Operational Reactor Safety
22.091/22.903

Professor Andrew C. Kadak
Professor of the Practice

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Overview

Course Learning Objectives

The course will focus on understanding the complete nuclear reactor system including the balance of plant, support systems and resulting interdependencies affecting the overall safety of the plant and regulatory oversight.

- Reactor Physics
- Power Conversion
- Safety Functions and Systems
- Risk Assessment
- Simulator Exercises
- Technical Specifications
- Safety Culture

Course Overview

Preliminary Syllabus

Operational Reactor Safety Course

Lecture #	Topic
1	Overview, Goals of Course - Review of Reactor Types
2	Review of Reactor Physics
3	Review of Reactor Kinetics and Control
4	Review of Feedback Effects and Depletion
5	MIT Reactor Physics Exercise - power change
6	Reactor Energy Removal
7	Power Conversion Systems - Rankine cycle
8	Power Conversion Systems - Brayton Cycle
9	Safety Systems and Functions
10	Reactor Safety - Safety Analysis Report Accident and Transients
11	Reactor Safety - Continued

Course Overview Cont'd

12	Probabilistic Safety Assessment
13	Integration of Safety Analysis into Operational Requirements (Technical Specifications)
14	Licensing and Design Bases
15	Simulator Exercise - Seabrook PWR - LOCA, Steam line break, etc
16	Simulator Exercise - Pilgrim BWR - LOCA, steam line break, rod repositioning
17	Significant Nuclear Accidents - Three Mile Island
18	Significant Nuclear Accidents - Chernobyl
19	Importance of Precursors - Davis Besse Events and others
20	Role of Safety Culture
21	New Safety Challenges - Terrorism, Spent Fuel Management, etc.
22	Advanced Reactor Designs - EPR, ABWR, ESBWR, AP-1000, Pebble Bed Reactor

Grading Components

Homework	15%
Quiz #1	20%
Quiz #2	20%
Quiz # 3	20%
Final Exam	25%

Late Homework will receive up to 1/2 full credit

Lecture 1:
Overview of Nuclear Reactors

Learning Objectives:

Gain broad understanding of PWRs, BWRs, HTGRs

Nuclear Fuel Cycle

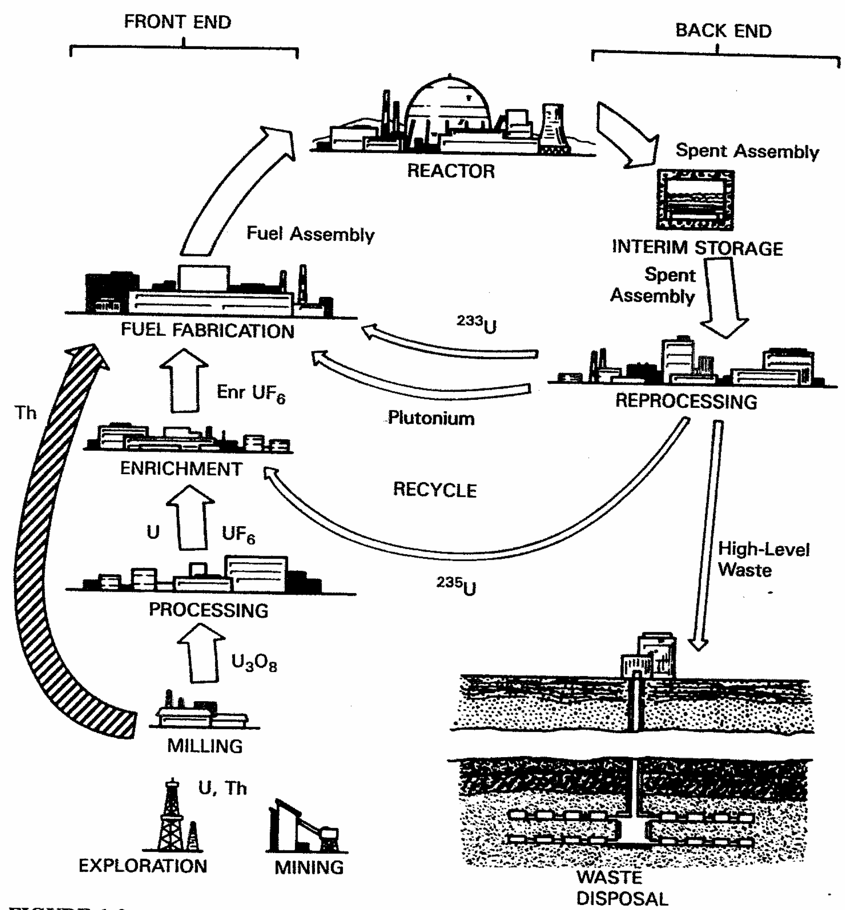
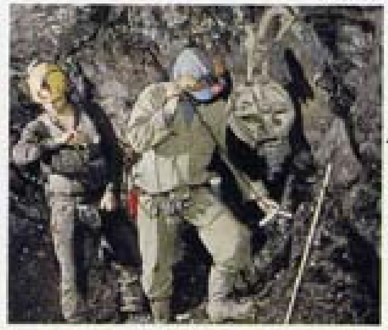


FIGURE 1-2
Nuclear fuel-cycle material flow paths.

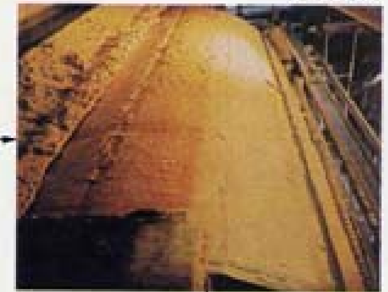
Making Nuclear Fuel

After uranium ore is mined, it must pass through several processing steps before it can be used in a power plant. The ore is milled to remove chemical impurities. Then, the fissionable uranium isotope (U235) is concentrated in a process called enrichment. The enriched uranium in powder form is pressed into small pellets and sealed into metal tubes. The tubes are bundled into fuel assemblies and shipped to a nuclear plant and put into the reactor.

MINING

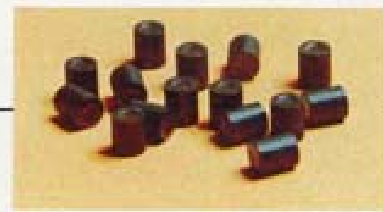


MILLING

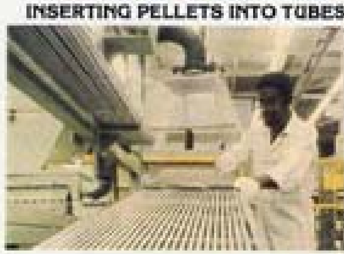


ENRICHMENT

PELLETS



INSERTING PELLETS INTO TUBES



BUNDLING

REACTOR

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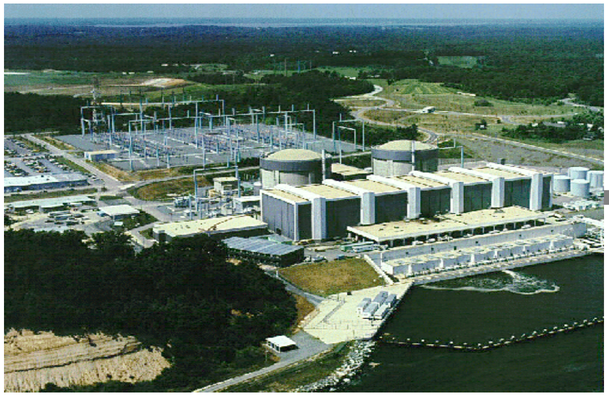
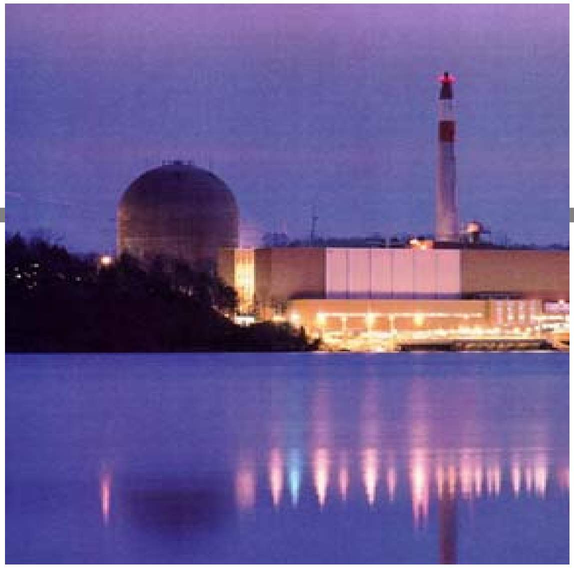


Calvert Cliffs - MD

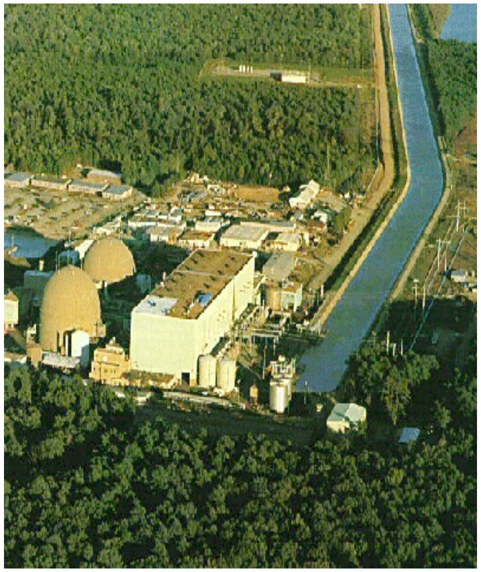


Indian Point - NY

Robinson - SC

Diablo Canyon

Prairie Island site - MN



Surry - VA

Prairie Island - MN

Objectives to Make Electricity

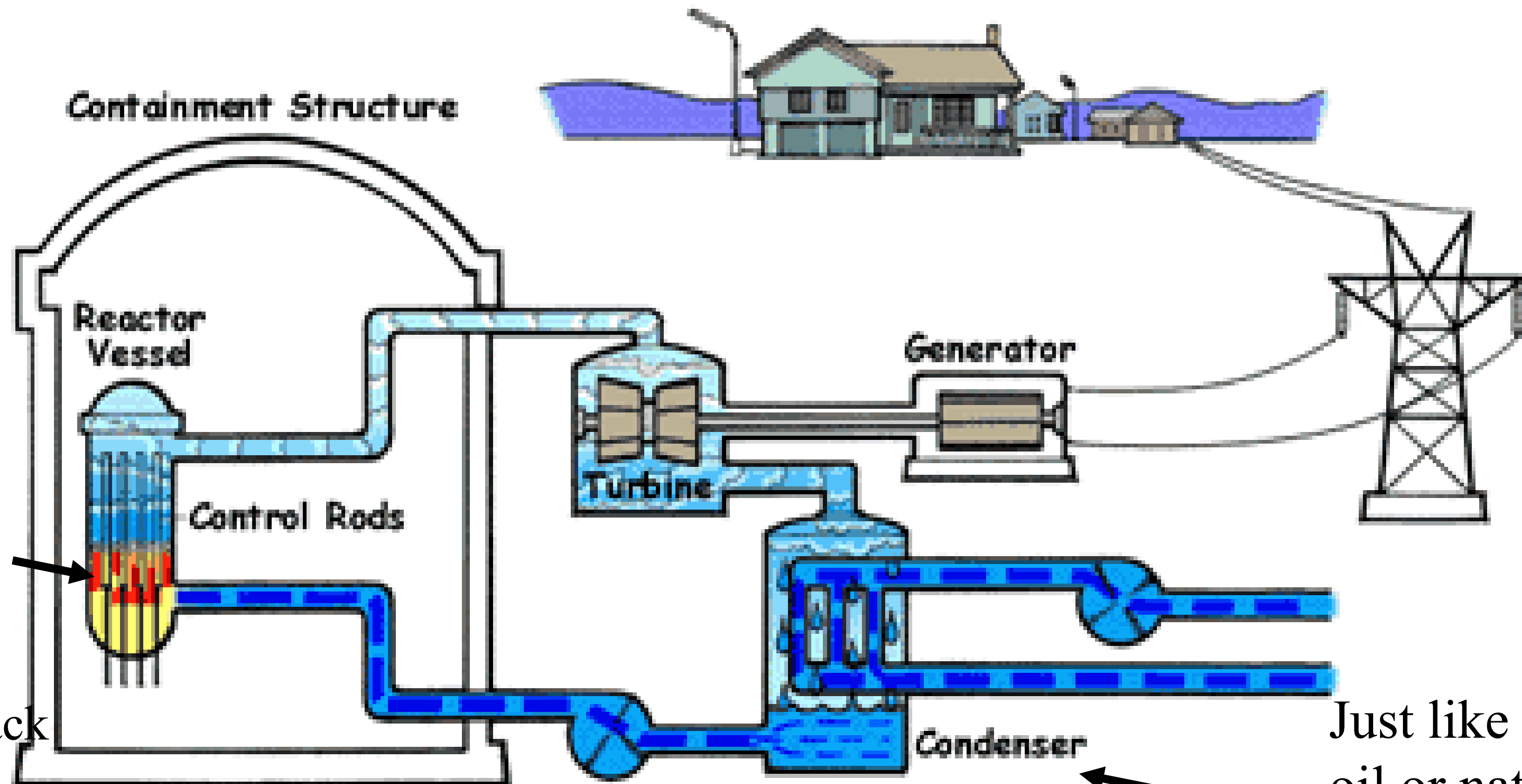
1. Make heat
2. Remove heat using a fluid or gas
3. Pass the fluid or gas through a turbine
4. Turning an electric generator to make Electricity

Removing Heat

- Fluid (water or liquid metal) or gas is pumped through the core to remove heat generated in fuel due to fissioning.
- Pumps needed to circulate coolant
- Transfer directly to turbines or to steam generators (PWRs)
- Condense steam to recirculate back to the core to provide cooling

Basics of Power Conversion

Replaces fossil Boiler but no smokestack



Just like a coal oil or natural gas plant

Boiling Water Reactor

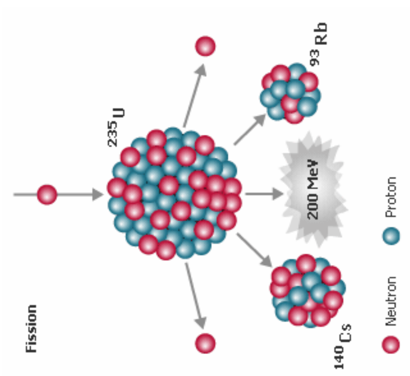
Power Reactor Types

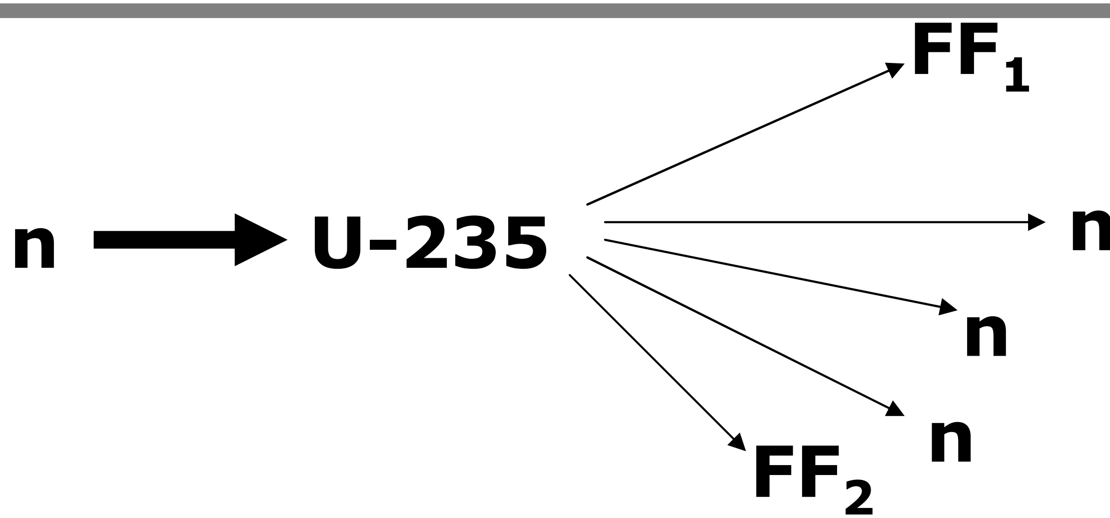
- Pressurized Water Reactor
- Boiling Water Reactor
- Natural Uranium Heavy Water Cooled Reactor (CANDU)
- RBMK - Russian Chernobyl Like - Water Cooled
- Fast Reactors - Liquid Metal (Sodium)
- Gas Reactors (CO_2 or Helium Cooled)
- Molten Salt Cooled Reactors (Organic Coolants)

Making Heat

- Use the fissioning of uranium atoms (or plutonium) to release 200 Million electron volts per fission.
- Need to enrich natural uranium to 3 to 4 weight percent U-235 (from 0.7% found in nature.
- Need to fabricate uranium into pellets clad in zironium fuel assemblies which are placed into the reactor core.

Fission Event





Release of excess neutrons creates the potential for chain reaction.

The energy (mostly as kinetic energy of the fission fragments) is substantial.

Energy Release

1 fission = 200 Mev

1 gram U-235 fissioned = 8.6×10^{10} joules = 24,000 kwh

(Equivalent to lighting a small city for overnight)

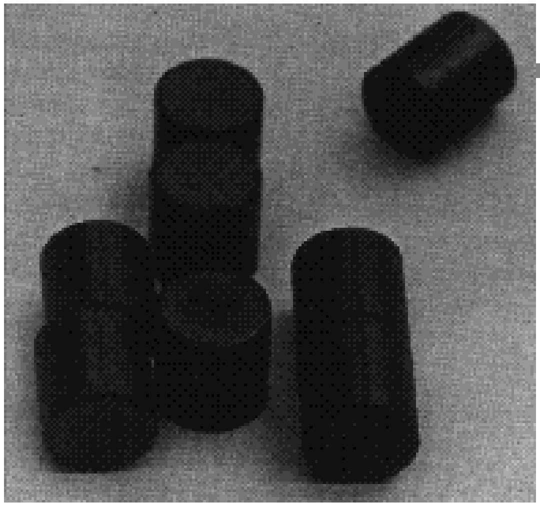
24,000 kwh requires 3.2 tons of coal

12.6 bbls oil

<u>Energy Density (energy / mass)</u>

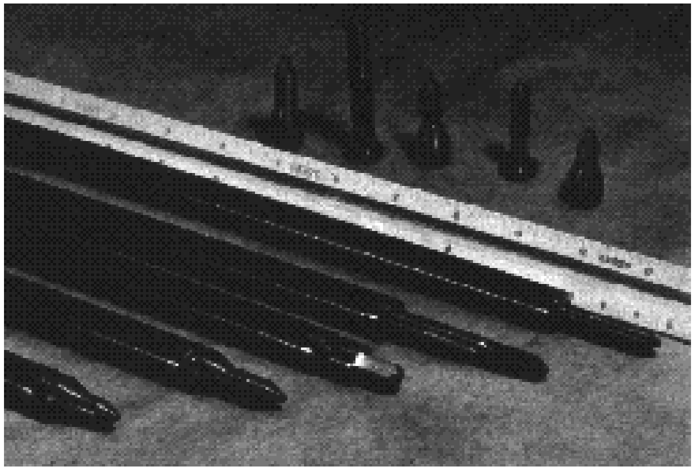
Energy Density of U-235 = 28,000 times energy density of coal

Pellets

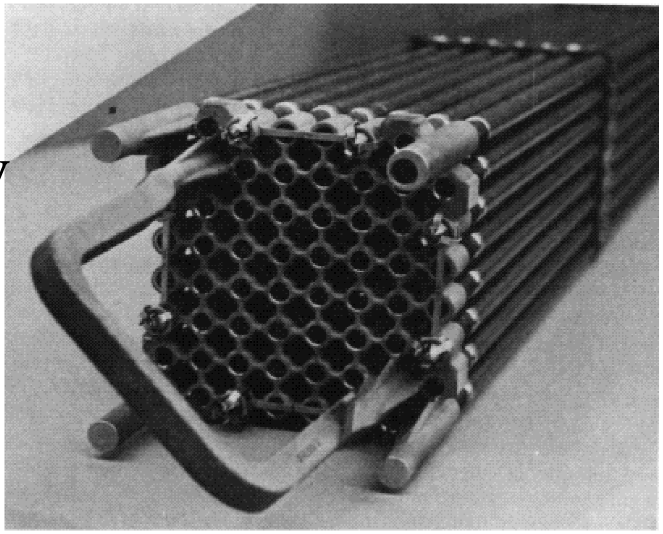


Inserting pellets into pins

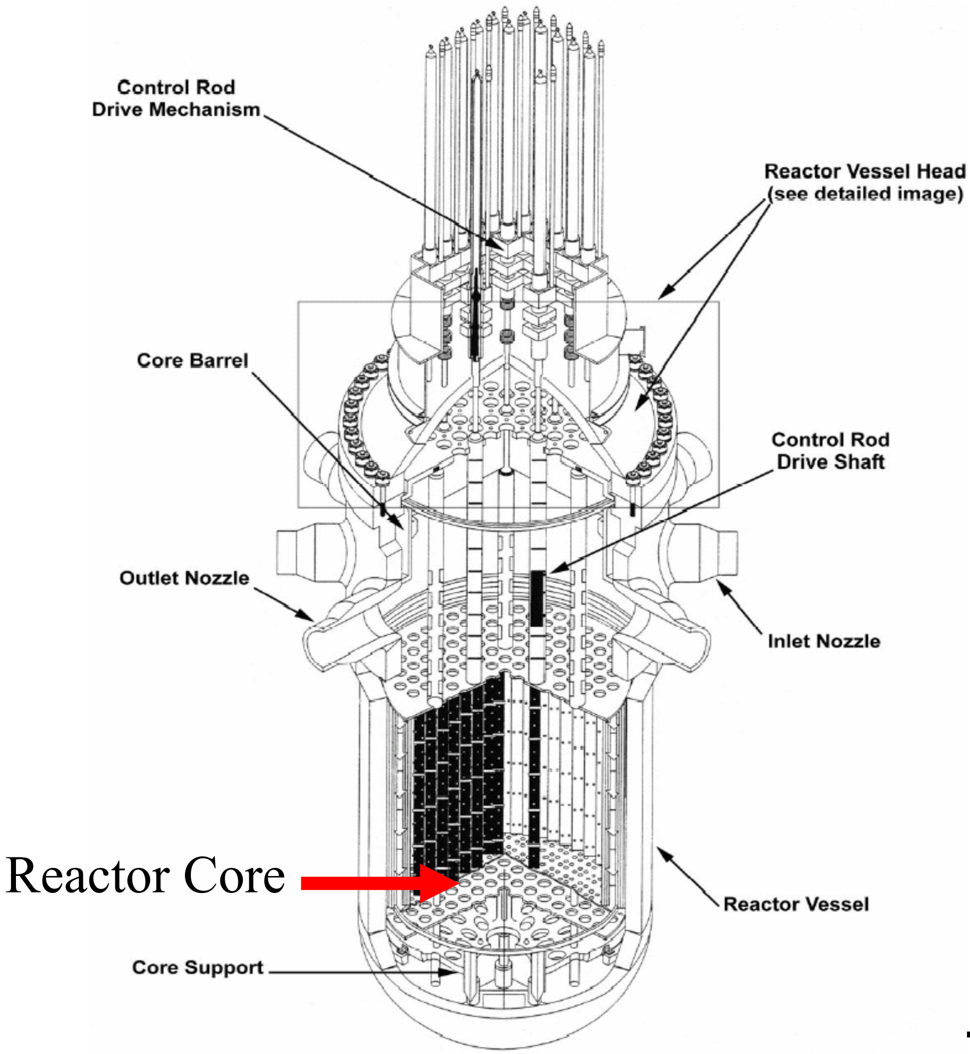
Fuel Pins



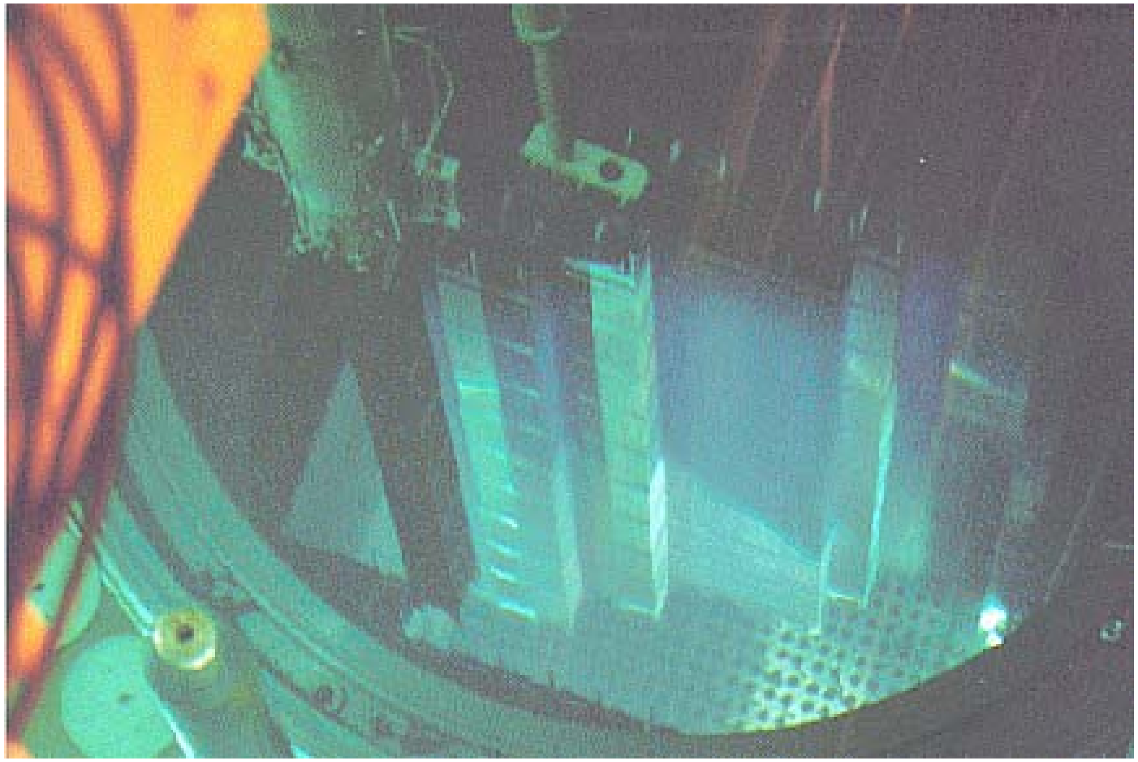
Fuel Assembly



Creating the Reactor Core

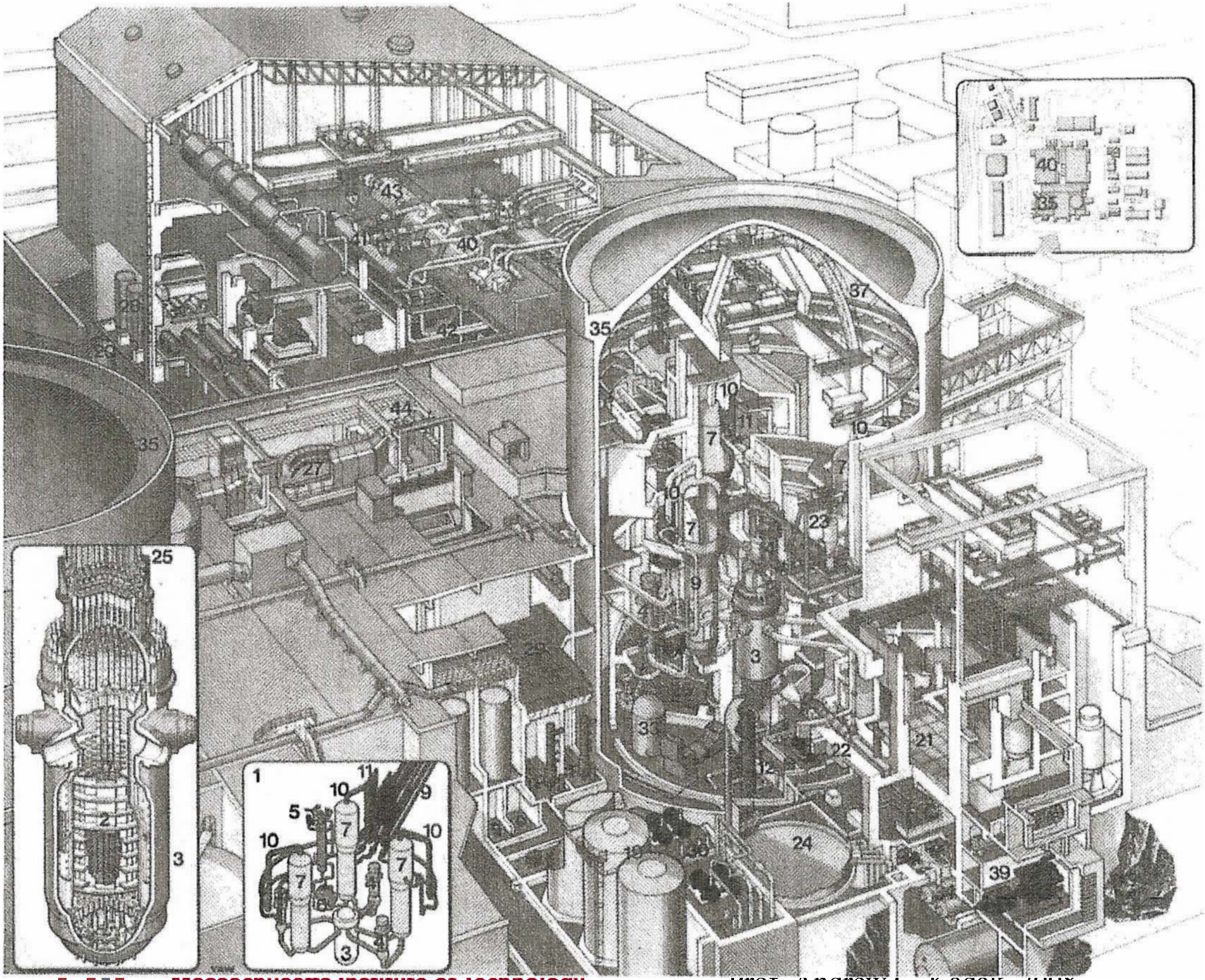


- Need to model uranium fuel
- Reactor internals
- Coolant flow
- Apply Reactor Physics
- Develop neutron flux solutions
- Yields power distributions
- Creates heat that must be removed



Important Factors in Design

- Reactor Core Design
  - Fuel Design
    - Reactor Physics - Core Power Distribution
    - Reactivity Control - Ability to shutdown plant
    - Safety Analysis - no fuel failure or melting
- Core Heat Removal
  - Coolant - Heat Transfer
  - Safety Systems (Emergency)
- Confinement of Radioactivity
- Electricity Production



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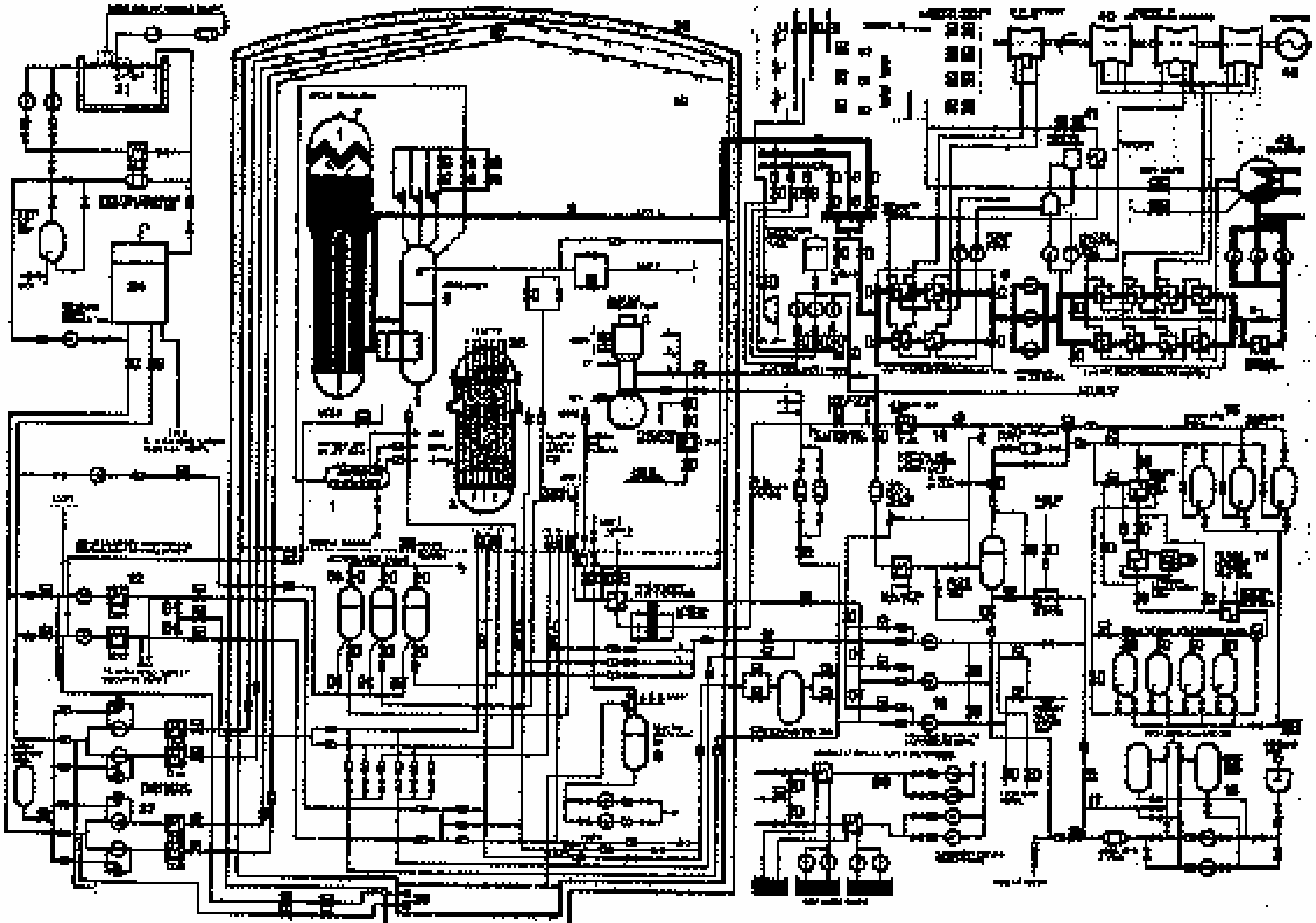
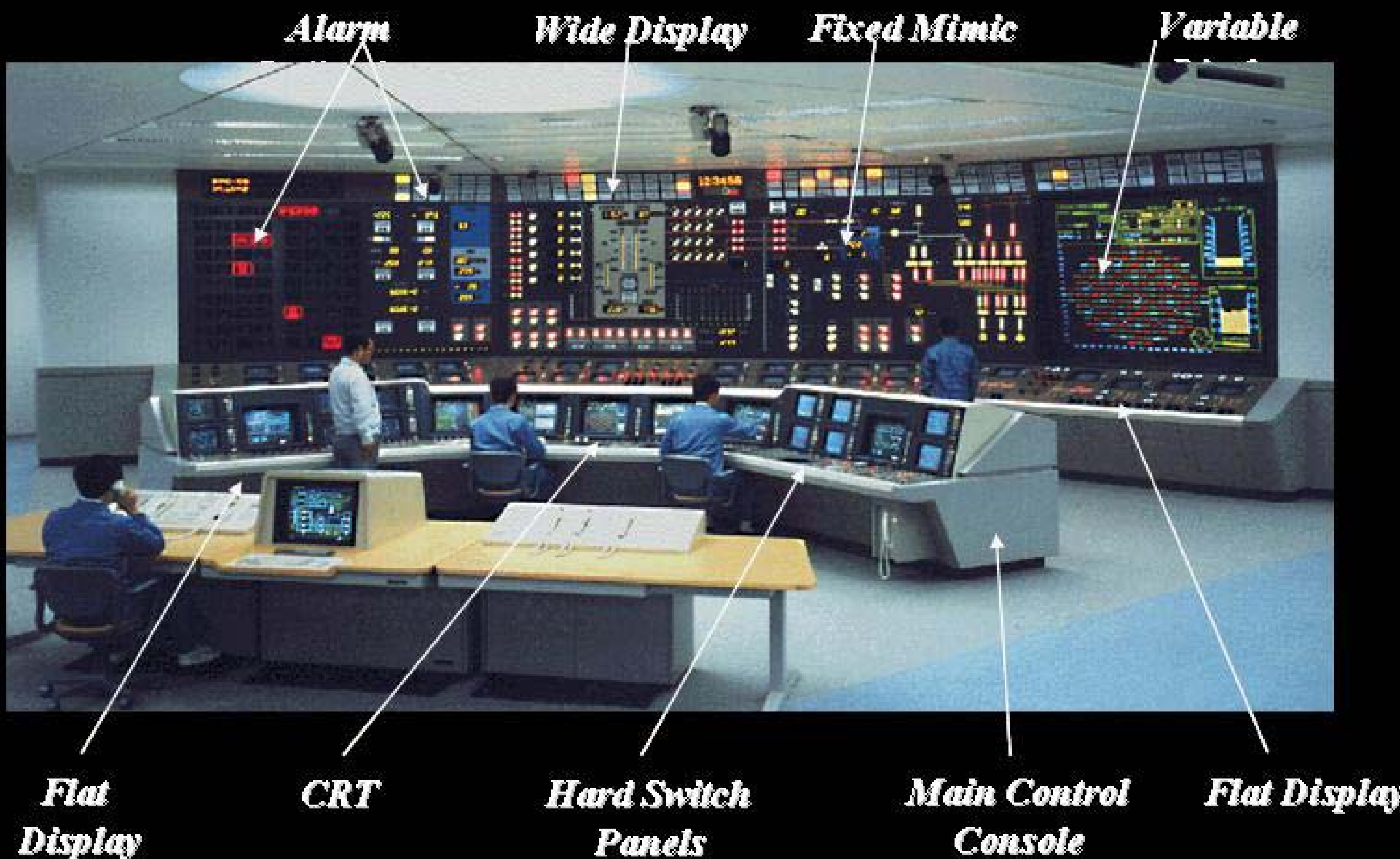


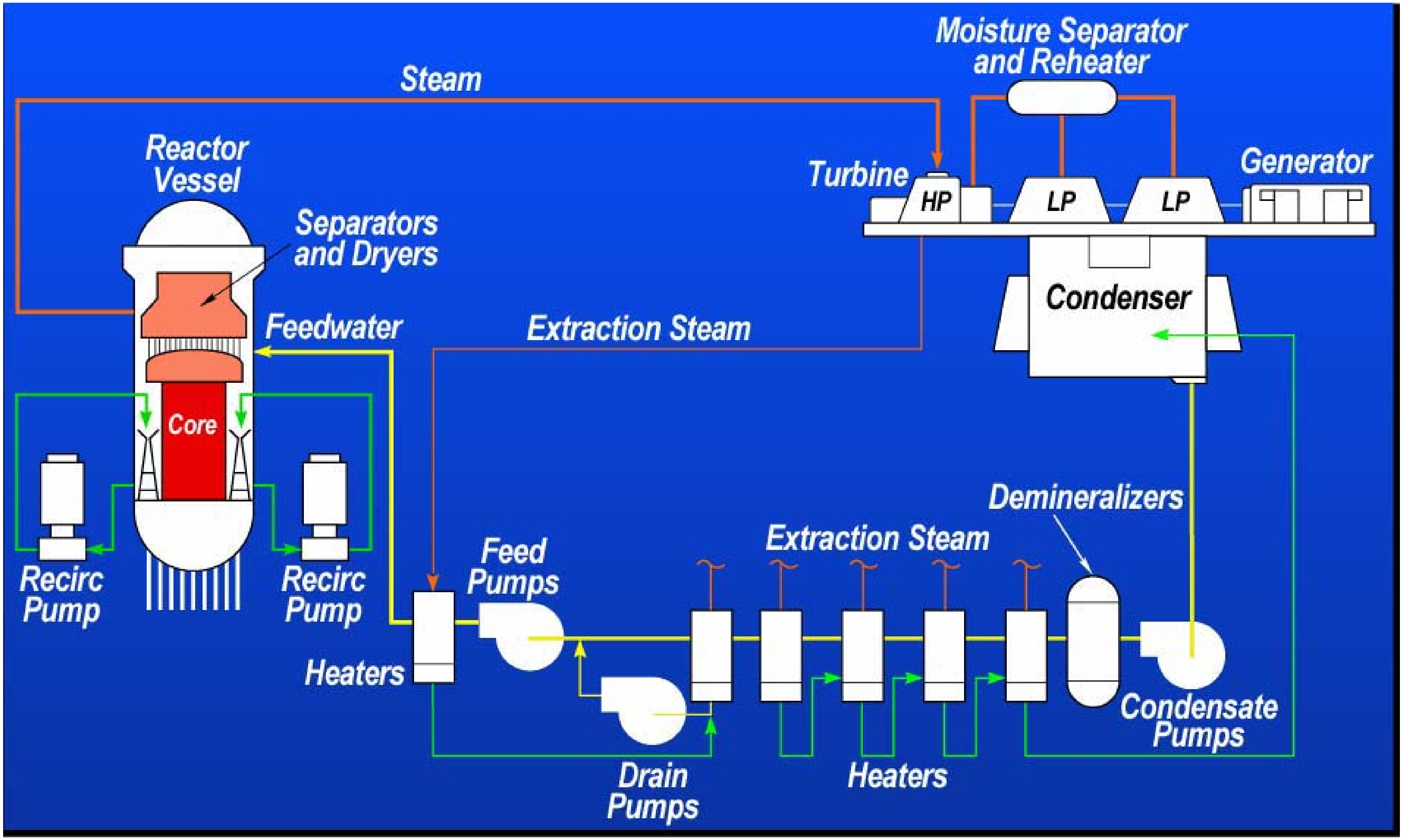
Main flow diagram unit 3—4 PWR 915 MW

ABWR Control Room

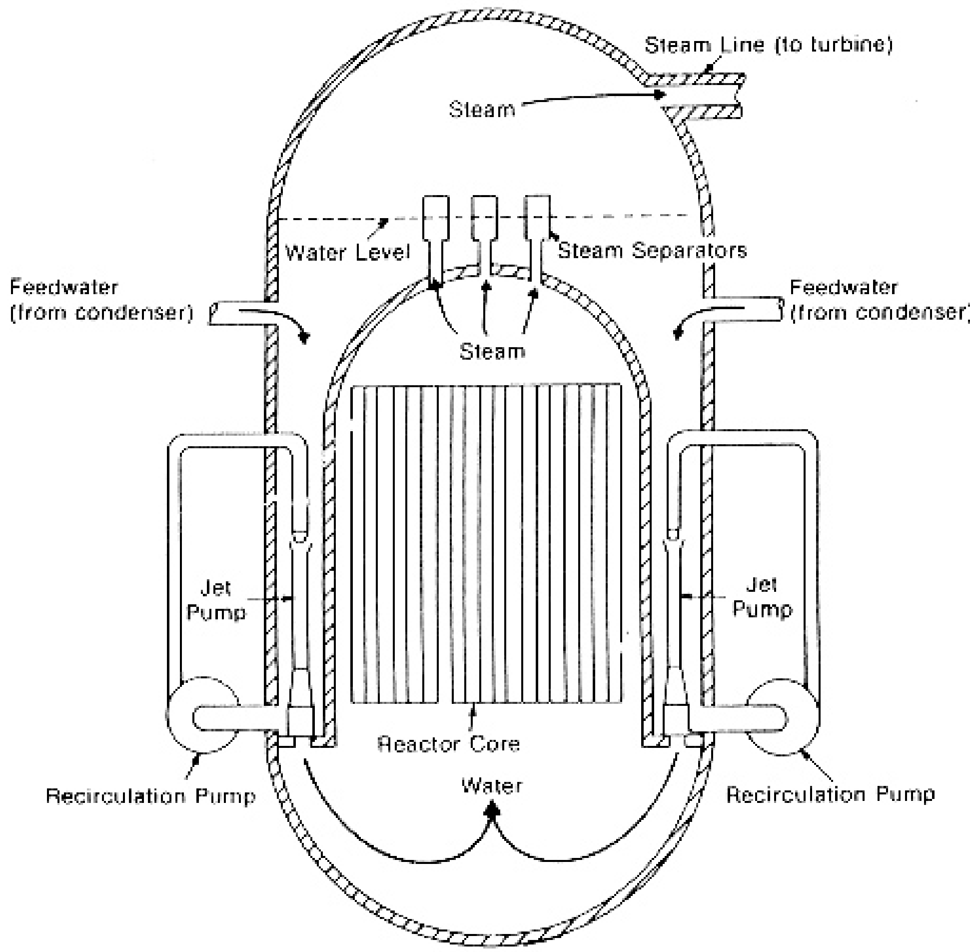


Boiling Water Reactors

BWR Power Cycle



Schematic Arrangement of a BWR



A.V. Nero, Jr., *A Guidebook to Nuclear Reactors*, 1979

BWR Fuel Assembly

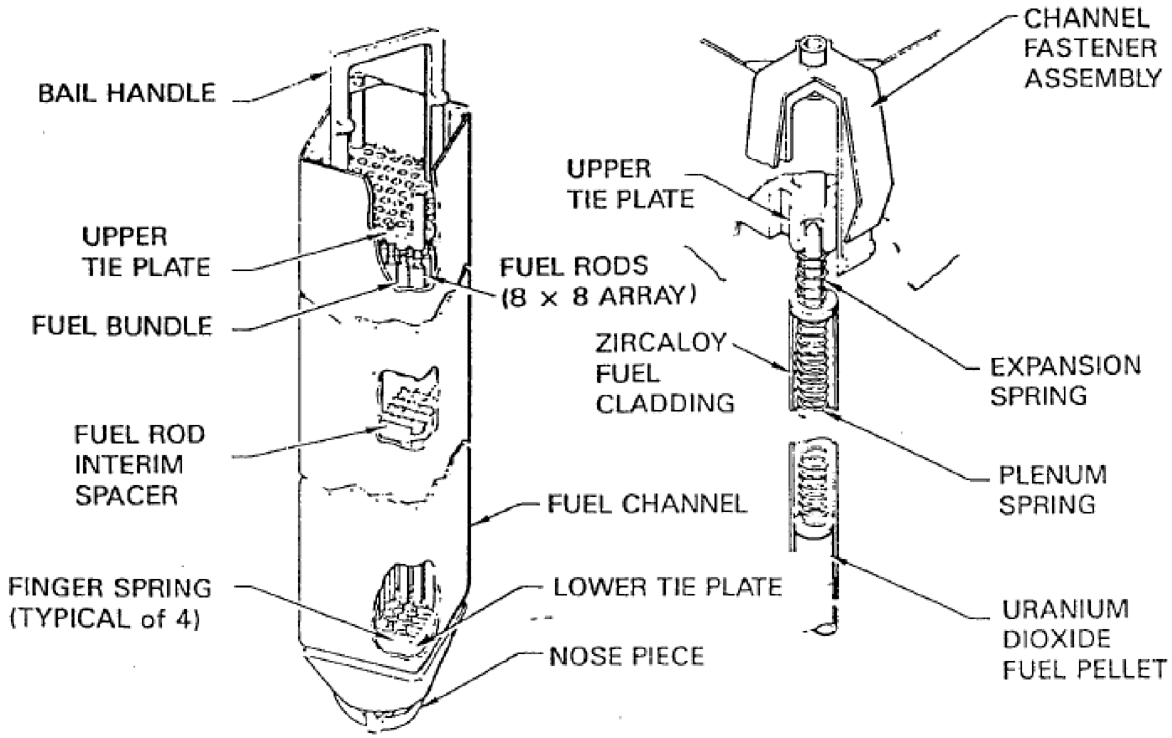
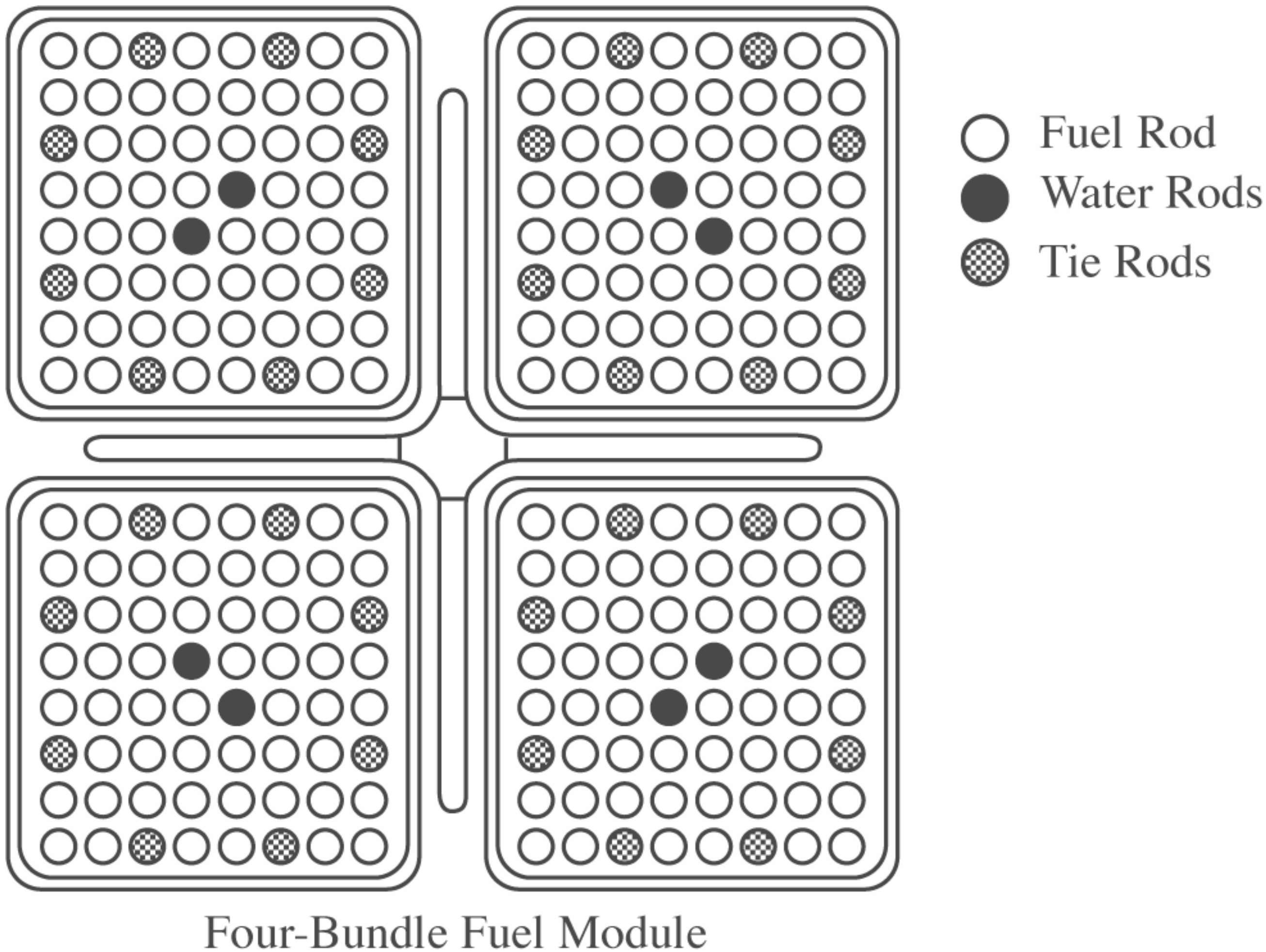


FIGURE 1-6
Fuel assembly for a representative boiling-water reactor. (Adapted courtesy of General Electric Company.)

BWR Core Lattice

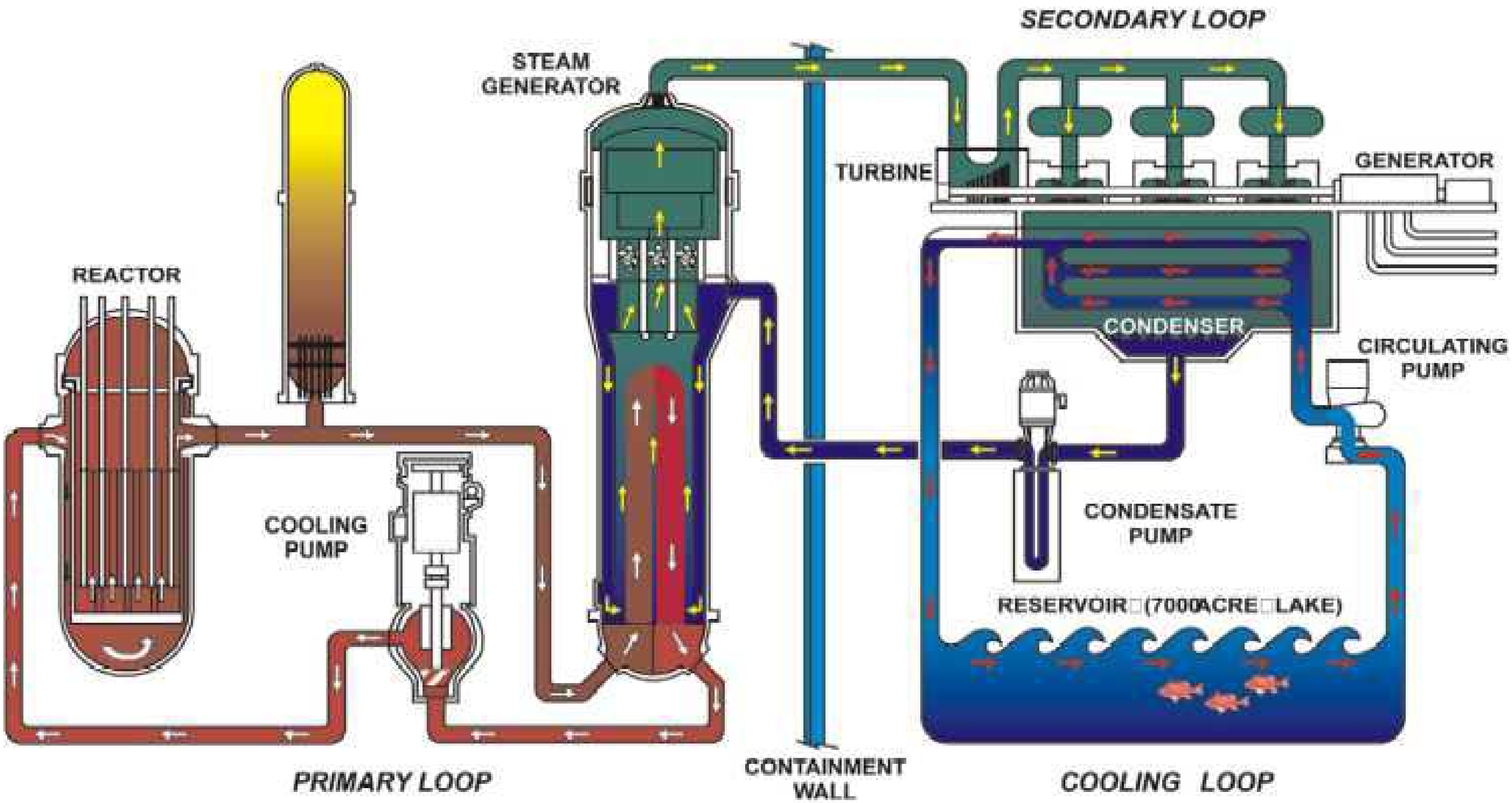


"BWR/6: General Description of a BWR," GE, 1980.

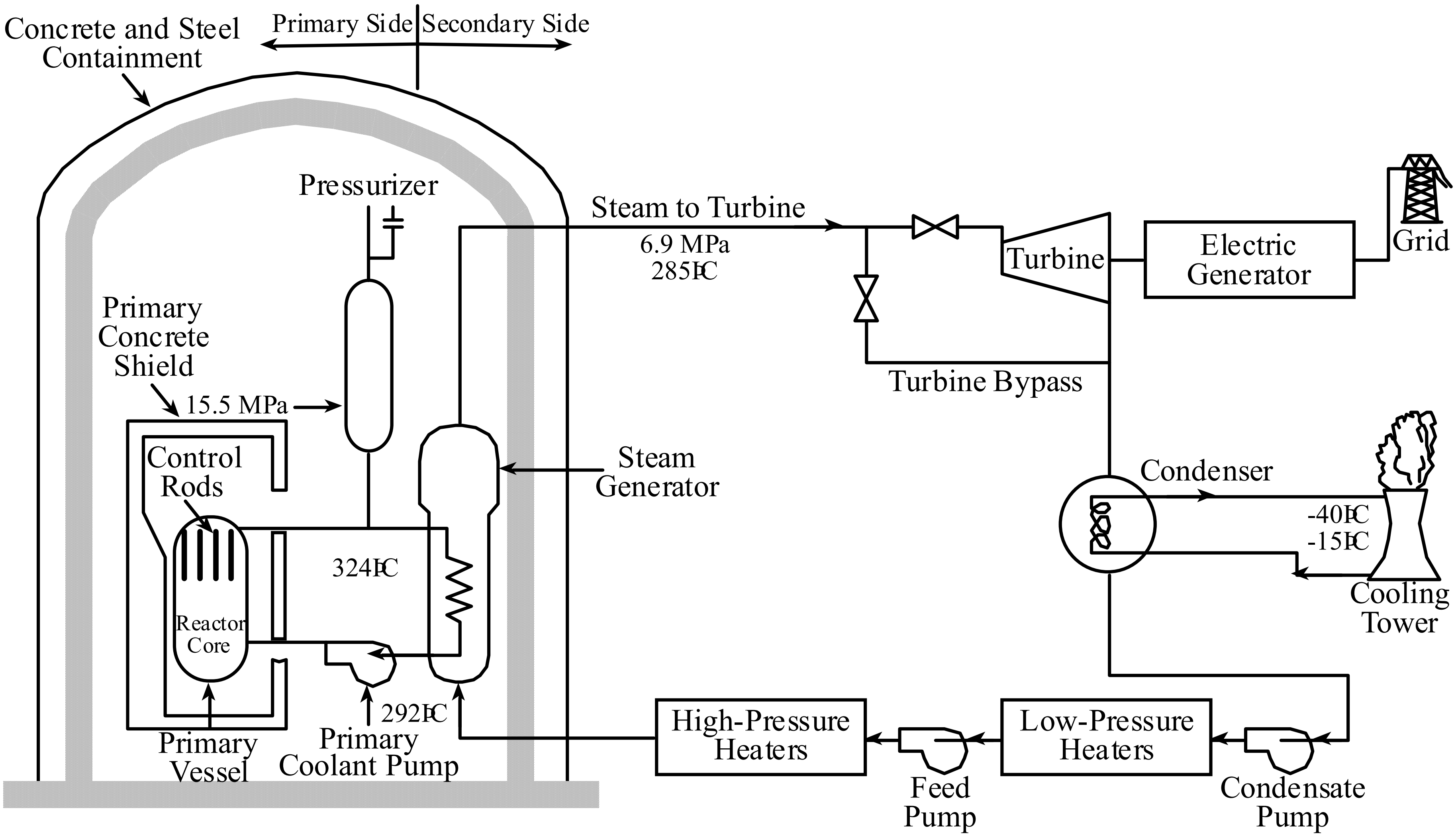
Pilgrim Nuclear Plant

Pressurized Water Reactors

Schematic of Pressurized Water Reactor

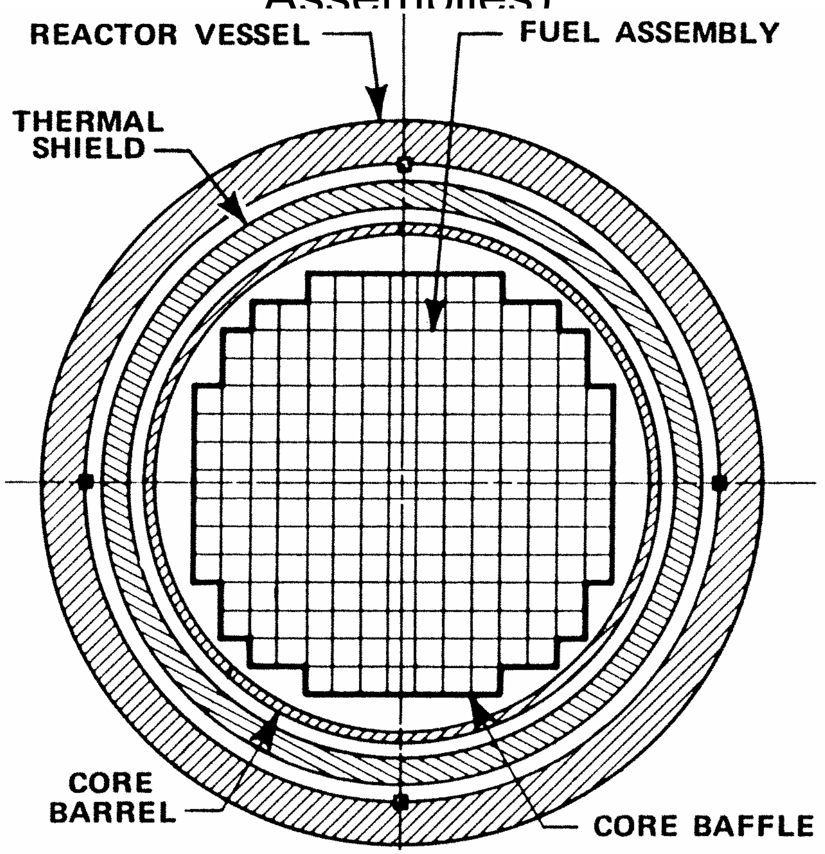


Pressurized Water Reactor Schematic



Typical Four-Loop Reactor Core

Cross Section (193 Fuel Assemblies)

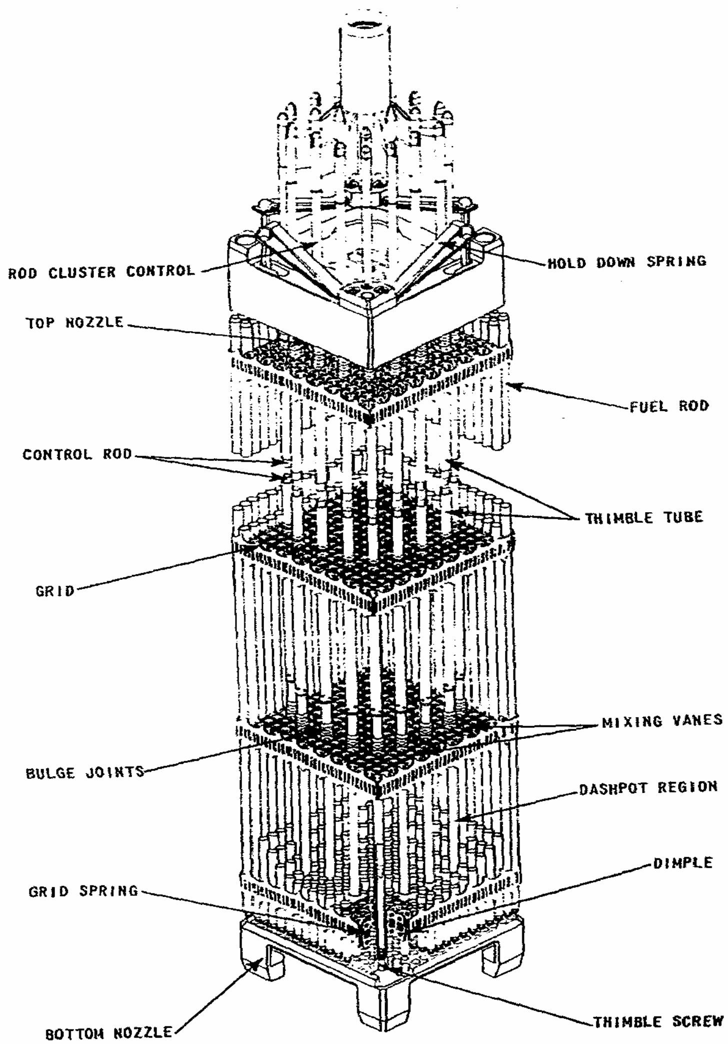


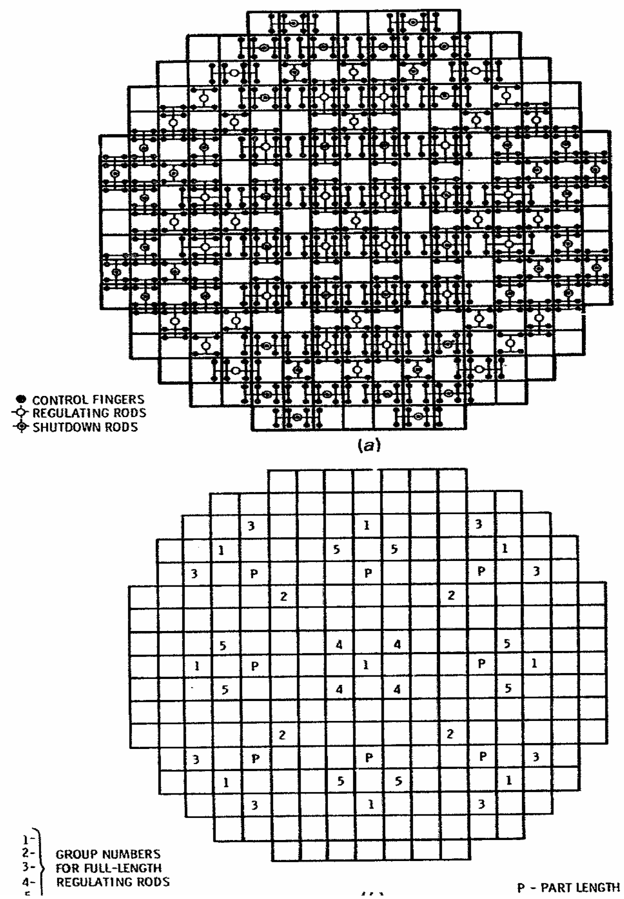
Parameters

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

PWR Fuel Assembly



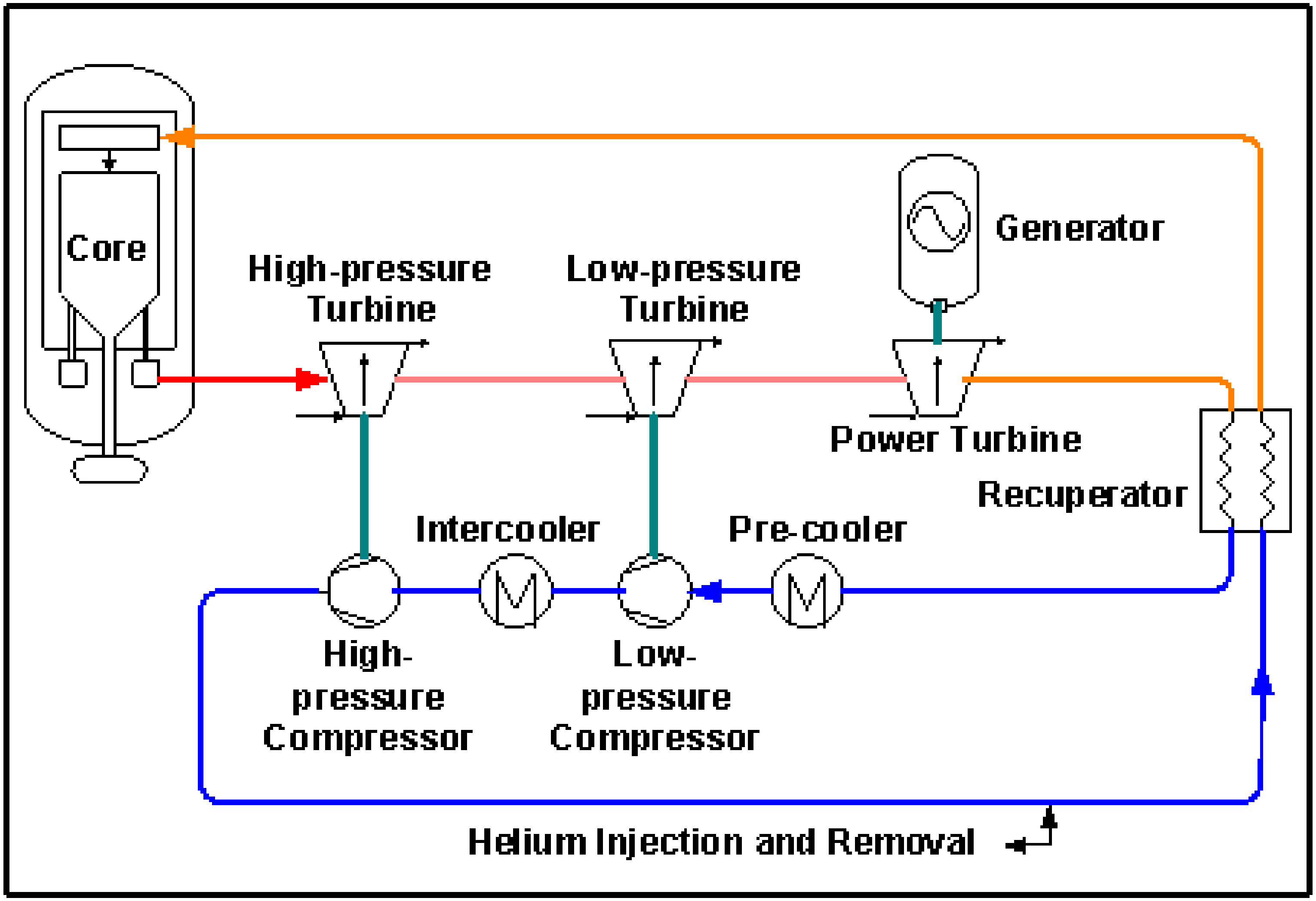


The Byron plant (photo courtesy Commonwealth Edison) is typical of a large US Pressurized Water Reactor plant. Each reactor is 1105 MWe and they came into commercial service in 1985 and 1987 respectively.

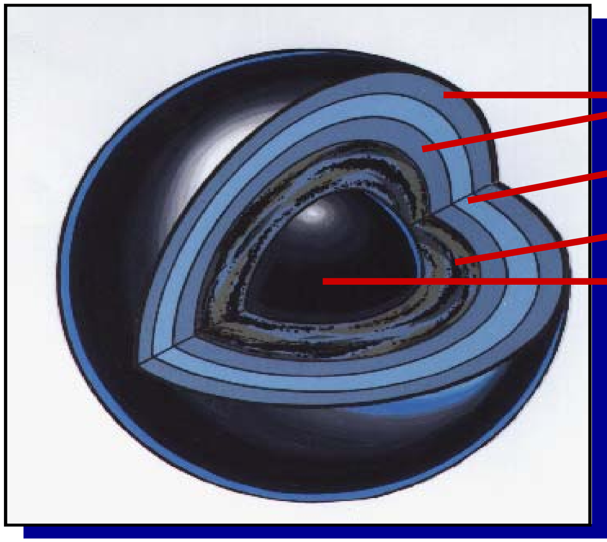
Gas Cooled Reactors

Fort St. Vrain - 330 MWe

Power Cycle - Brayton



Ceramic Fuel



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

PARTICLES

COMPACTS

FUEL ELEMENTS

L-029(5)
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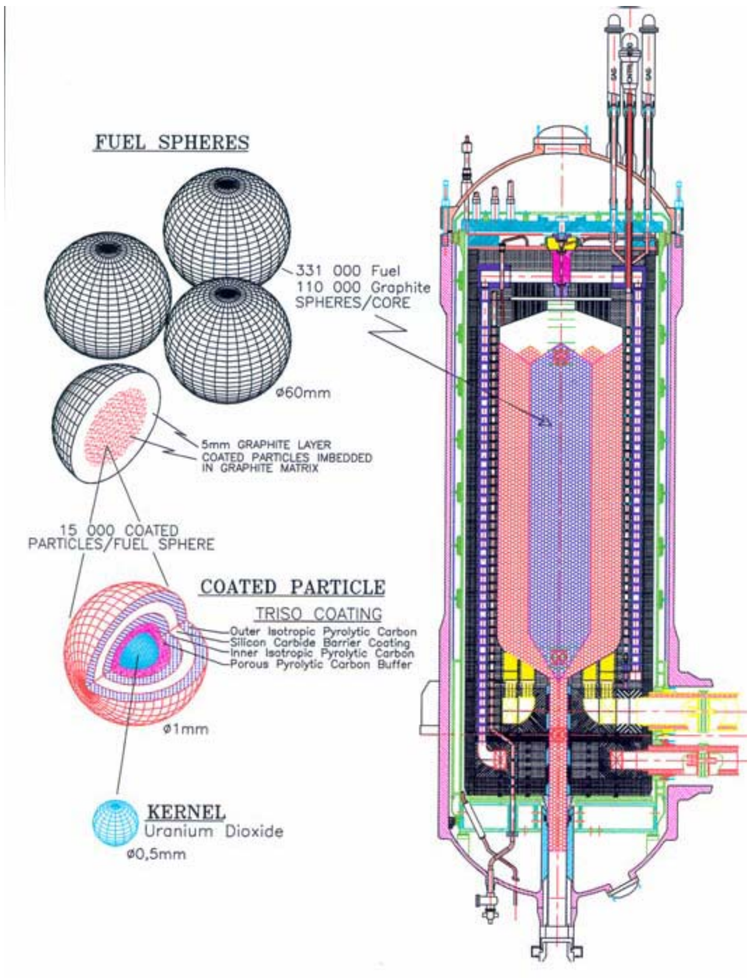
GENERAL ATOMICS

Modular Pebble Bed Reactor



Thermal Power	**250 MW**
Core Height	**10.0 m**
Core Diameter	**3.5 m**
Fuel	**UO_2**
Number of Fuel Pebbles	**360,000**
Microspheres/Fuel Pebble	**11,000**
Fuel Pebble Diameter	**60 mm**
Microsphere Diameter	**~ 1mm**
Coolant	**Helium**

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.

Reading and Homework Assignment

1. Read Knief Chapter 1

   Problems: 1.9, 1.10, 1.12

2. Read Knief Chapter 2

   Problems: 2.7, 2.12

3. Read Knief Chapter 4