Operational Reactor Safety

22.091/22.903

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Professor of the Practice

Lecture 6
Reactor Energy Removal

Topics to Be Covered

- Power Distributions
- Peaking Factors
- Fuel-Pin Heat Transfer
- Nuclear Limits in Design
- Peak Centerline Temperature
- Peak Clad Temperature
- Departure From Nucleate Boiling
- Control Rod Impacts

FIGURE 10-1

Boiling-water reactor steam cycle schematic diagram. (Courtesy of General Electric Company.)

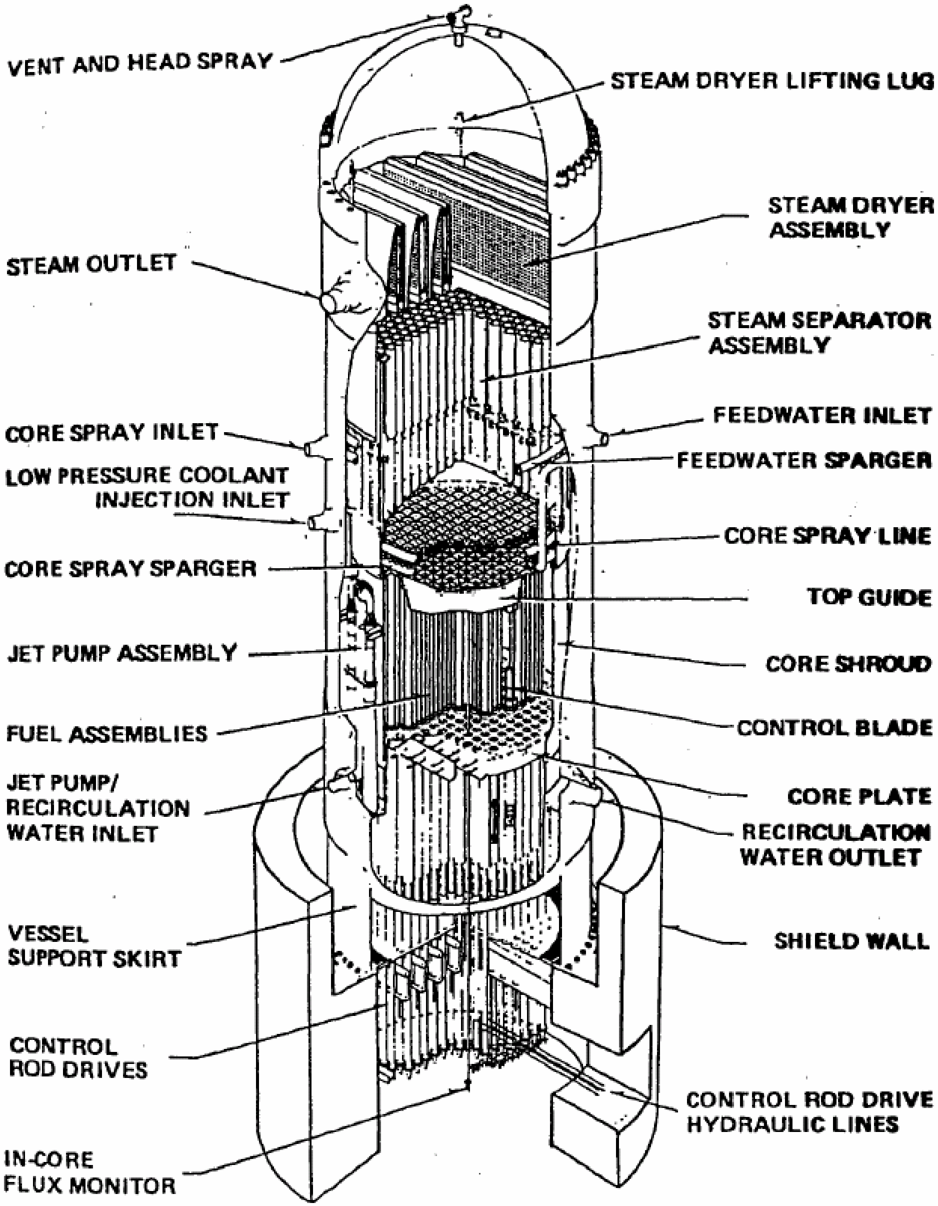
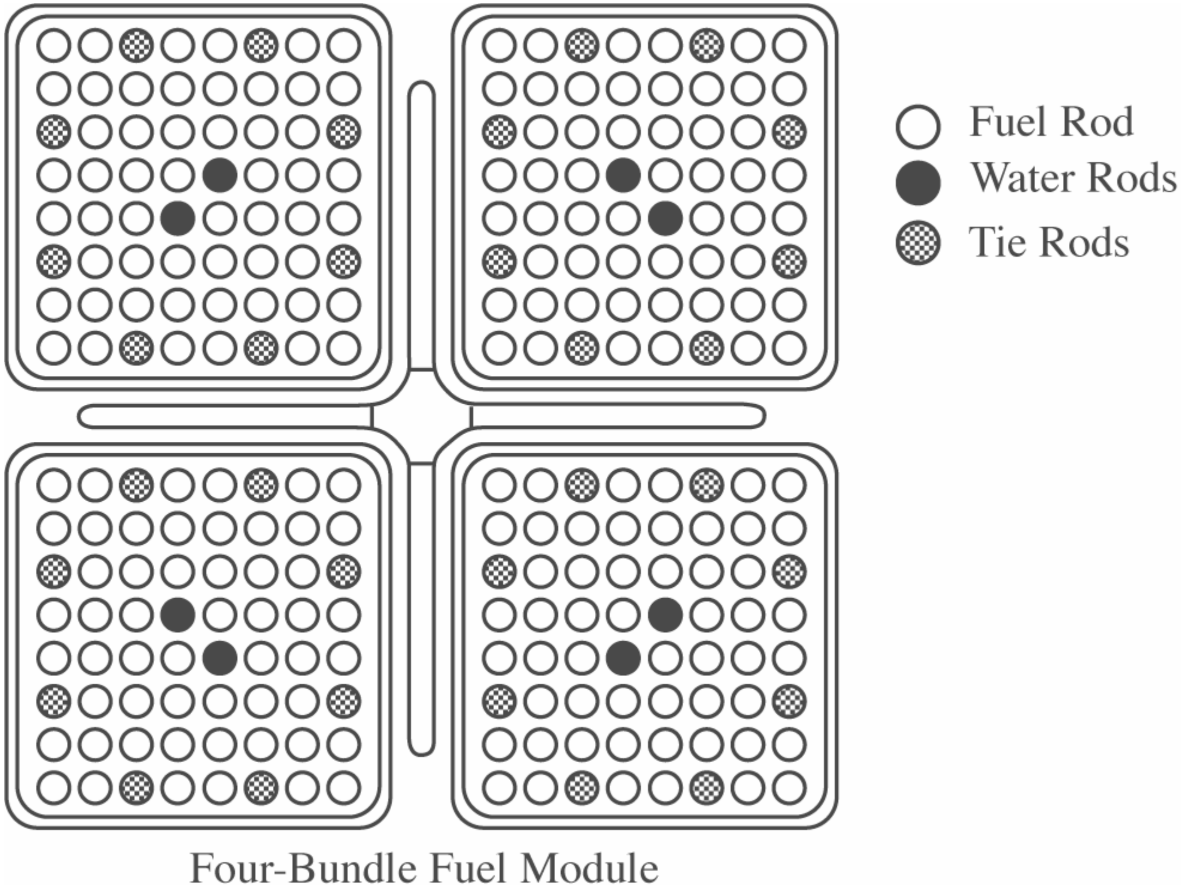


FIGURE 10-2

Boiling-water reactor vessel. (Courtesy of the General Electric Company.)

BWR Core Lattice



“BWR/6: General Description of a BWR,” GE, 1980.

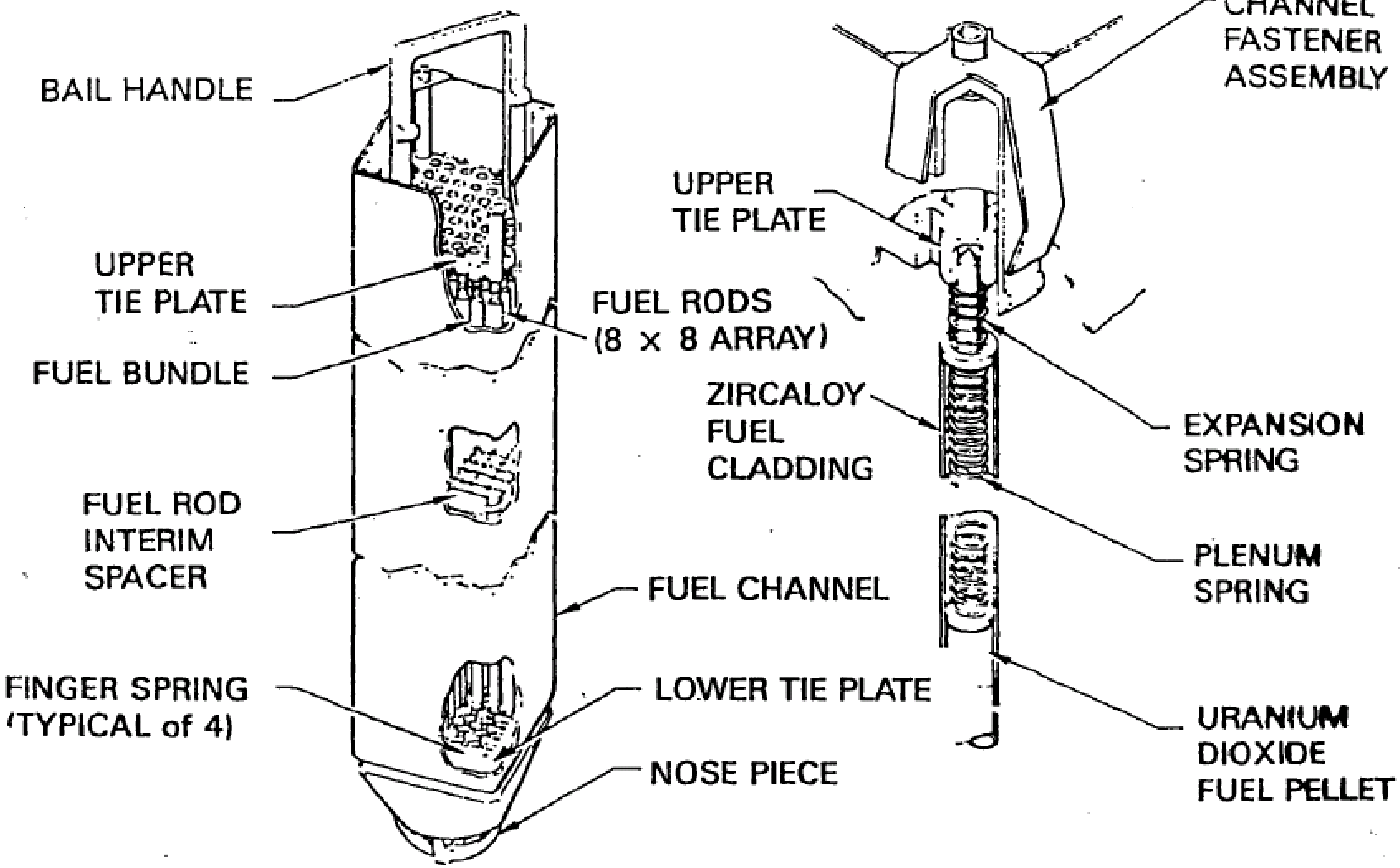


FIGURE 1-6

Fuel assembly for a representative boiling-water reactor. (Adapted courtesy of General Electric Company.)

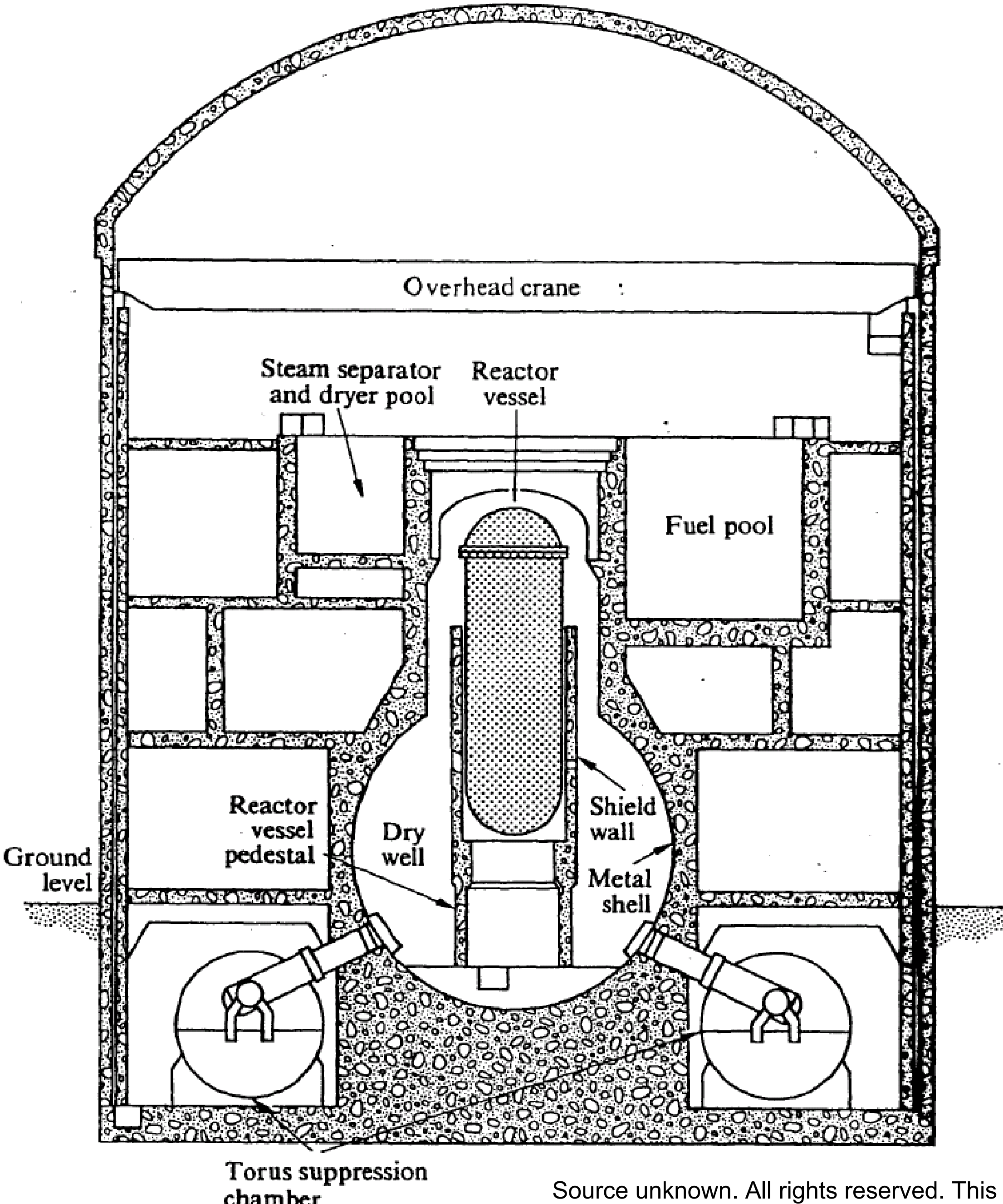


Fig. 11.3 Light bulb and torus containment for a BWR.

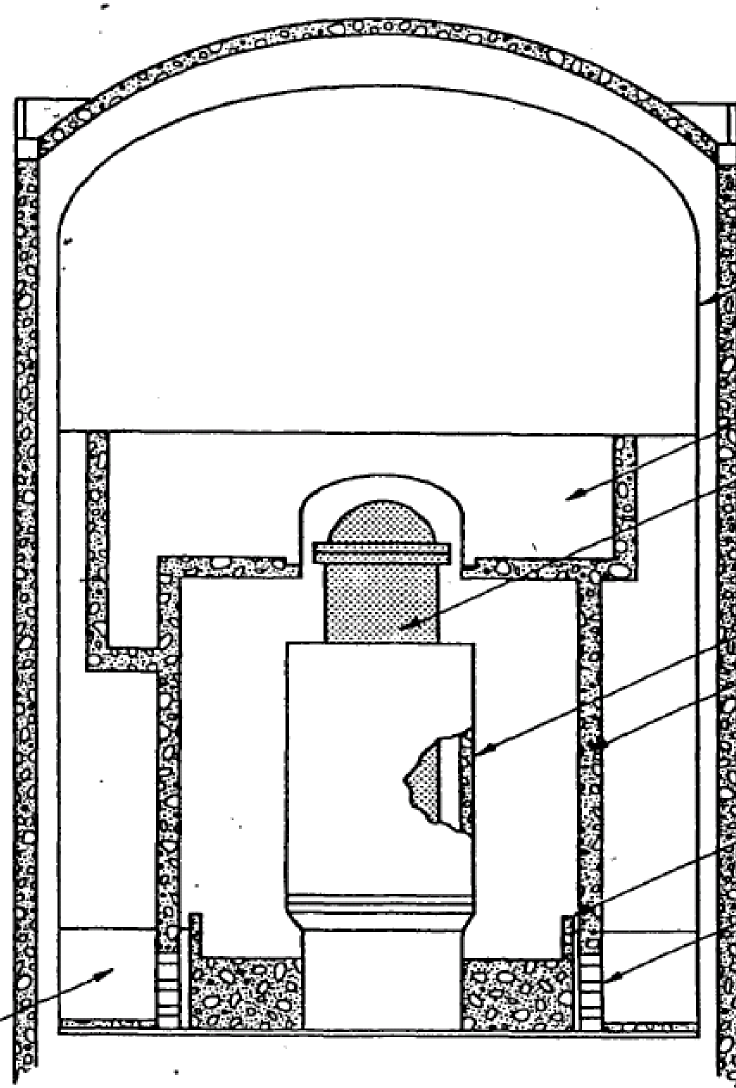
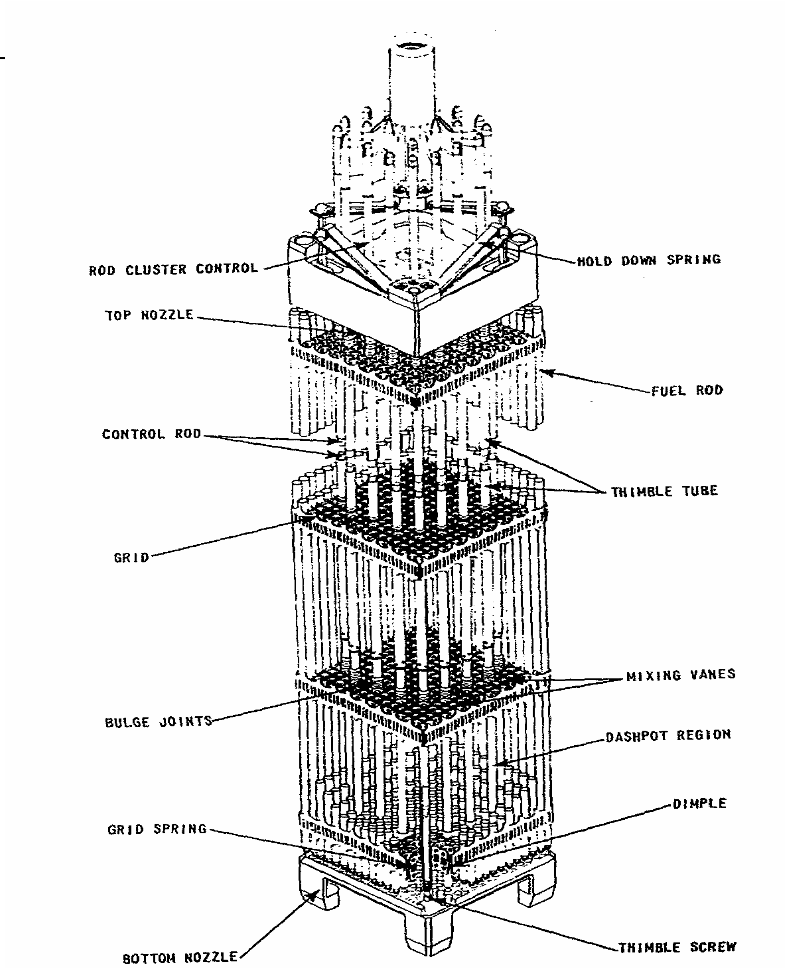
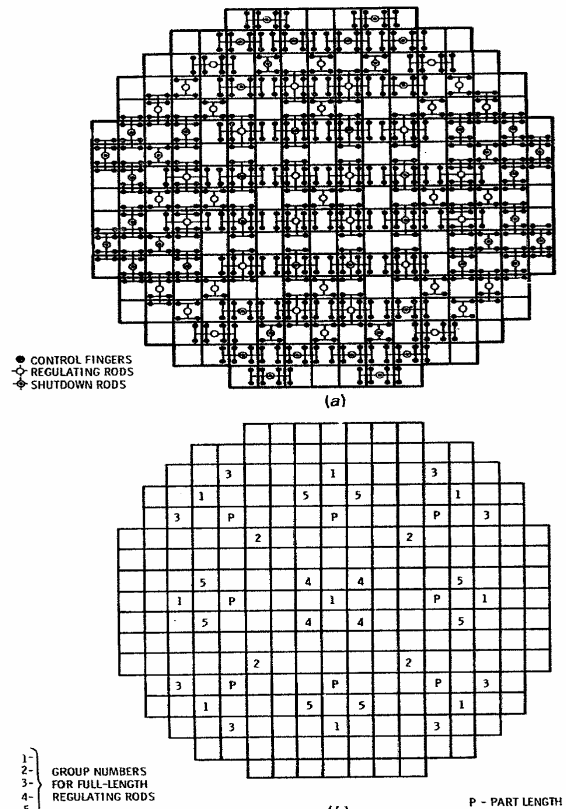
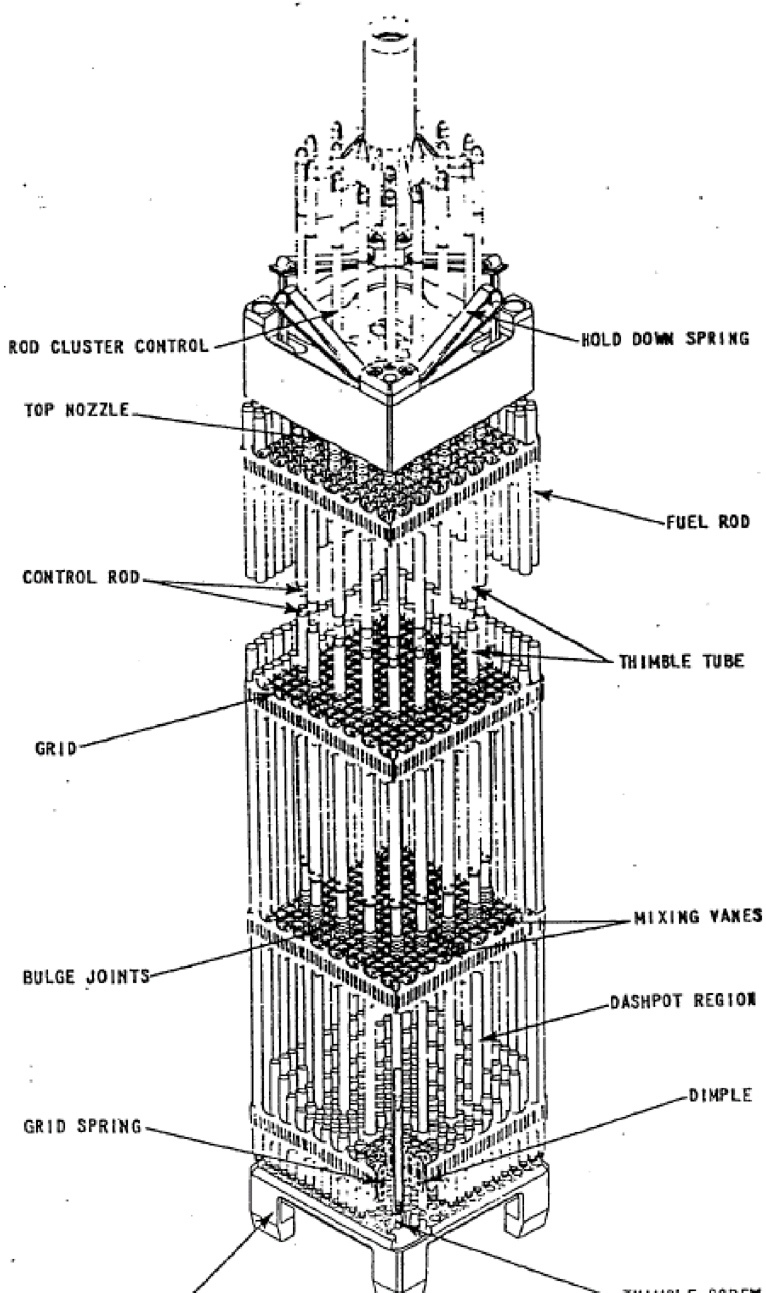


Fig. 11.4 A recent form of BWR containment. (Courtesy General Electric Company.)

PWR Fuel Assembly







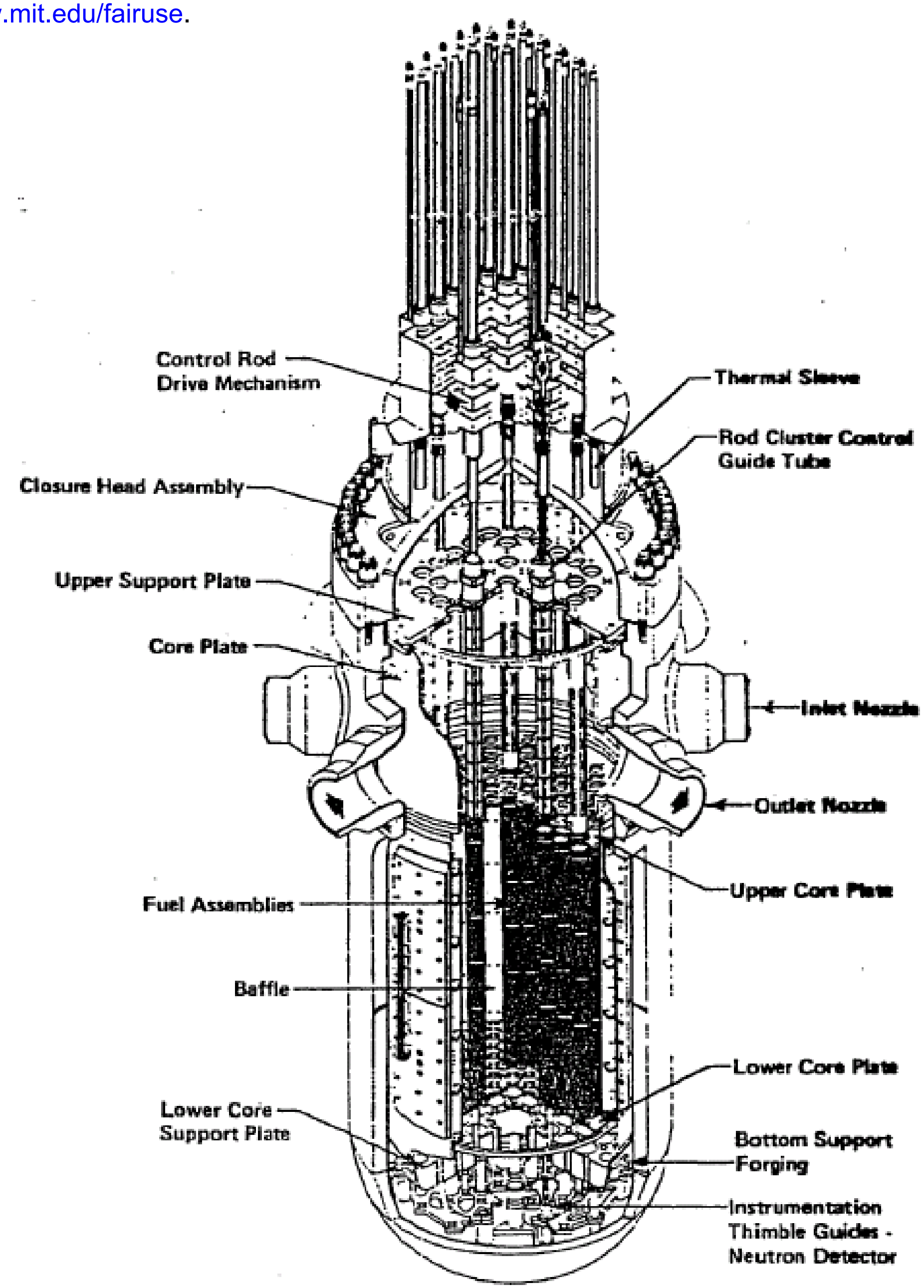
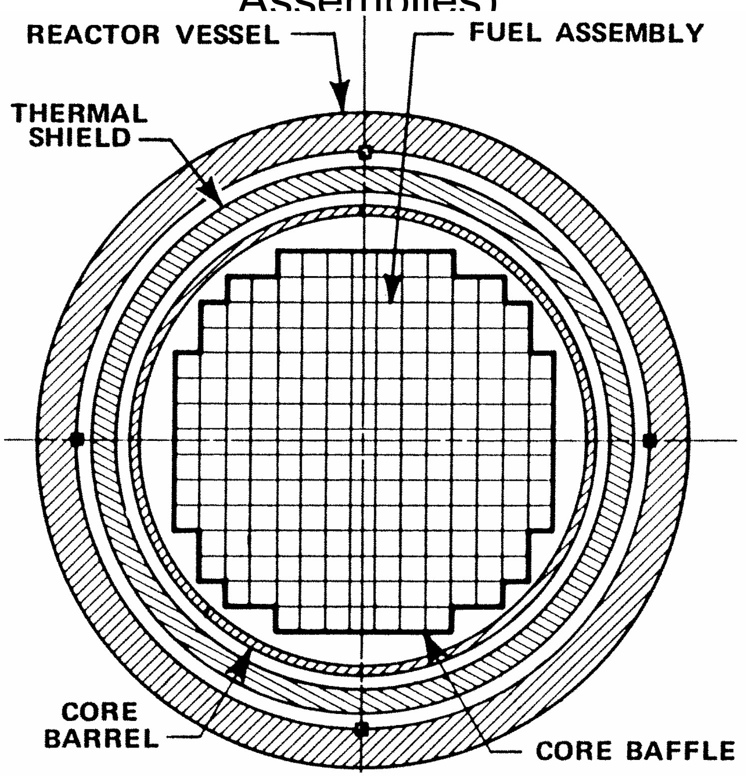


FIGURE 10-6
Pressurized-water reactor vessel. (Courtesy of Westinghouse Electric Corporation.)

Typical Four-Loop Reactor Core

Cross Section (193 Fuel Assemblies)



Parameters

Total heat output	~3250-3411 MWT
Heat generated in fuel	97.4%
Nominal system pressure	2250 psia
Total coolant flow rate	~138.4 x 10^6 lb/hr
Coolant Temperature	
Nominal inlet	557.5˚F
Average rise in vessel	61.0˚F
Outlet from vessel	618.5˚F
Equivalent core diameter	11.06 ft
Core length, between fuel ends	12.0 ft
Fuel weight, uranium (first core)	86,270 kg
Number of fuel assemblies	193

Masche, G., Systems Summary: W PWR NPP, 1971

TABLE 1-2
Characteristics of the Fuel Cores of Six Reference Reactor Types†

Component	Boiling-water reactor [BWR]	Pressure-tube Graphite reactor [PTGR]	Pressurized-water reactor [PWR]	Pressurized-heavy-water reactor [PHWR]	High-temperature gas-cooled reactor [HTGR]‡	Liquid-metal fast-breeder reactor [LMFBR]
Fuel particle(s)						
Geometry	Short, cylindrical pellet	Short, cylindrical pellet	Short, cylindrical pellet	Short, cylindrical pellet	Multiply coated microspheres	Short, cylindrical pellet
Chemical form	UO_2	UO_2	UO_2	UO_2	UC/ThC	Mixed oxides UO_2 and PuO_2
Fissile	2–4 wt % ^{235}U	1.8–2.4 wt % ^{235}U	2–4 wt % ^{235}U	Natural uranium	20–93 wt % ^{235}U microsphere	10–20 wt % Pu
Fertile	^{238}U	^{238}U	^{238}U	^{238}U	Th microsphere	^{238}U in depleted U
Fuel pins	Pellet stacks in long Zr-alloy cladding tubes	Pellet stacks in long Zr-alloy cladding tubes	Pellet stacks in long Zr-alloy cladding tubes	Pellet stacks in short Zr-alloy cladding tubes	Microsphere mixture in short graphite fuel stick	Pellet stacks in medium-length stainless steel cladding tubes
Fuel assembly	8 × 8 square array of fuel pins	18-pin concentric-circle arrangement	16 × 16 or 17 × 17 square array of fuel pins	37-pin concentric-circle arrangement	Hexagonal graphite block with stacked fuel sticks	Hexagonal array of 271 fuel pins
Reactor core§						
Axis	Vertical	Vertical	Vertical	Horizontal	Vertical	Vertical
Number of fuel assemblies along axis	1	2	1	12	8	1
Number of fuel assemblies in radial array	748	1661	193–241	380	493	364 driver, 233 blanket

† More detailed data and references are contained in App. IV.
‡ The HTGR fuel geometry is different from that of the other reactors, leading to some slightly awkward classifications.
§ All of the cores approximate right circular cylinders. Fuel assemblies are loaded and/or stacked lengthwise parallel to the axis of the cylinder.

TABLE IV-1
Typical Characteristics for Six Reference Power Reactor Types (*Continued*)

Reference design	BWR	PWR(B&W)	PWR(CE)	PWR(W)	PWR(F)	PWR(V)	PTGR	PHWR	HTGR	LMFBR
Core (*continued*)										
No. of assemblies										
Axial	1	1	1	1	1	1	2	12	8	1
Radial	748	241	241	193	205	151	1661	380	493	364 [C] 233 [BR]
Assembly pitch, mm	152	218	207				250	286	361	179
Active fuel height, m	3.81	3.63	3.81	3.66	4.267	3.56	7	5.94	6.30	1.0 [C] 1.6 [C+BA]
Equivalent diameter, m	4.70	3.82	3.81	3.37	3.37	3.16	12	6.29	8.41	3.66
Total fuel weight, tU	156 UO_2	125 UO_2	117 UO_2	101 UO_2	125 UO_2	80 UO_2	204 UO_2	98.4 UO_2	1.72 U 37.5 Th	32 MO_2
Performance										
Equilibrium burnup, MWD/T	27,500	33,000	34,400	27,500	35,000	25,000-41,000	18,500	7,500	95,000	100,000
Average assembly residence, full-power days								470	1,170	

TABLE IV-1
Typical Characteristics for Six Reference Power Reactor Types (*Continued*)

Reference design	BWR	PWR(B&W)	PWR(CE)	PWR(W)	PWR(F)	PWR(V)	PTGR	PHWR	HTGR	LMFBR
Fuel§										
Particles									(9-9)	
Geometry	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Cylindrical pellet	Coated microspheres	Cylindrical pellet
Dimensions, mm	10.4 *D* × 10.4 *H*	8.2 *D* × 9.5 *H*	8.3 *D* × 9.9 *H*	8.2 *D* × 13.5 *H*		7.55 *D*	·	12.2 *D* × 16.4 *H*	400-800 μm *D*	7.0 *D*
Chemical form	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UC/ThO_2	PuO_2/UO_2
Enrichment initial core, wt% ^{235}U	1.71 (ave)	2.79 (ave)	1.92/2.78	2.1/2.6/3.1	1.8/2.4/3.1	3.3-4.4	1.1-2.4	0.711	93	15-18 Pu
Enrichment, reload, wt% ^{235}U	2.81 (ave)		3.3			4.0		0.711	93	
Fertile	^{238}U	^{238}U	^{238}U	^{238}U				^{238}U	Th	Depl. U
Pins	(9-7)	(9-7)	(9-7)	(9-7)	(9-7)	(9-7)			(1-10)	(9-8)
Geometry	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Pellet stack in clad tube	Cylindrical fuel stick	Pellet stack in clad tube
Dimensions, mm	1.27 *D* × 4.1 m *H*	9.6 *D* × 4 m *H*	9.7 *D* × 4.1 m *H*	9.5 *D* × 4 m *H*		9.1 *D* × 3.55 m *H*	13.5 *D* × 3.64 m *H*	13.1 *D* × 490 *L*	15.7 *D* × 62 *L*	8.5 *D* × 2.7 m *H* [C] 15.8 *D* × 1.95 m *H* [BR]
Clad material	Zircaloy-2	Zircaloy-4	Zircaloy-4	Zircaloy-4	Zircaloy-4		Zr-Nb alloy	Zircaloy-4	Graphite	Stainless steel
Clad thickness, mm	0.813	0.6	0.64	0.57	0.57	0.65	0.9	0.42	—	0.7
Assembly	(1-6)	(10-11)	(1-7)	(10-11)	(10-11)		(1-8)	(1-9)	(1-10/11-8)	(1-11/12-7)
Geometry	8 × 8-Square array	17 × 17-Square array	16 × 16-Square array	17 × 17-Square array	17 × 17-Square array	Hexagonal array	Concentric circles	Concentric circles	Hexagonal graphite block	Hexagonal array
Pin pitch, mm	16.2	12.7	12.9	12.6	1.26	1.28		14.6		9.7 [C]/ 17.0 [BR]†
No. pin locations	64	289	256	289		331 }	18 }	37 }	132 [SA]/ 76 [CA]# }	271 [C]/ 91 [BR]
No. fuel pins	62	264	236	264	274	317 }				
Outer dimensions, mm	139	217	203	214	215		<80	102 *D* × 495 *L*	360 *F* × 793 *H*	173 *F*
Channel	Yes	No	No	No	No	Yes	No	No	No	Yes
Total weight, kg	273	652								
Core	(10-4)	(9-11)	(9-11)	(9-11)	(9-11)			(11-2)	(11-7)	
Axis	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Horizontal	Vertical	Vertical

See footnotes on page 717.

Power Density

TABLE 7-1
Power Densities for the Reference Reactors and Other Systems

System	Power density (kW/liter) Core average	Fuel average†	Fuel maximum†
Fossil-fuel plant	10	—	—
Aircraft turbine	45	—	—
Rocket	20,000	—	—
HTGR	8.4	44	125
PTGR	4.0	54	104
CANDU	12	110	190
BWR	56	56	180
PWR	95–105	95–105	190–210
LMFBR	280	280	420

†Includes interspersed-coolant volume for systems with fuel-pin lattices; includes only fuel sticks for HTGR.

Energy Removal

- Heat Balance in a reactor
  - Power Equation function of neutron flux
- Impact of Power Distribution on ability to remove heat and maintain temperature limits
  - Material and Fuel limitations

Diffusion Theory Flux

TABLE 4-2
Diffusion Theory Fluxes and Bucklings for Bare Critical Systems of Uniform Composition

Geometry	Dimensions	Normalized flux $\frac{\Phi(r)}{\Phi(0)}$	Geometric buckling B_g^2
Sphere	Radius R	$\frac{1}{r}\sin\left(\frac{\pi r}{R}\right)$	$\left(\frac{\pi}{R}\right)^2$
Finite cylinder	Radius R, height H (centered about $z = 0$ and extending to $z = \pm H/2$)	$J_0\left(\frac{2.405r}{R}\right)\cos\left(\frac{\pi z}{H}\right)$	$\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2$
Infinite cylinder	Radius R	$J_0\left(\frac{2.405r}{R}\right)$	$\left(\frac{2.405}{R}\right)^2$
Rectangular parallelepiped [cuboid]†	$A \times B \times C$ (centered about $x = y = z = 0$ and extending to $x = \pm A/2$, etc.)	$\cos\left(\frac{\pi x}{A}\right)\cos\left(\frac{\pi y}{B}\right)\cos\left(\frac{\pi z}{C}\right)$	$\left(\frac{\pi}{A}\right)^2 + \left(\frac{\pi}{B}\right)^2 + \left(\frac{\pi}{C}\right)^2$
Infinite slab	Thickness A (centered about $x = 0$ and extending to $x = \pm A/2$)	$\cos\left(\frac{\pi x}{A}\right)$	$\left(\frac{\pi}{A}\right)^2$

†The term *cuboid*—a synonym for rectangular parallelepiped used in the KENO Monte Carlo code—is commonly employed in the field of nuclear criticality safety (and may catch on elsewhere).

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Flux Shapes

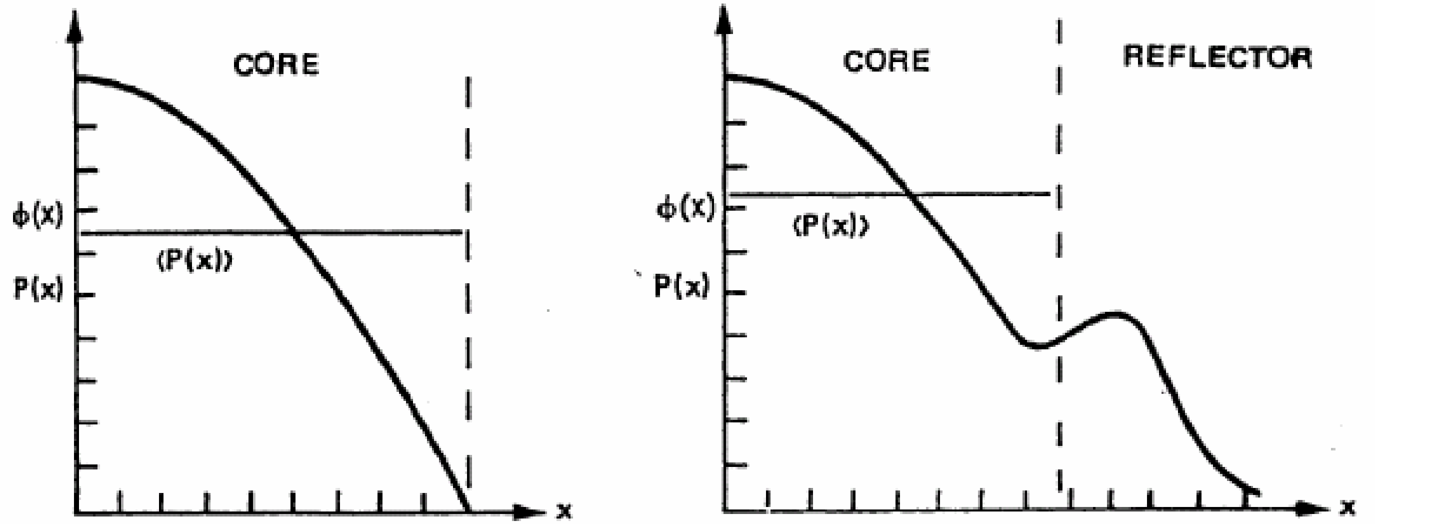

FIGURE 7-1
Flux shapes and average power densities for bare and reflected slab geometries.

Power Peaking Factors

TABLE 7-2
Power Peaking Factors for Reactors of Various Geometric Shapes

	Peaking factor	
Geometry	Total	Constituents
Sphere, bare	3.29	
Infinite slab, bare	1.57	
Cuboid,† bare	3.87	$x = 1.57$
		$y = 1.57$
		$z = 1.57$
Infinite cylinder, bare	2.32	
Cylinder, bare	3.64	$r = 2.32$
		$z = 1.57$
Cylinder, fully reflected	2.03	$r = 1.50$
		$z = 1.35$
Cylinder, fully reflected, enrichment-zoned radially	1.62	$r = 1.20$
		$Z = 1.35$

†A cuboid is a rectangular parallelepiped (see note on Table 4-2).

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Power Distributions

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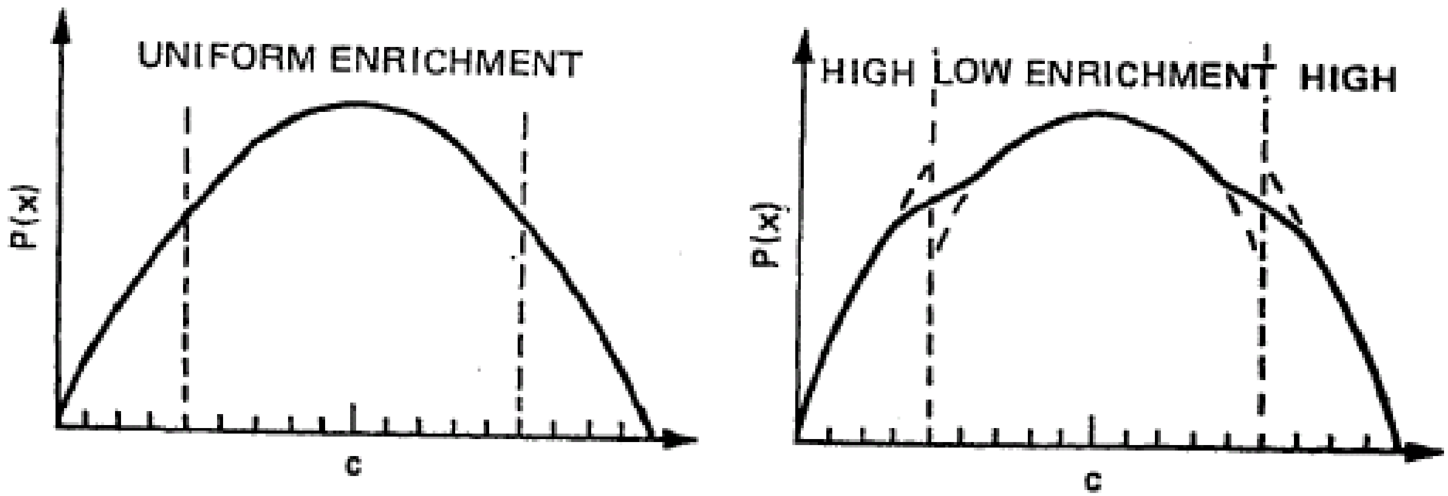

FIGURE 7-2
Power distributions for one- and two-batch fuel-management patterns in a bare-slab geometry.

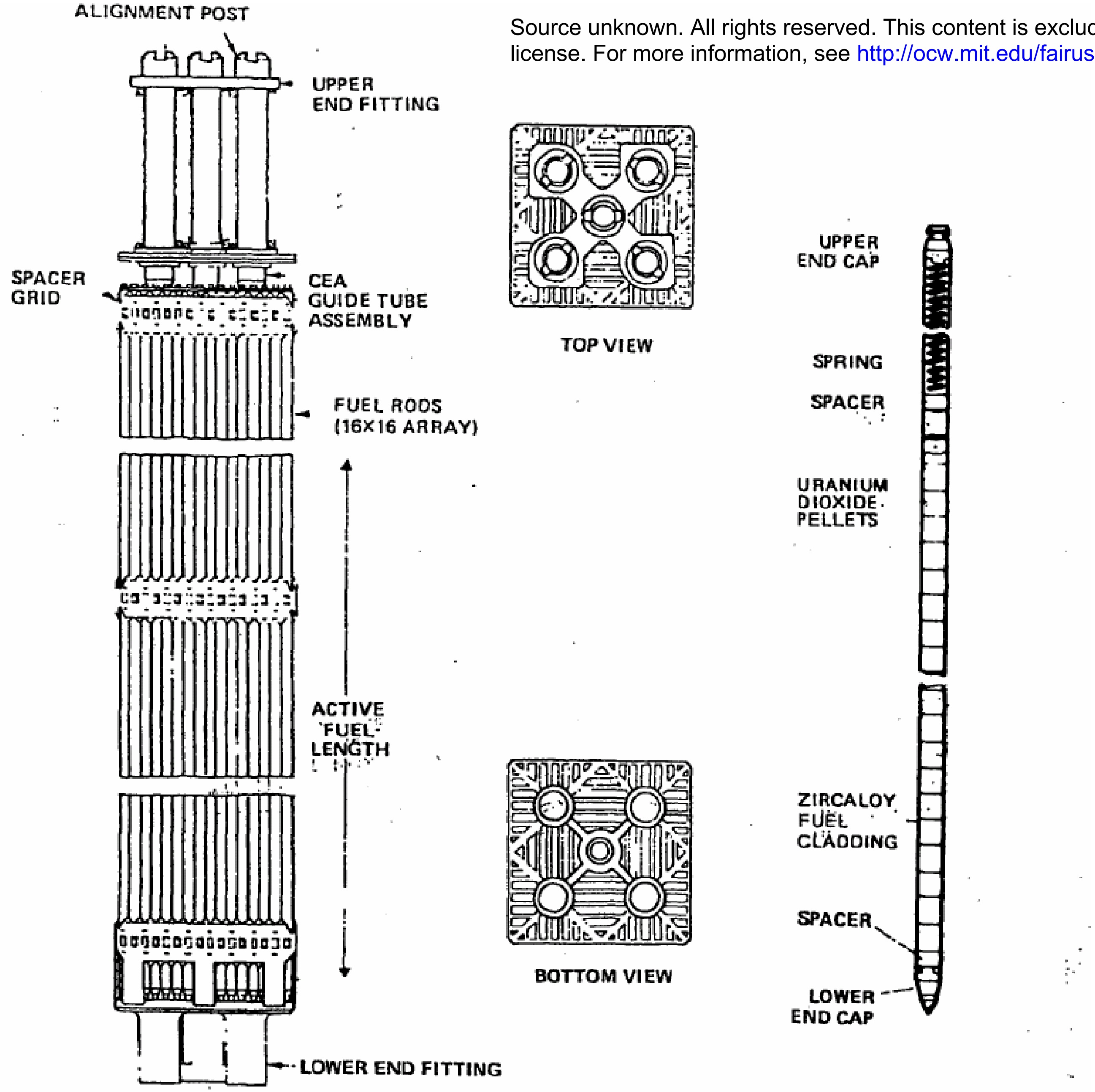

FIGURE 1-7

Fuel assembly for a representative pressurized-water reactor. (Adapted courtesy of Combusti Engineering, Inc.)

Fuel Pin Cross Section

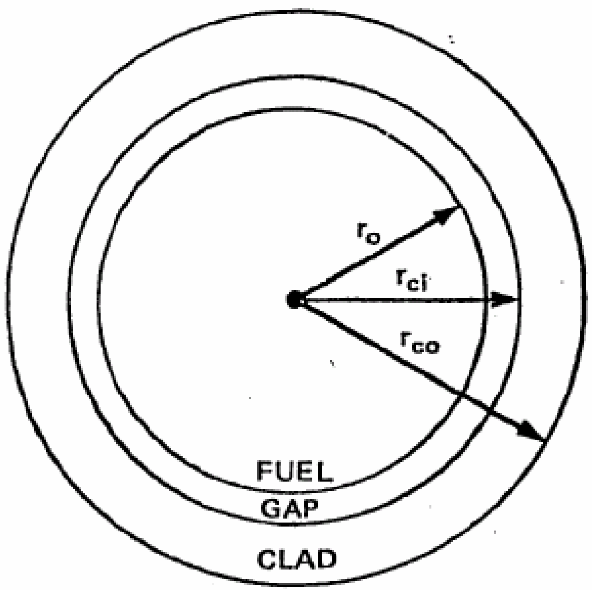

FIGURE 7-3
Cross section of a representative fuel pin (not drawn to scale).

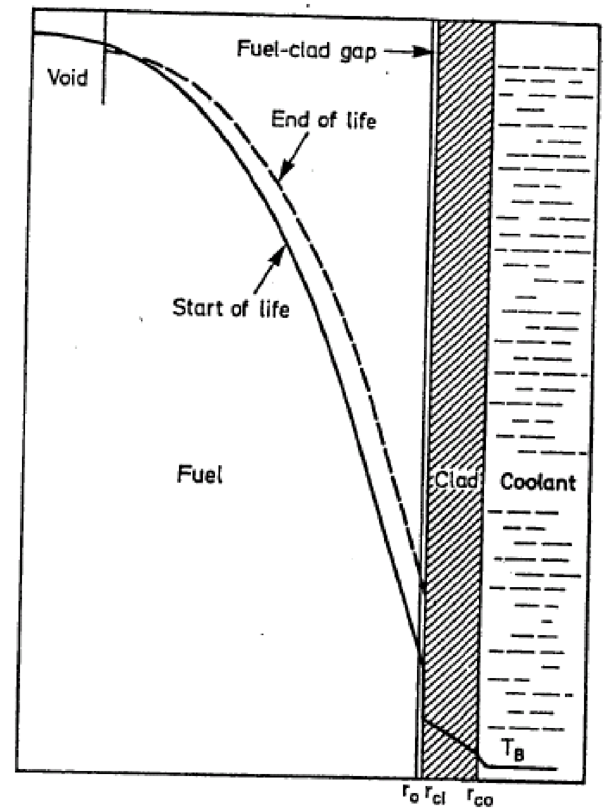

FIGURE 7-4
Representative temperature profile for a PWR fuel pin. (Adapted from J. C
Introduction to Nuclear Power, Hemisphere Publishing, New York, 1987.)

Heat Removal Governing Processes

- Fuel Pin Power Production
  - Conductive heat transfer
  - Fourier Law of Heat Conduction
  - Poisson’s Equation
- Clad Heat Transfer
  - Poisson’s Equation but no heat source
- Clad to Coolant
  - Newton’s law of cooling
  - Convective Heat Transfer
- Gap to Clad
  - Convective
  - Conductive heat transfer coefficient – hgap

Nuclear Limits

- Hot spot factor –
  - Peak power in pin
  - Prevent Fuel Melting
- Hot Channel Factor
  - Assure heat removal from pin
  - Minimum Departure from Nucleate Boiling Ratio
- Design Considerations
  - Limits on Power
  - Materials

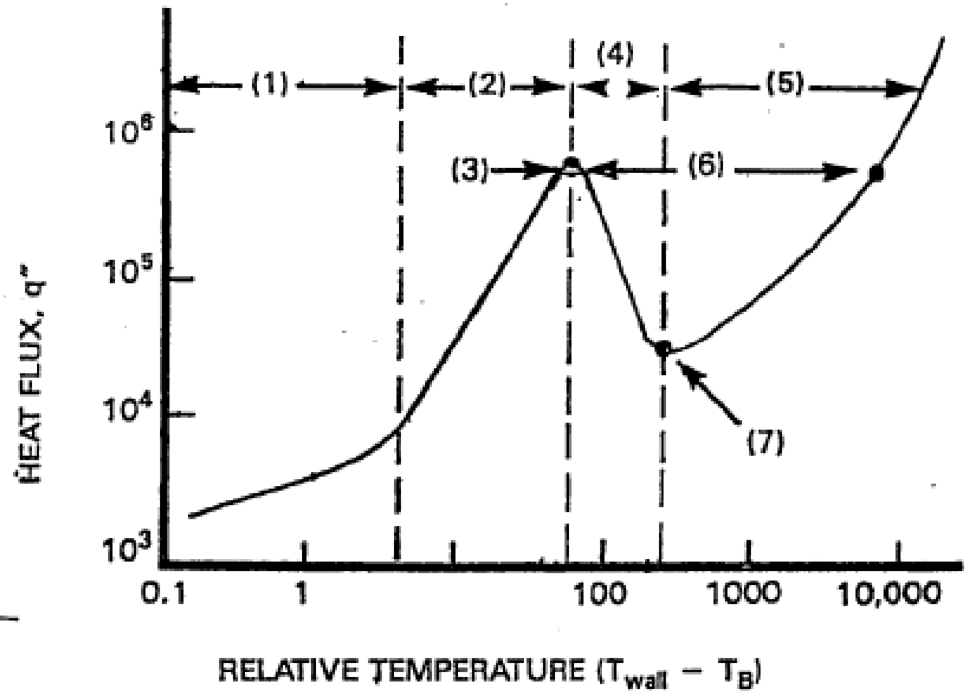

FIGURE 7-6
Heat flux versus surface temperature for a heated pin in a pool of water at saturation temperature.

Axial Peaking

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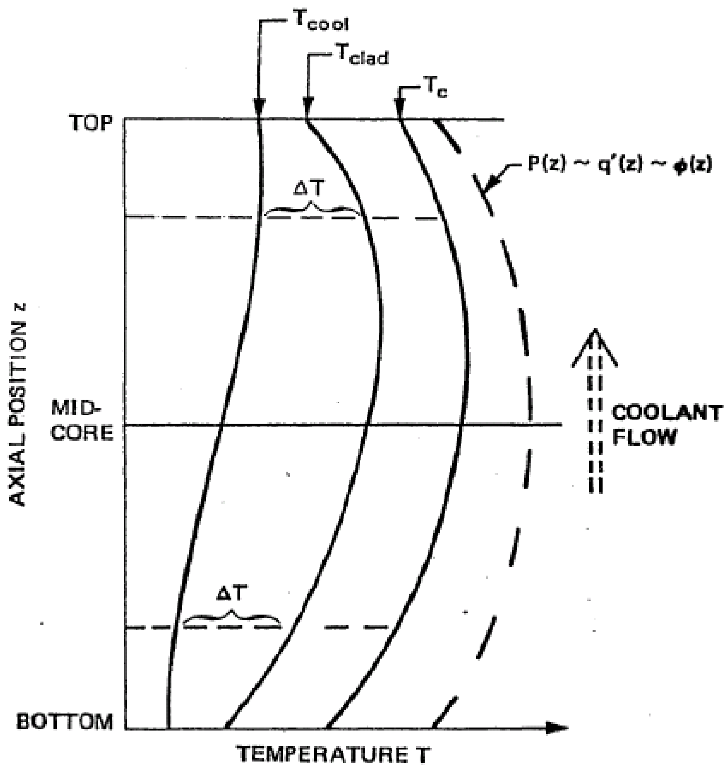

FIGURE 7-5
Axial temperature for the coolant (T_{cool}), the clad (T_{clad}), and fuel pellet center line (T_c) based on cosine flux distribution.

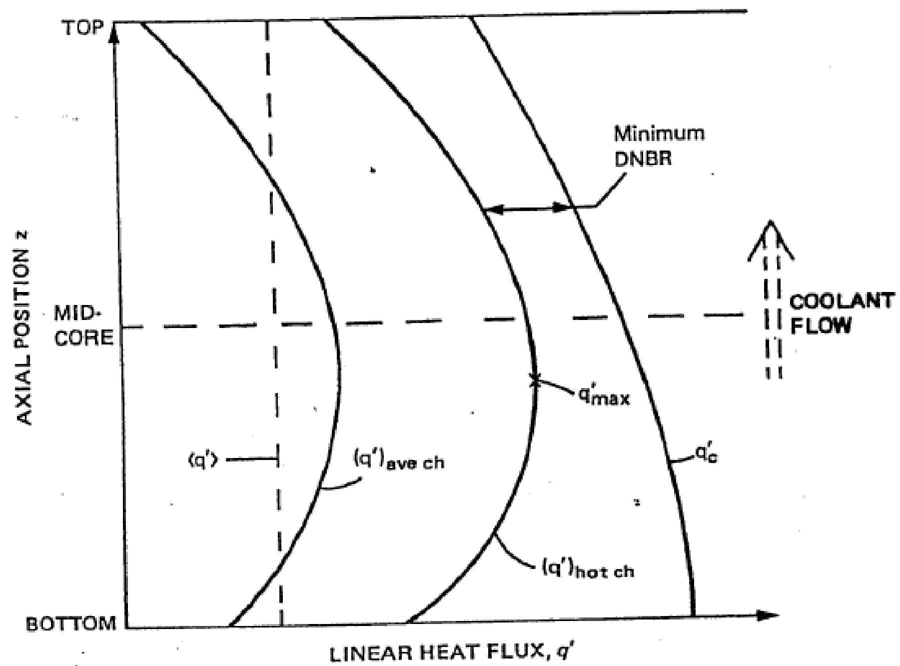

FIGURE 7-8
Characteristic relationship between the core average $\langle q' \rangle$, average channel $(q')_{ave\ ch}$, hot channel $(q')_{hot\ ch}$, and critical q'_c linear heat rates along the core axis of a PWR.

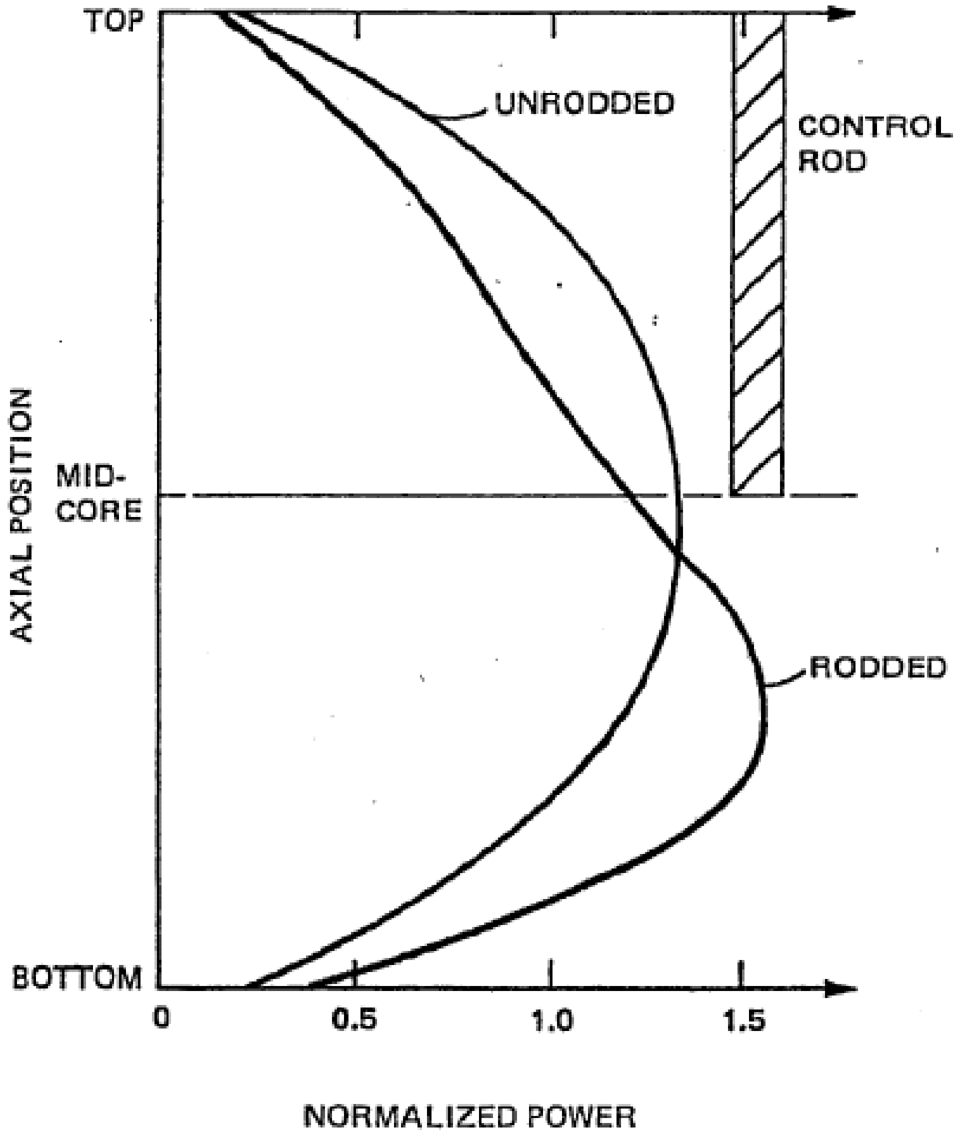

FIGURE 7-9

Effect of control-rod group insertion on PWR power shape axially for the core as a whole.

Control Rod Insertion

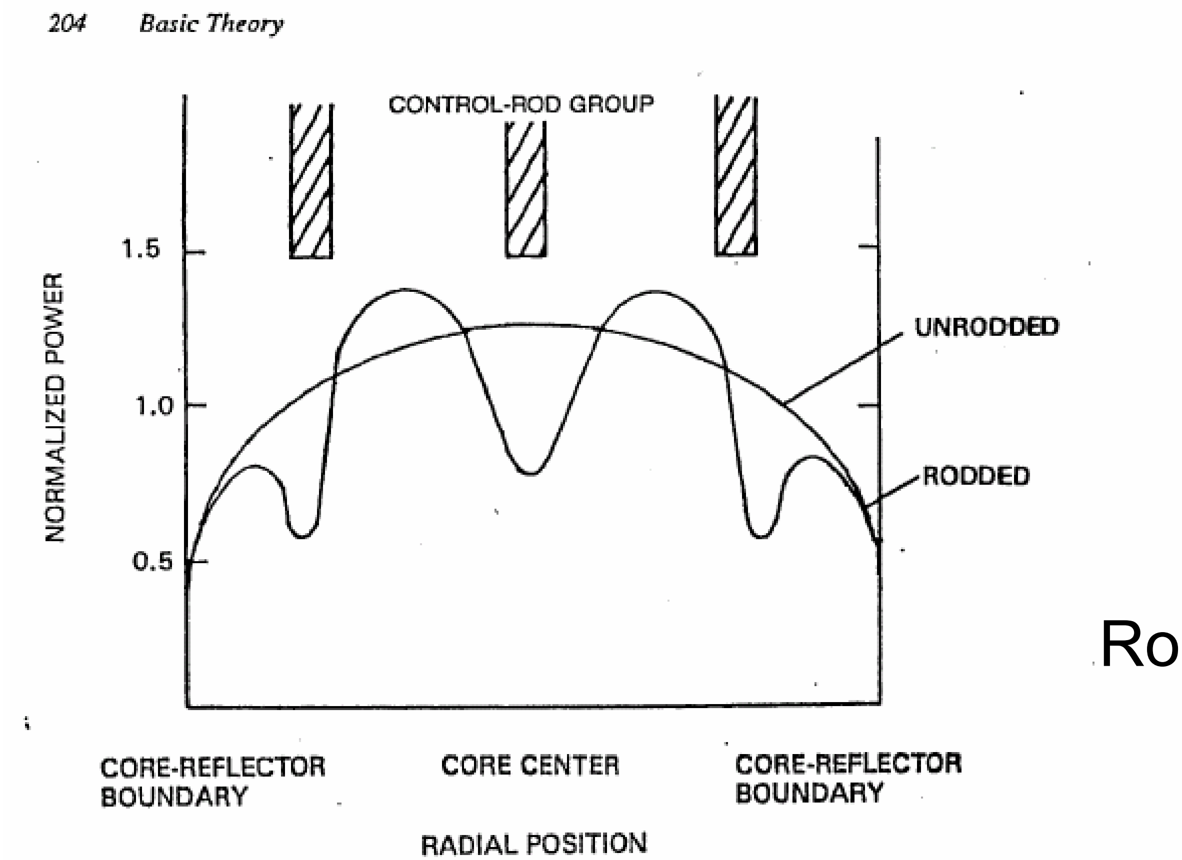

FIGURE 7-10
Effect of control-rod group insertion on PWR power shape radially in a plane through the control rods.

Rod "bite"

Homework Assignment

Homework: Problems 7.2,5,6,8

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