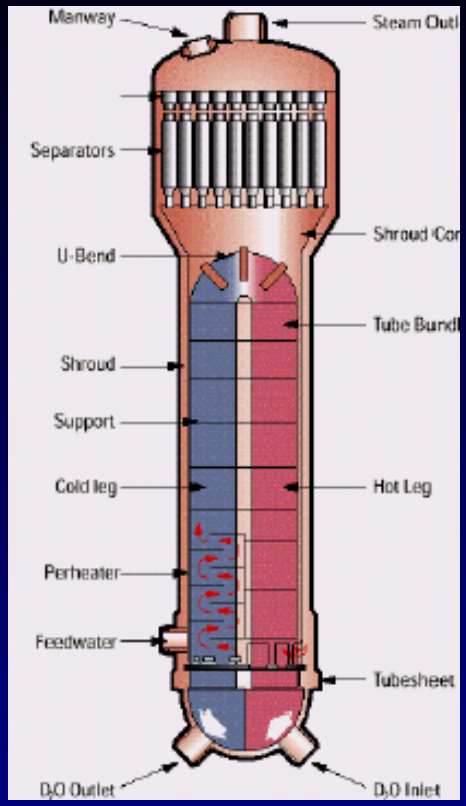
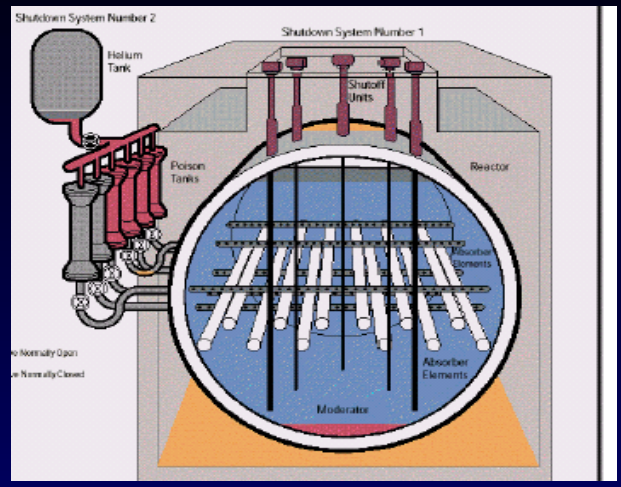
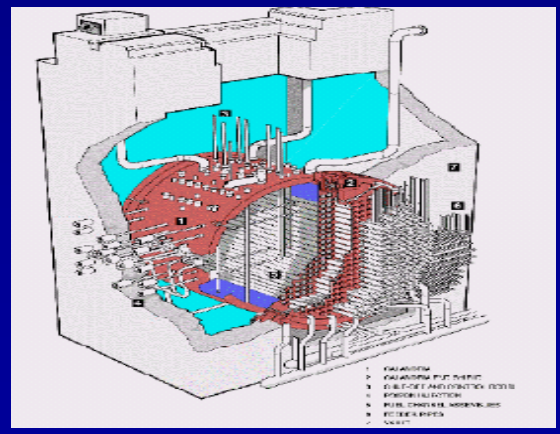




Module 07
Heavy Water Moderated and Cooled Reactors (CANDU)



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CANDU = CANADIAN -DEUTERIUM-URANIUM REACTOR

- ZEEP reactor – first nuclear reactor outside the USA, September 5th, 1945
- NRX reactor – first large scale (40 MW_{th}) research reactor in the world, operated for 44 years in Chalk River
- NRU – source of 85% of world's supply of medical isotopes, operating since 1957
- NPD- prototype CANDU power reactor operated from 1962 to 1987
- Douglas point – evolutionary CANDU design, 10 x power of NPD
- Led to construction of four Pickering NPP 1971

CANDU´s Worldwide

- Canada: 22
- India: 12 + 6 under construction
- Pakistan: 1
- Korea: 4 + 1 under construction
- Romania: 1 + 1 under construction
- Argentina: 1
- China: 2

Darlington NPP

- Ontario Power Generation

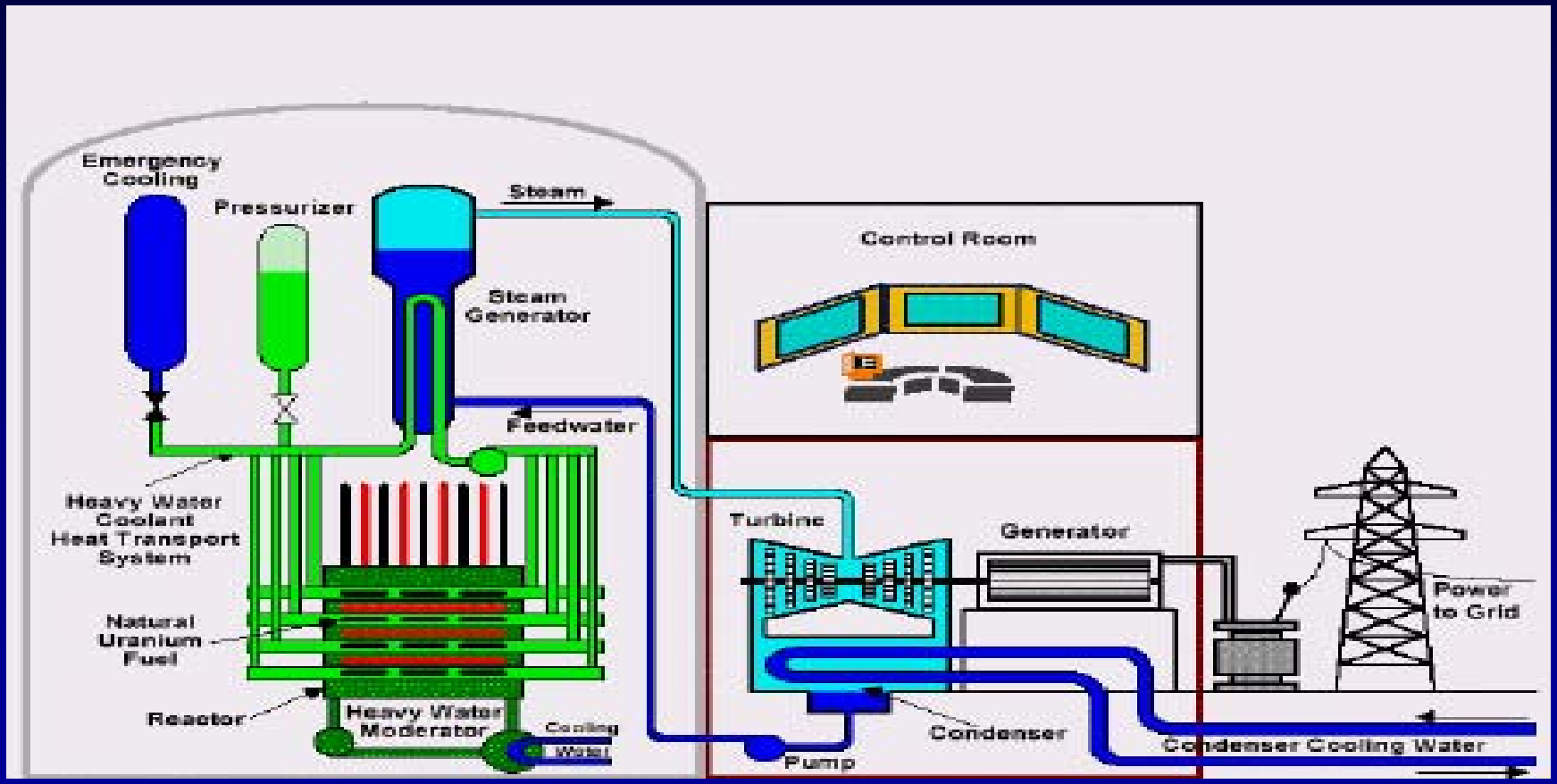
4 units operating
881 $MW_{e\ net}$ each

Pickering NPP

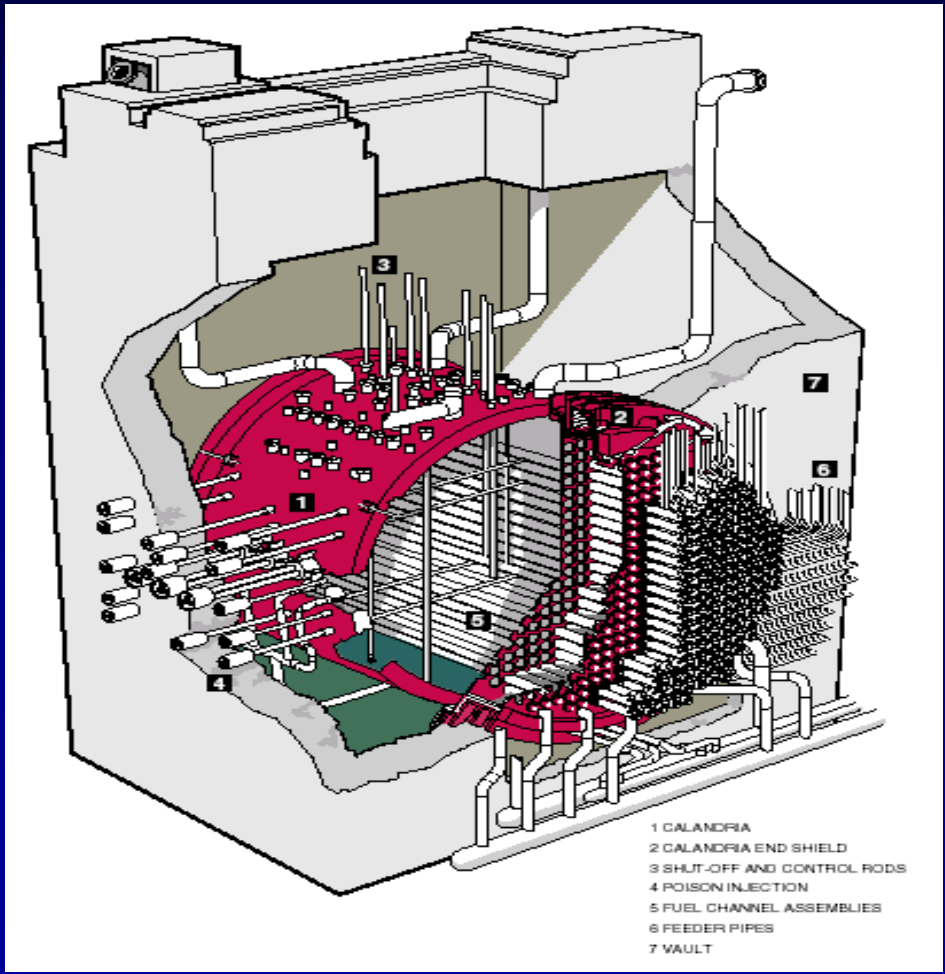
Ontario Power Generation

8 units
(Units 2&3 shut down)
516 $MW_{e\ net}$ each

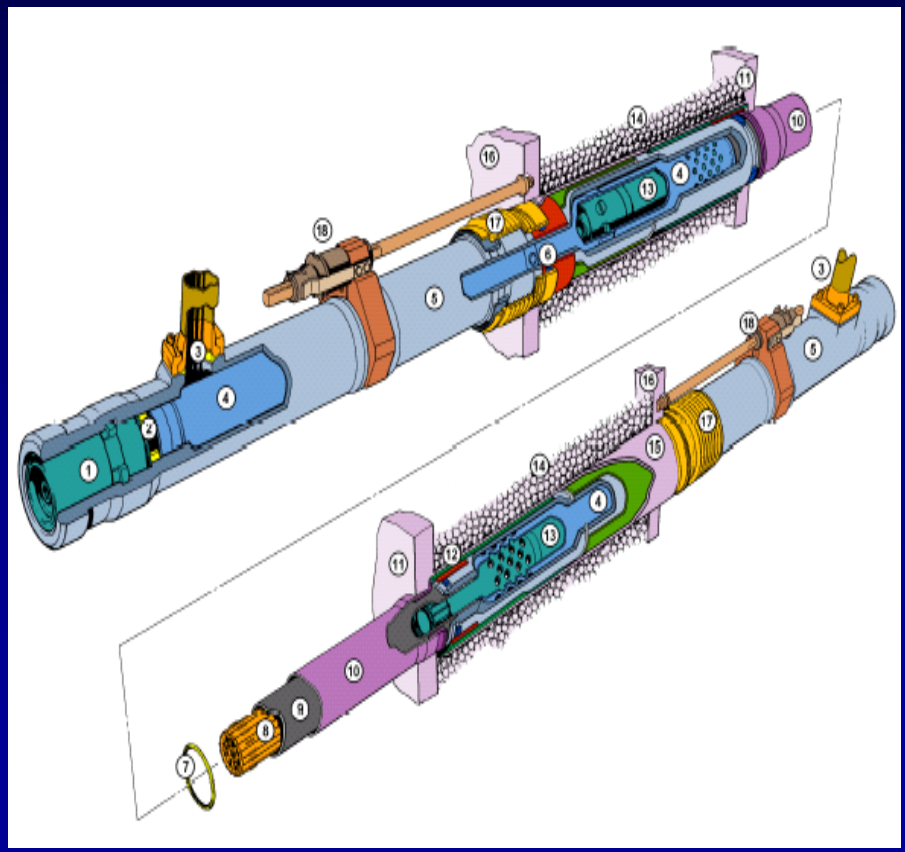
CANDU System



Calandria and Pressure Tubes



CANDU 6 Fuel Channel



- CANDU-6 fuel channel consists in a series of 12 *fuel bundles* in a single reactor channel.
- Each bundle has a length 495 mm, diameter 102.4 mm.
- Each assembly composed of 37 fuel pins (small zircaloy tubes).
- Containing 18.5 kg of natural uranium in form of UO2 pellets,

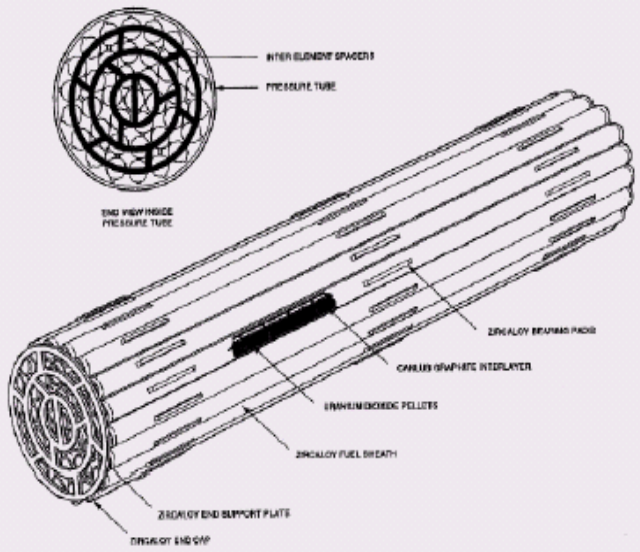
Fuel Bundle

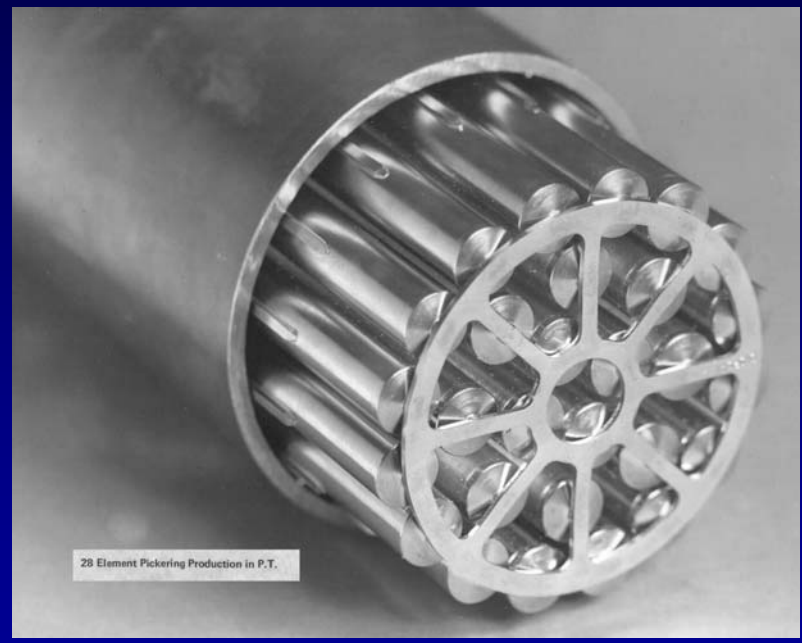
(1) CANDU 6 and CANDU 9 reactors use the 37-element fuel bundle design;

(2) the fuel sheath is made from Zircaloy-4:
- low neutron absorption,
- good corrosion resistance,
- low hydrogen pickup;

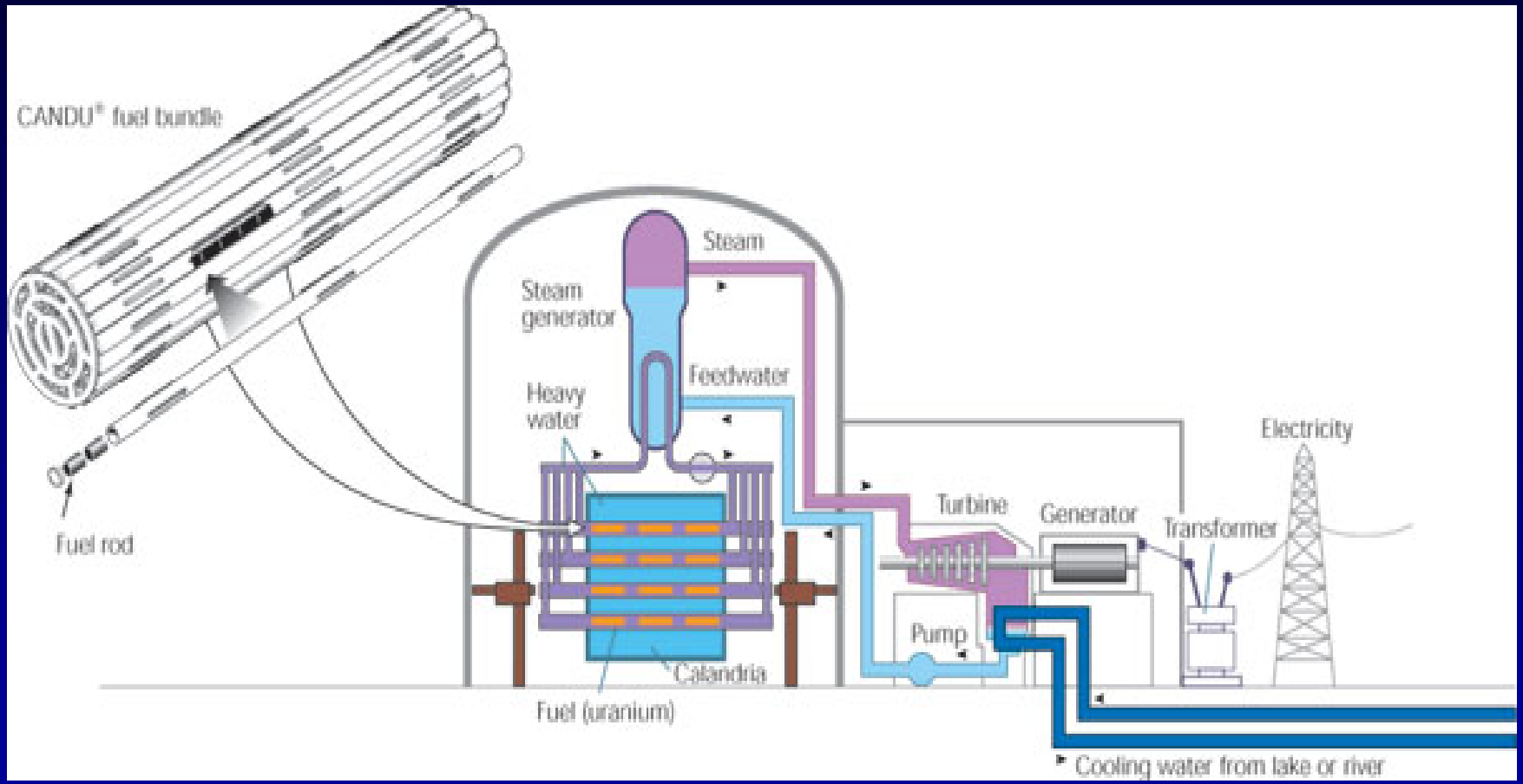
(3) the fuel pellets are made from uranium dioxide with 0.71% U235;

(4) a fully loaded fuel bundle weighs about 24 kg, of which more than 90% is uranium oxide fuel; bundle length is 495.3 mm, outside diameter is 102.4 mm.

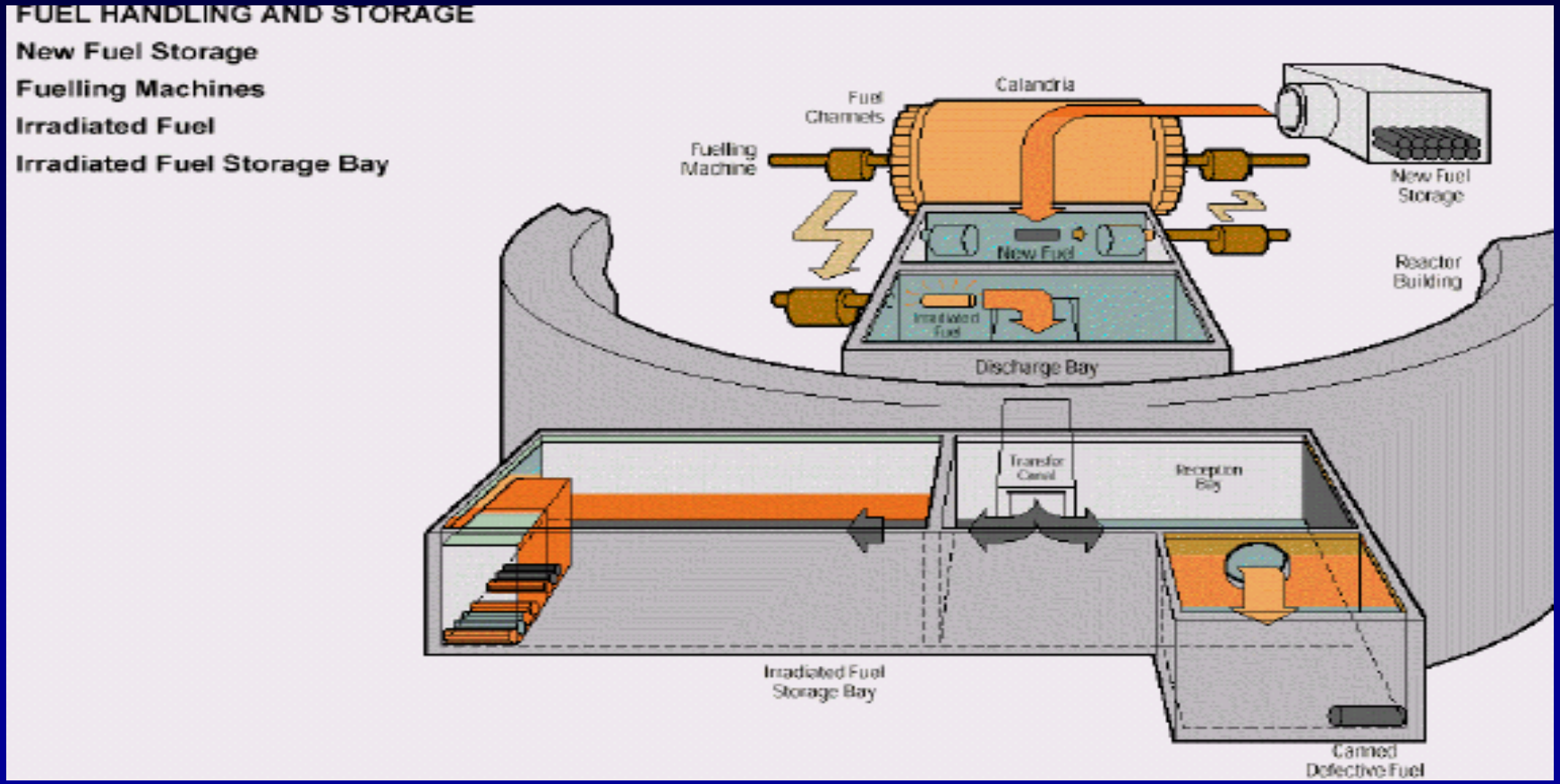




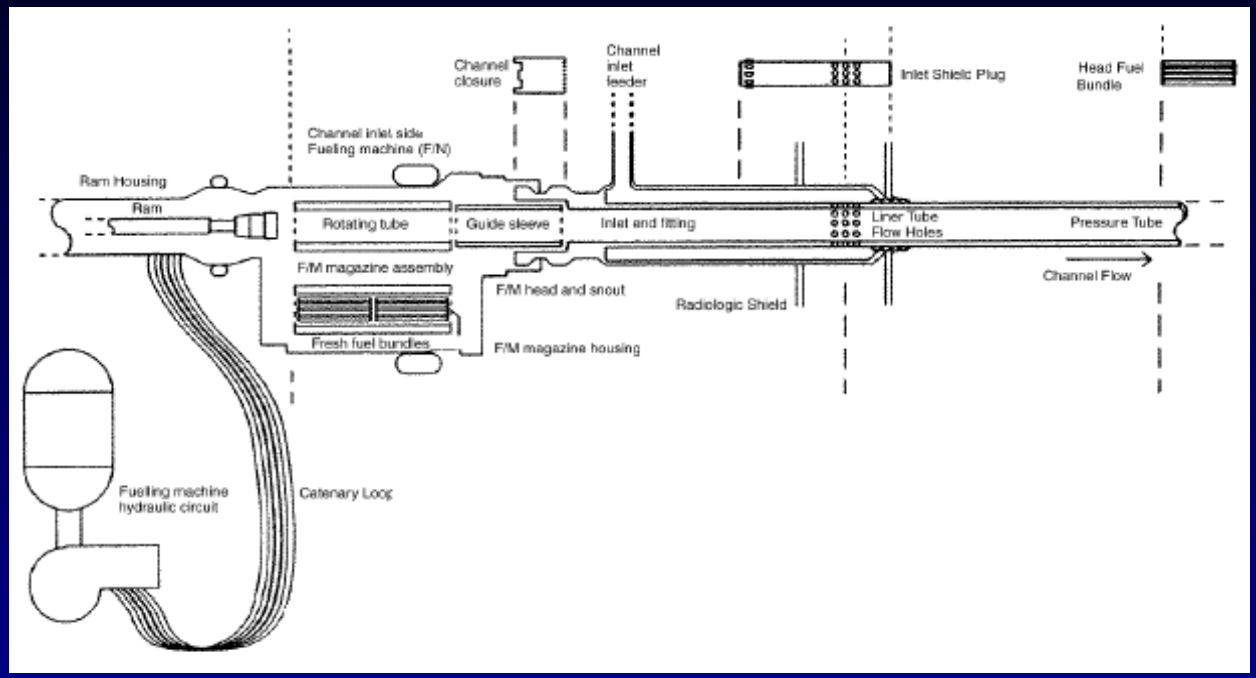
Core and Fuel



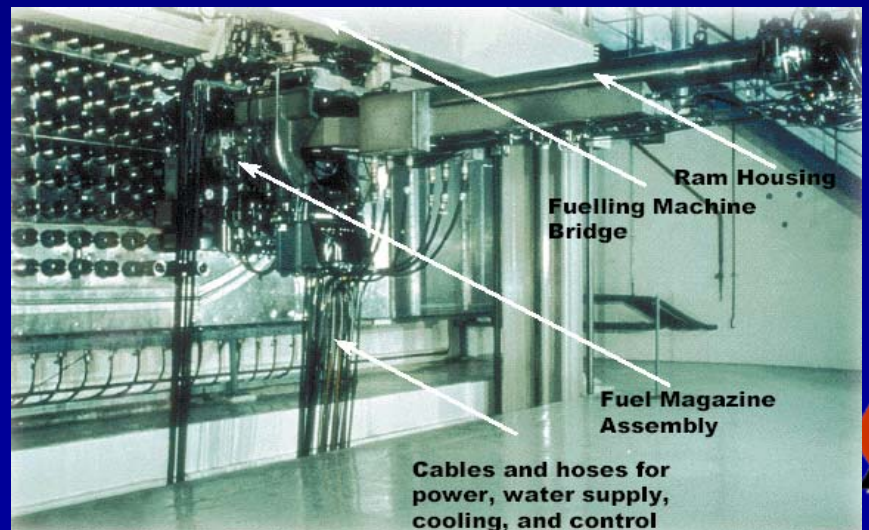
Fuel Handling and Storage



Refuelling Device



- Normally 112 fuel assemblies or 14 channels pe rweek
- 2-bundle, 4-bundle or 8- bundle fuel shuffling is possible



Refuelling Cycle

- Each complete fuelling cycle (from pickup of fresh fuel to discharge of used fuel) takes about 2.5 hours
- In a standard CANDU 6 five distinct phases occur during the flow assisted fuelling (FAF):
- Channel opening to the fuelling machines
- Shield plugs removal
- Insertion of the required number of fresh fuel bundles
- Removal of irradiated bundles
- Replacement of the plugs to close the channel

Spent Fuel Handling System

- After approximately one year spent fuel bundles removed from fuel channel by remote controlled fuel handling system
- Transferred to the irradiated fuel bay cooling period at least seven years before transferred to dry storage

Nuclear Steam Supply System

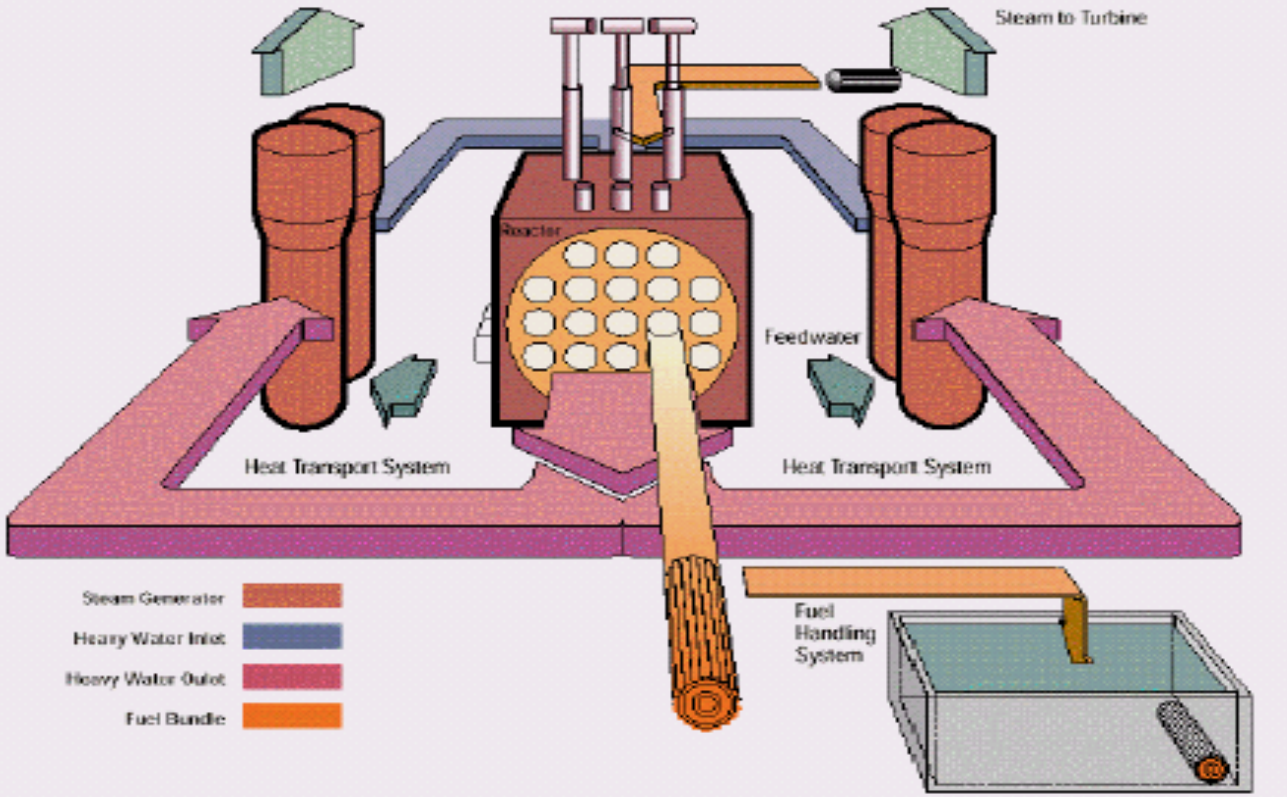
NUCLEAR STEAM SUPPLY SYSTEM

Reactor Assembly
(a) Calandria
(b) Fuel channels
(c) Shielding
(d) Flux detectors
(e) Reactivity Mechanisms

Heat Transport System
(a) Two Loops
(b) 'Hot Leg"
(c) Steam Generators
(d) 'Cold Leg'

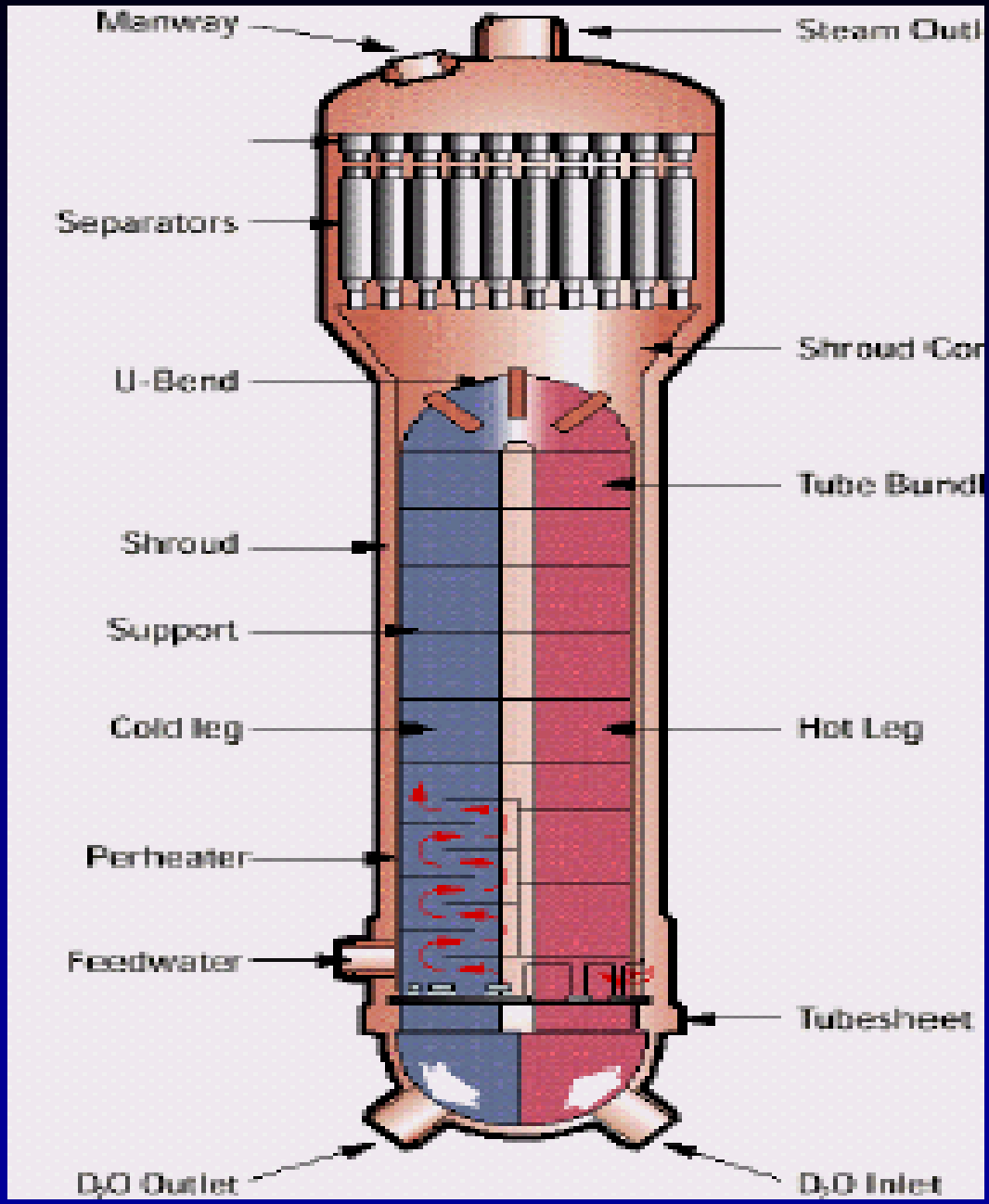
Feedwater and Steam

Fuel Handling
(a) Fresh Fuel
(b) Spent Fuel



Heat Transfer System

- It consists of two main loops each has a ‘hot-leg’, a pair of boilers in each loop and two circulation pumps
- Heavy water is continuously circulated through each loop, carrying the heat from the reactor to the steam generators and back to the reactor
- Steam Generators transfer the heat from the heavy water coolant on the primary side to the light water on the secondary side to form steam



Steam Generator

Example: Pickering A CANDU 6

- Built
  - 1986

  by AECL
- 508 $MW_{e\ net}$
- 1742 MW_{th}
- Operating pressure : 9.5 MPa
- Operating temperature: 293ºC

Pickering A Technical Data

- Fuel rods:
  - Outer diameter: 13 mm
  - Wall thickness: 0.42 mm
  - Diameter pellet: 12.15 mm
  - Fuel: Natural uranium, sintered to ceramic UO_2 pellets, density: 10.6g/cm^3
  - Uranium pellets per rod: 29
  - Cladding material: Zircaloy 4 (99% Zr, Sn, Fe, Ni)
- Fuel bundle:
  - Length: 495 mm
  - Diameter: 102.4 mm
  - Fuel rods per bundle: 28
  - Weight of bundle: 23 kg
  - Weight of uranium: 18.5 kg
  - Fuel bundles per channel: 12
  - Total number of fuel bundles in core: 4680

Pickering A Technical Data

- Reactivity control:
  - Stainless steel clad cadmium tubes: 11
  - Cobalt adjuster rods: 18
  - Boric acid into moderator for fresh fuel only, later on Gadolinium Nitrate used
  - Moderator dump: D_2O is rapidly pumped into a tank, thus the reactor looses it‘s moderator

Pickering A Technical Data

- Calandria: Two concentric, horizontal stainless steel cylinders
- Inner cylinder: core tank, diameter 8.04 m, length 5.94 m, heavy water moderator and coolant with 380 channels in CANDU 6 and 480 in CANDU 9
- Outer cylinder: shield tank diameter:

  8.5 m, length: 6 m holding light water as radiation shield

CANDU 6 vs CANDU 9

- Presently 43 CANDU 6 in operation, (approx. 730 MW_e)
- CANDU 9 single unit design, power > 935 MW_e, but no orders up to now
- Many features from CANDU 6
- Design improvements based on industry, utility and licensing experience
- Major improvements in instrumentation and control

CANDU 6 vs CANDU 9

- Fuel channels:

  CANDU 6: 380, CANDU 9: 480
- Fuel bundles: 37 fuel pencils
- Coolant pressure: 9.9 MPa
- Number of primary pumps: 4
- Number of steam generators: 4

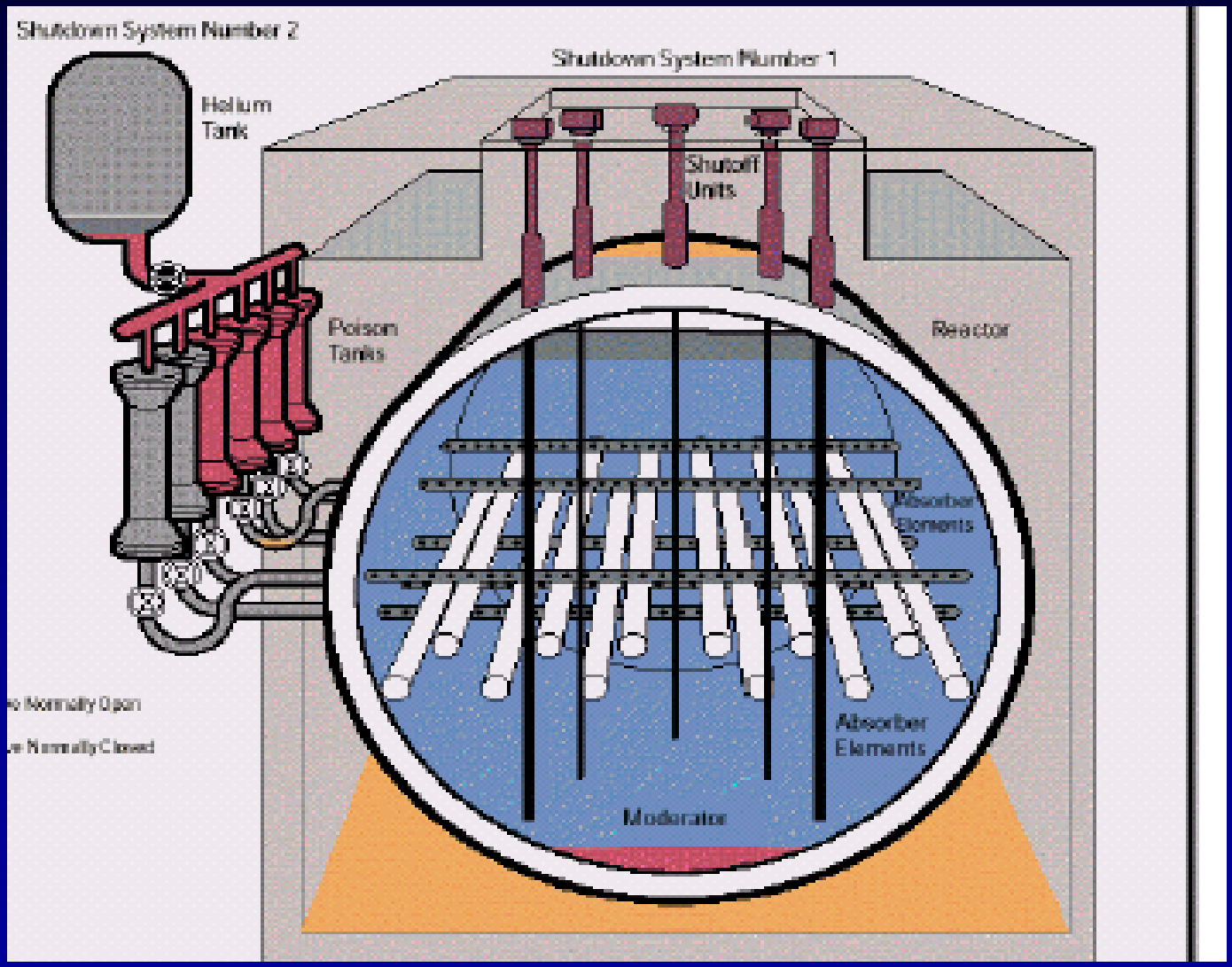
Reactivity Control

- Two types of control rods are used:
  Adjusters and Mechanical Control Absorbers
- Adjuster Rods: to achieve maximum burn-up and to prevent local flux peaks
- Mechanical Control Absorbers: tubes of cadmium sandwiched between stainless steel tubes for large power level reductions
- CANDU 6: 21 Adjuster Rods
- CANDU 9: 24 Adjuster Rods

Reactivity Control

- CANDU 6 and 9 reactors have two fully independent reactor shutdown systems
- Shutdown System Number 1: Shutdown Rods provide large reactivity insertion by 32 solid neutron absorbing rods that are dropped into the core
- Shutdown System Number 2: uses the rapid injection of concentrated gadolinium nitrate (poison) into the moderator

Reactor Shut Down System



Other D_2O Moderated Reactors

- Steam Generating Heavy Water Reactor (SGHWR) developed in UK without any success:92 MW_e 1967 to1990: Light water in coolant channels with steam production in the core surrounded by a heavy water reflector
- Pressurized Heavy Water Reactor (PHWR) developed by Germany: Installed in Atucha/Argentina 335 MW_e operating since 1974

  Embalse/Argentina 600 MW_e operating since 1984

Isotopic Composition of Various Grades of Plutonium in wt%

Grade	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Super-grade		98.0	2.0		
Weapons-grade	0.012	93.8	5.8	0.35	0.022
MOX-grade	1.9	40.4	32.1	17.8	7.8
A typical PWR	2.6	52.4	23.2	15.0	6.8
High burnup UO_2	7.1	48.7	20.6	15.9	7.7
A typical CANDU	0.074	69.4	25.9	3.3	1.3

Pu-Production in kg/GWe-yr

Isotope	A typical PWR	High burnup UO_2	A typical CANDU
Pu-238	6.05	12.11	0.39
Pu-239	121.89	82.96	374.03
Pu-240	53.85	35.06	139.90
Pu-241	34.86	27.13	17.52
Pu-242	15.86	13.25	7.03
Fissile Pu	156.75	110.09	391.55
Total Pu	232.51	170.51	538.87

[1] for 4.5 wt% enriched UO_2 fuel, and burnup of 50 MWd/kgHM (where HM = initial heavy metal)
[2] for 9.75 wt% enriched UO_2 fuel, and burnup of 100 MWd/kgHM
[3] for natural uranium UO_2 fuel, and burnup of 7.5 MWd/kgHM

Critical Mass for Different Plutonium Compositions

Plutonium source	Critical mass, kg
Weapons-grade	11.8
A typical PWR	22.1
High burnup UO_2	22.2
A typical CANDU	18.2

Further Information on CANDUs

- http://canteach.candu.org
- http://www.candu.org/
- http://www.nucleartourist.com/type/candu.htm
- http://www.aecltechnologies.com/Content/ACR/Facts.htm
- CANDU 9 ATW 11/1996