Special Topics: Computers & Nuclear Energy

Reactor Concepts

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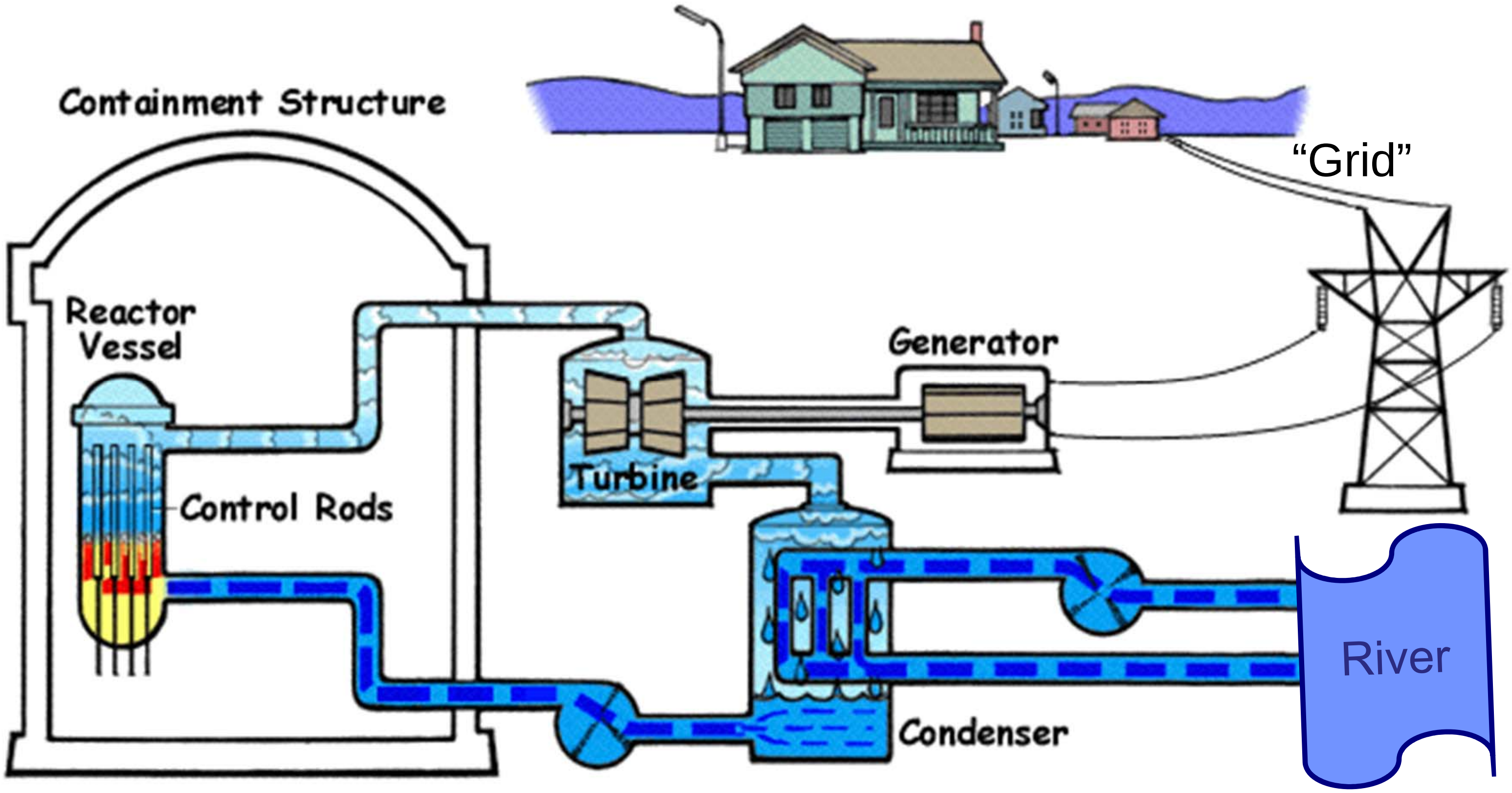
September 1, 2011

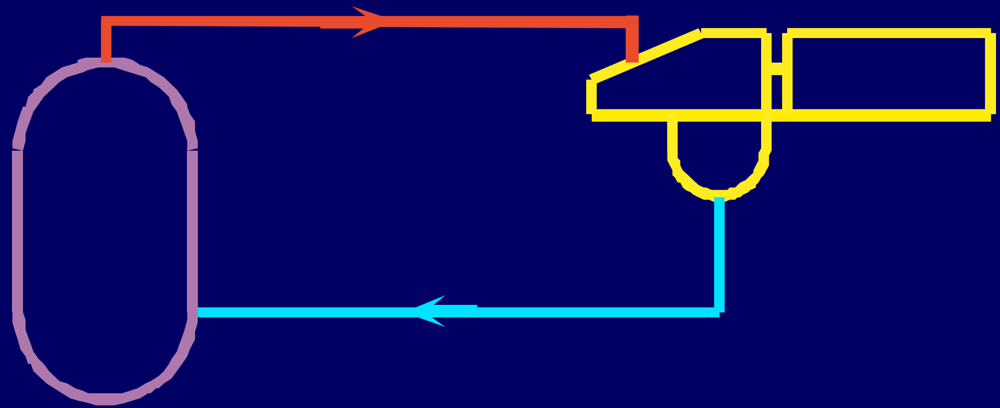
Commercial Nuclear Power Plant Design Categories

- Dual-cycle plants
  - Two, physically independent, fluid systems which separate the high pressure radioactive reactor coolant (primary system) from the low pressure non-radioactive steam/condensate systems (secondary system)
    - Pressurized Water Reactor
- Direct-cycle plants
  - Fundamentally different from dual-cycle plants; generate steam in the reactor and pass the steam directly to the turbine
    - Boiling Water Reactor



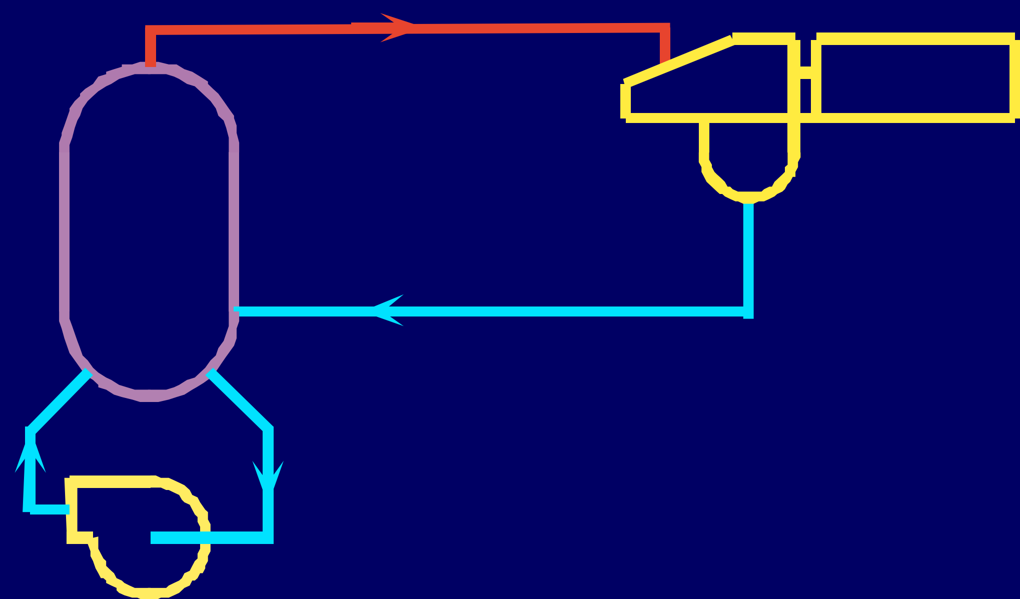
BOILING WATER REACTOR SYSTEMS

HUMBOLDT BAY (BWR/1)
Simplified BWR



NATURAL CIRCULATION, DIRECT CYCLE

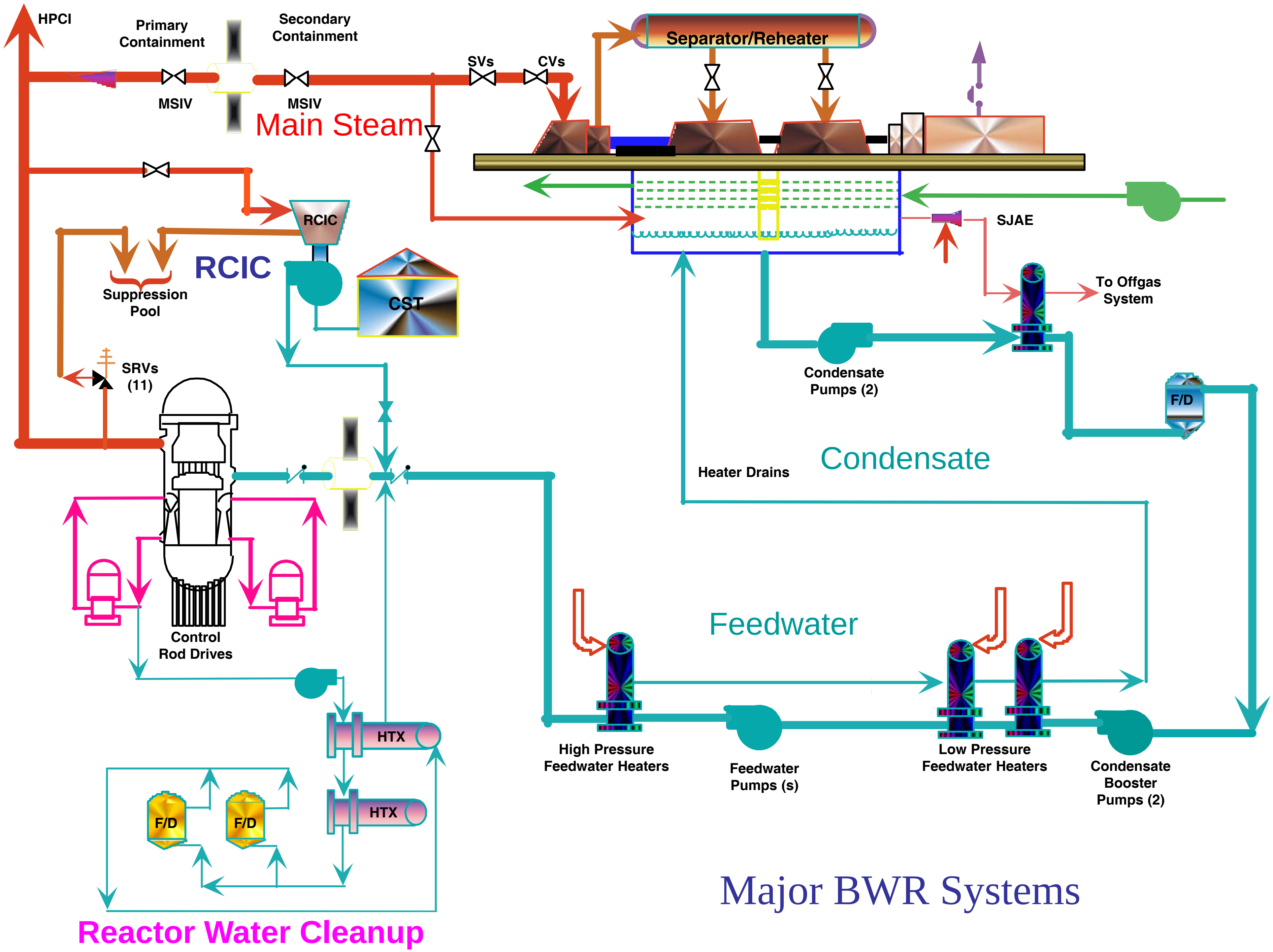
BIG ROCK POINT (BWR/1)
OYSTER CREEK (BWR/2)
DRESDEN 2&3 (BWR/3)
BROWNS FERRY (BWR/4)
LASALLE 1&2 (BWR/5)
GRAND GULF 1&2 (BWR/6)
Advanced BWR



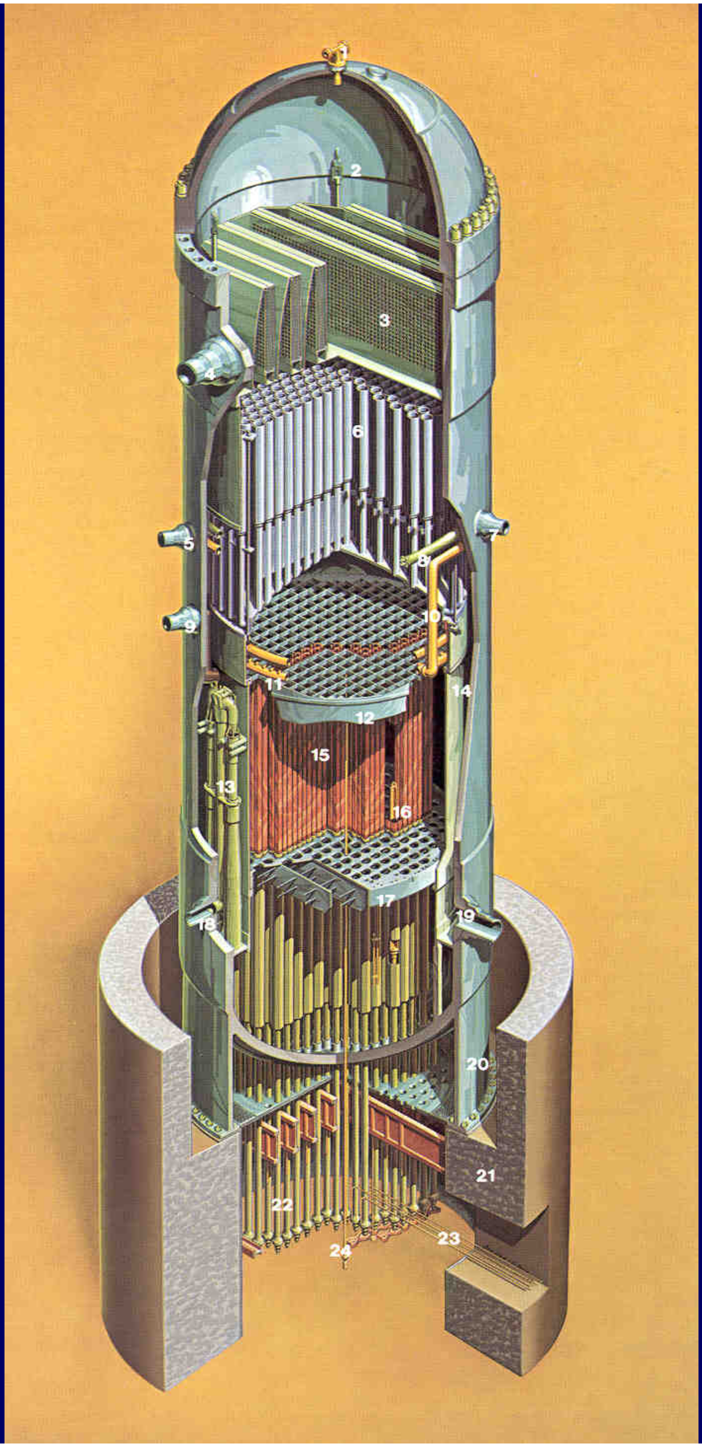
FORCE CIRCULATION, DIRECT CYCLE

GE/BWR Product Lines

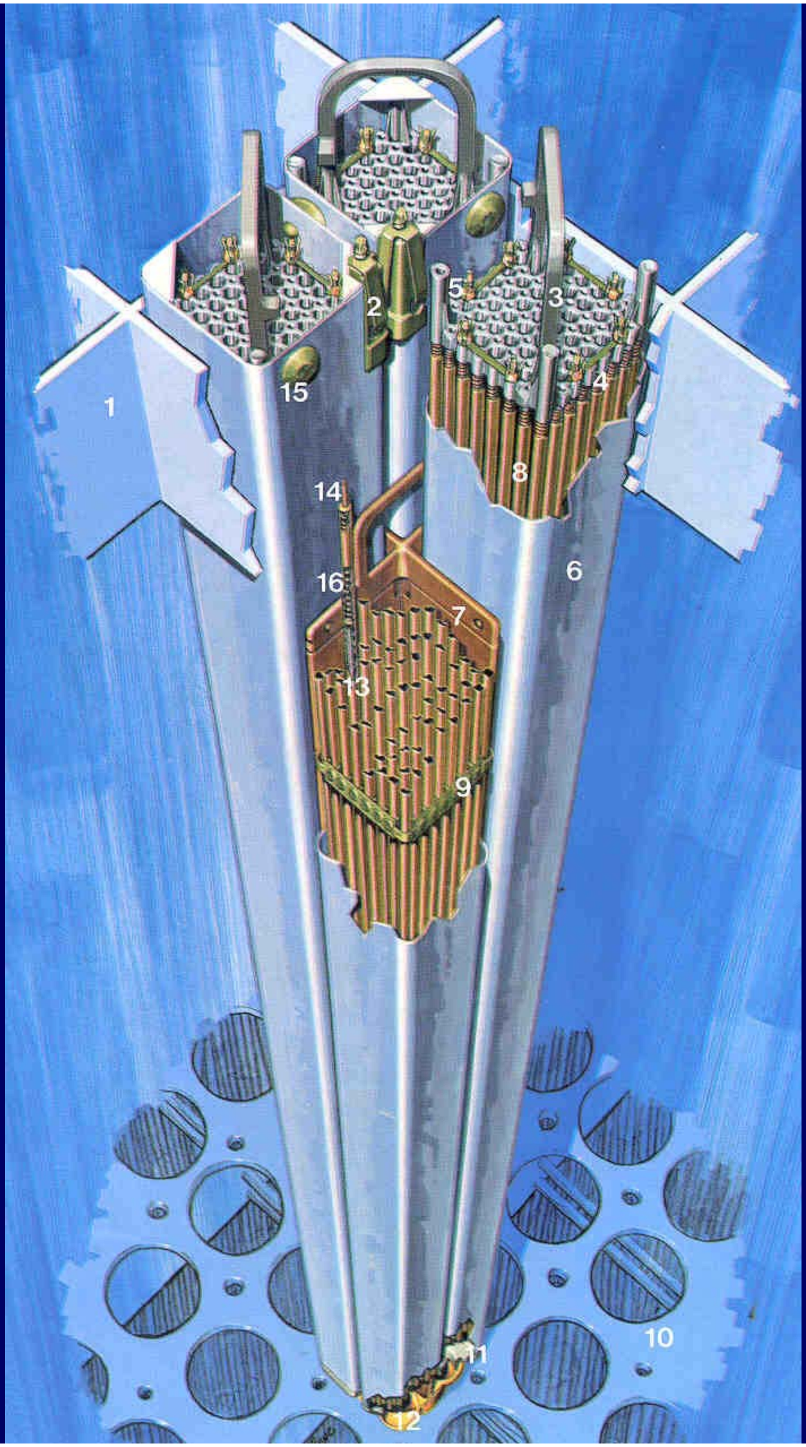
Product Line	Year	Characteristic
BWR/1	1955	Dresden 1, Big Rock Point, Humboldt Bay, KRB - Initial commercial BWRs - First internal steam separation
BWR/2	1963	Oyster Creek - The first turnkey plant - Elimination of dual cycle
BWR/3	1965	Dresden 2 - The first jet pump application - Improved emergency core cooling system
BWR/4	1966	Browns Ferry - Increased power density 10%
BWR/5	1969	LaSalle - Improved Recirculation System performance - Improved ECCS performance - Mark II Containment
BWR/6	1972	Grand Gulf - Improved core performance - Improved rod control system - Mark III containment



Major BWR Systems



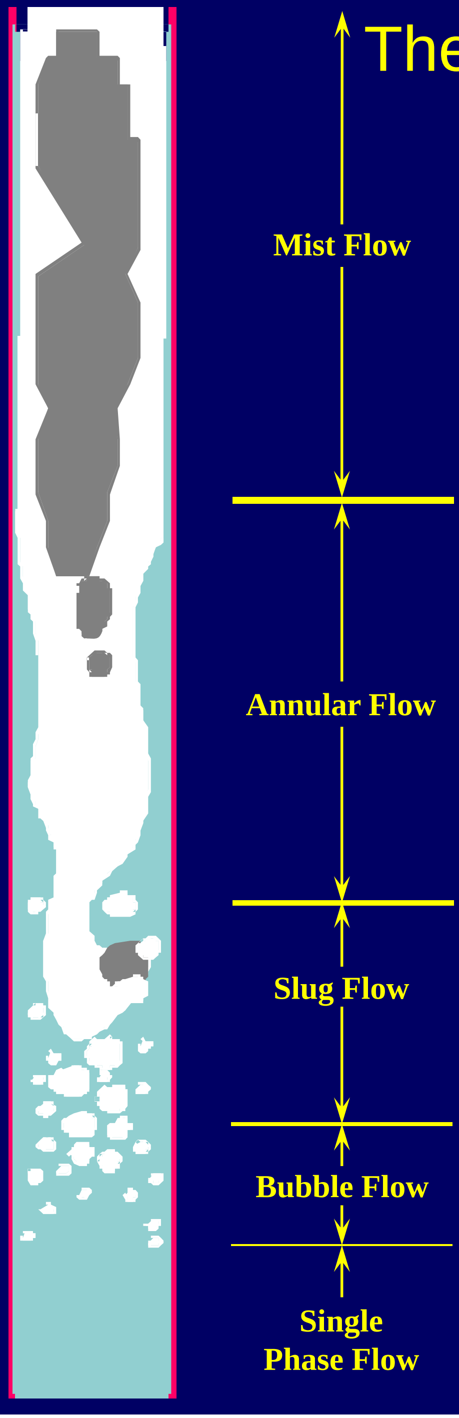
1. Vent and Head Spray
2. Steam Dryer Lifting Lug
3. Steam Dryer Assembly
4. Steam Outlet
5. Core Spray Inlet
6. Steam Separator Assembly
7. Feedwater Inlet
8. Feedwater Sparger
9. LPCI Injection
10. Core Spray Line
11. Core Spray Sparger
12. Top Guide
13. Jet Pump Assembly
14. Core Shroud
15. Fuel Assembly
16. Control Blade
17. Core Plate
18. Jet Pump/recirculation Inlet
19. Recirculation Water Outlet
20. Vessel Support
21. Shield Wall
22. Control Rod Drives
23. Control Rod Drive Hydraulic Lines
24. In-Core Flux Monitors



BWR Control Cell

1. Top Guide
2. Channel Fastener
3. Upper Tie Plate
4. Expansion Spring
5. Locking Tab
6. Channel
7. Control Rod
8. Fuel Rod
9. Spacer
10 Core Plate Assembly
11. Lower Tie Plate
12. Fuel Support Piece
13. Fuel Pellets
14. End Plug
15. Channel Spacer
16. Plenum Spring

The water boils as it flows up a BWR fuel assembly.

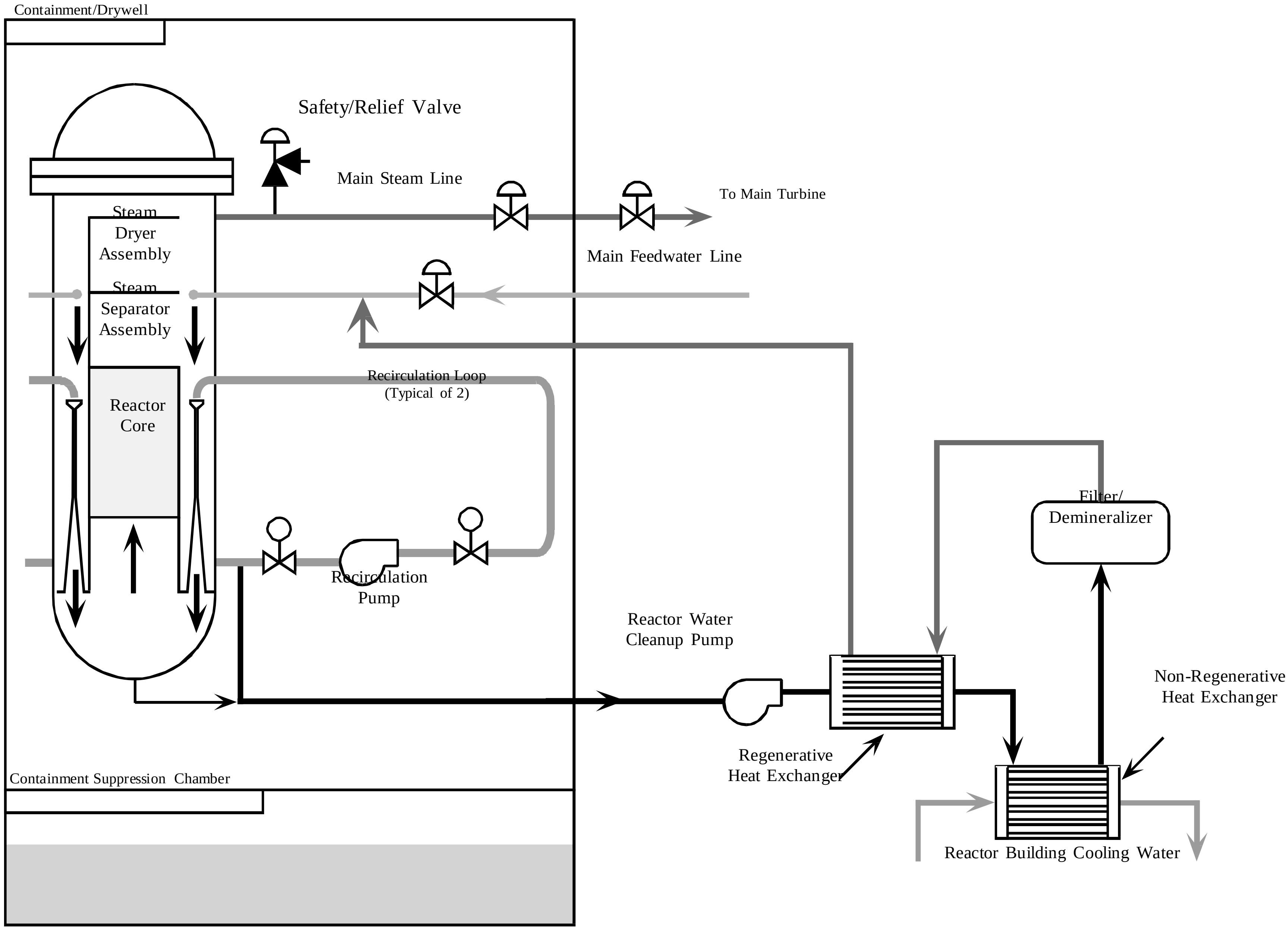


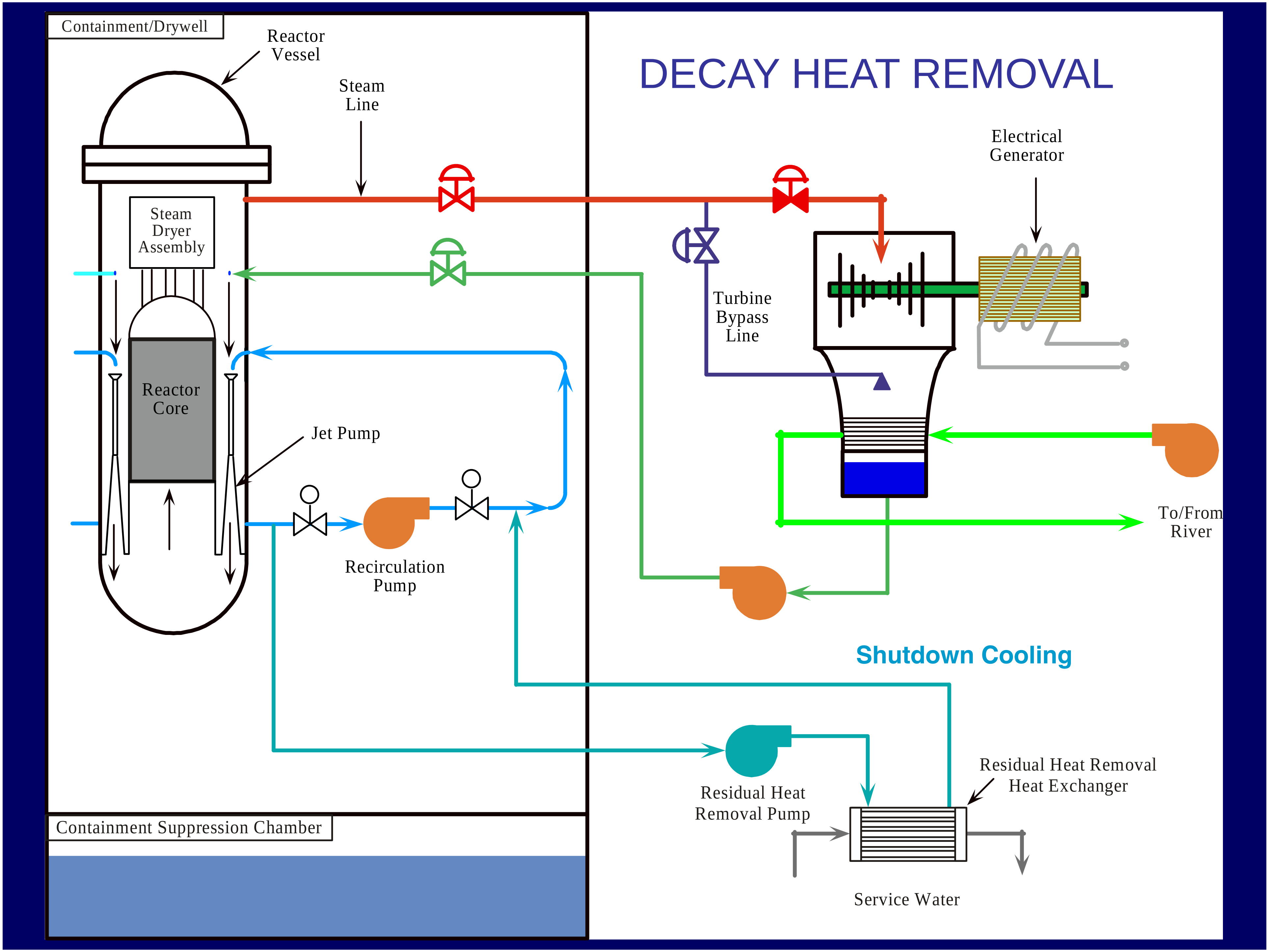
At the outlet of the highest powered fuel bundle, steam may fill most of the bundle flow area between the fuel rods with a thin film of water adhering to the fuel rod surfaces. Heat transfer from the fuel pin to the water is still by nucleate boiling.

As the two phase flow, steam and water, traverses up the bundle, more bubbles are added, forming bigger bubbles until annular flow is achieved.

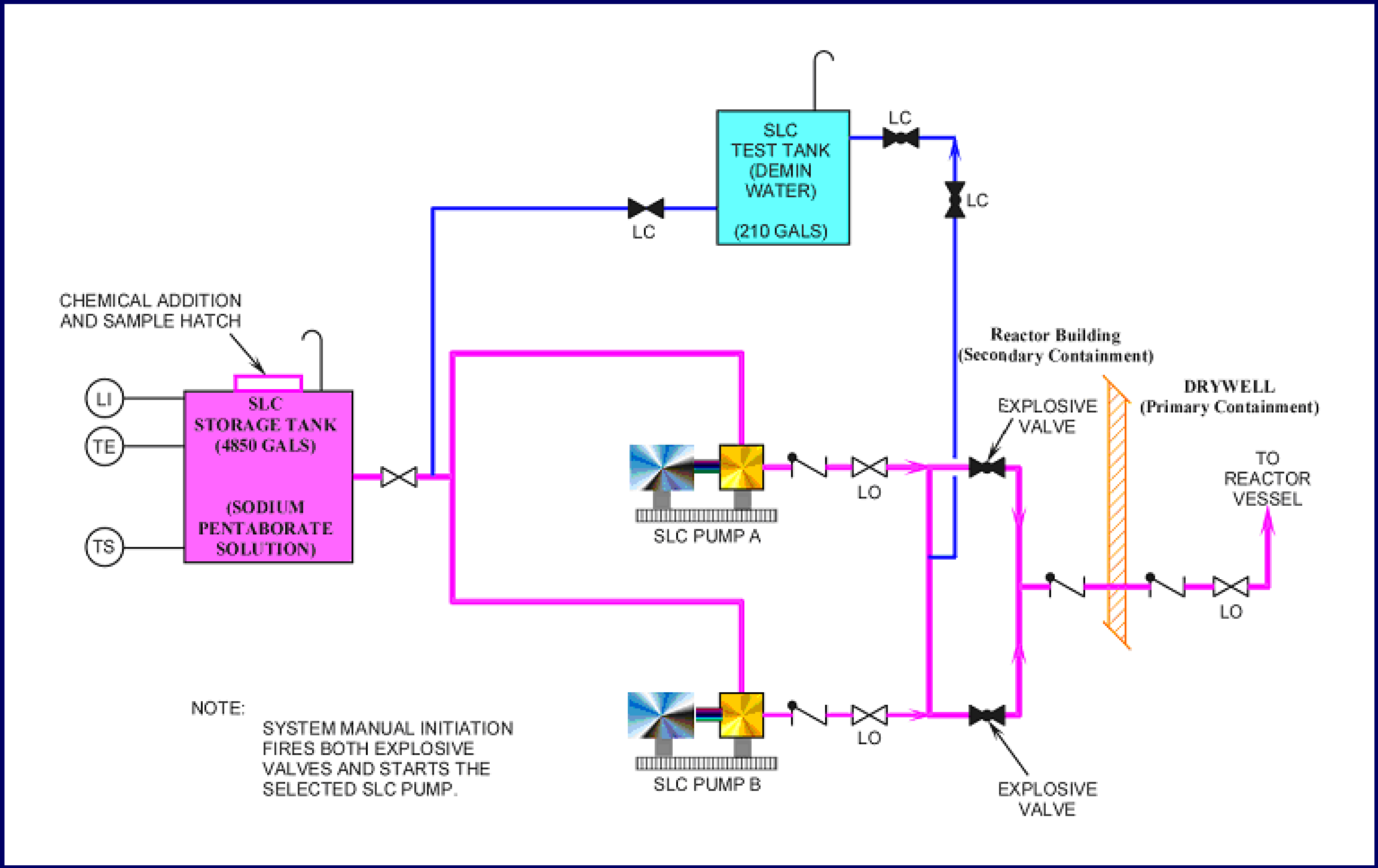
A point will be reached where the bulk of the coolant is at saturation temperature, and the bubbles will no longer collapse in the coolant as they are swept away. The bubbles begin to exist separately throughout the bulk coolant, causing a significant steam fraction to be present in the coolant.

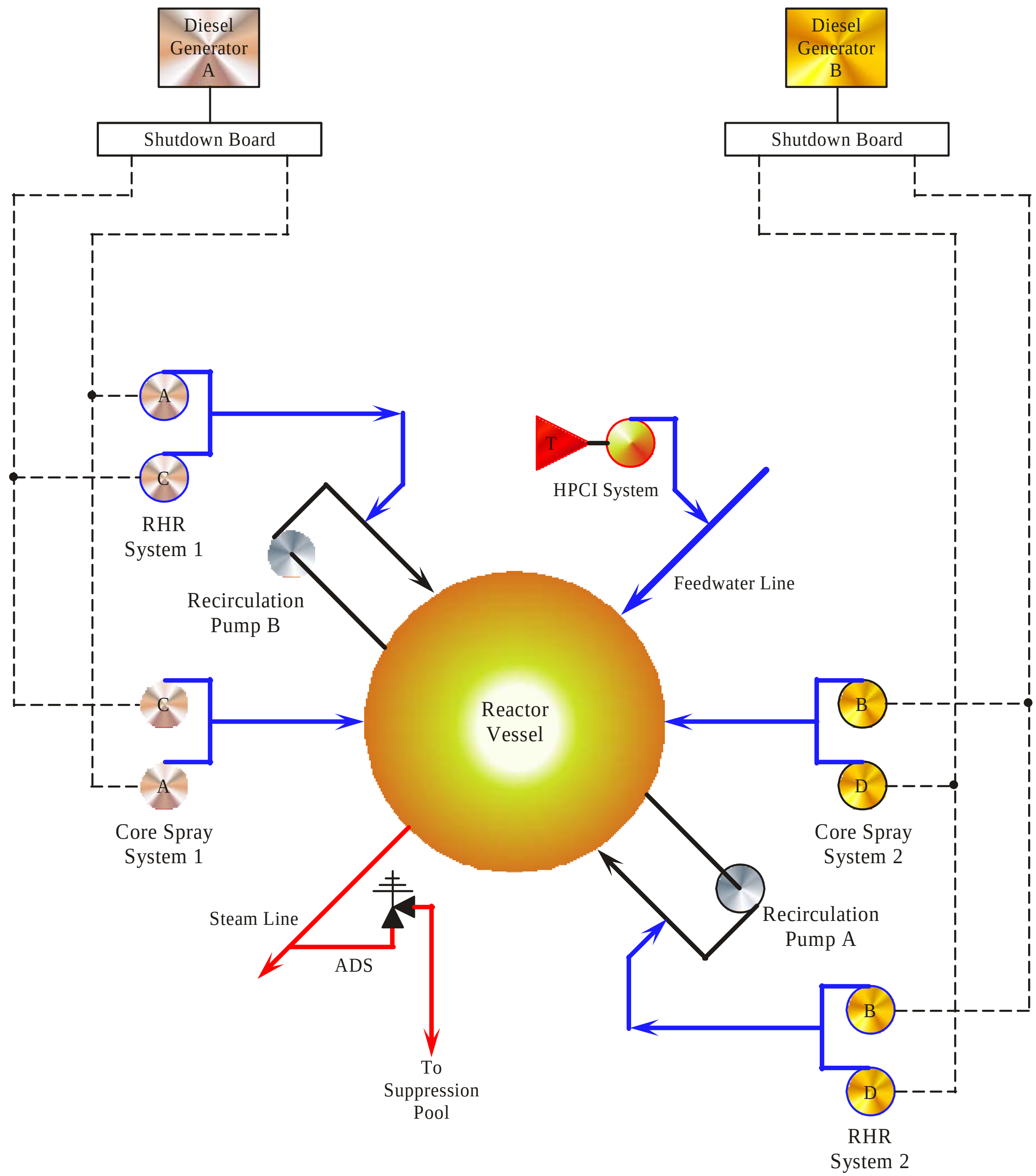
As coolant enters the core, it is a slightly subcooled liquid. As the coolant gains energy from the fuel, its temperature increases until nucleate boiling or bubble formation begins.


Containment/Drywell
Safety/Relief Valve
Main Steam Line
To Main Turbine
Steam Dryer Assembly
Main Feedwater Line
Steam Separator Assembly
Recirculation Loop (Typical of 2)
Reactor Core
Filter/ Demineralizer
Recirculation Pump
Reactor Water Cleanup Pump
Non-Regenerative Heat Exchanger
Regenerative Heat Exchanger
Containment Suppression Chamber
Reactor Building Cooling Water

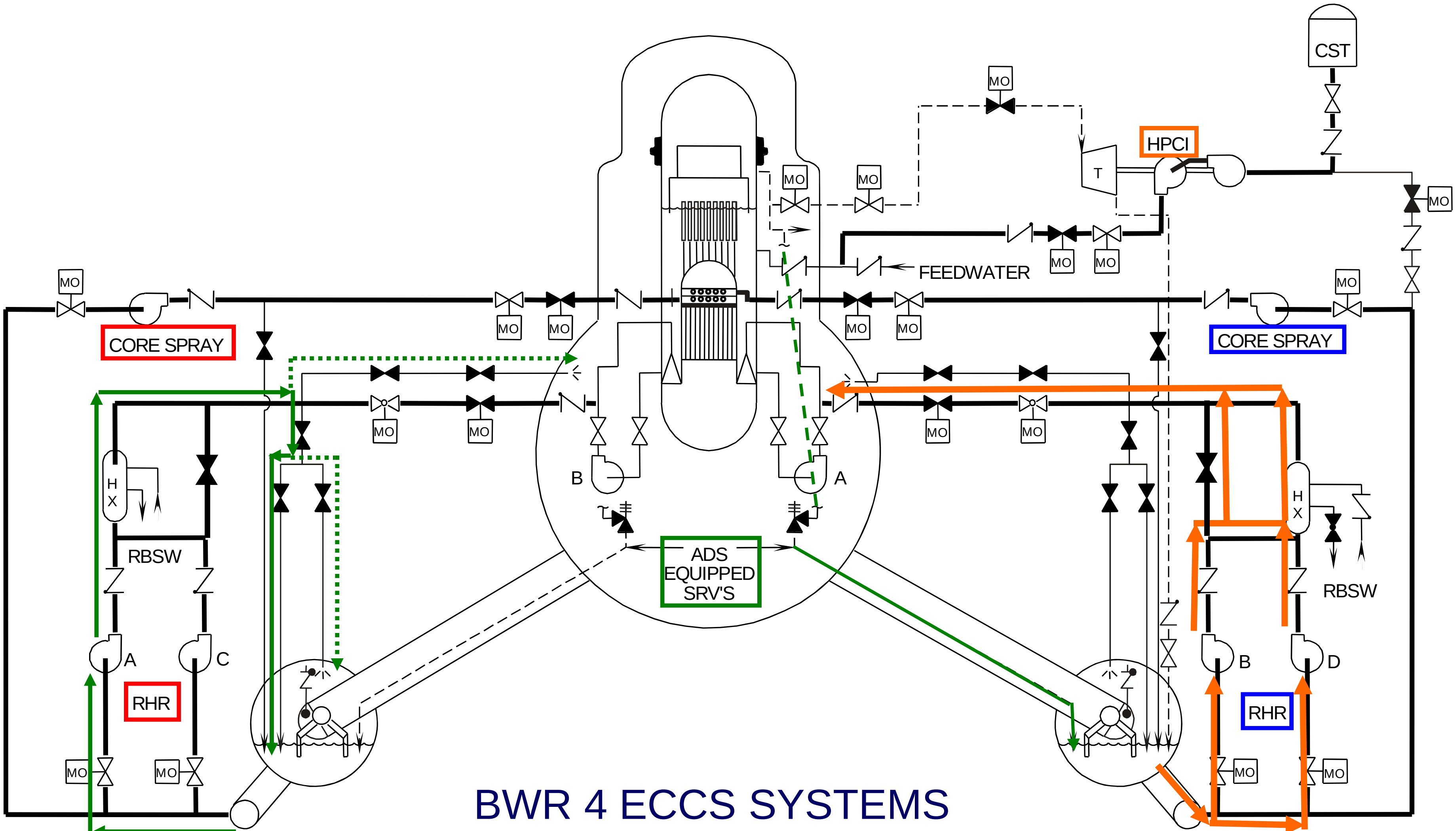

DECAY HEAT REMOVAL
Containment/Drywell
Reactor Vessel
Steam Line
Steam Dryer Assembly
Reactor Core
Jet Pump
Recirculation Pump
Electrical Generator
Turbine Bypass Line
To/From River
Shutdown Cooling
Residual Heat Removal Pump
Residual Heat Removal Heat Exchanger
Service Water
Containment Suppression Chamber

Standby Liquid Control System





Emergency Core Cooling System Network



BWR 4 ECCS SYSTEMS

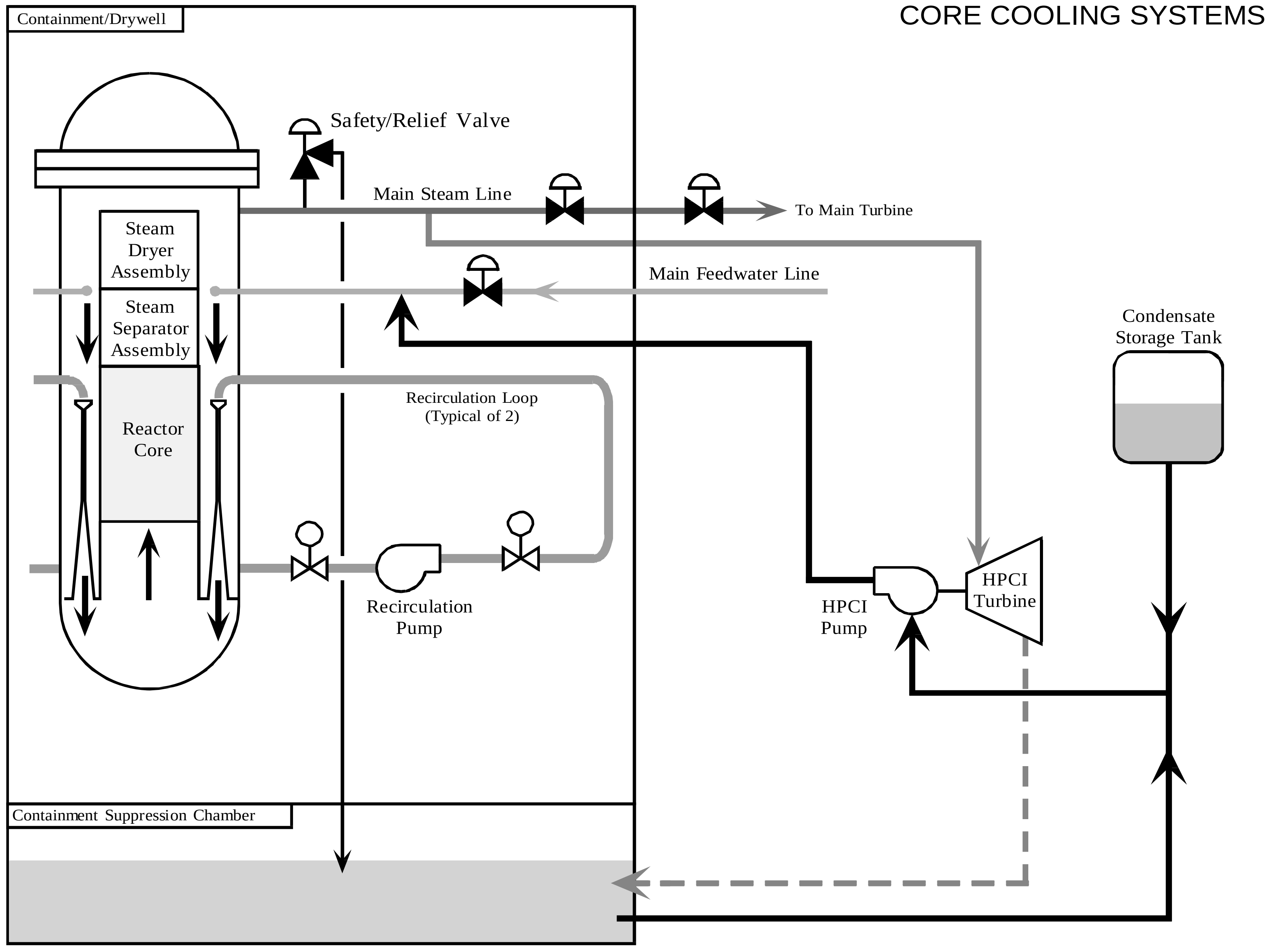
RHR Modes: Shutdown Cooling (on previous slide)

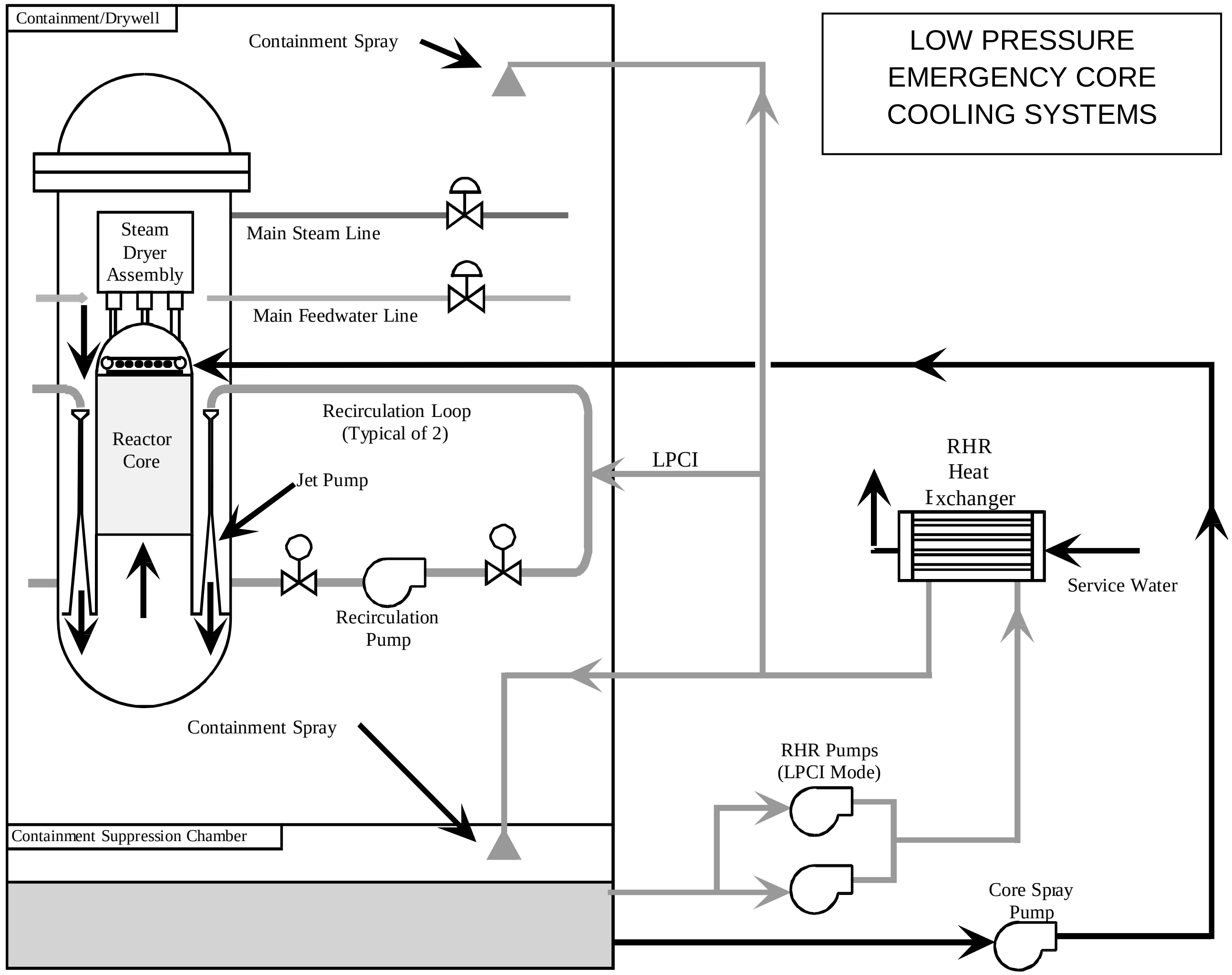
Low Pressure Coolant Injection

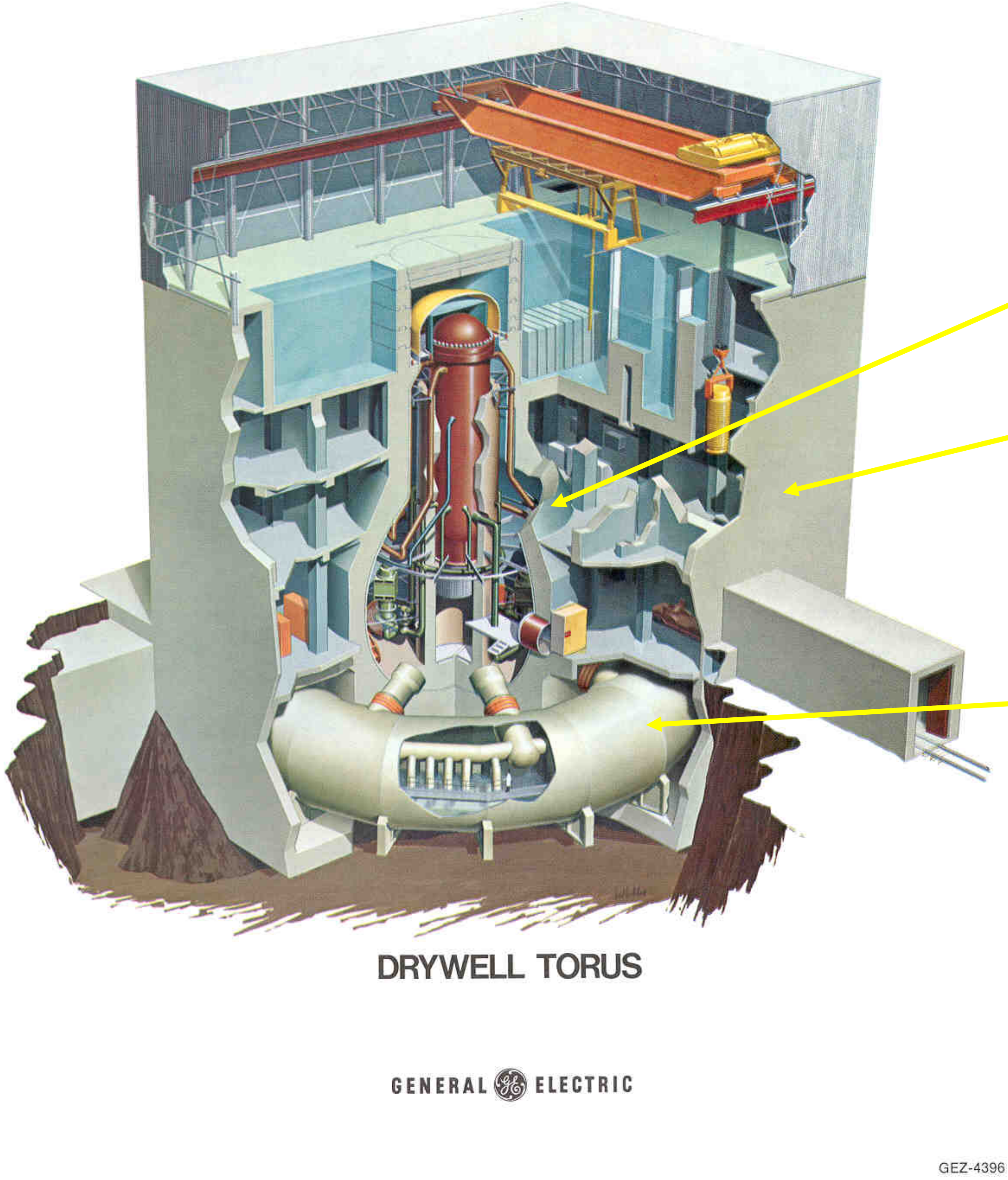
Suppression Pool Cooling

Drywell and Torus Spray

HIGH PRESSURE EMERGENCY CORE COOLING SYSTEMS




LOW PRESSURE
EMERGENCY CORE
COOLING SYSTEMS
Containment/Drywell
Containment Spray
Steam
Dryer
Assembly
Main Steam Line
Main Feedwater Line
Reactor
Core
Recirculation Loop
(Typical of 2)
Jet Pump
LPCI
RHR
Heat
Exchanger
Service Water
Recirculation
Pump
Containment Spray
RHR Pumps
(LPCI Mode)
Containment Suppression Chamber
Core Spray
Pump

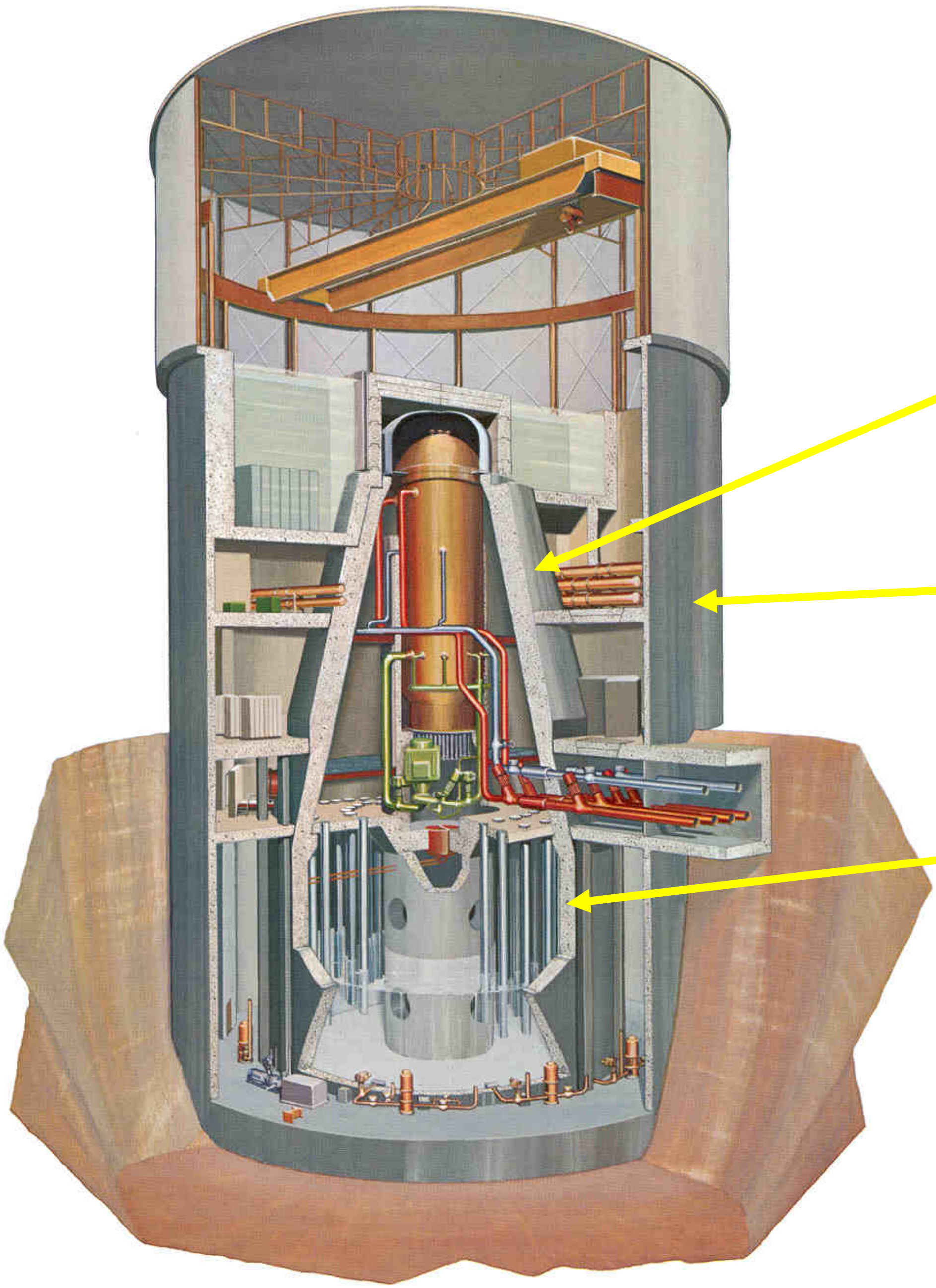


Primary Containment (Drywell)

Secondary Containment (Reactor Building)

Primary Containment (Suppression Chamber)

BWR Mark I Containment



Primary Containment (Drywell)

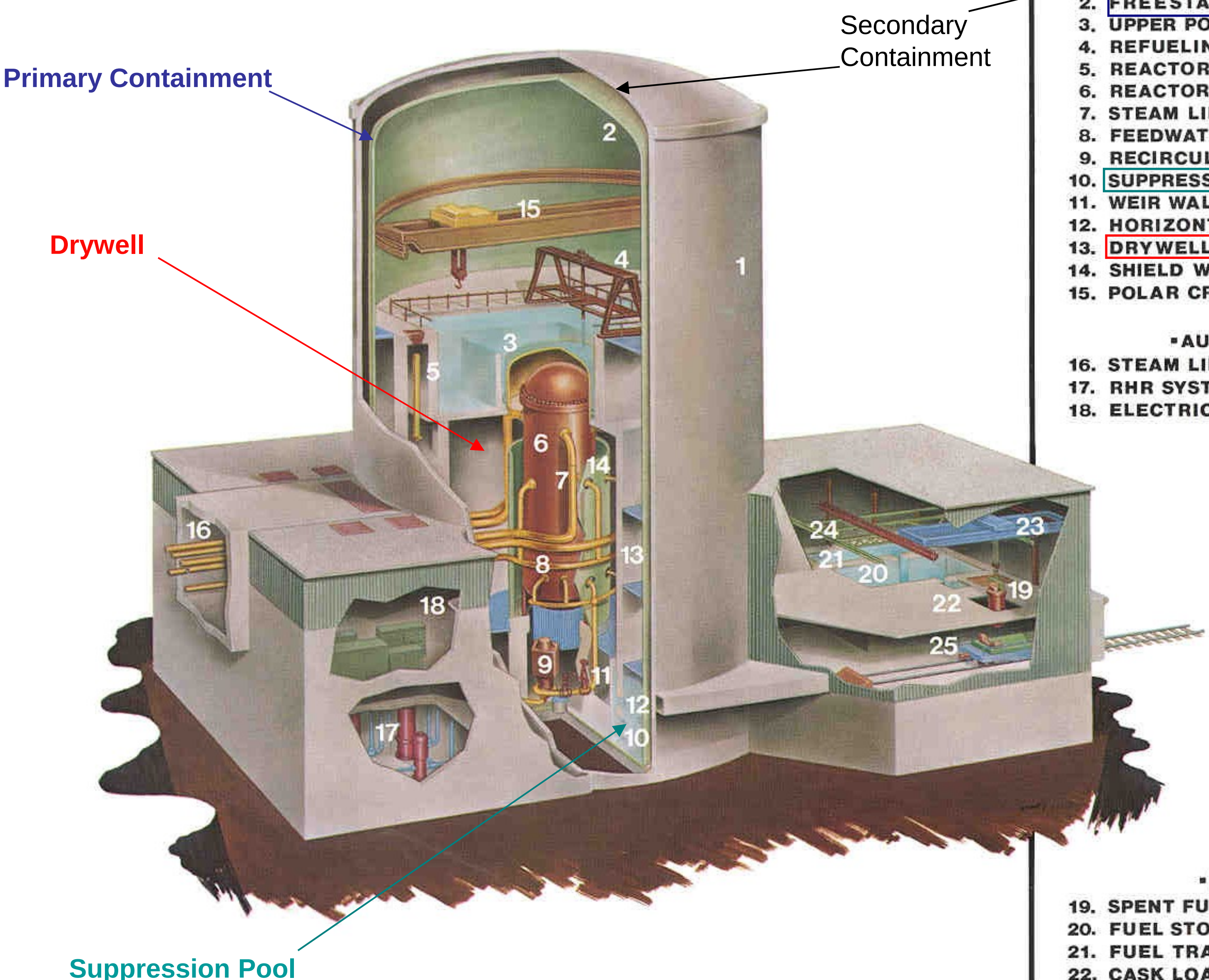
Secondary Containment (Reactor Building)

Primary Containment (Suppression Chamber)

BWR Mark II Containment

GEZ-4370

MARK III CONTAINMENT



▪REACTOR BUILDING▪

1. SHIELD BUILDING
2. FREESTANDING STEEL CONTAINMENT
3. UPPER POOL
4. REFUELING PLATFORM
5. REACTOR WATER CLEANUP
6. REACTOR VESSEL
7. STEAM LINE
8. FEEDWATER LINE
9. RECIRCULATION LOOP
10. SUPPRESSION POOL
11. WEIR WALL
12. HORIZONTAL VENT
13. DRYWELL
14. SHIELD WALL
15. POLAR CRANE

▪AUXILIARY BUILDING▪

16. STEAM LINE TUNNEL
17. RHR SYSTEM
18. ELECTRICAL EQUIPMENT ROOM

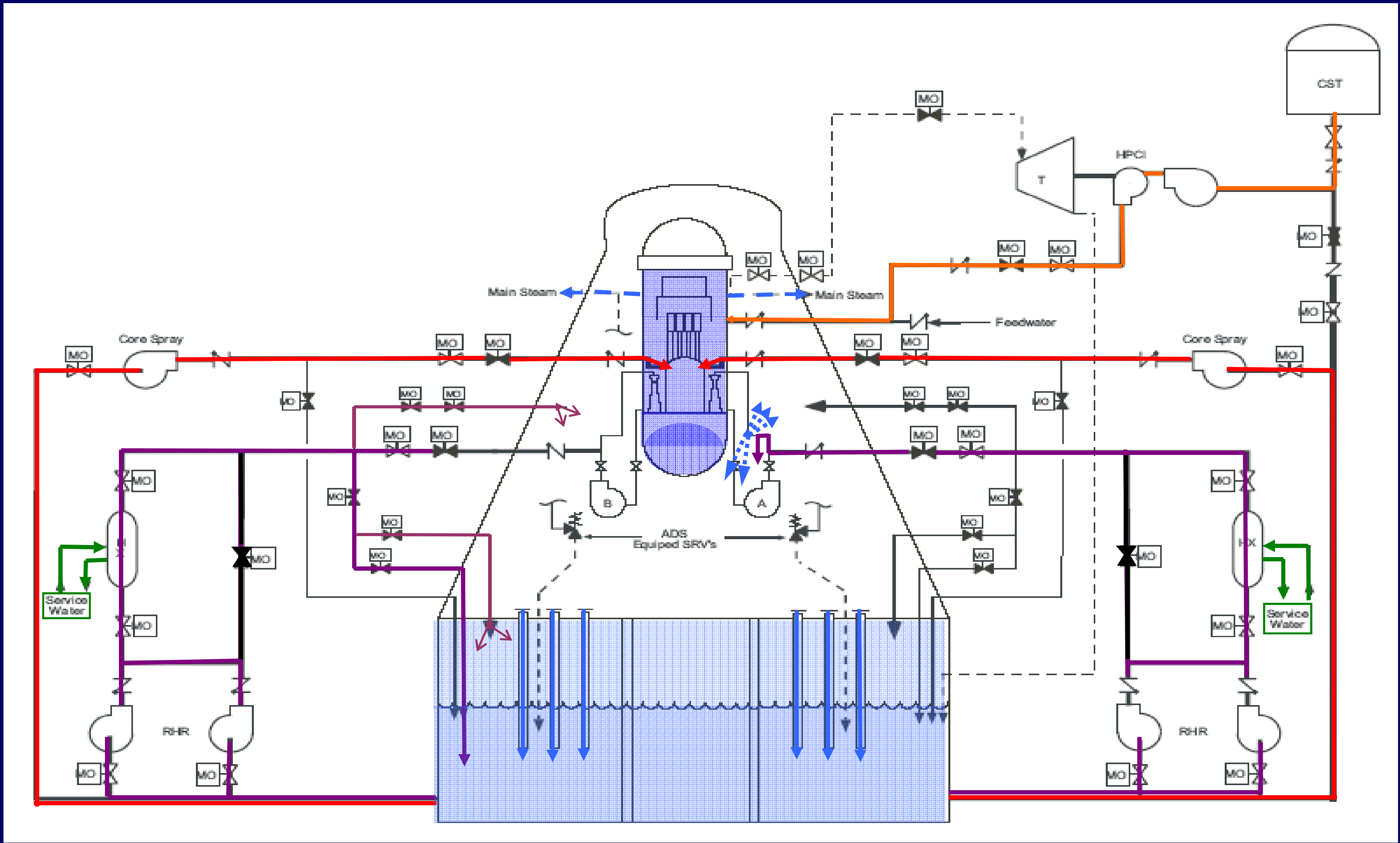
▪FUEL BUILDING▪

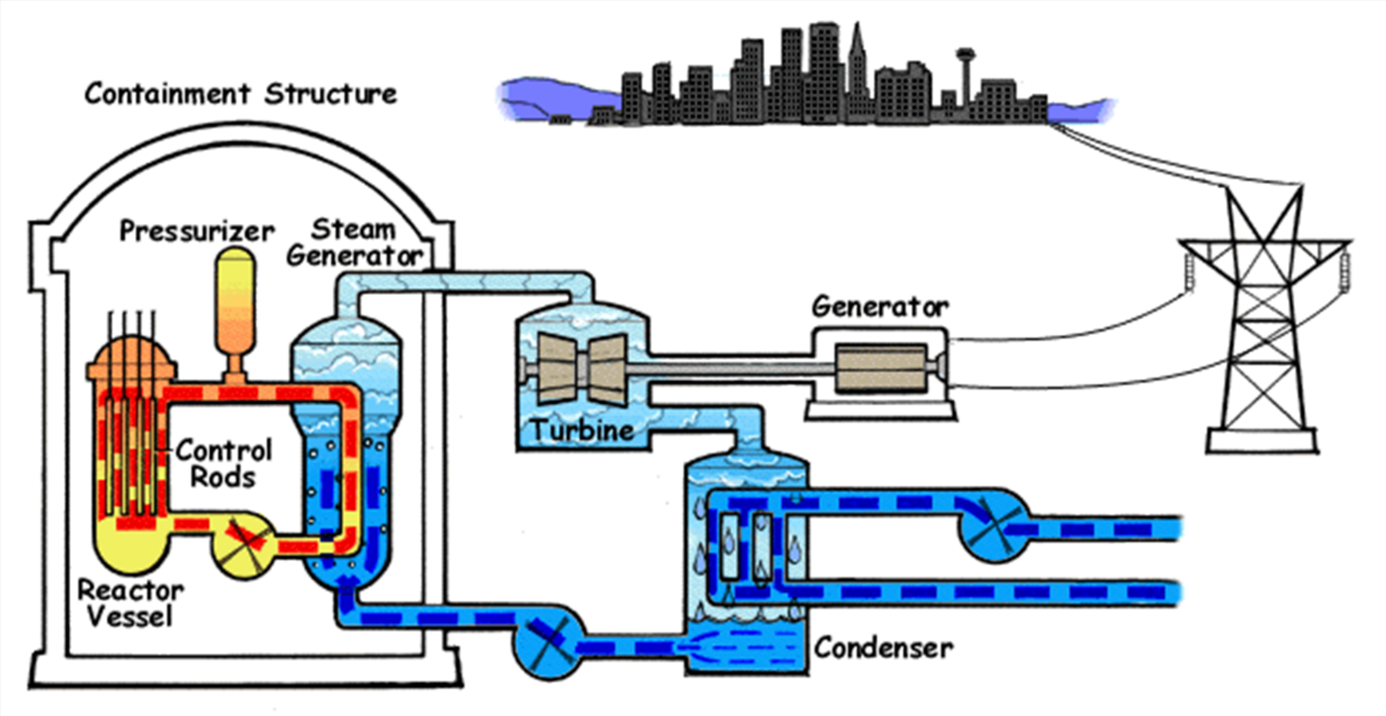
19. SPENT FUEL SHIPPING CASK
20. FUEL STORAGE POOL
21. FUEL TRANSFER POOL
22. CASK LOADING POOL
23. CASK HANDLING CRANE
24. FUEL TRANSFER BRIDGE
25. FUEL CASK SKID ON RAILROAD CAR

GENERAL ELECTRIC

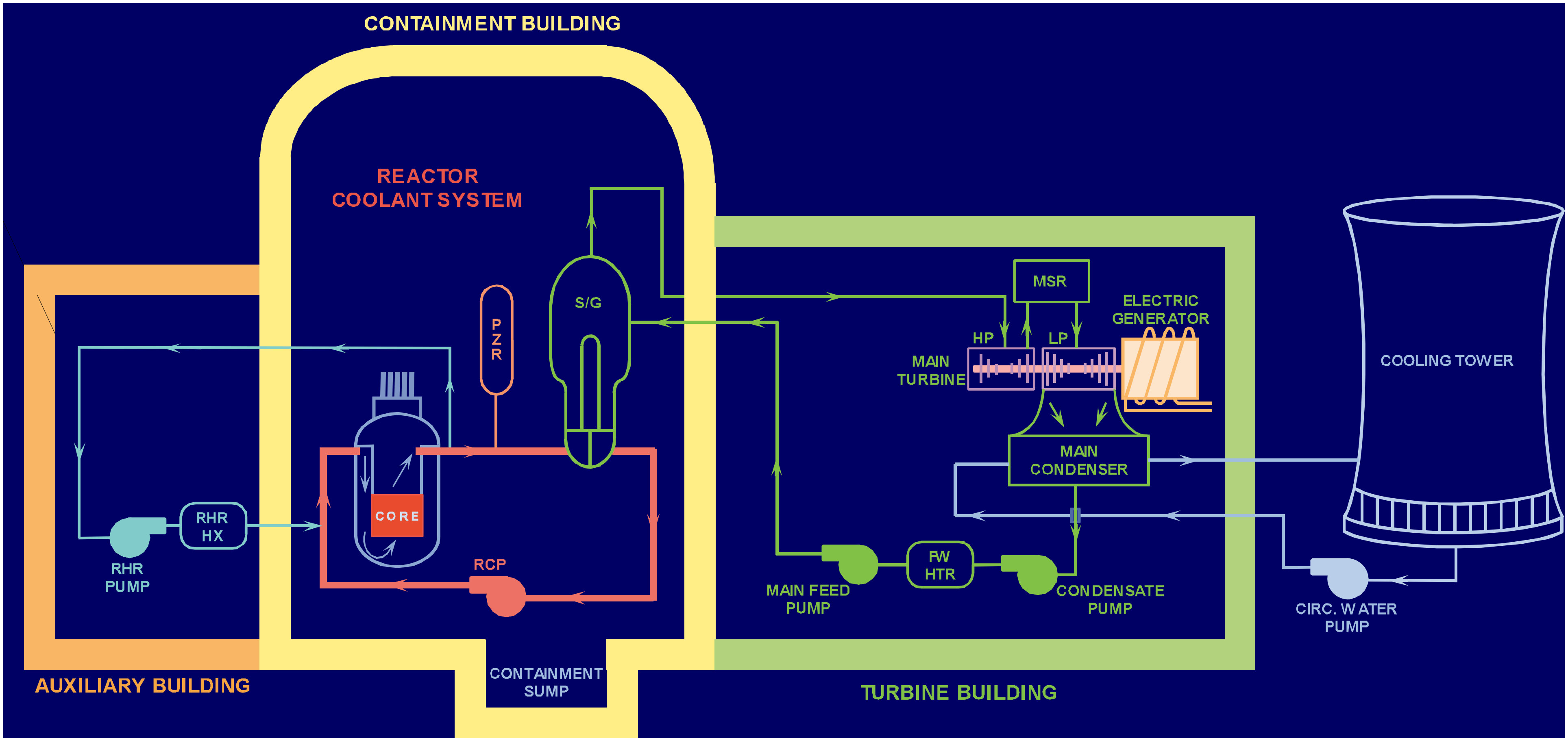
GEZ-4385.1

LOCA Sequence Review





PRESSURIZED WATER REACTOR SYSTEMS

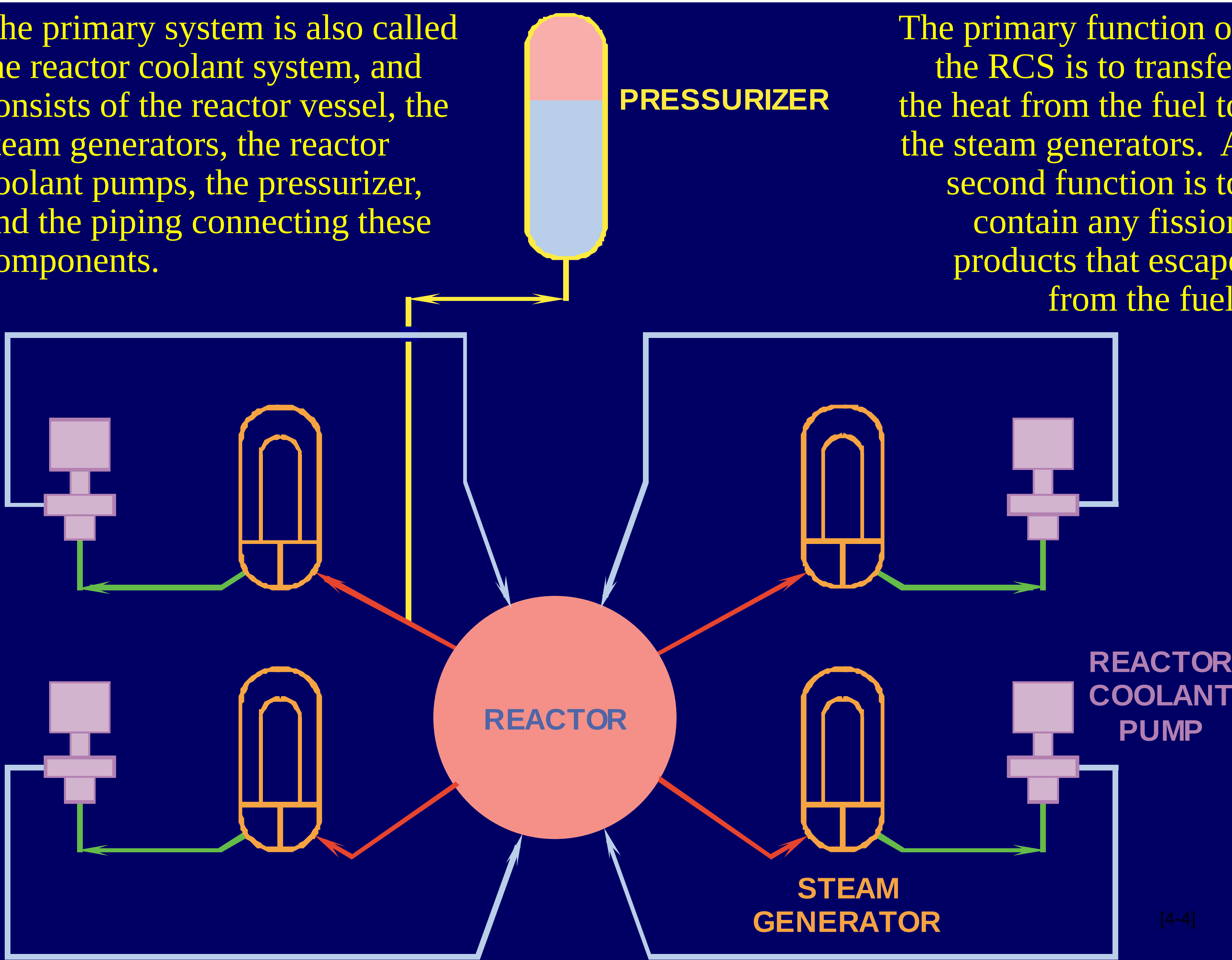


For a nuclear power plant to perform the function of generating electricity, many systems, over 100, must function together. The two major systems that are used to convert the heat generated in the fuel into electrical power is the primary system (transfer the heat from the core to the steam generator) and the secondary system (which converts the heat energy into electrical energy).

[4-3]

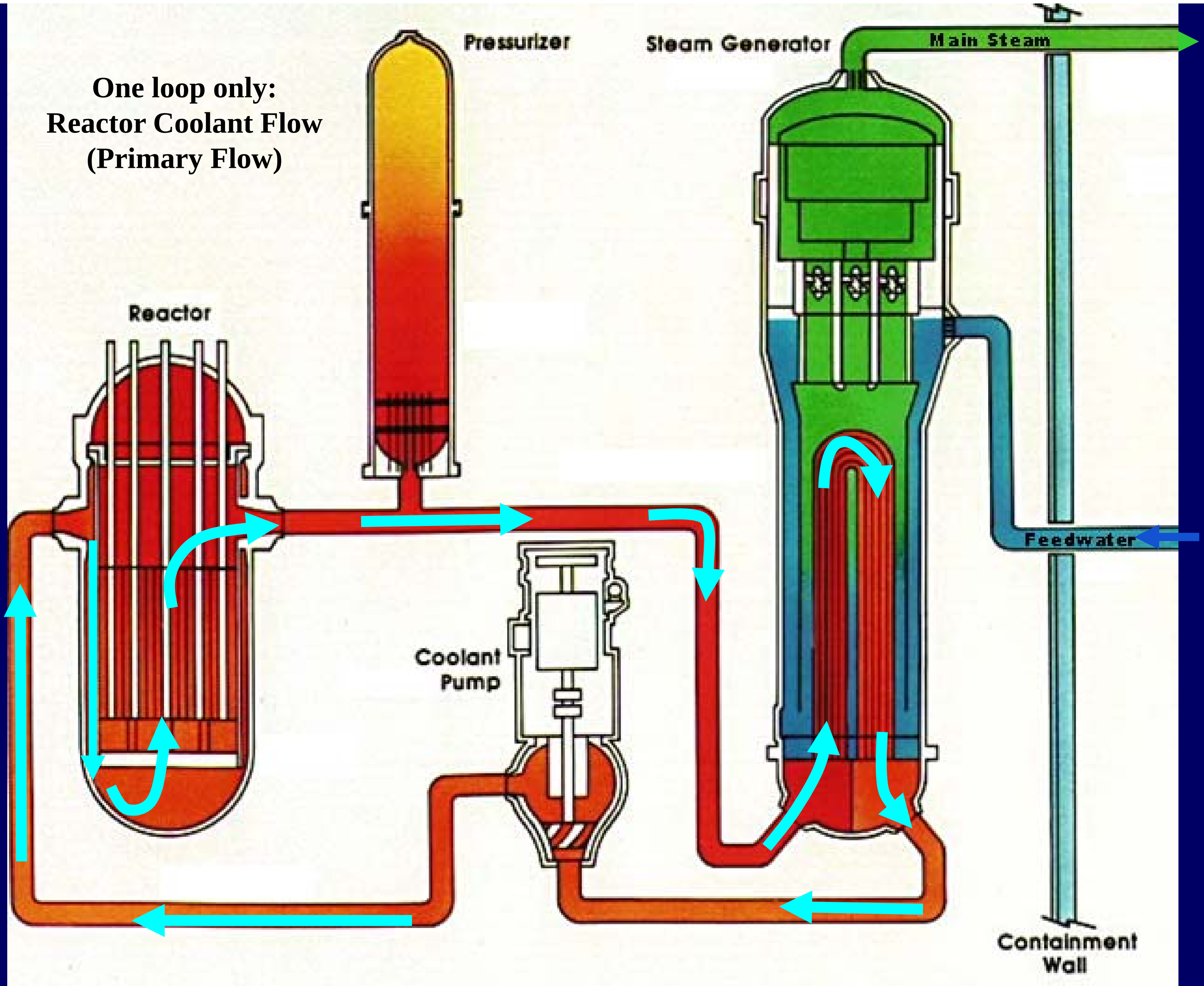
The primary system is also called the reactor coolant system, and consists of the reactor vessel, the steam generators, the reactor coolant pumps, the pressurizer, and the piping connecting these components.

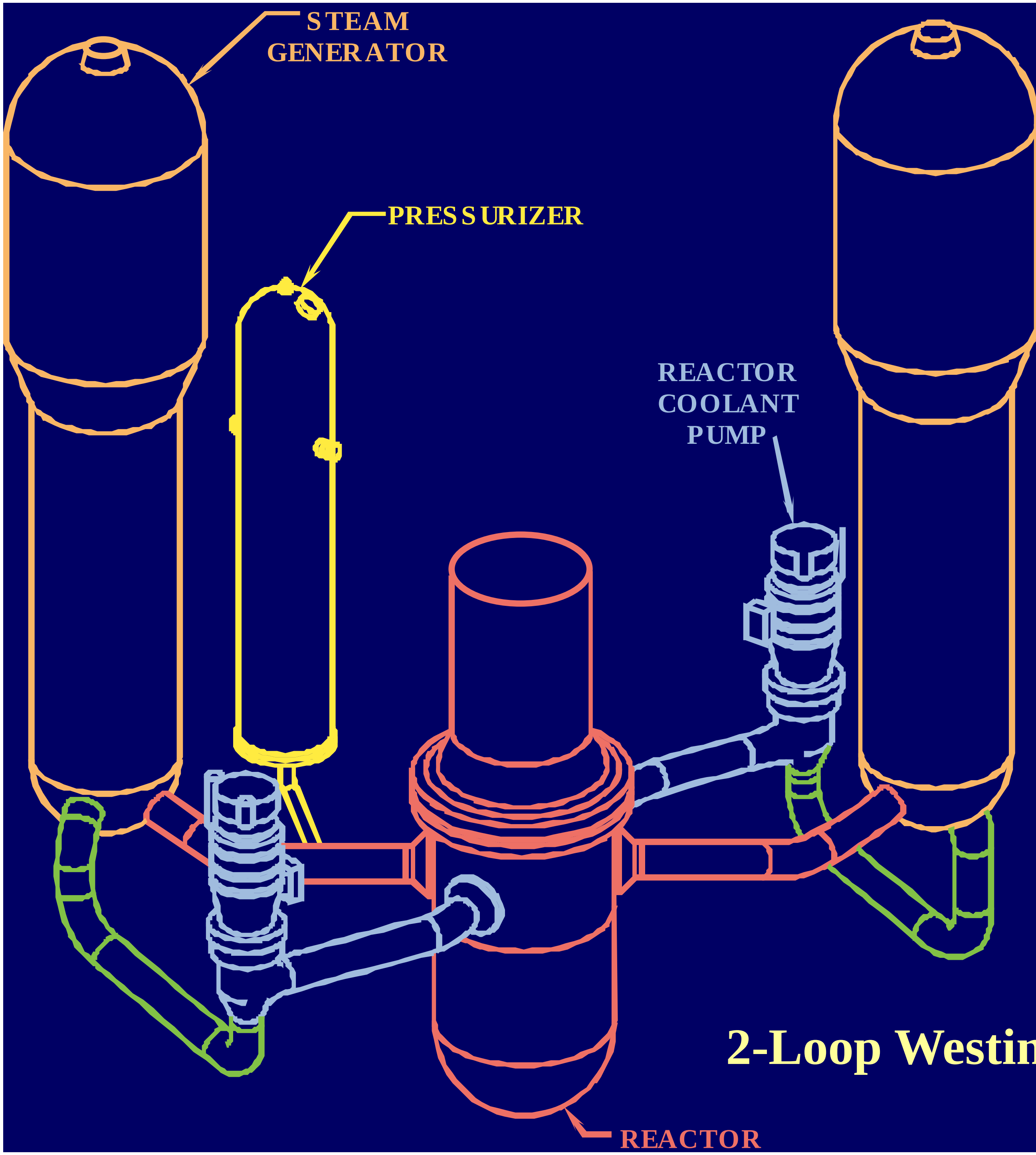
The primary function of the RCS is to transfer the heat from the fuel to the steam generators. A second function is to contain any fission products that escape from the fuel.



[4-4]

One loop only:
Reactor Coolant Flow
(Primary Flow)





2-Loop plants currently in operation:

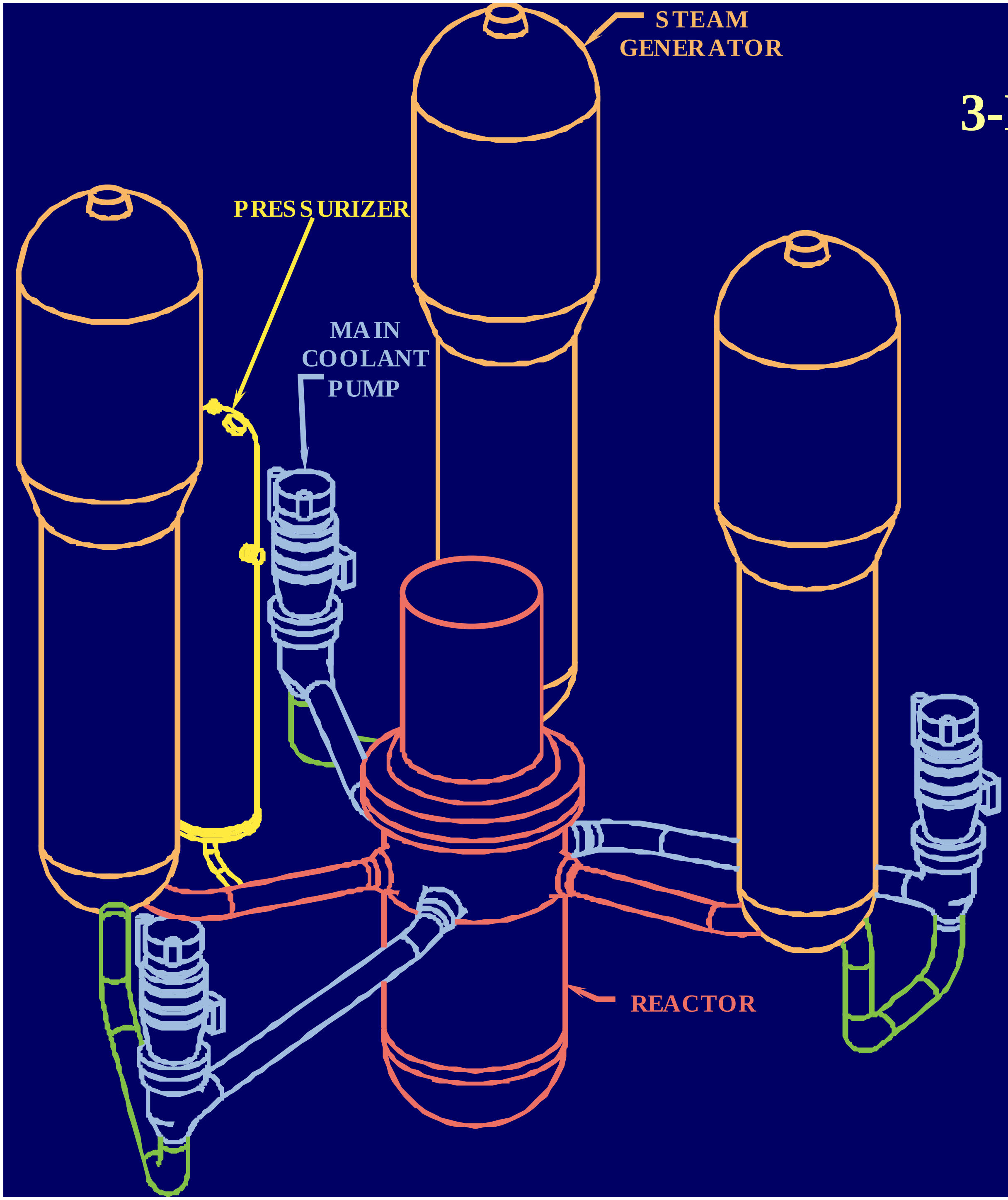
- Ginna
- Kewaunee
- Point Beach 1 and 2
- Prairie Island 1 and 2

Westinghouse has constructed plants with 2, 3, and 4 loops. A reactor coolant loop is a reactor coolant pump, a steam generator, and the piping that connects these components to the reactor vessel. This is a drawing of a 2-loop Westinghouse plant.

2-Loop Westinghouse Plant

[4-5]

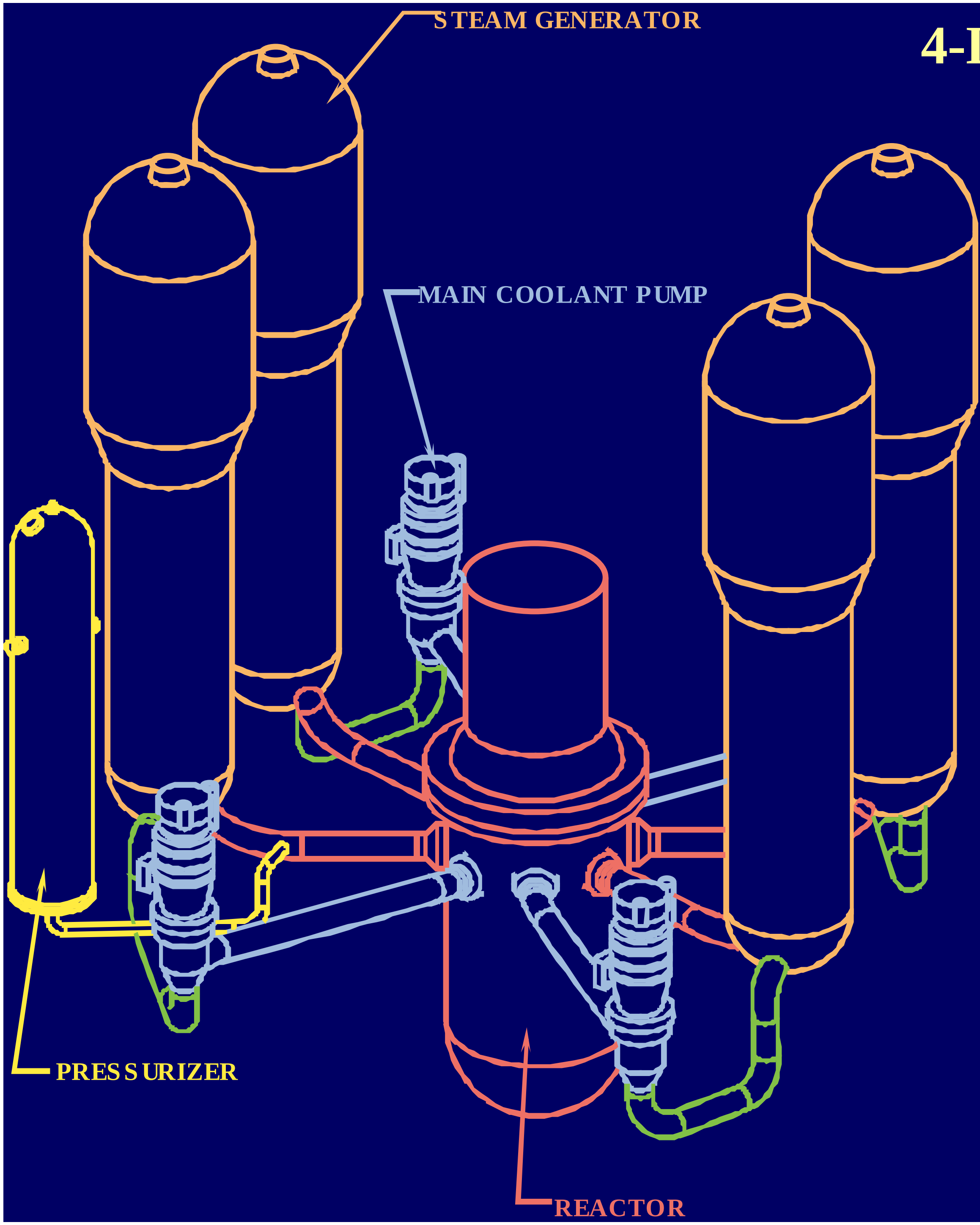
3-Loop Westinghouse Plant



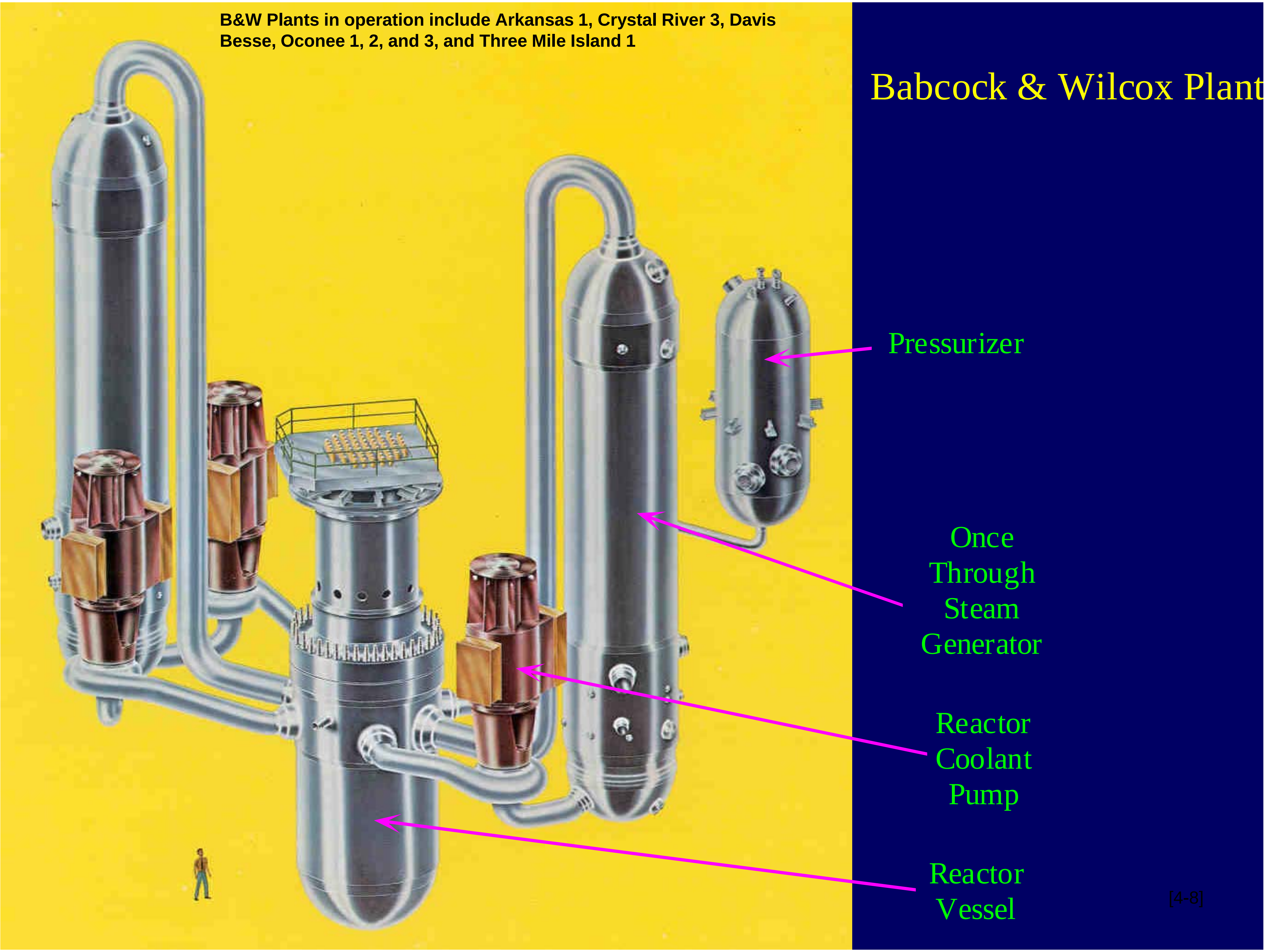
3-Loop plants currently in operation:

- Beaver Valley 1 and 2
- Farley 1 and 2
- H. B. Robinson 2
- North Anna 1 and 2
- Shearon Harris 1
- V. C. Summer
- Surry 1 and 2
- Turkey Point 3 and 4

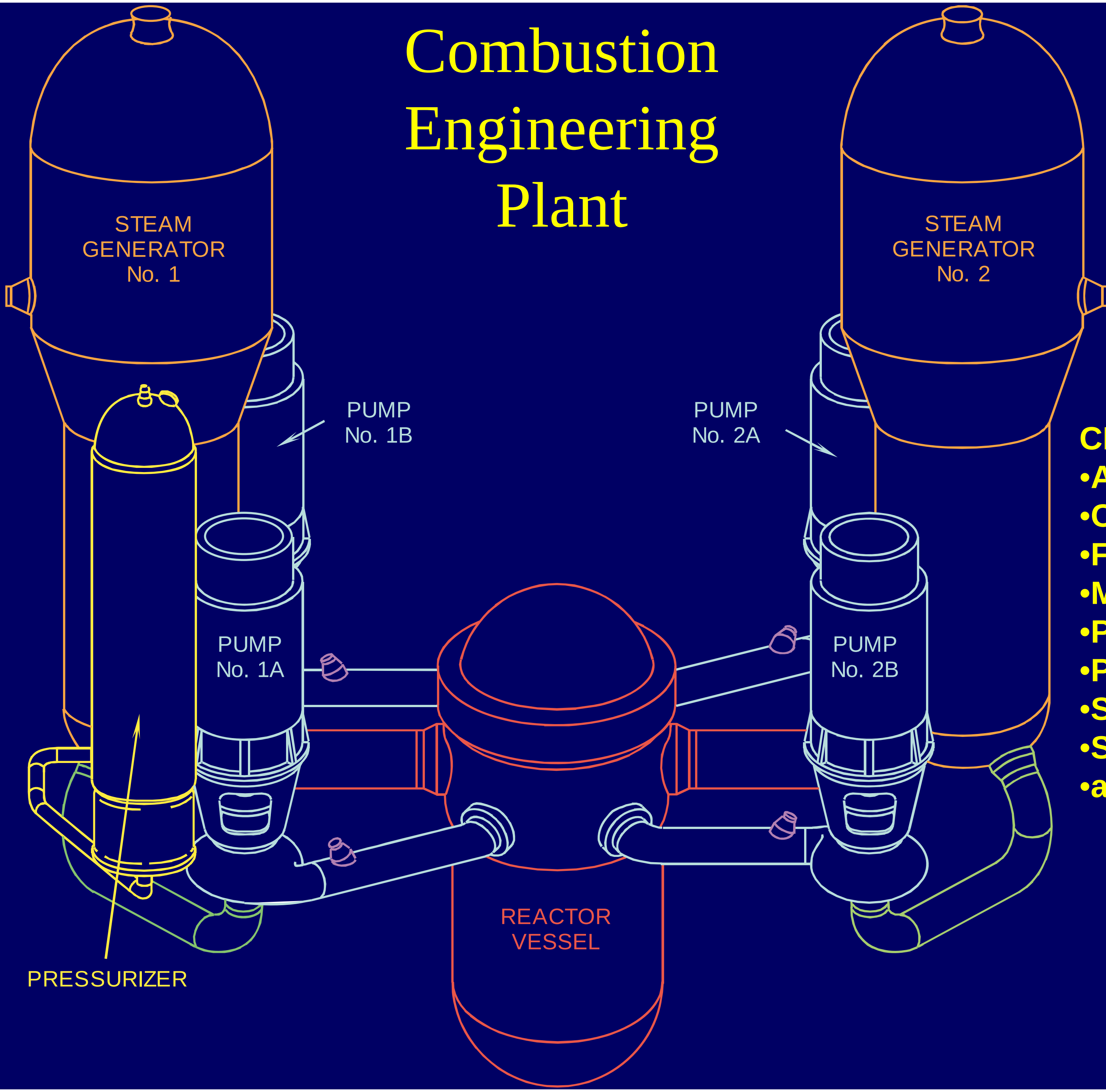
4-Loop Westinghouse Plant



4-Loop plants currently in operation:
Braidwood 1 and 2,
Byron 1 and 2,
Callaway,
Catawba 1 and 2,
Comanche Peak 1 and 2,
D. C. Cook 1 and 2,
Diablo Canyon 1 and 2,
Indian Point 2 and 3,
McGuire 1 and 2,
Millstone 3,
Salem 1 and 2,
Seabrook,
Sequoyah 1 and 2,
South Texas 1 and 2,
Vogtle 1 and 2,
Watts Bar 1, and
Wolf Creek

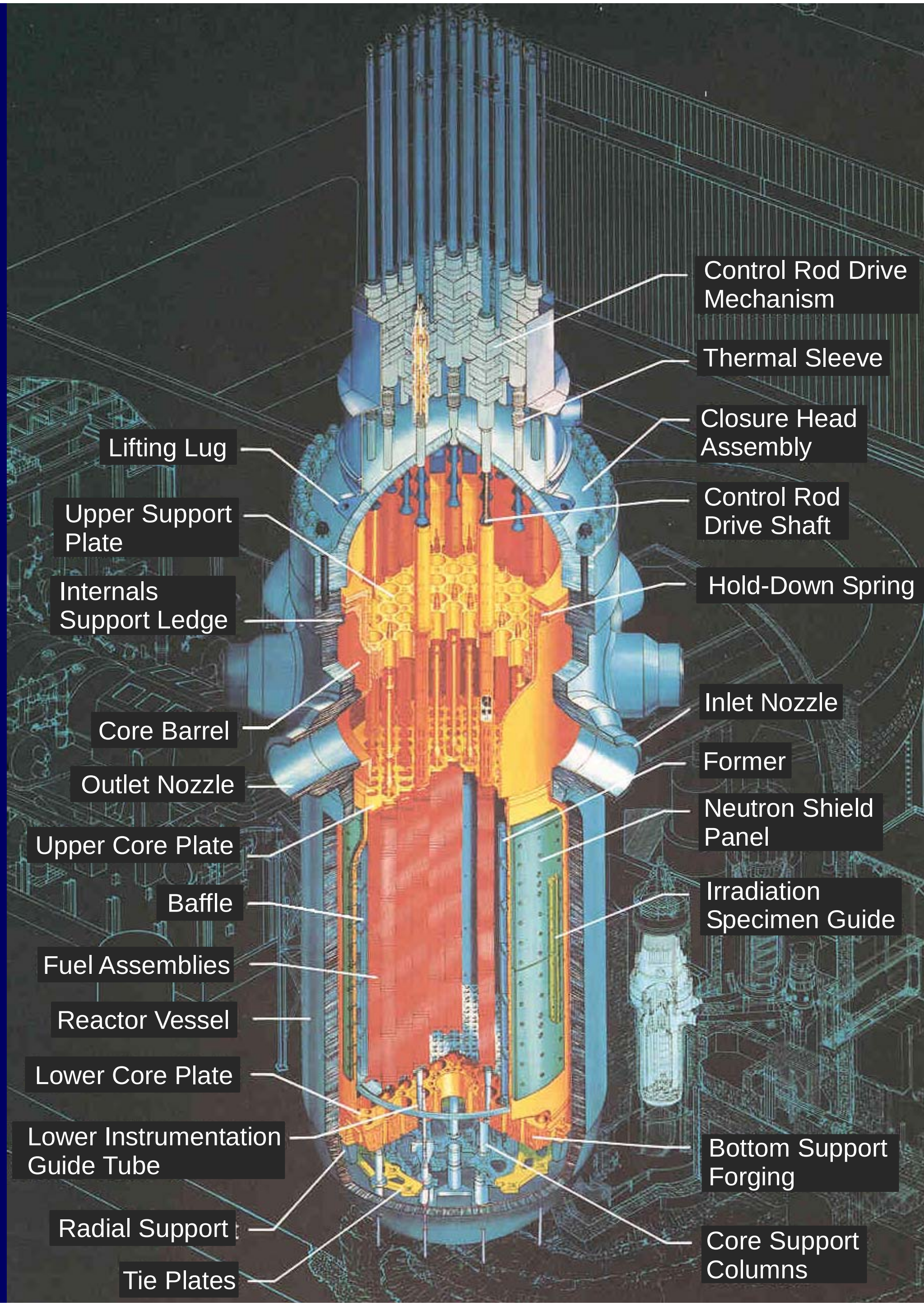

B&W Plants in operation include Arkansas 1, Crystal River 3, Davis Besse, Oconee 1, 2, and 3, and Three Mile Island 1
Babcock & Wilcox Plant
Pressurizer
Once Through Steam Generator
Reactor Coolant Pump
Reactor Vessel
[4-8]

Combustion Engineering Plant



CE Plants:
- **Arkansas 2,**
- **Calvert Cliffs 1 and 2,**
- **Fort Calhoun,**
- **Millstone 2,**
- **Palisades,**
- **Palo Verde 1, 2, and 3**
- **San Onofre 2 and 3,**
- **Saint Lucie 1 and 2,**
- **and Waterford 3**

PWR **Reactor Vessel**, Westinghouse design



[4-10&11]

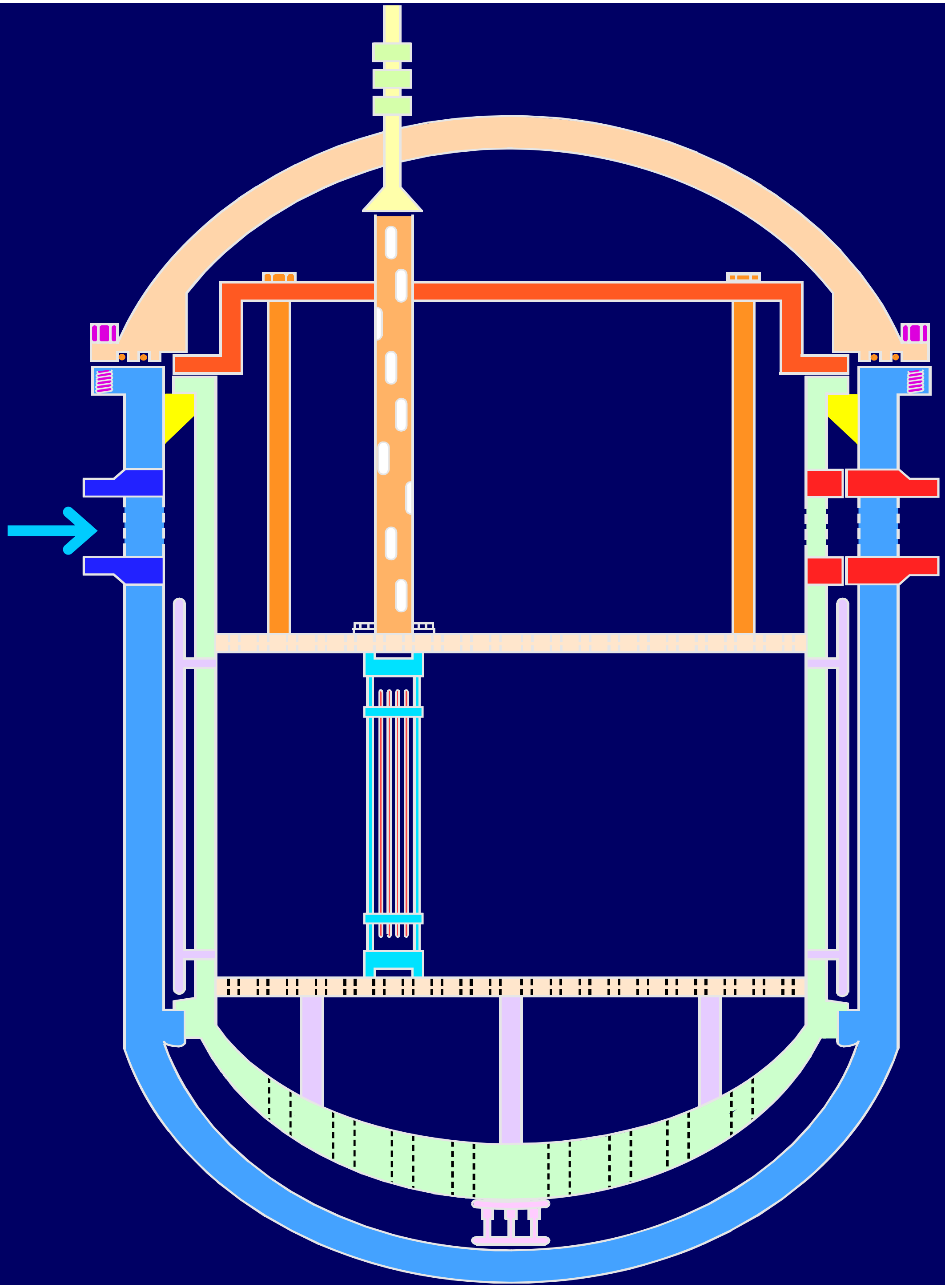
Reactor Vessel

Core Barrel with fuel

Upper internals

Vessel head

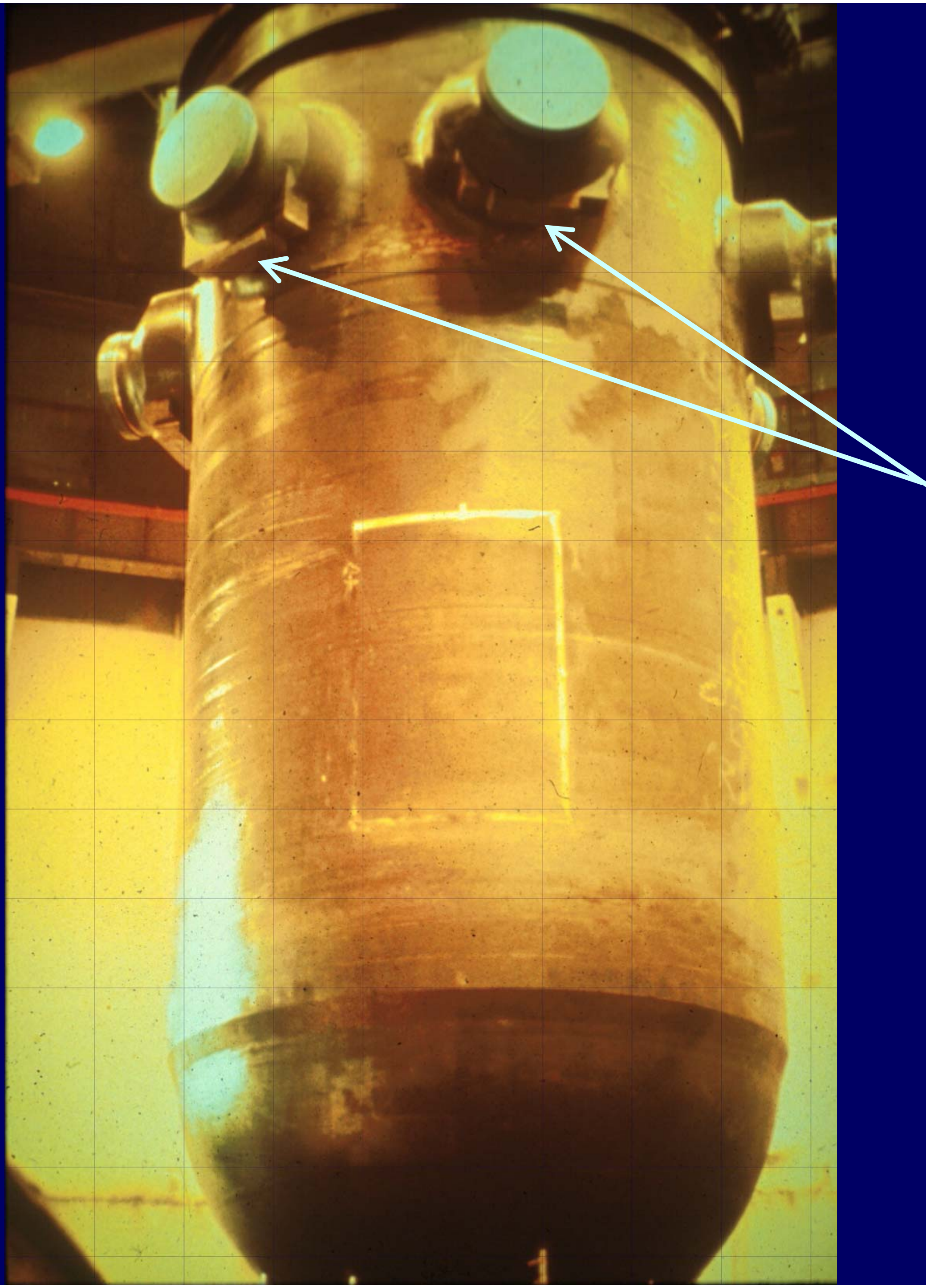
Flow path through Vessel



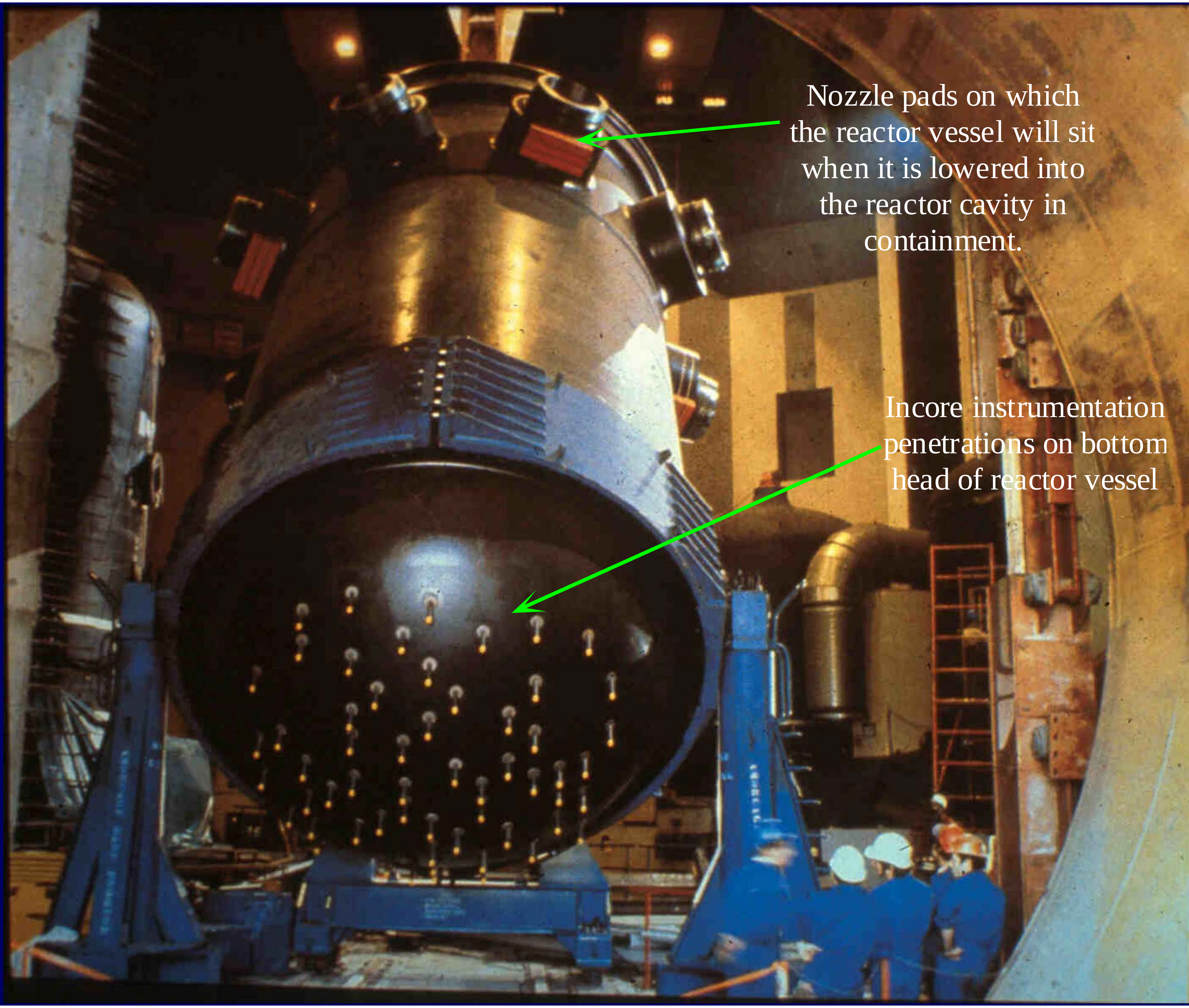
Westinghouse PWR Reactor Vessel Cutaway

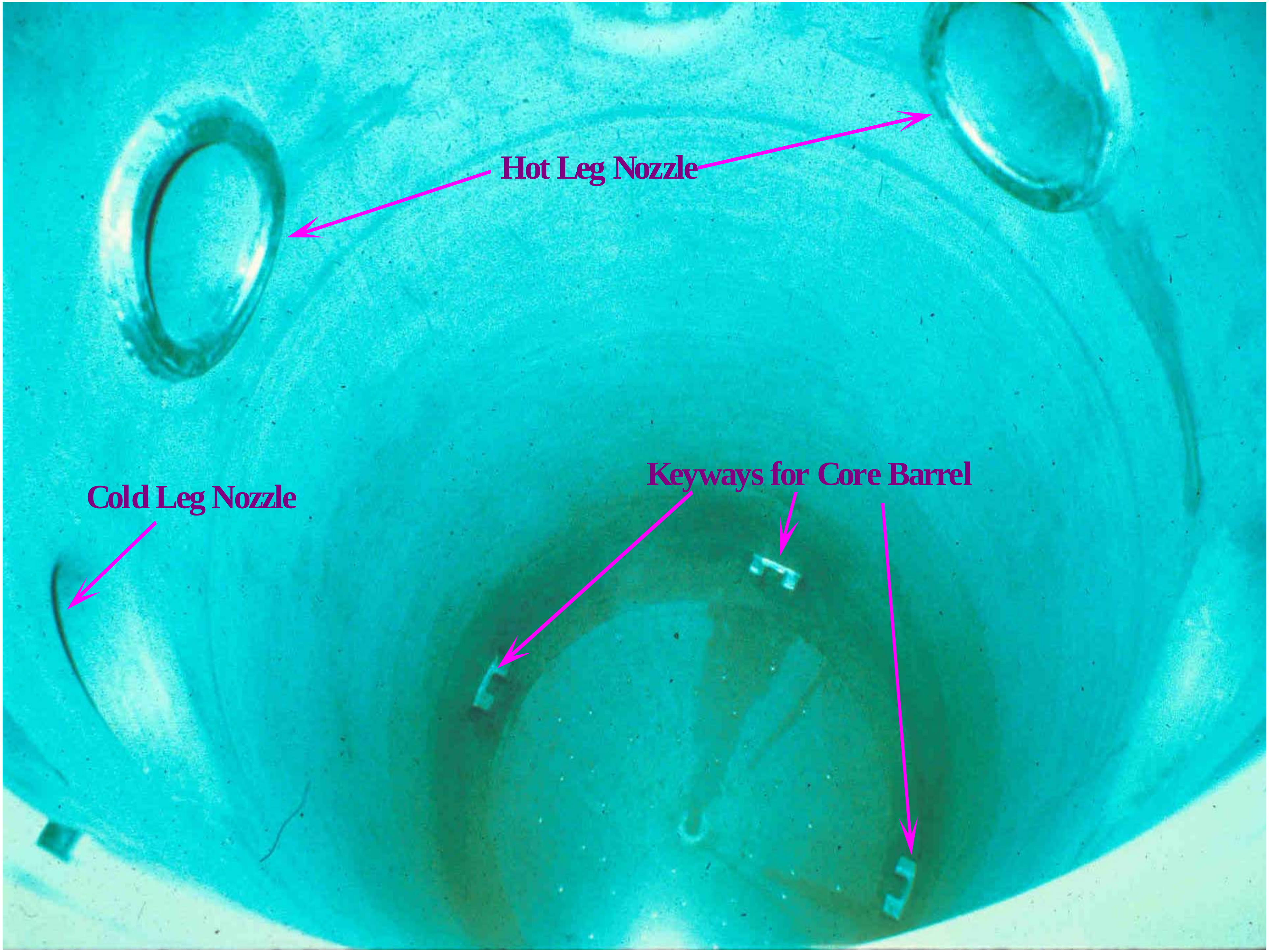
(simplified)


INTENDED FOR TVA SEQUOYAH I
NUCLEAR POWER STATION TENNESSEE U.S.A
GROSS WEIGHT 351.
NET WEIGHT 320.5
MEASUREMENTS
LENGTH
WIDTH 12186 mm
HEIGHT 6360 mm
VOLUME 7048 mm
350
CONTRACT NUMBER 34-B-CVQ 84996 BP



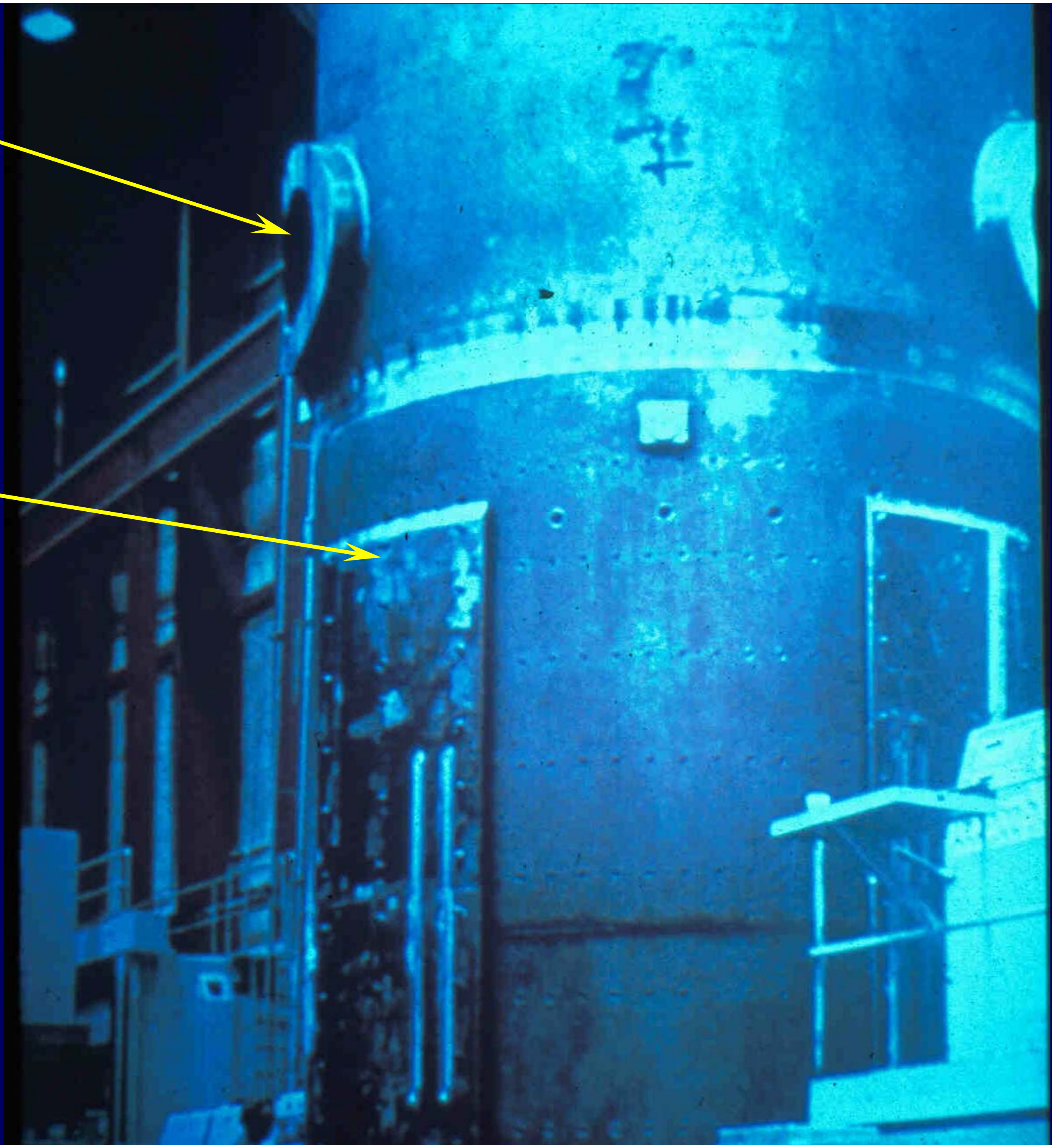
Nozzle pads on which the reactor vessel will sit when it is lowered into the reactor cavity in containment.

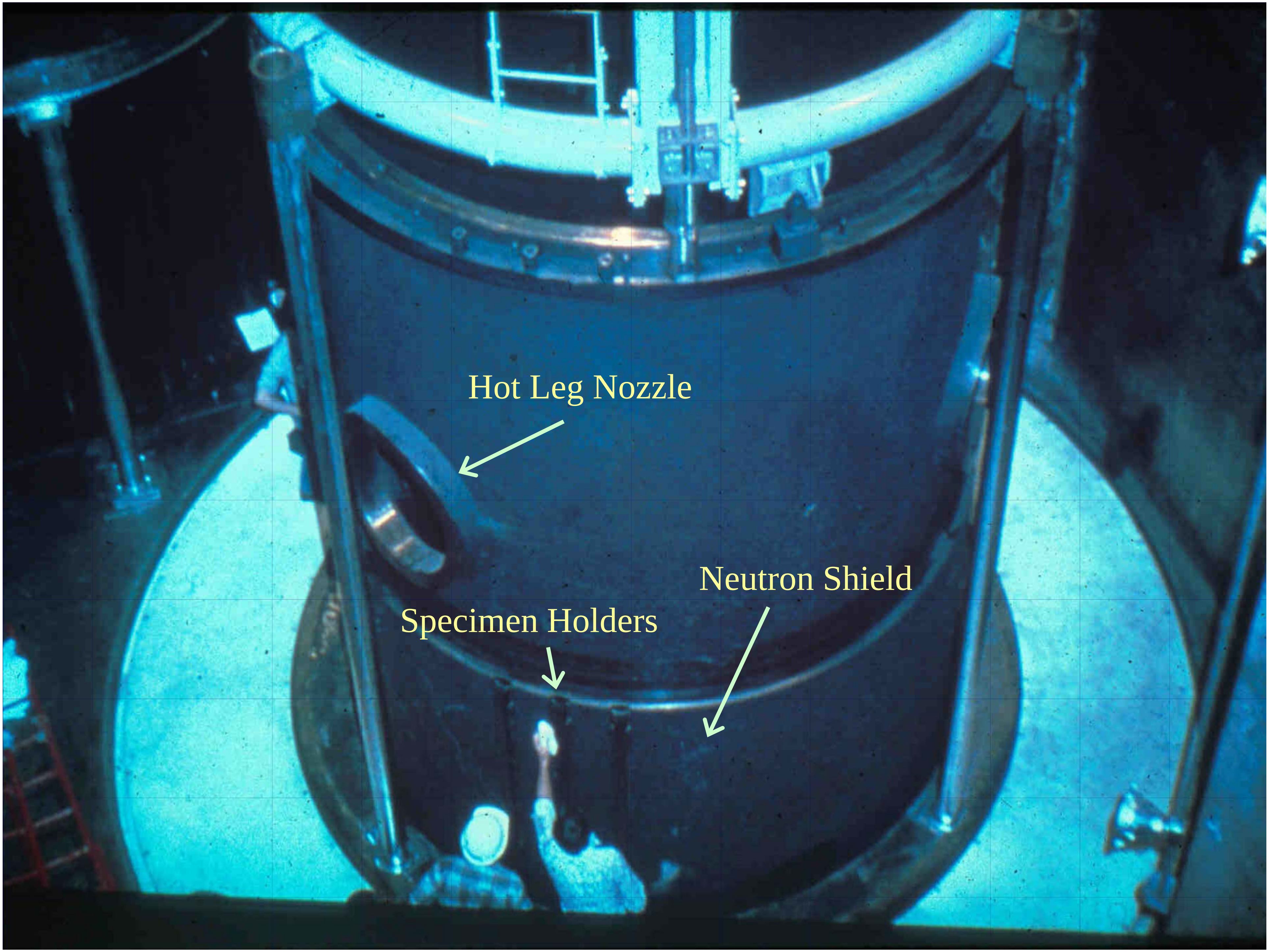

Nozzle pads on which the reactor vessel will sit when it is lowered into the reactor cavity in containment.
Incore instrumentation penetrations on bottom head of reactor vessel

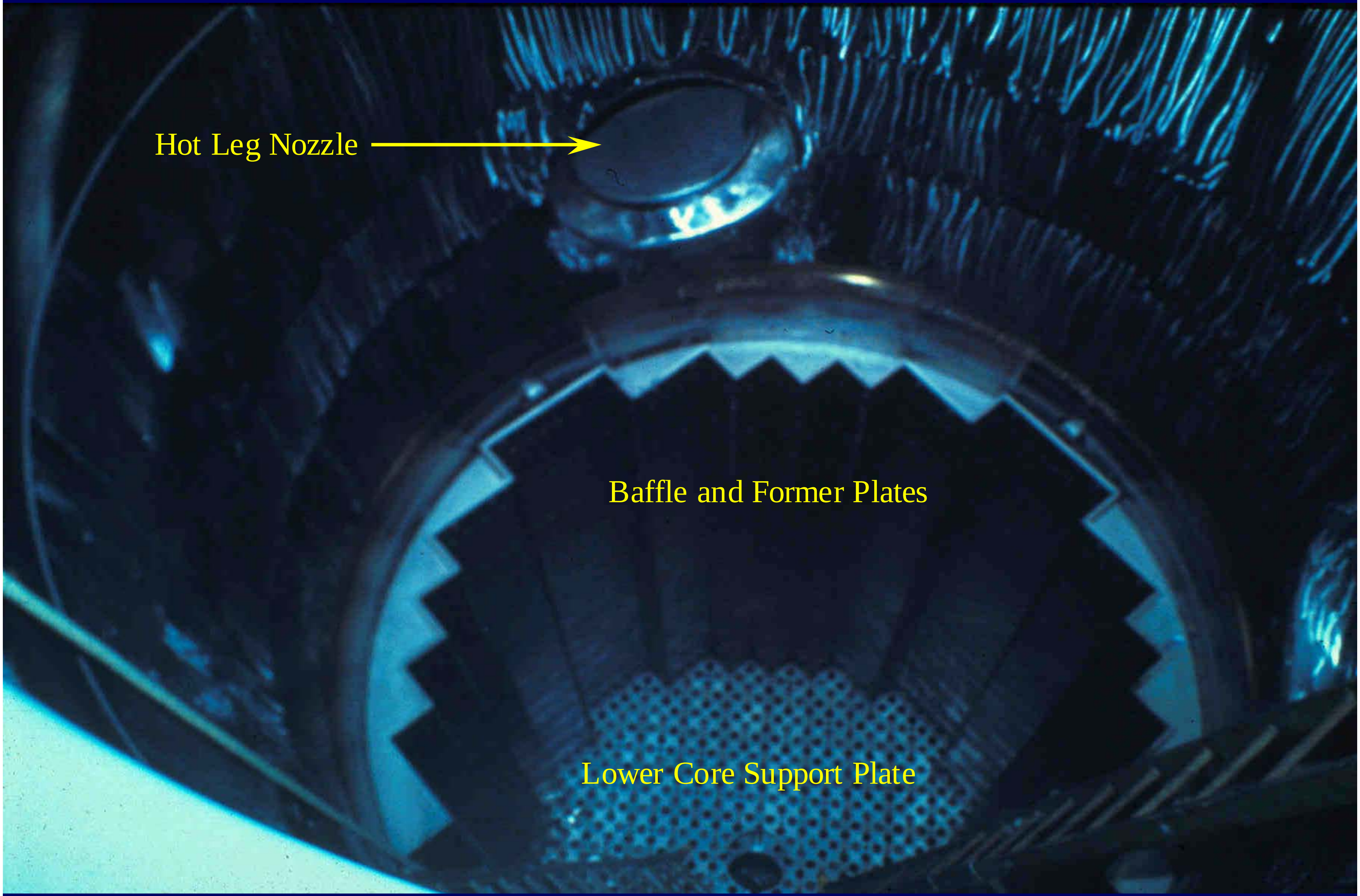

Hot Leg Nozzle
Cold Leg Nozzle
Keyways for Core Barrel

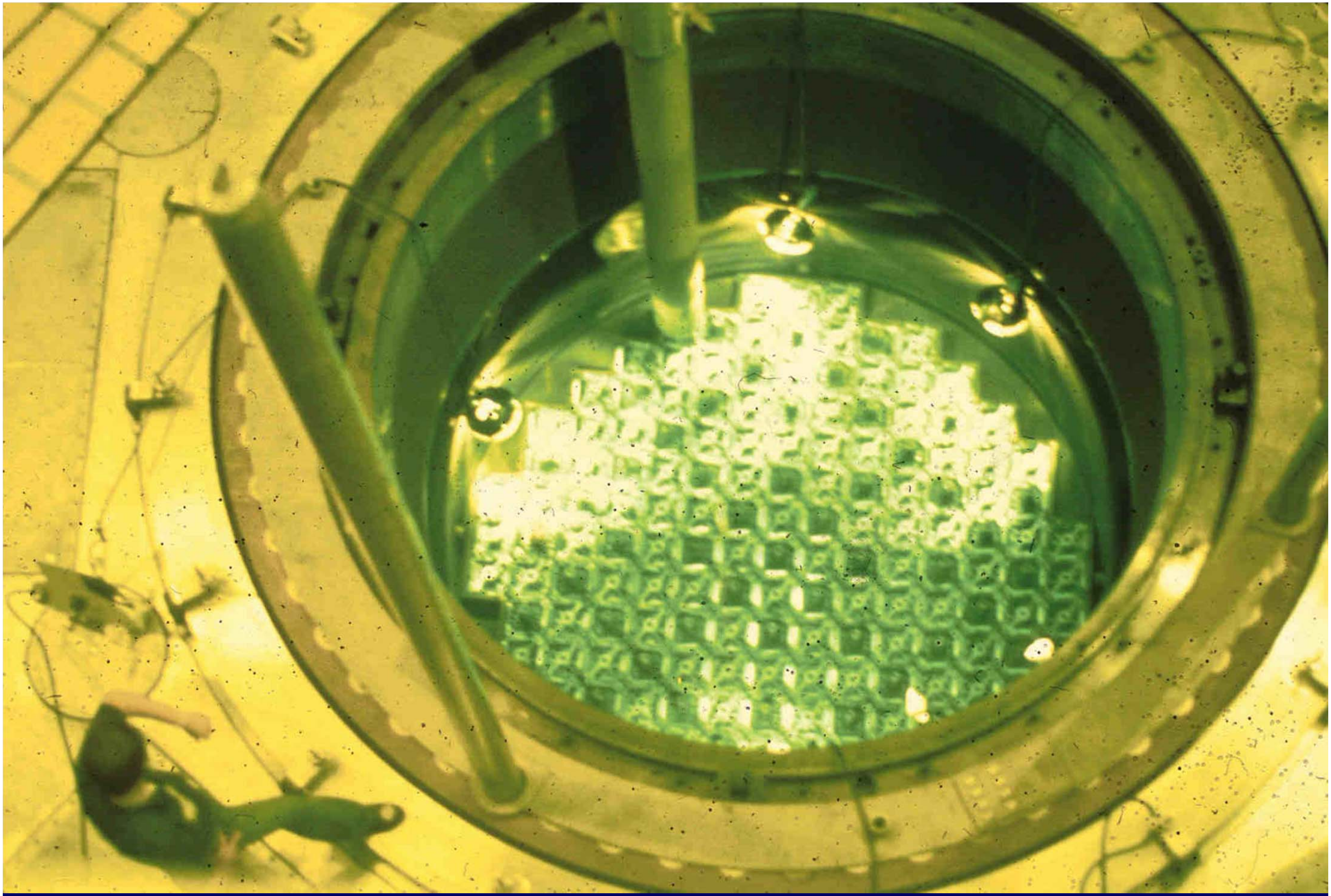
Hot Leg Nozzle

Neutron pad with specimen holders




Hot Leg Nozzle
Neutron Shield
Specimen Holders


Hot Leg Nozzle
Baffle and Former Plates
Lower Core Support Plate



What does this tell you?

- **Fuel Assembly:** fuel rods that are grouped together in an assembly
  - Also known as *Fuel element* or *Fuel bundle*
- **Control Rods:** strong neutron absorbers connected to a cluster assembly that can be moved in and out of the core to control the nuclear fission process
  - Consist of a silver-indium-cadmium or a boron carbide mixture sealed inside stainless steel tubes
  - *Rod Cluster Control Assembly (RCCA)* is the formal name for a control rod

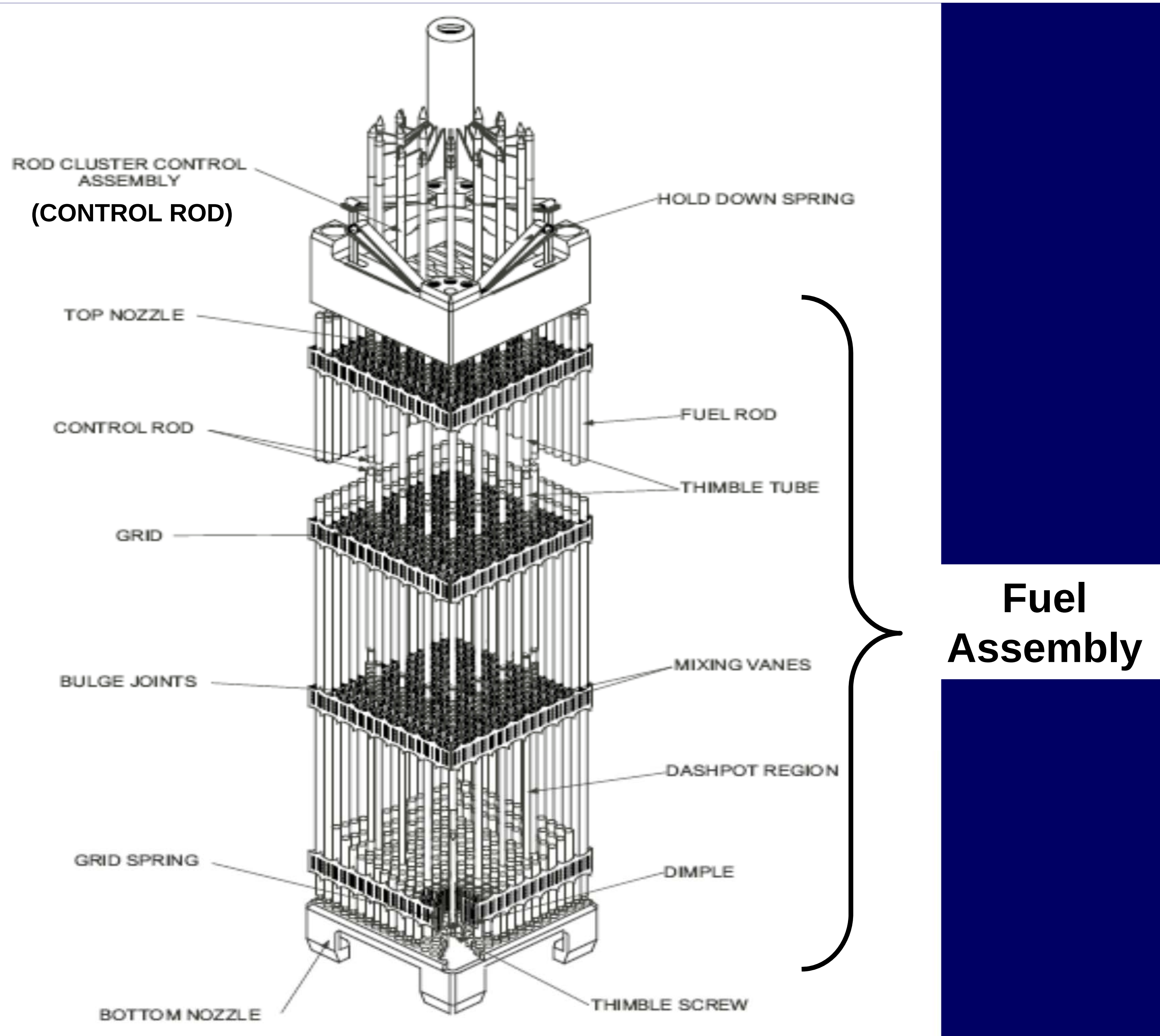
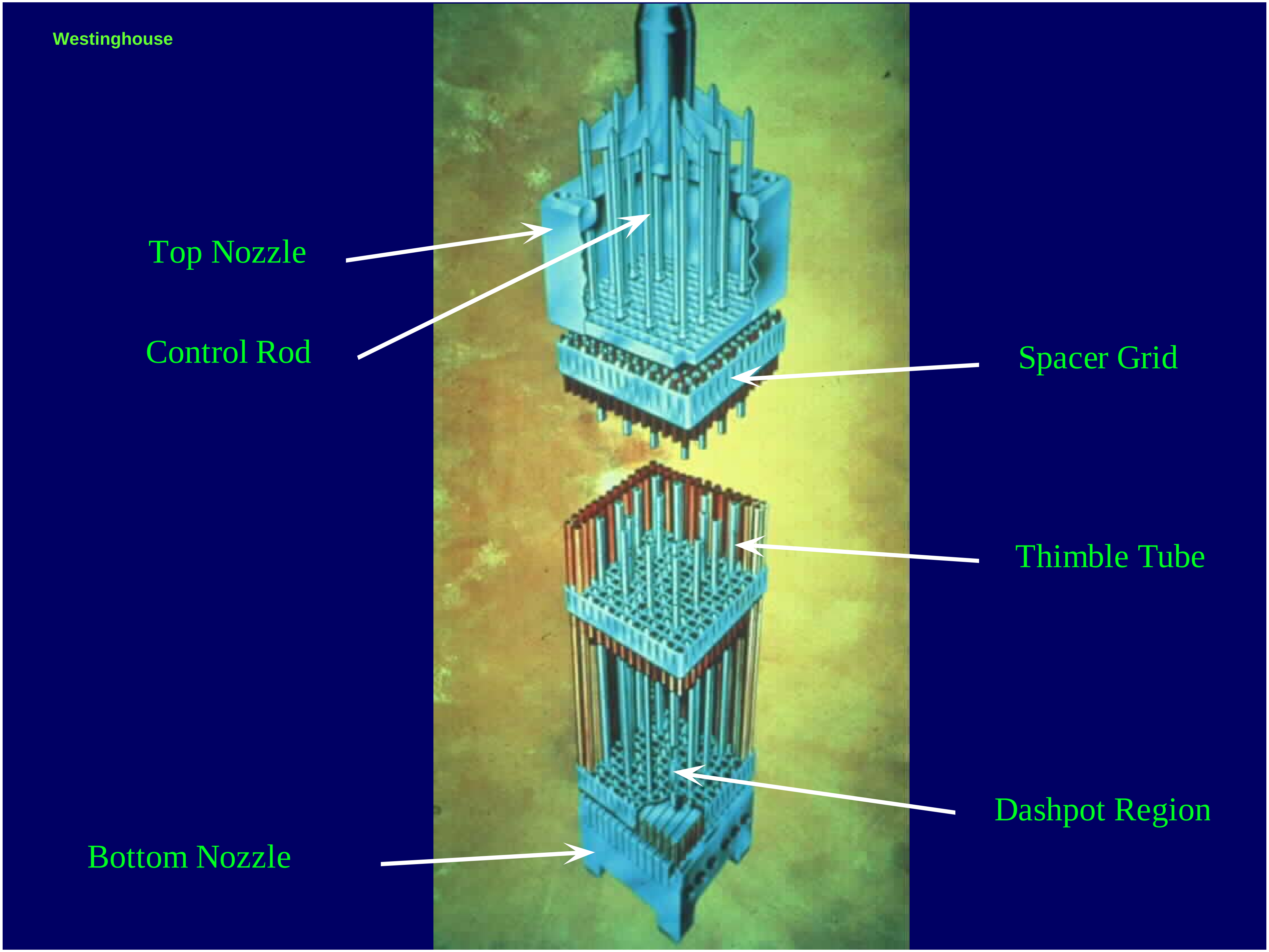
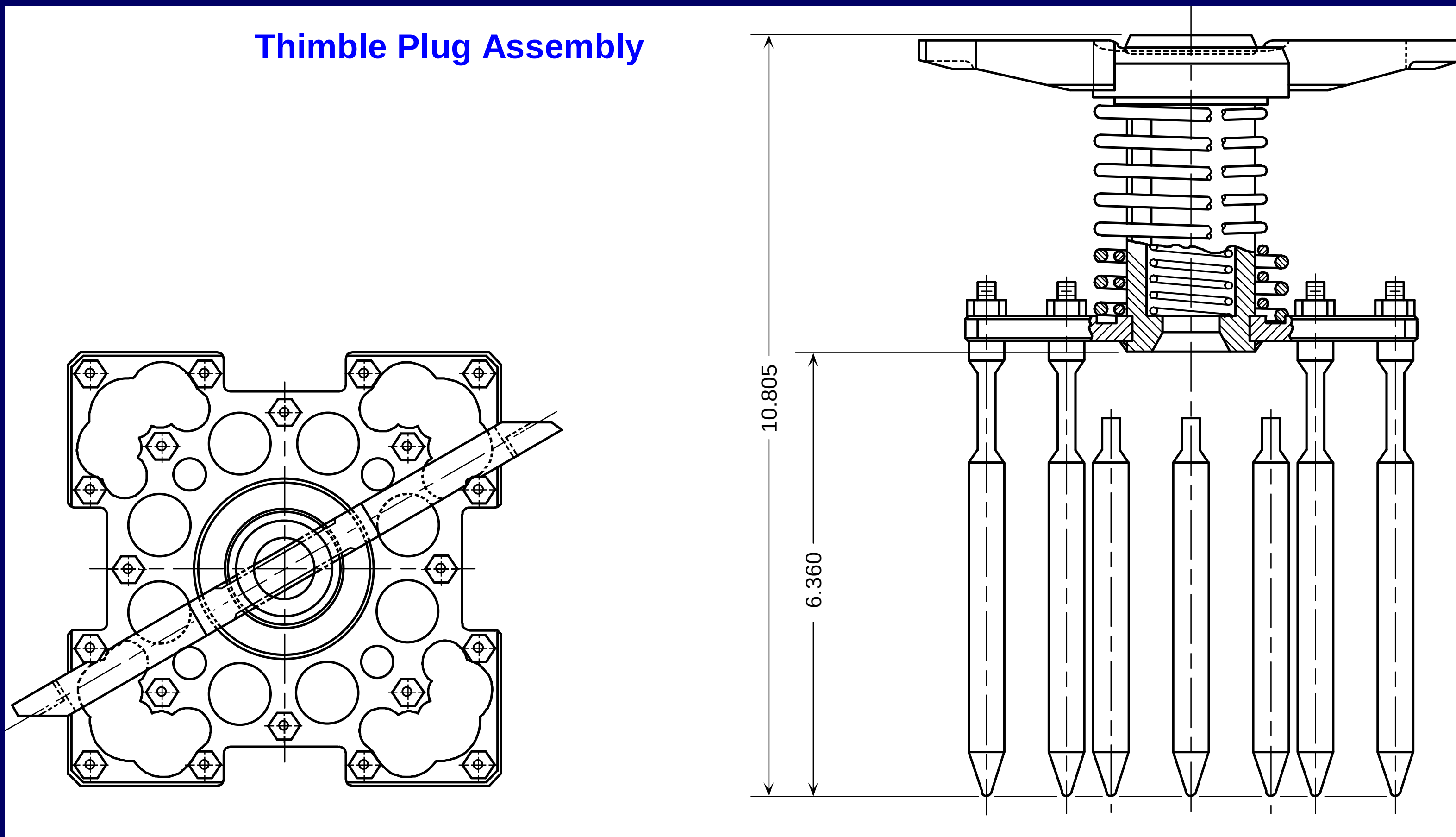


Figure 1-11 Typical PWR Fuel Assembly with Control Rod


Westinghouse
Top Nozzle
Control Rod
Spacer Grid
Thimble Tube
Dashpot Region
Bottom Nozzle

Thimble Plug Assembly

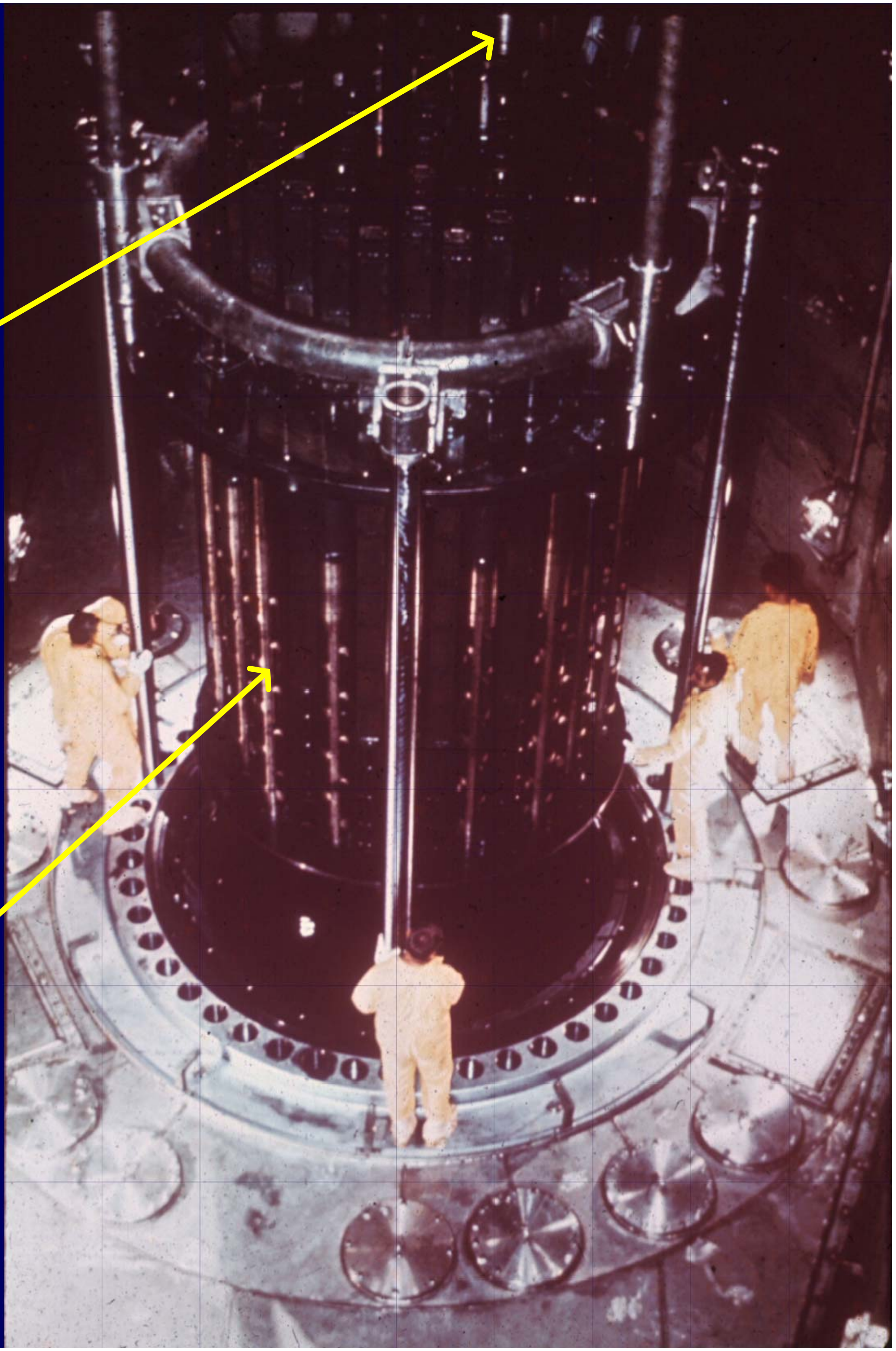


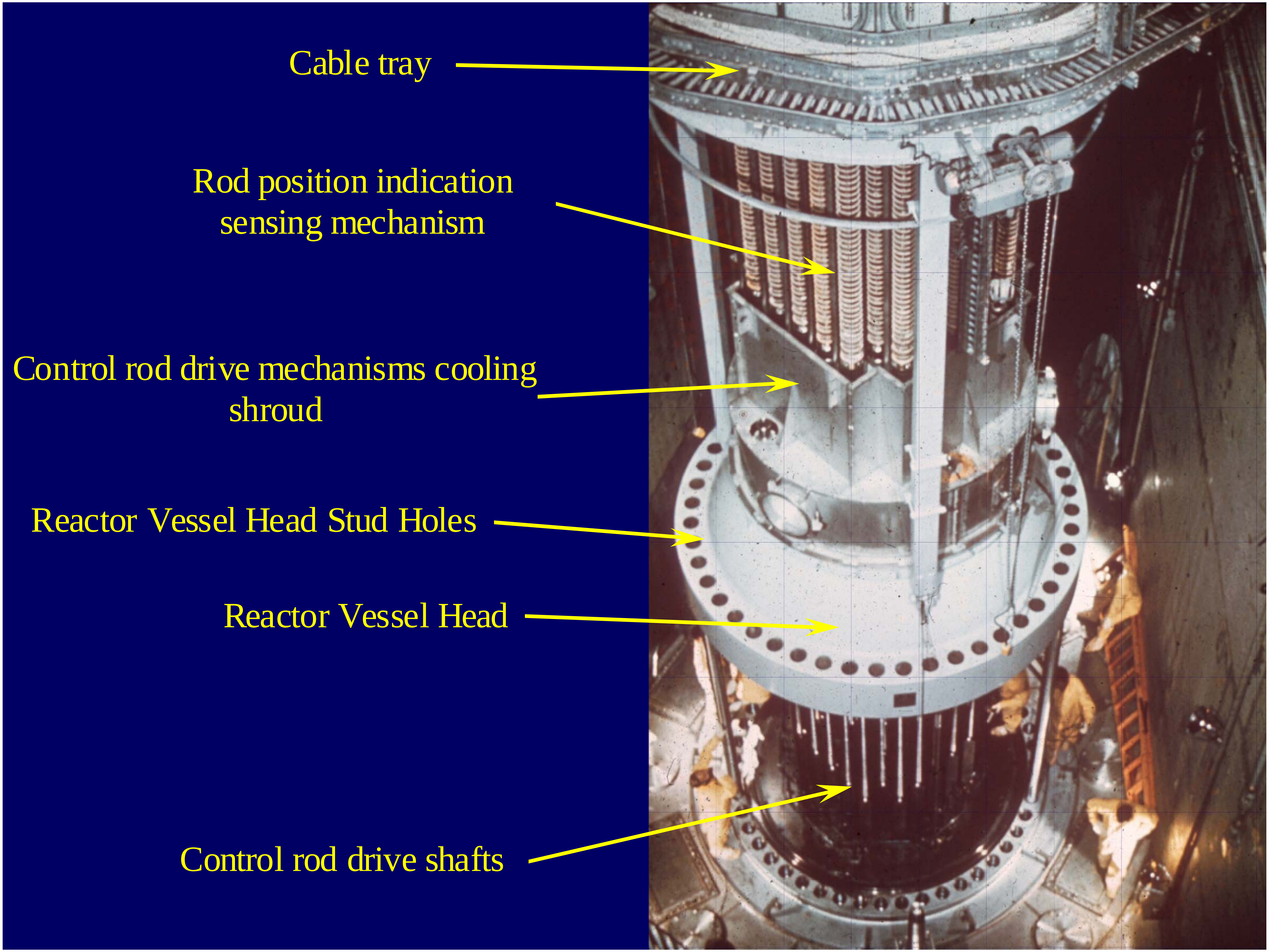
NOTE: ALL DIMENSIONS ARE IN INCHES.

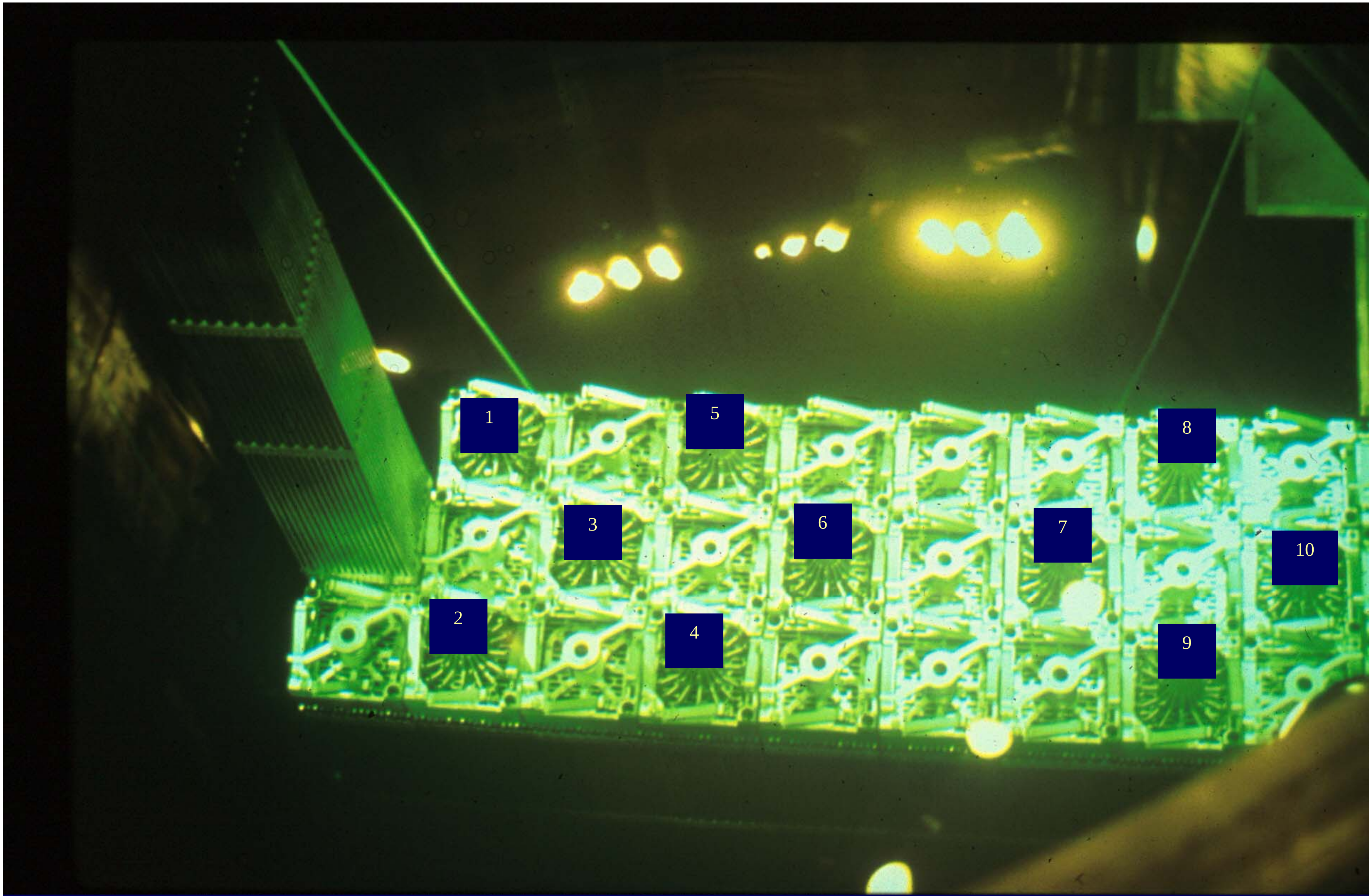
Upper internals package being placed into the reactor vessel

Control rod drive shafts

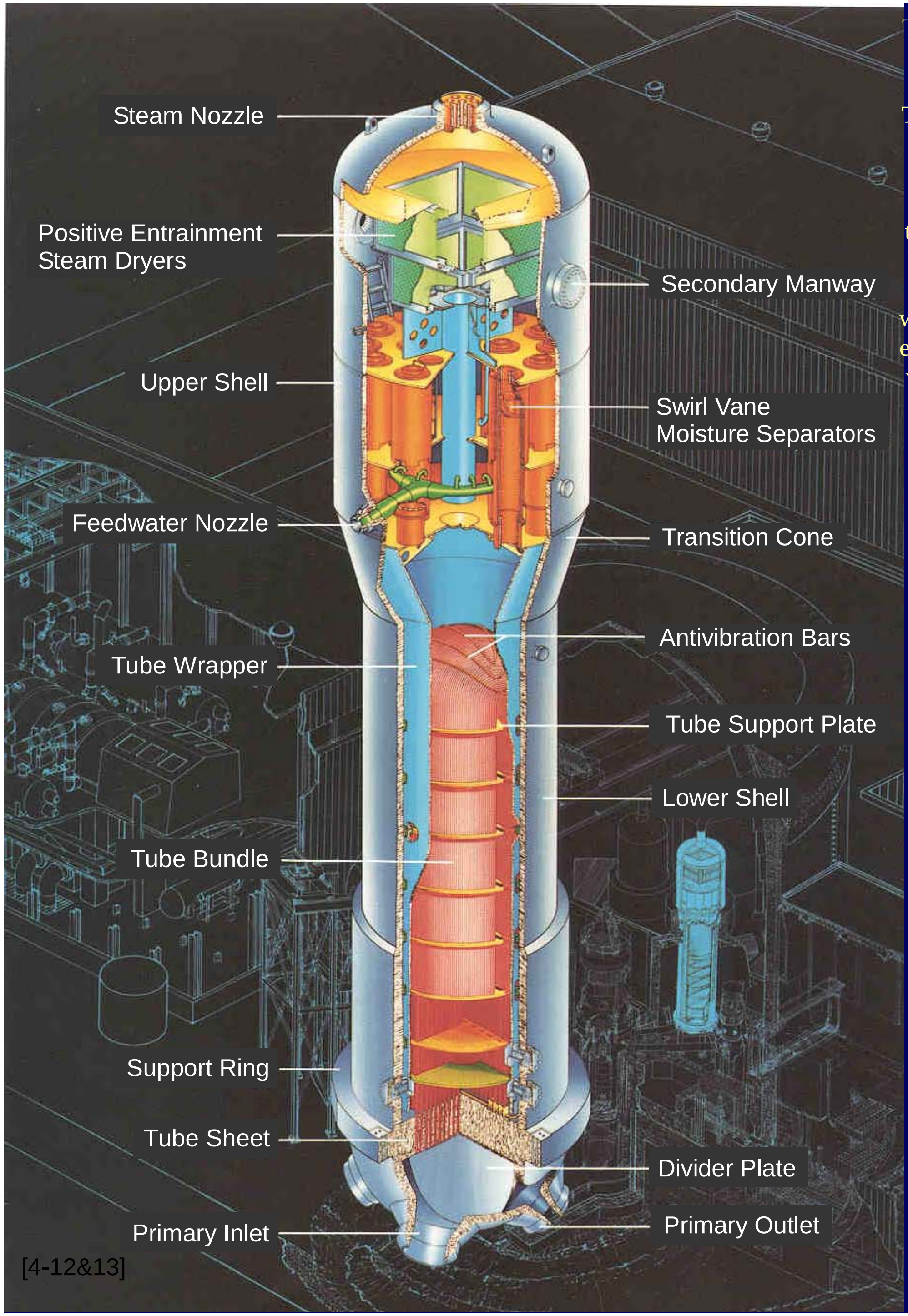
Control rod guide tube assemblies




Cable tray
Rod position indication sensing mechanism
Control rod drive mechanisms cooling shroud
Reactor Vessel Head Stud Holes
Reactor Vessel Head
Control rod drive shafts



How many control rods are shown in this picture?



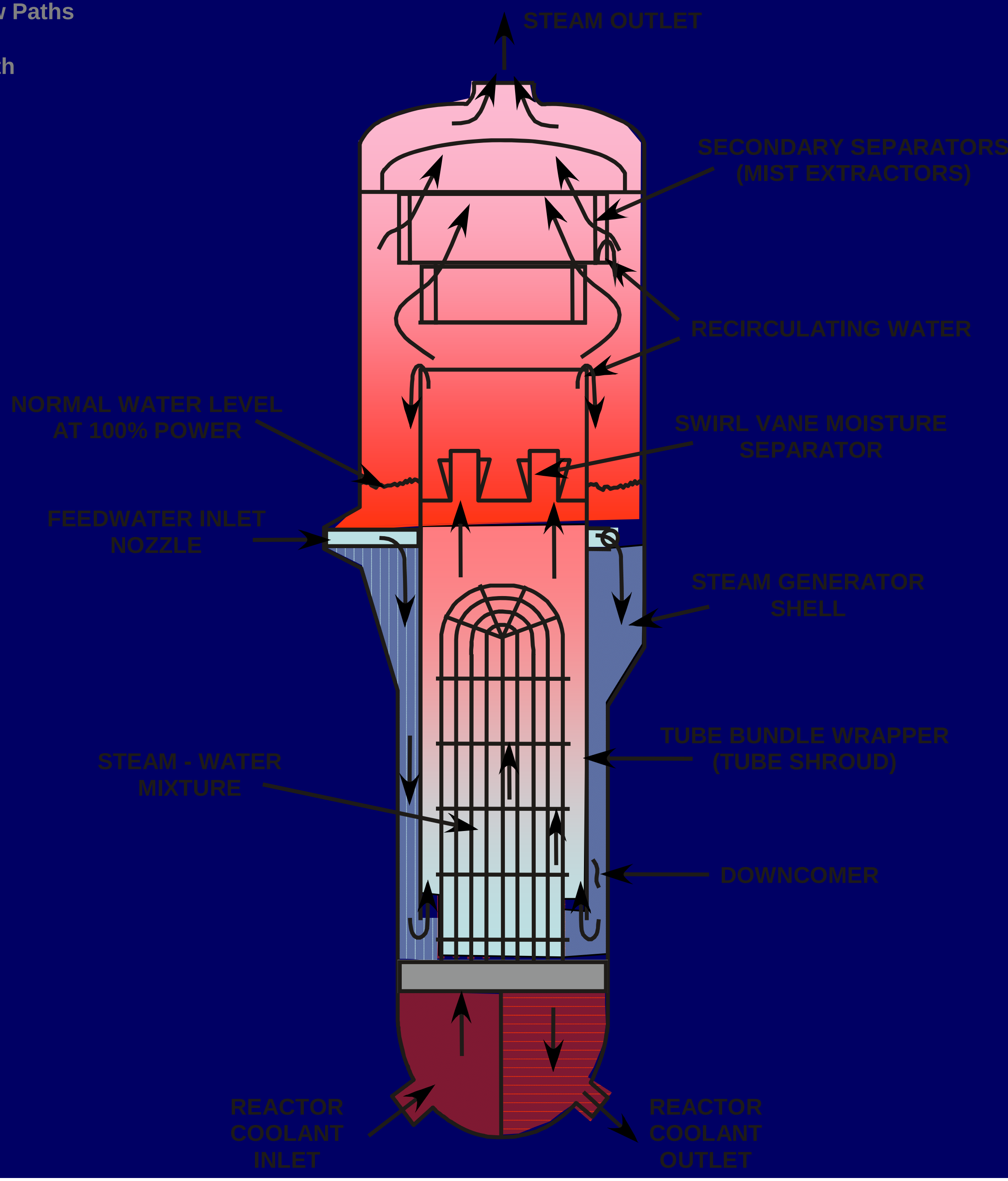
[4-12&13]

This is a drawing of one type of steam generator. Some of the differences can be the number and size of the swirl vane separators, the location of the feedwater nozzle, the number of U-tubes, and therefore, the total heat transfer area.

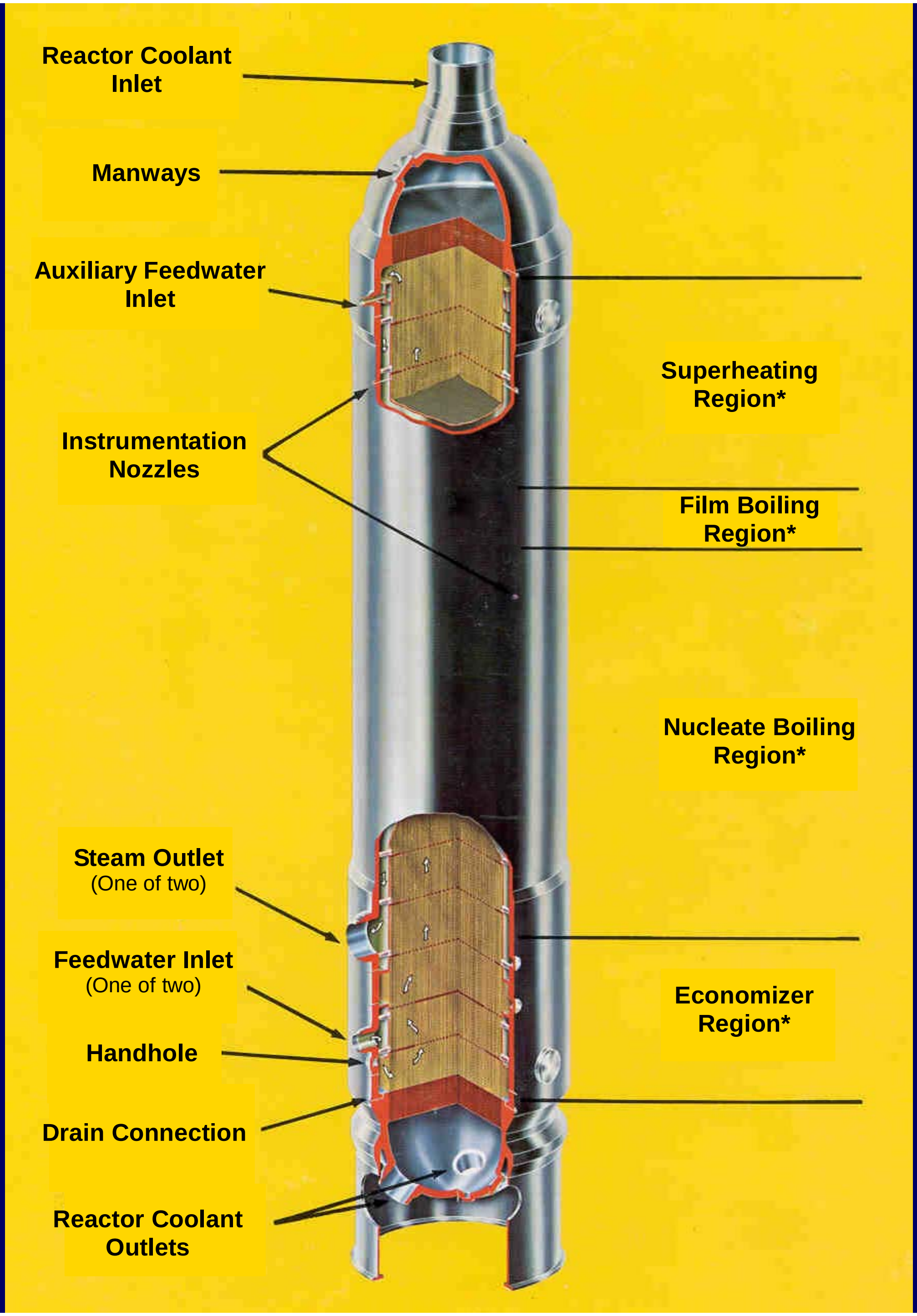
The flow path for reactor coolant is in the primary inlet, around the U-tubes, and out the primary outlet.

The flowpath for the secondary coolant is into the feedwater nozzle and around the feedwater ring, through the j-tubes and down between the steam generator shell and the tube wrapper to the tube sheet region. The feedwater will then flow between the bottom of the tube wrapper and the tube sheet into the tube bundle region. Here the water picks up heat from the primary and begins to boil. It becomes a steam and water mixture. The mixture passes through the two stages of moisture separation and exits the steam generator as dry steam. The moisture separated from the steam mixes with the feedwater coming out of the j-tubes and is made into a steam water mixture again.

Steam Generator Flow Paths
- Primary Flow Path
- Secondary Flow Path

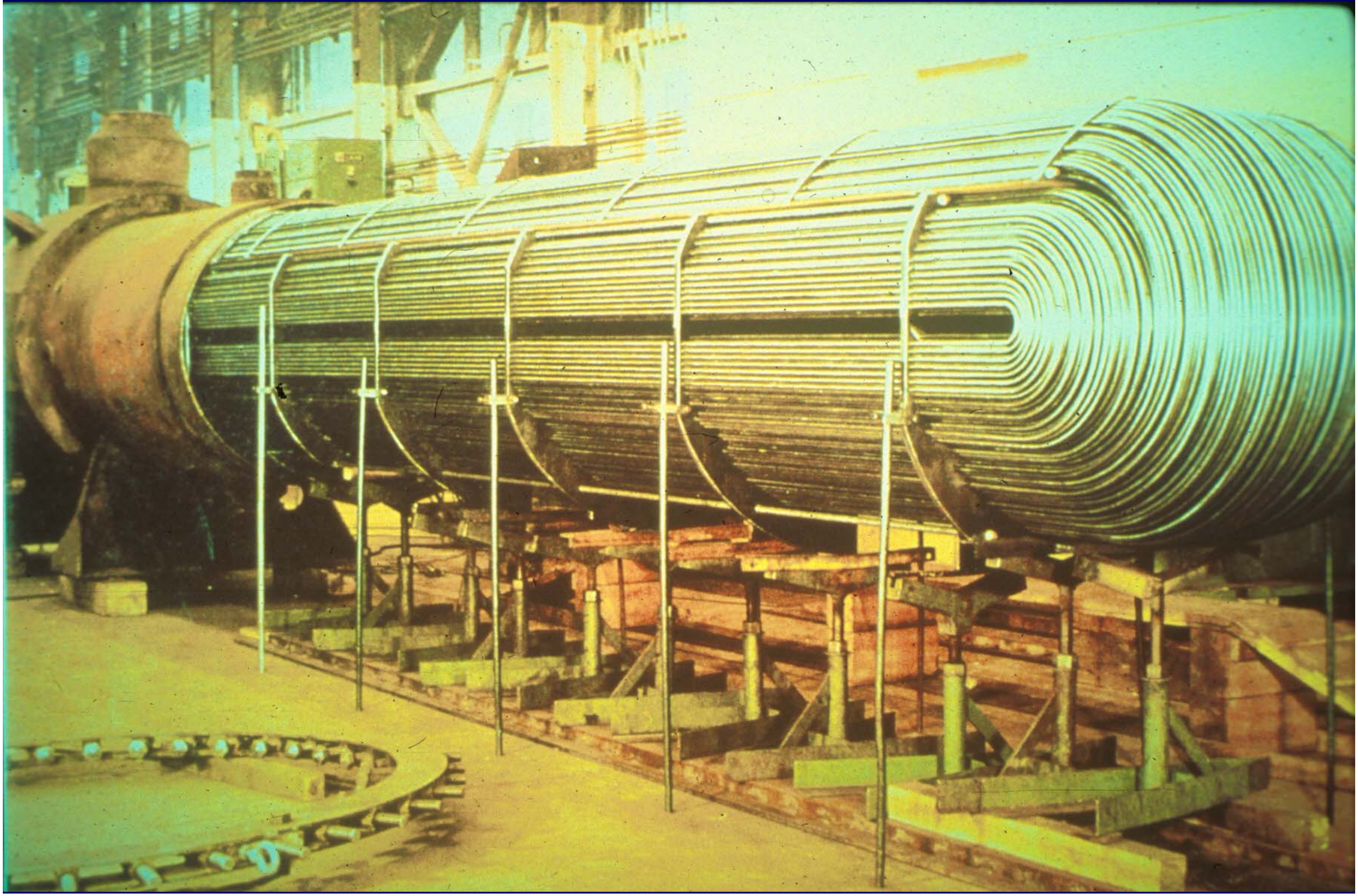


Babcock & Wilcox Once Through Steam Generator

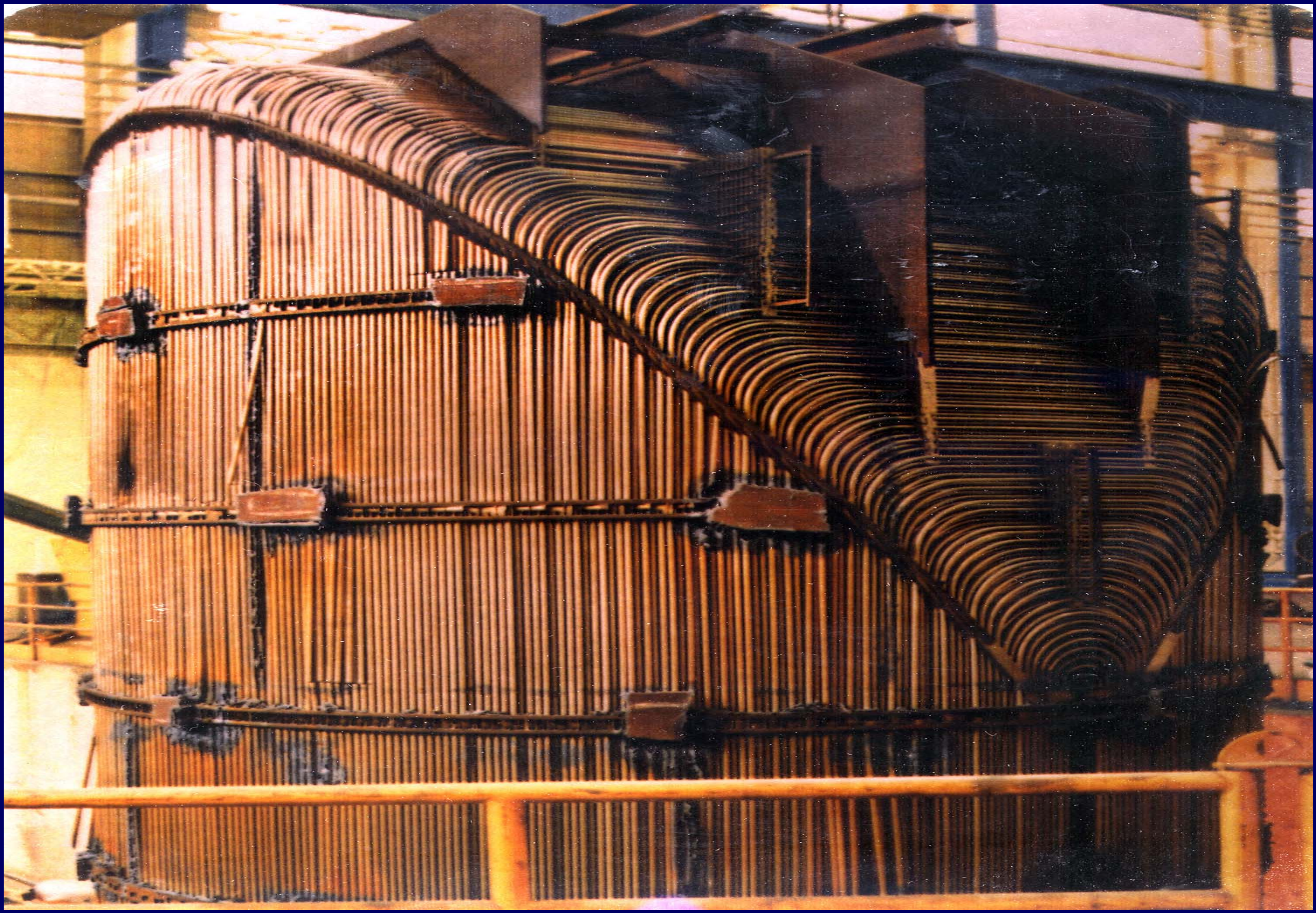


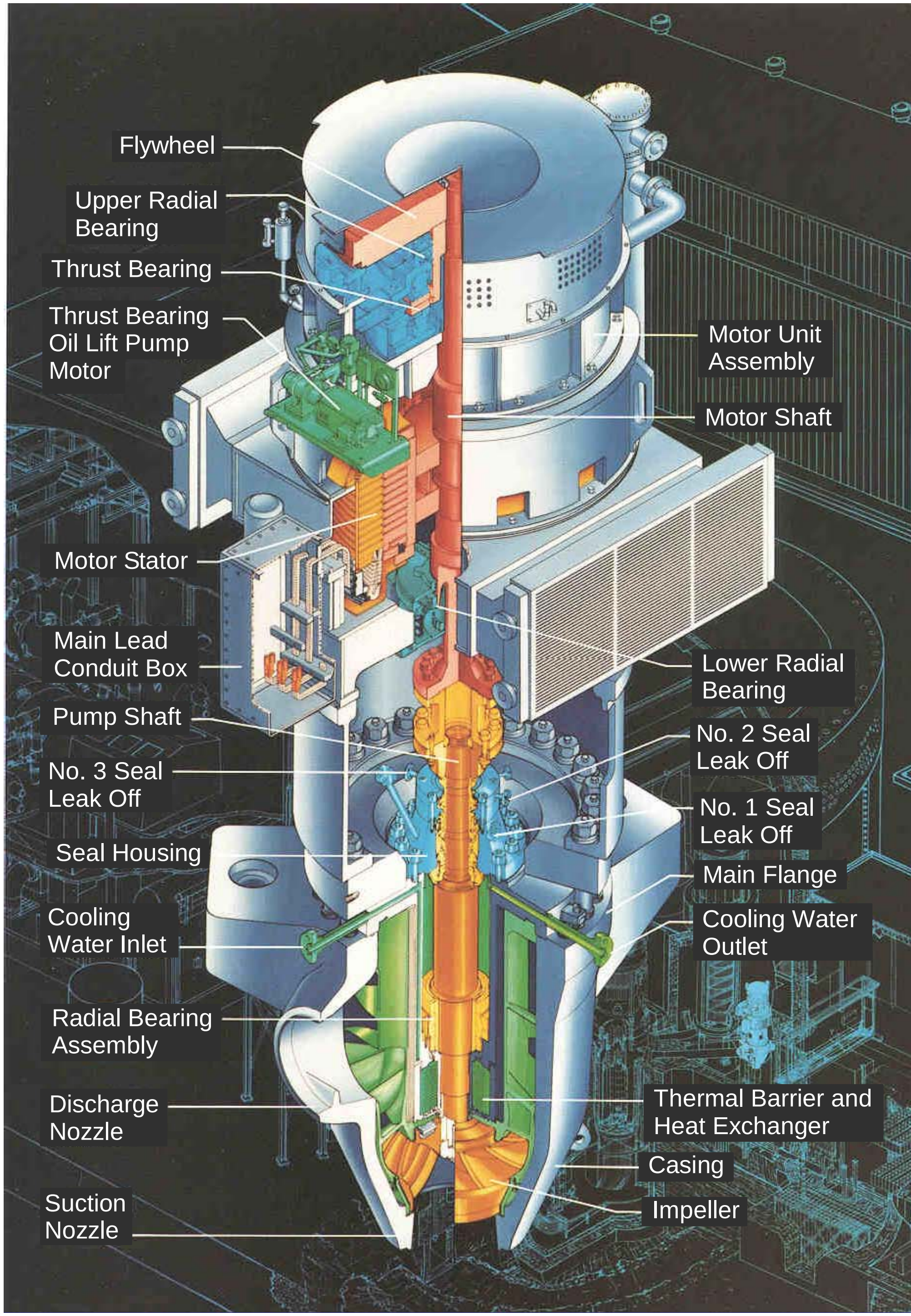
[4-15]

Example of U-tube bundle in a heat exchanger, not a steam generator



Top Section of SG U-Tubes:

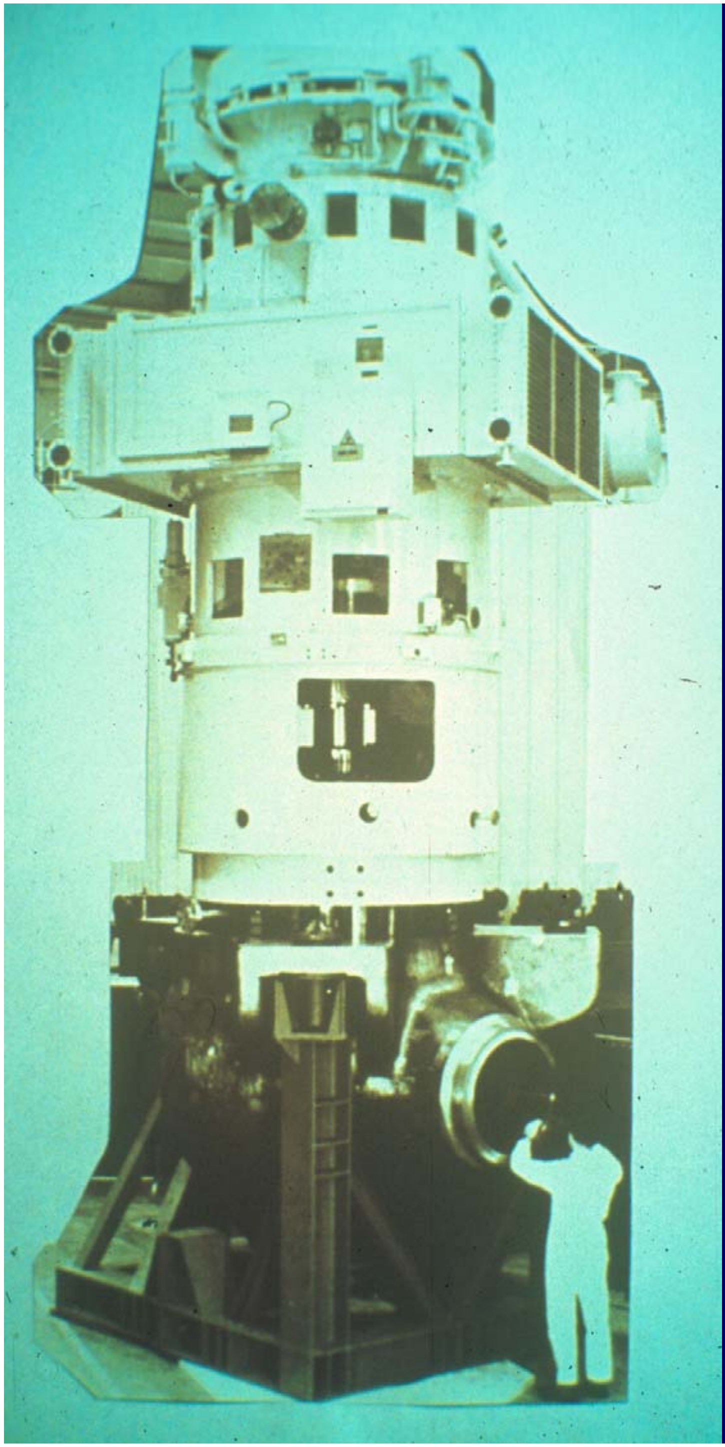




The purpose of the reactor coolant pump is to pump sufficient reactor coolant through the core to remove the heat being generated by the reactor fuel. If the pump is not running, there will still be some flow through the core due to natural circulation. However, the amount of flow is not sufficient to remove the full rated power of the core.

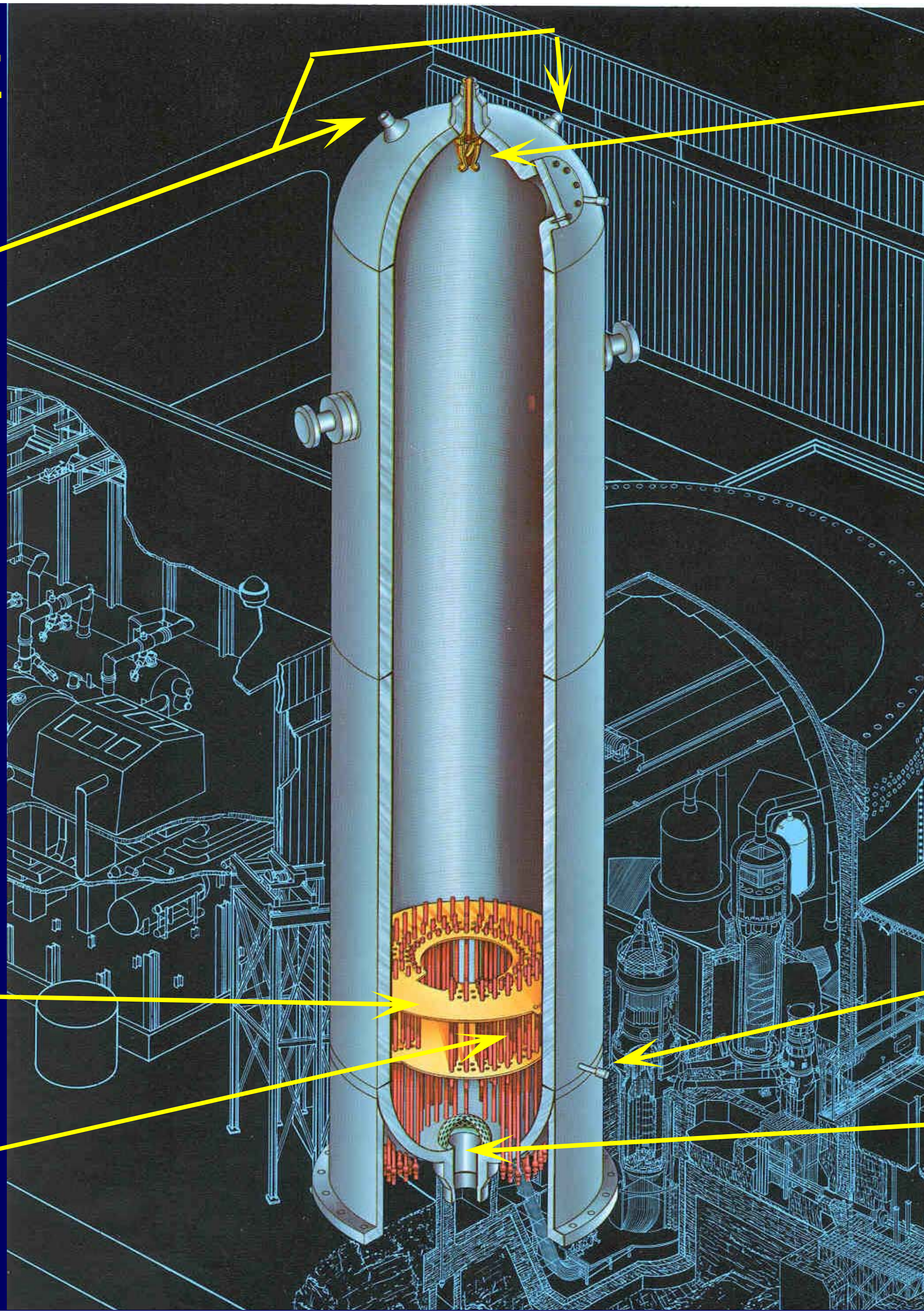
The pump illustrated is a Westinghouse reactor coolant pump. Babcock & Wilcox and Combustion Engineering pumps will be similar, but not necessarily exactly alike.

[4-16&17]

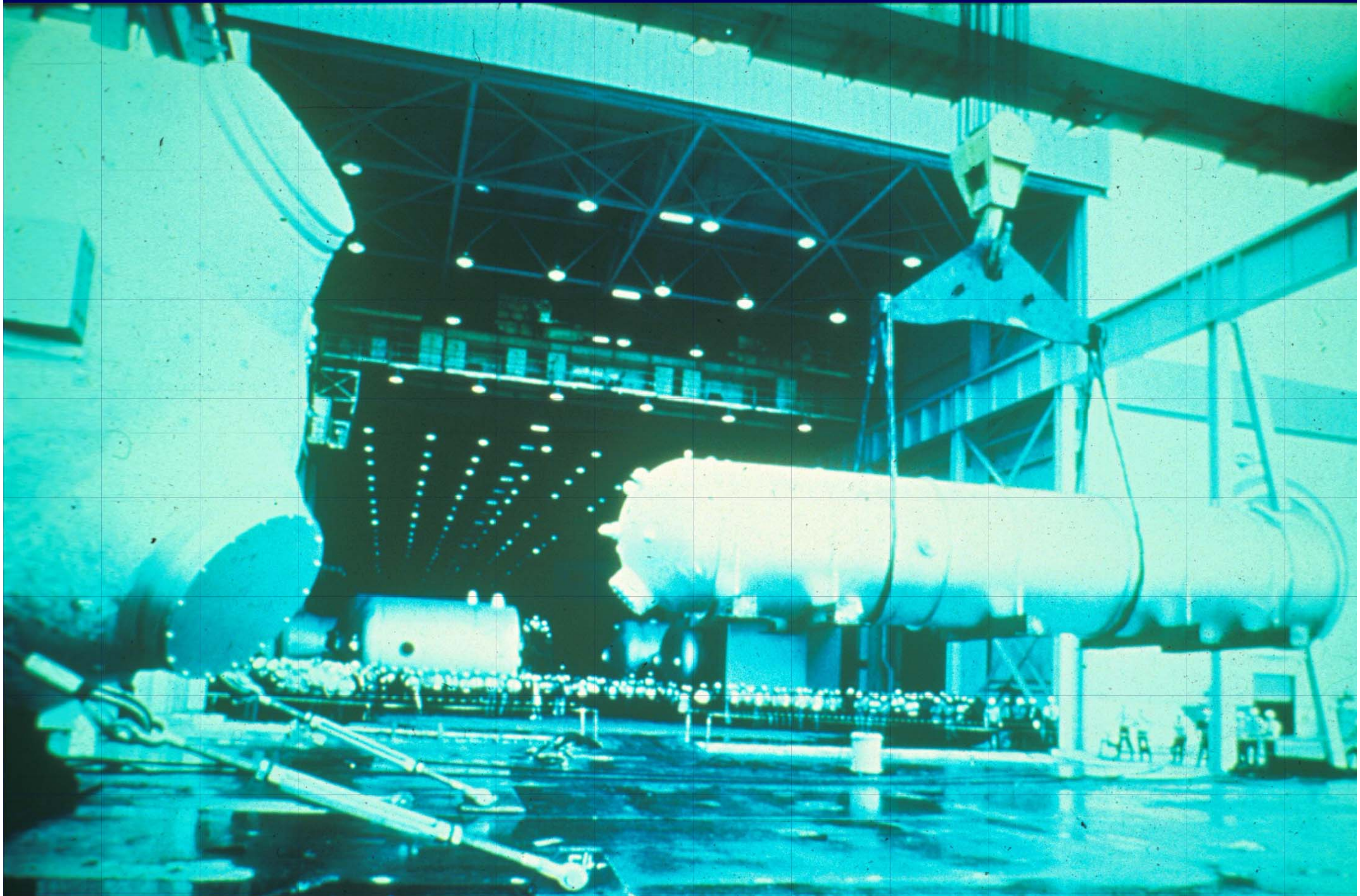


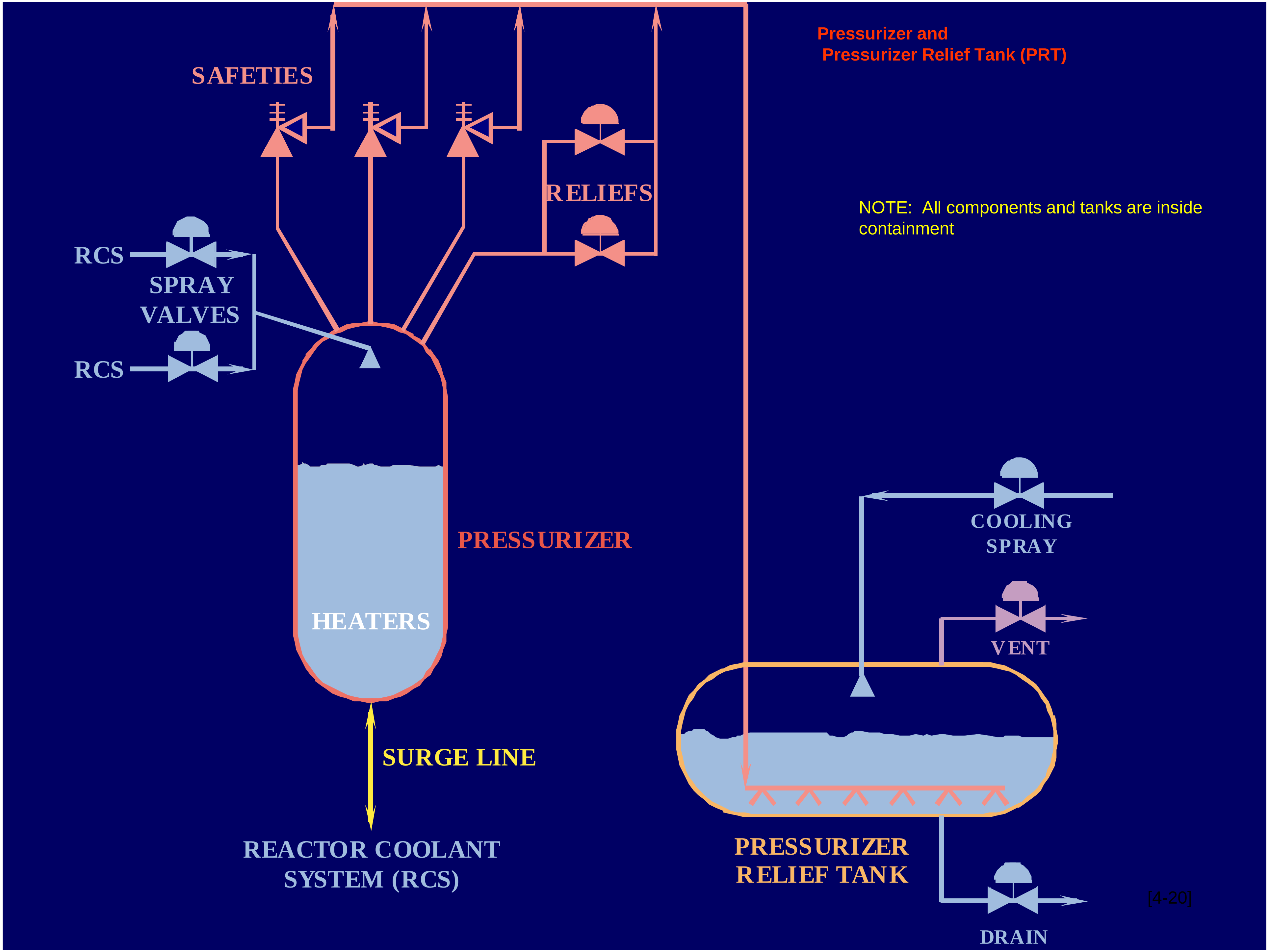
Reactor Coolant Pump

Pressurizer



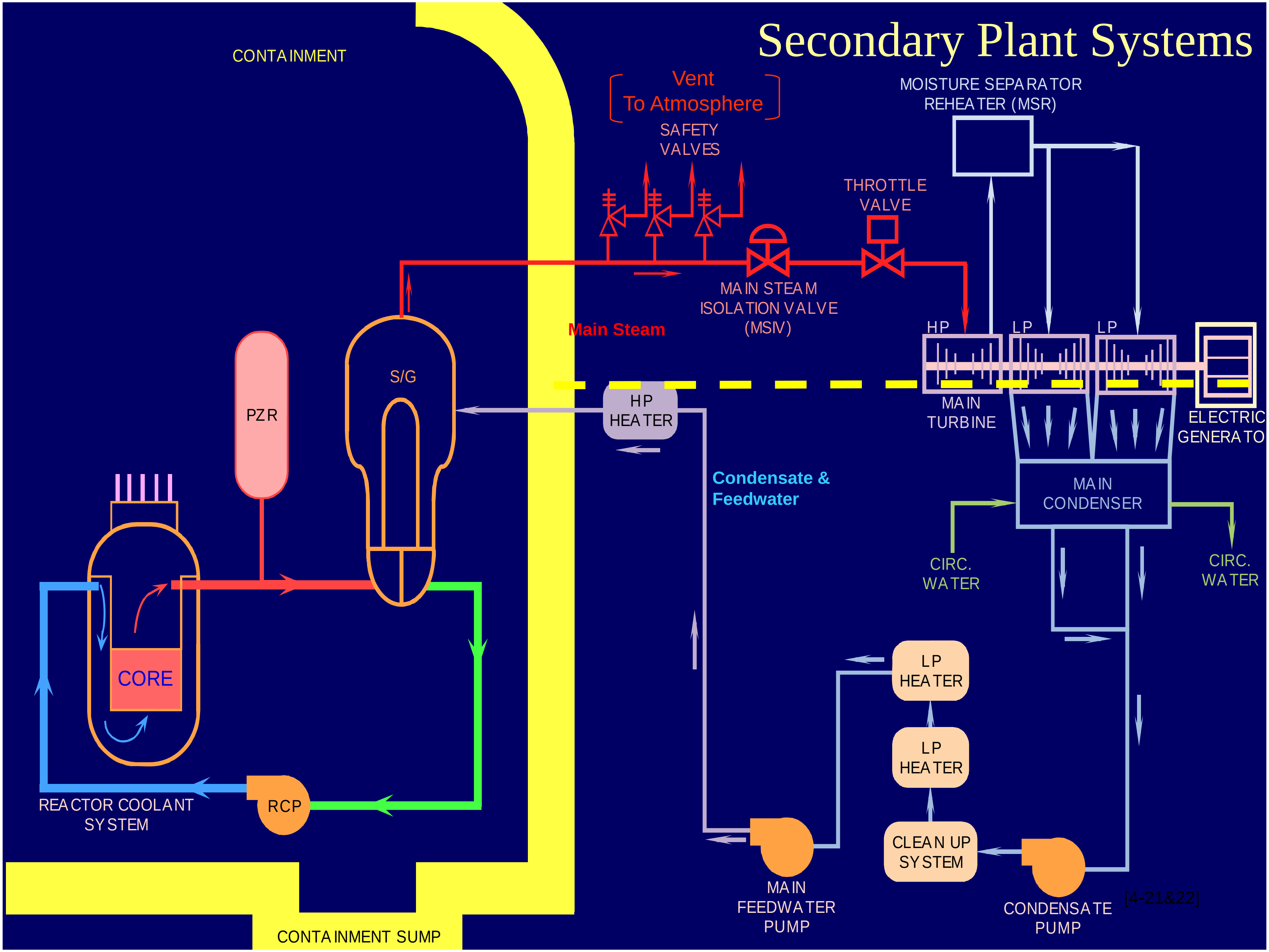
[4-18&19]



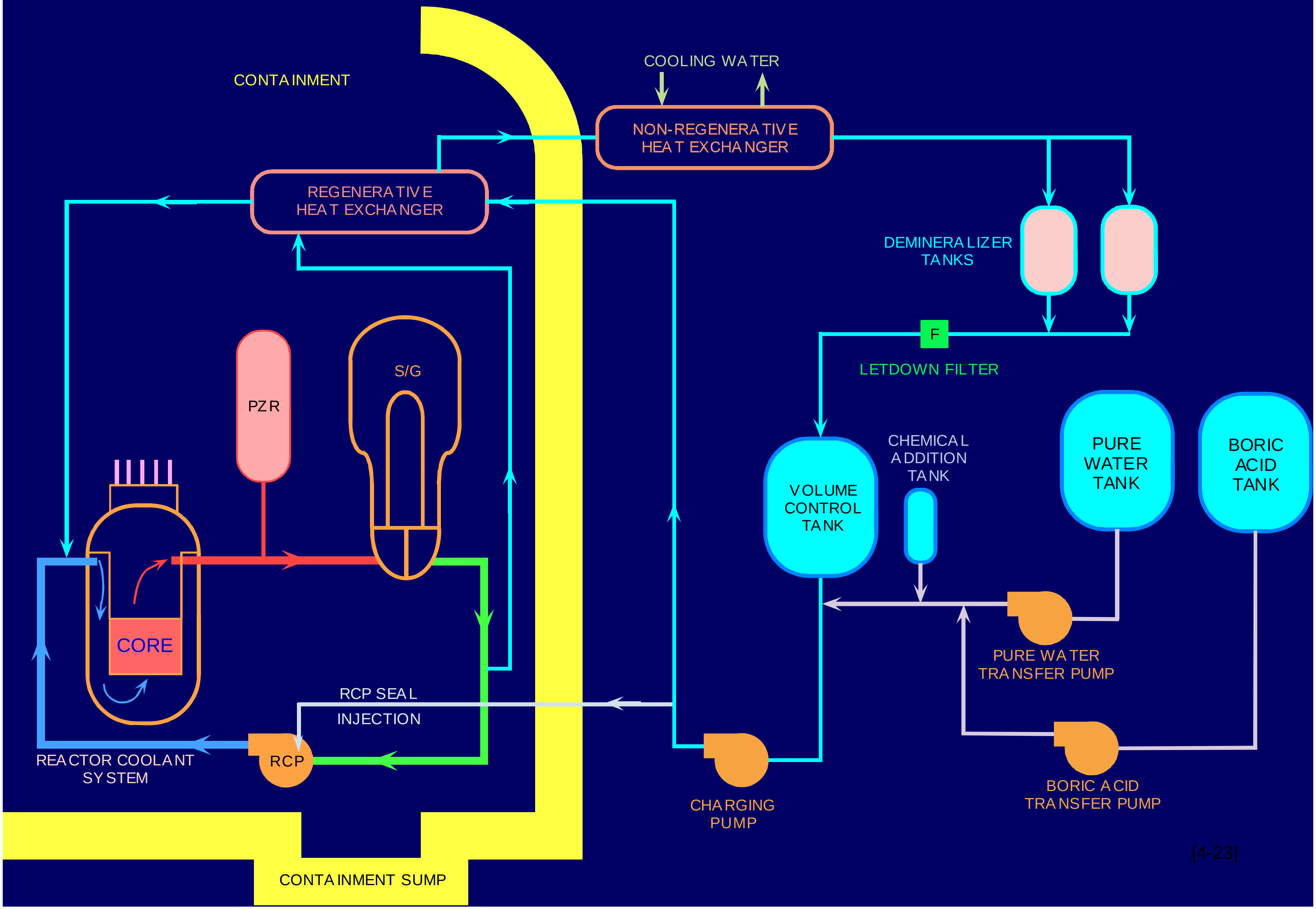


Pressurizer and
Pressurizer Relief Tank (PRT)
NOTE: All components and tanks are inside containment
SAFETIES
RELIEFS
RCS
SPRAY
VALVES
RCS
PRESSURIZER
HEATERS
SURGE LINE
REACTOR COOLANT
SYSTEM (RCS)
COOLING
SPRAY
VENT
PRESSURIZER
RELIEF TANK
DRAIN
[4-20]

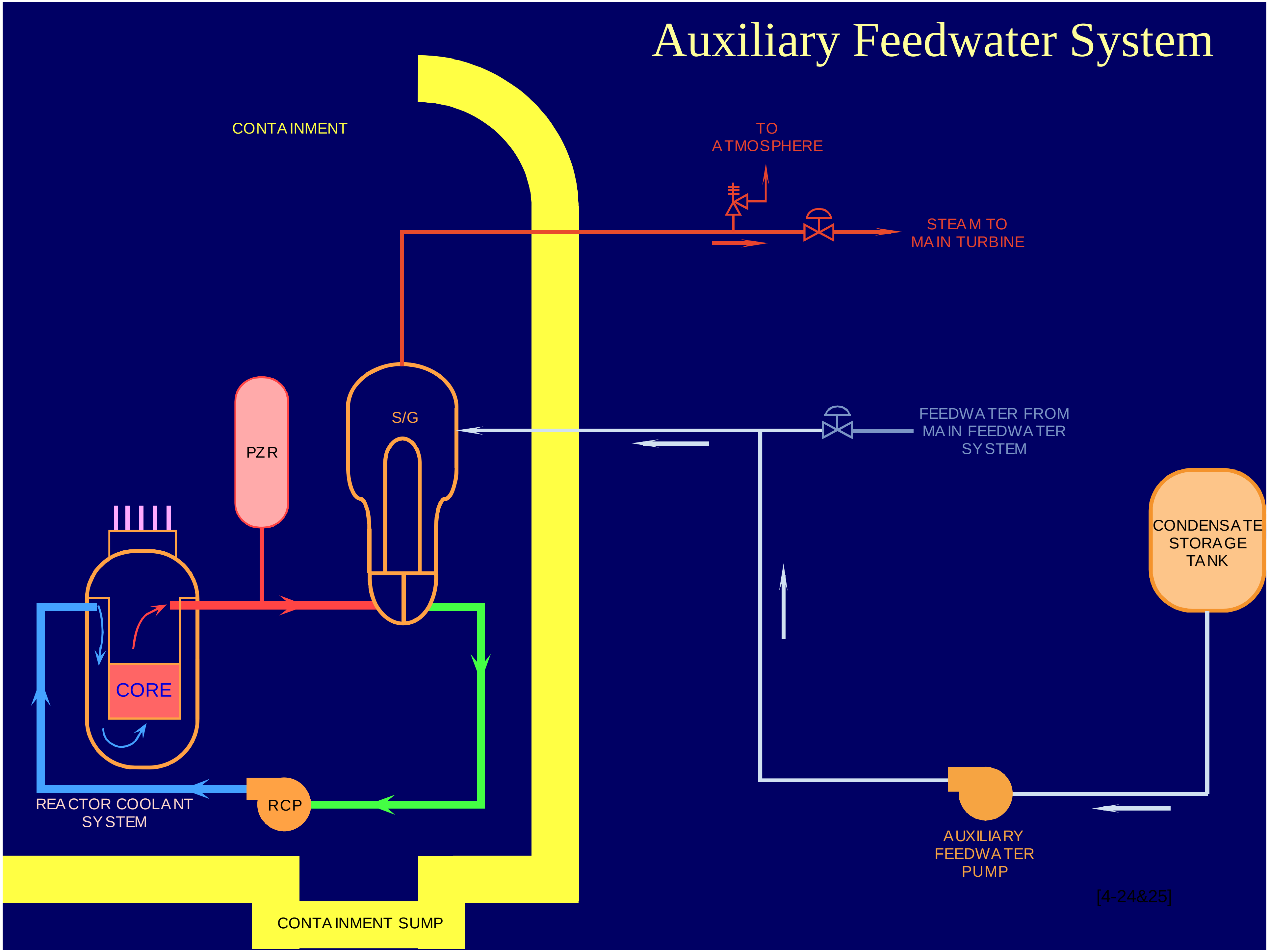
Secondary Plant Systems



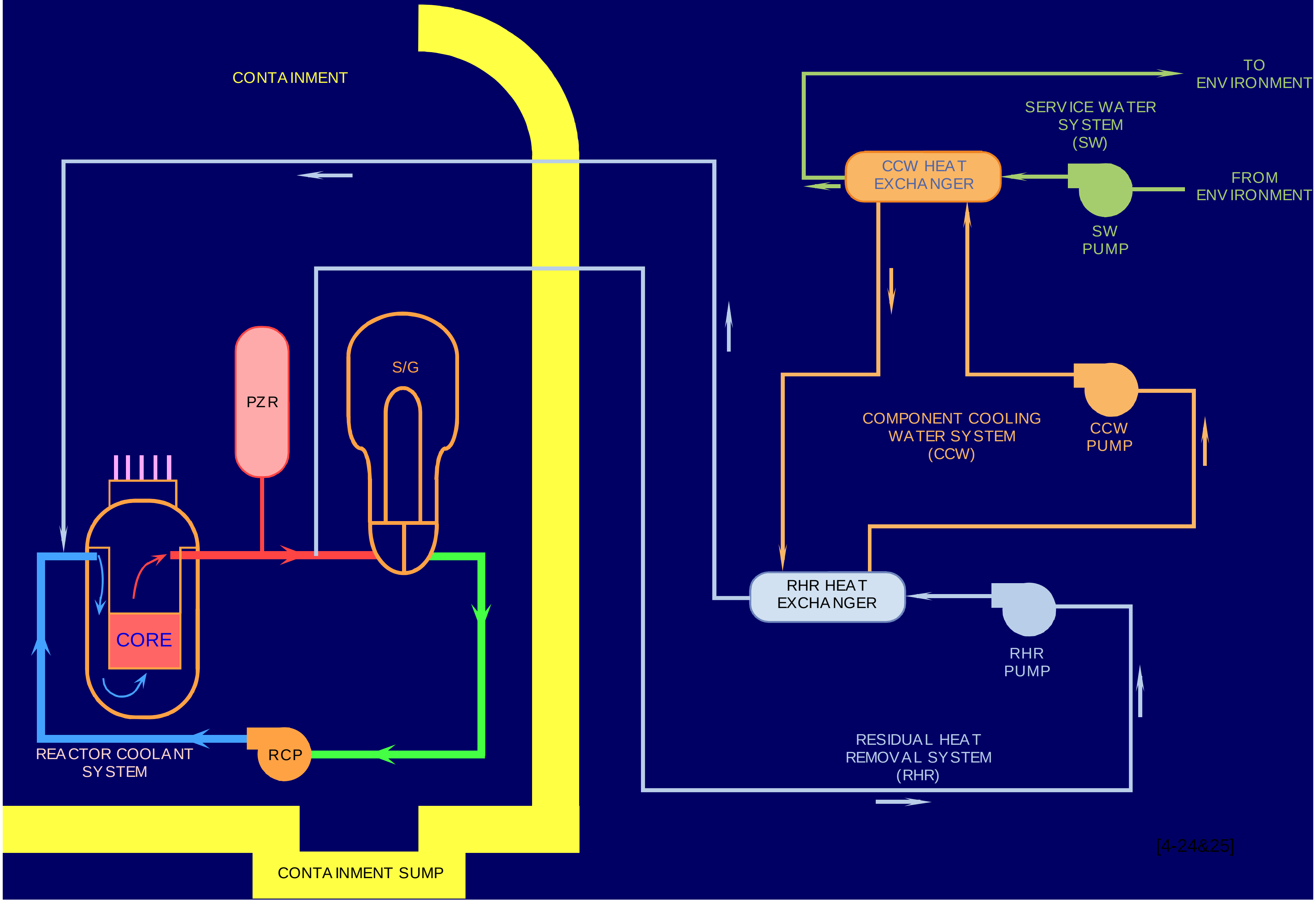
Chemical and Volume Control System



[4-23]


Auxiliary Feedwater System
CONTAINMENT
TO
ATMOSPHERE
STEAM TO
MAIN TURBINE
S/G
PZR
FEEDWATER FROM
MAIN FEEDWATER
SYSTEM
CONDENSATE
STORAGE
TANK
CORE
REACTOR COOLANT
SYSTEM
RCP
AUXILIARY
FEEDWATER
PUMP
[4-24&25]
CONTAINMENT SUMP

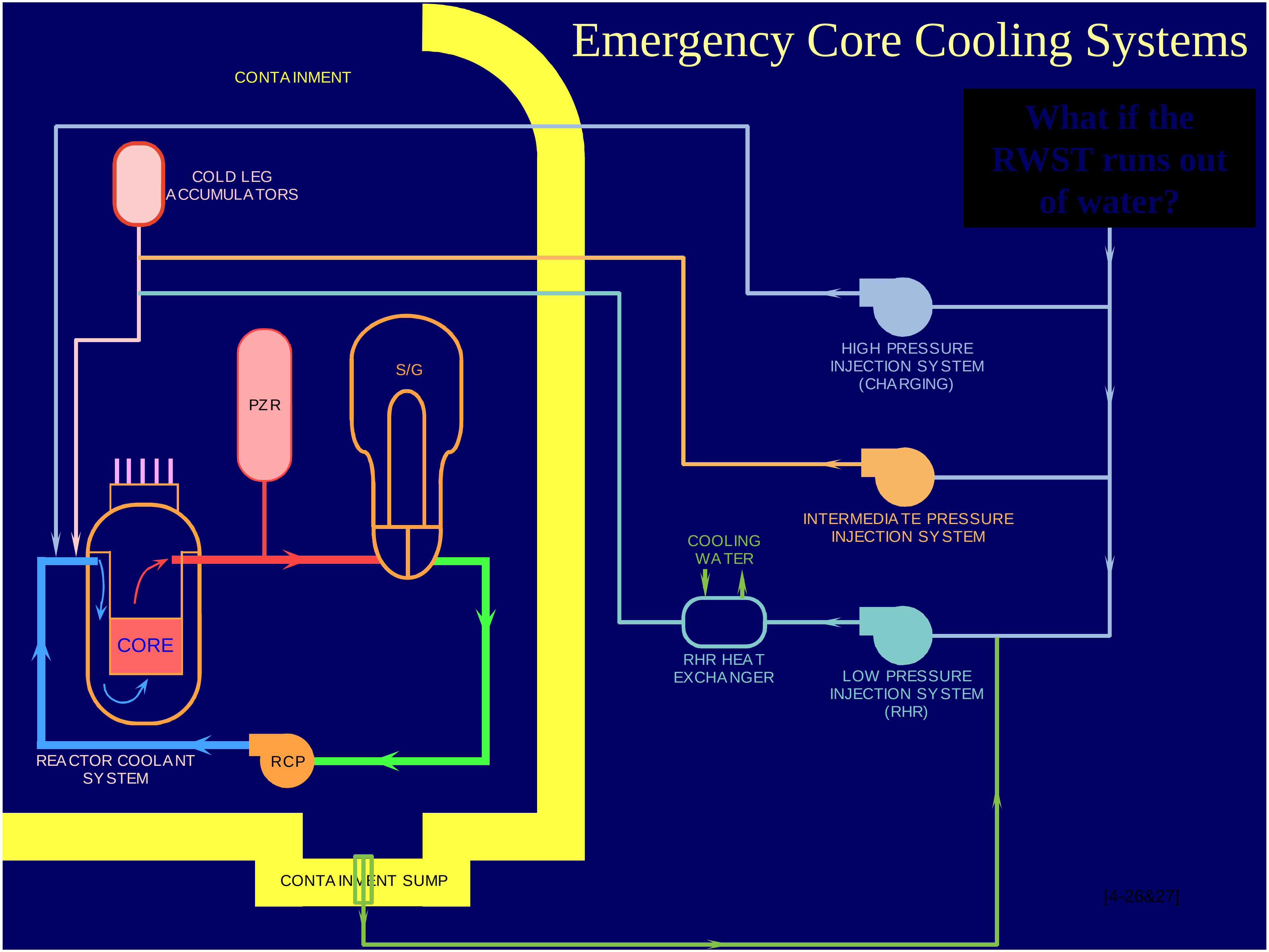
Residual Heat Removal System

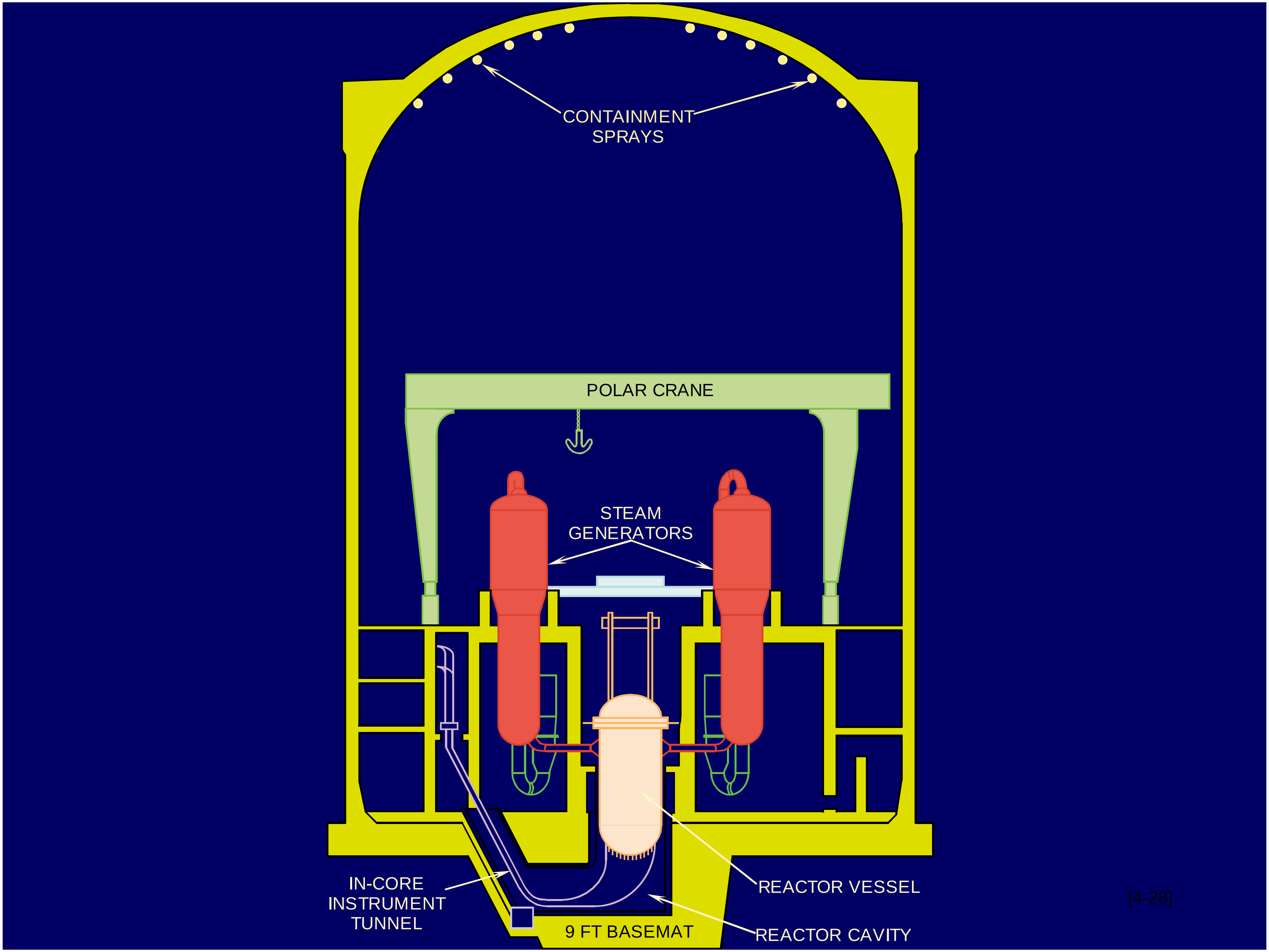


[4-24&25]

Emergency Core Cooling Systems

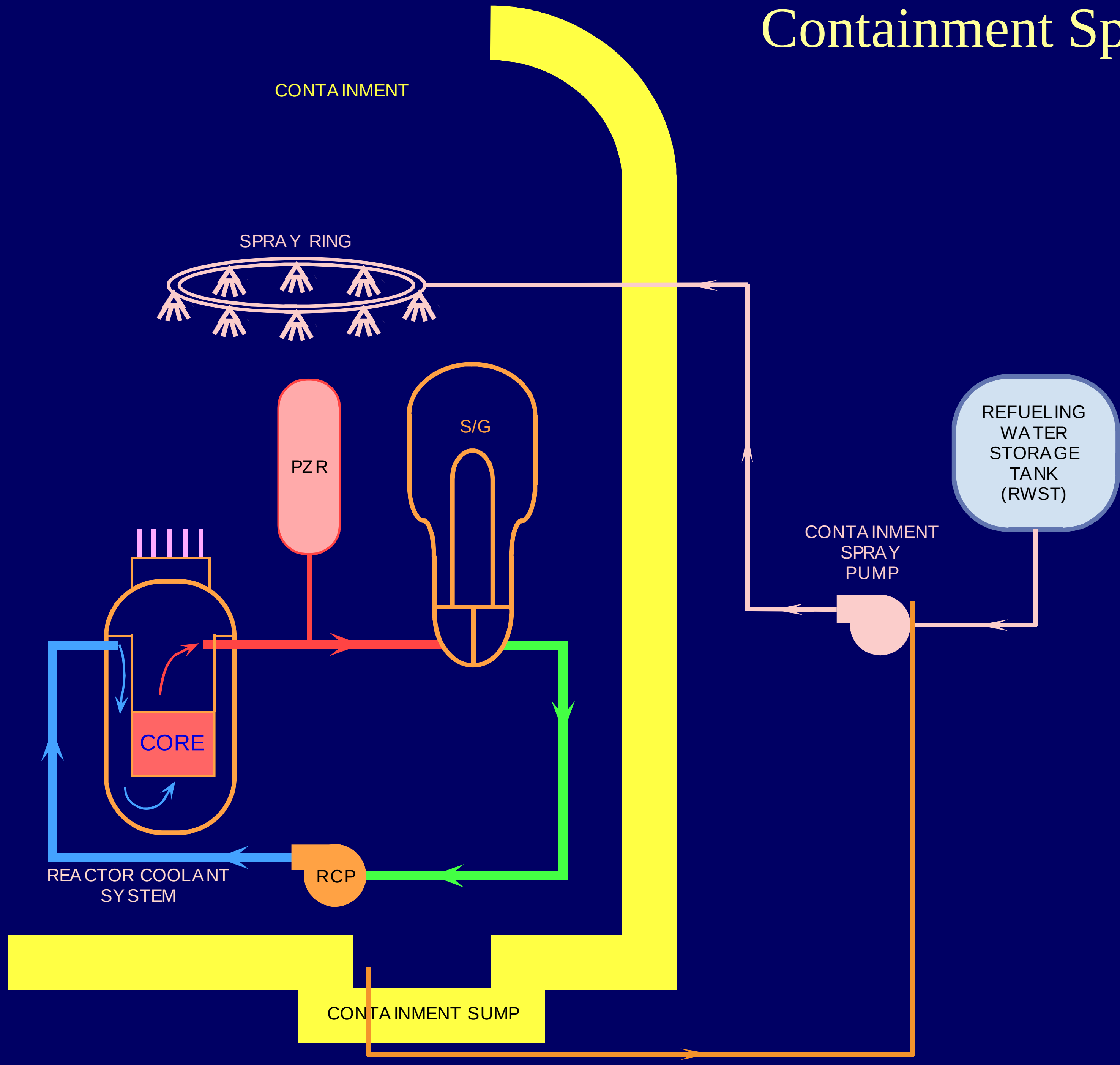
What if the RWST runs out of water?



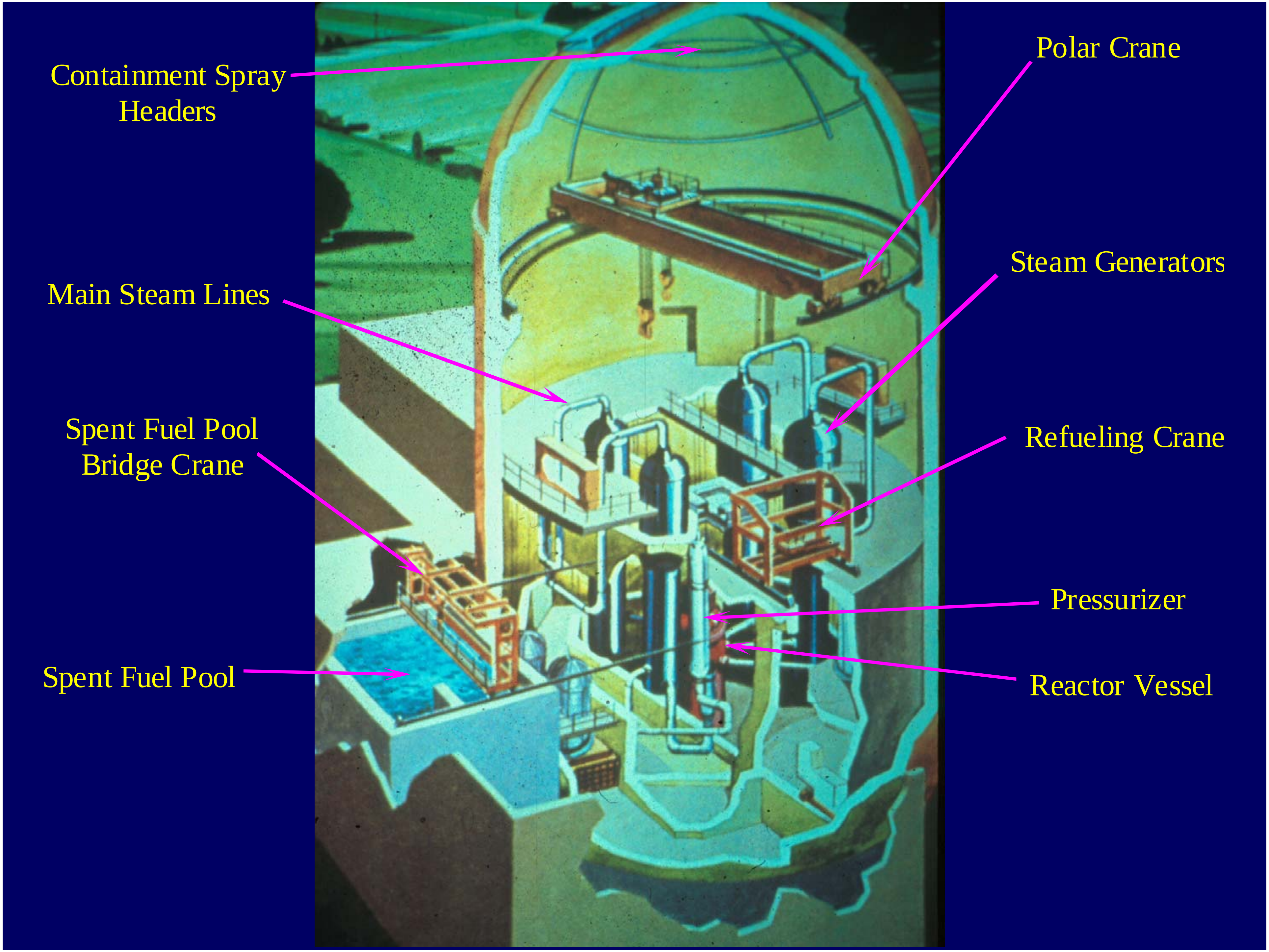

CONTAINMENT
SPRAYS
POLAR CRANE
STEAM
GENERATORS
IN-CORE
INSTRUMENT
TUNNEL
9 FT BASEMAT
REACTOR VESSEL
REACTOR CAVITY

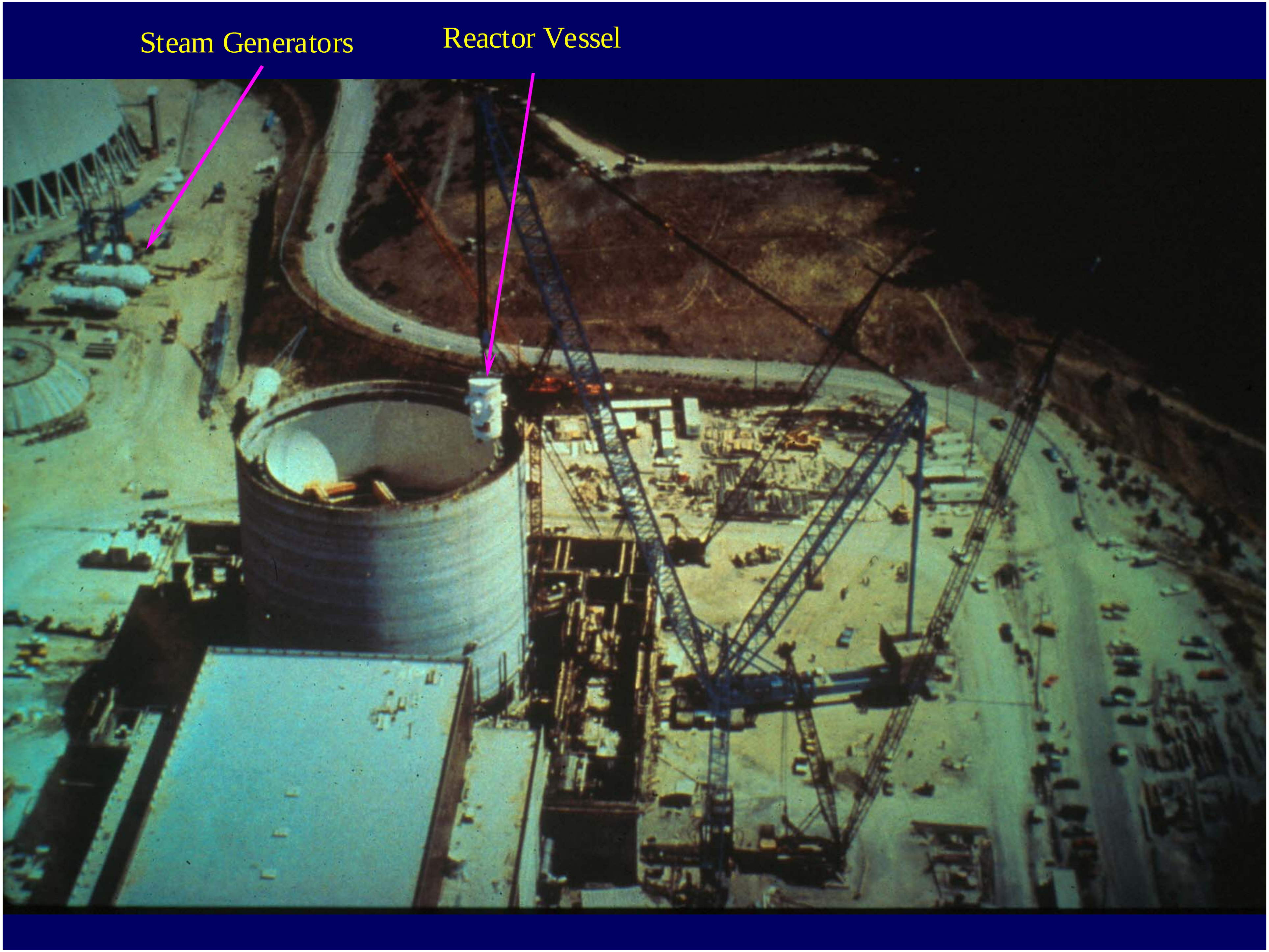
[4-28]

Containment Spray System

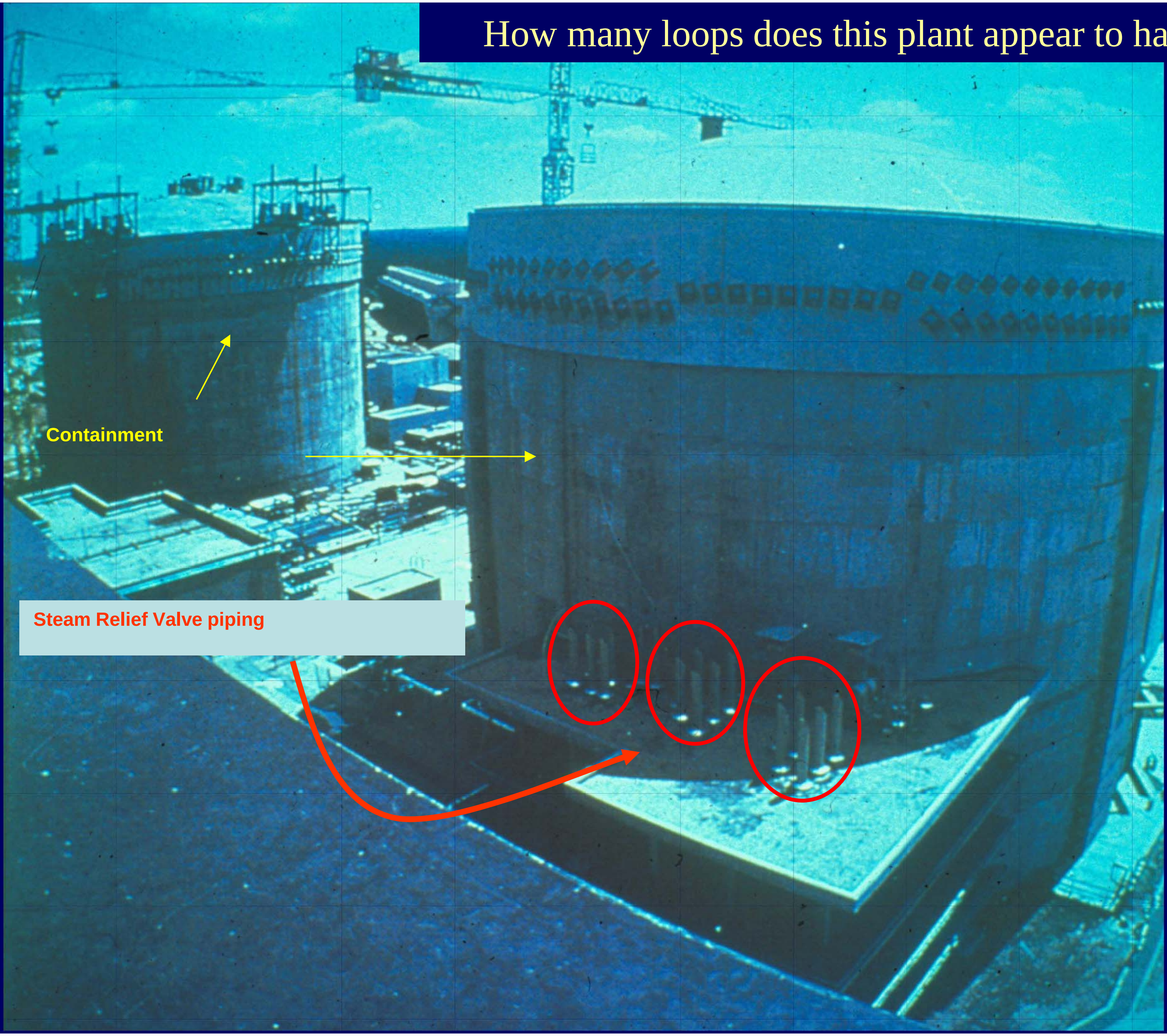


[4-29]


Containment Spray Headers
Polar Crane
Main Steam Lines
Steam Generators
Spent Fuel Pool Bridge Crane
Refueling Crane
Pressurizer
Spent Fuel Pool
Reactor Vessel


Steam Generators
Reactor Vessel

How many loops does this plant appear to have?



Names are different, but the function is the same:

Chemical and Volume Control System (W, CE) ⇨
Makeup and Purification System (B&W)

Cold Leg Accumulators (W) ⇨
Core Flood Tanks (B&W) ⇨
Safety Injection Tanks (CE)

Residual Heat Removal (W) ⇨
Decay Heat Removal System (B&W) ⇨
Shutdown Cooling System (CE)

Auxiliary Feedwater System (W) ⇨
Emergency Feedwater System (CE, B&W)