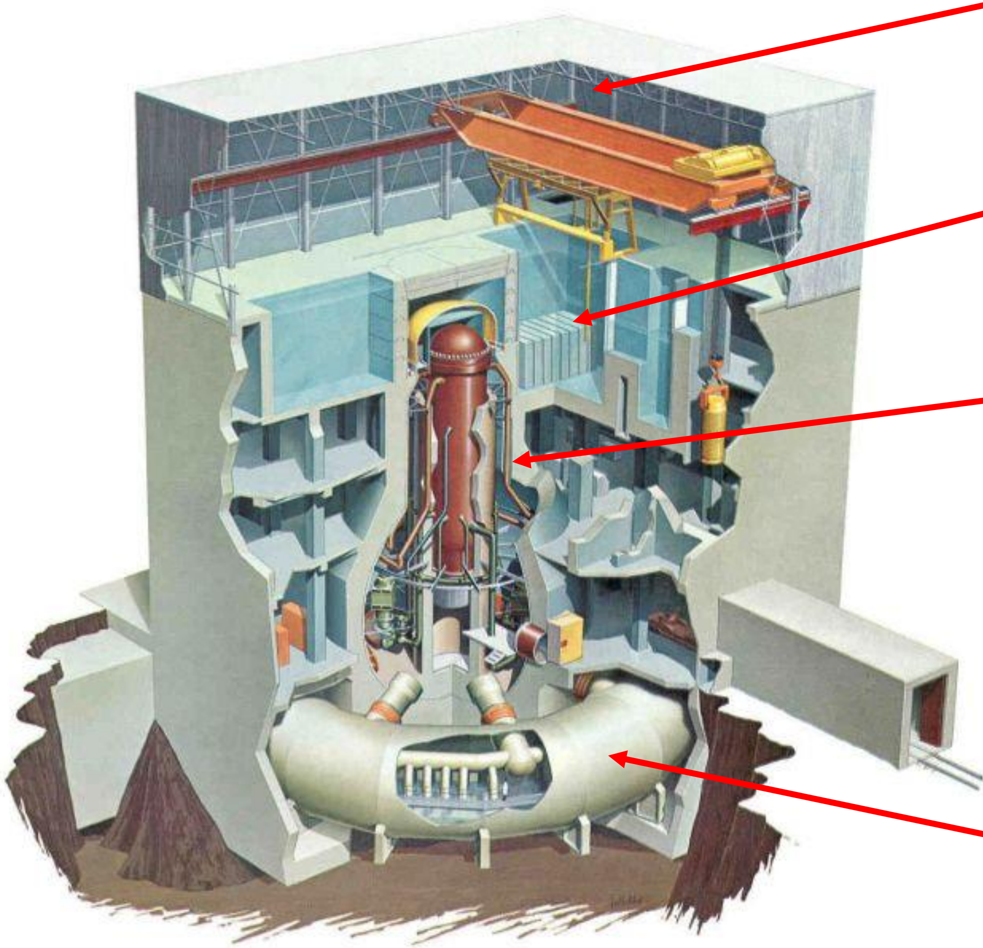
Auxiliary Building
- Steam Line Tunnel
- Motor Control Centers
- RHR System

Fuel Building
19. Fuel Transfer Bridge
20. Fuel Transfer Tube
21. Cask Handling Crane
22. Fuel Storage Pool
23. New Fuel Vault
24. Cask Loading Pool
25. Spent Fuel Shipping Cask
26. Fuel Cask Skid



Source: Internet

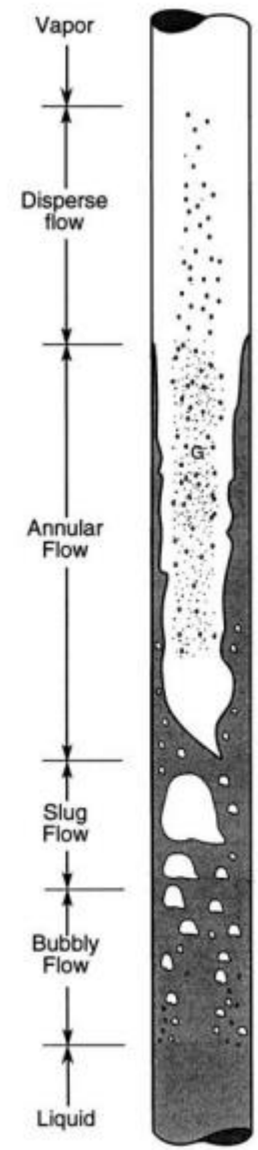
Mark I Containment



Containment Type used at Fukushima Units 1-3

BWR Void

- Boiling water provides a very strong negative reactivity feedback.
- As the power increases, more water will boil, this will decrease the density and moderation, and the power will decrease.
- As the power decreases, the density will increase, which will increase power.
- Void feedback is a very important quantity in BWR cross sections



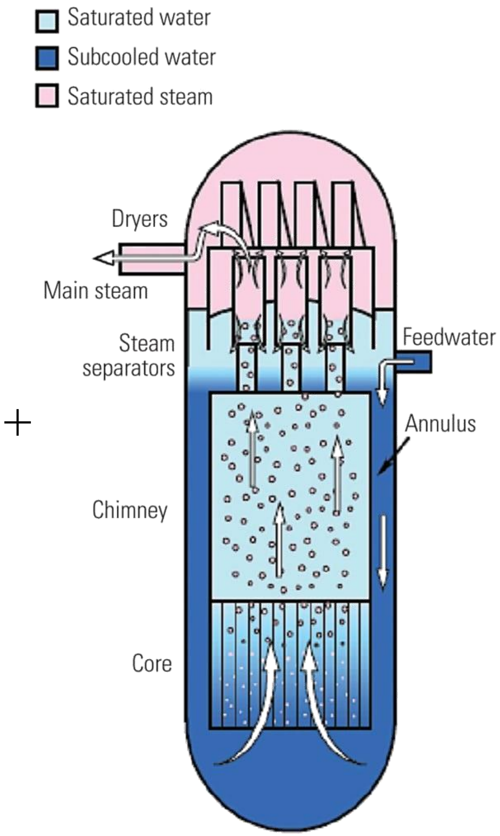
BWR Excess Reactivity

- Since a BWR core has boiling water, it cannot have boron in the coolant
- Excess reactivity is controlled by
  - Integral burnable poisons (gadolinia) that burn out with depletion
  - Reactor operates with control blades inserted in the core
- End-of-life achieved when all control blades are withdrawn

Latest BWR Designs

- The **ESBWR** reactor is the latest BWR design
  - Designed by GE Hitachi
  - Natural Circulation Reactor
  - 1520 MWe (very large)
  - Design certified by NRC in 2014
  - "It has the lowest core damage frequency (industry standard measure of safety) of any Generation III or III+ reactor and can safely cool itself with no AC electrical power or human action for more than seven days." [website]
  - No units are currently planned

  https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/esbwr

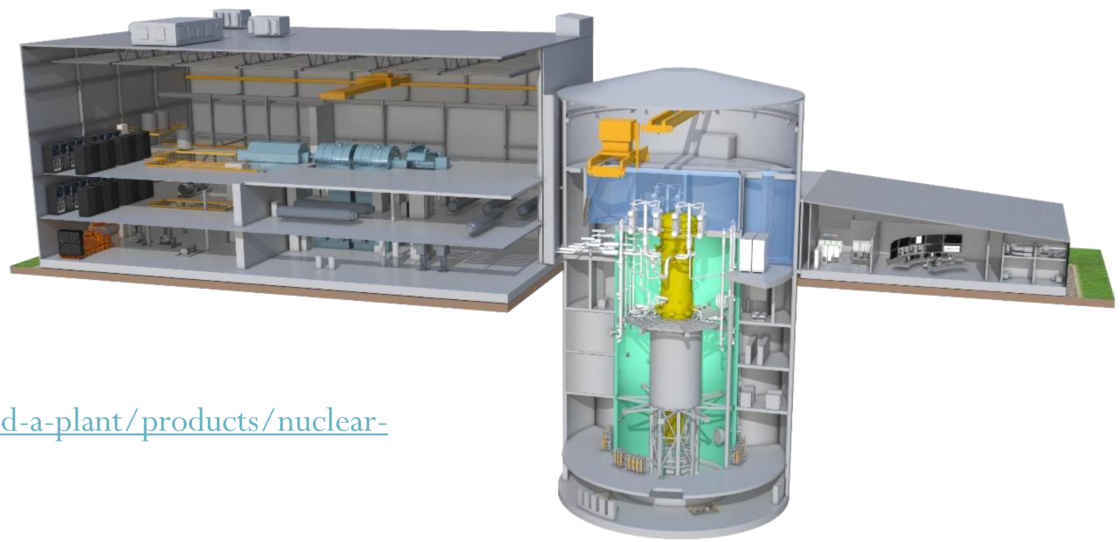


- The **ABWR** reactor is a somewhat older design
  - Offered by both GE Hitachi and Toshiba
  - Six ABWR units operating in Japan and Taiwan

  https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/abwr

BWRX-300

- The BWRX-300 is most recent design from GE-Hitachi
  - Small Modular Reactor – 300 MWe
  - Natural Circulation Reactor
  - Passive Safety systems
  - Claims to have lifecycle costs of typical natural gas combined cycles [website]



https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/bwrx-300

Questions?

Finished with BWR Description

A book with a description of GE BWR reactors is on the class website.