TOPIC 5

Gen-III Systems – From the Initial Requirements to the Designers' Choices

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5.4. Advanced Heavy Water Reactors (AHWRs)

Supplement 2: Alternative Concepts and Early HWR Prototypes

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Outline

- Deuterium-Based Moderators.
- Alternative Uses for D_2O.
- Alternative Coolants.
- International Participation in HWR Technology.
  - Historical.
- Alternative HWR Reactor Designs.
  - Historical.
- Cancelled / Abandoned HWR Projects.
  - Perhaps ahead of their time.
  - More time and effort needed to perfect.
  - Shift in government policy.
  - Consolidation of financial resources.
  - Availability of enriched uranium.

Principles in Reactor Design

- Do not be constrained by "tradition" or the "mainstream".
  - Be willing to try something new, different, or unconventional.
- "What's old is new."
  - Changes in materials and manufacturing technologies.
  - Changes in economics.
- "If you do what you always did, you'll get what you always got."
- "Make the problem the solution".
- However, always be mindful about:
  - The long-term costs.
  - The utility (electric power company) that has to run this.
    - Be as practical as possible.
    - Design must be cost-effective (at least in long-term).
    - They will buy into different designs if they can save money.

Deuterium-Based Moderators

- Heavy Water, D_2O
  - Conventional, extracted from water (0.015 at%)
  - Cost of purification to > 99.75 wt%D_2O
  - Must be pressurized to prevent boiling at higher temp.
- Zirconium Deuteride, $ZrD_{1.6}$
  - Chemically similar to $ZrH_{1.6}$, although more expensive.
  - High-temp. operation (~750°C) with Na, Na/K, or gas coolant.
- Lithium-7 Deuteride, ^{7}LiD
  - Similar to LiH, but reduced neutron absorption.
  - Li-7 separation more costly.
  - High-temp (~600°C) operation with Na, Na/K, or gas coolant.

Deuterium-Based Moderators

- Deuterated Diphenyl/Terphenyl, C_xD_y
  - Reduced neutron absorption (relative to hydrogen organics).
  - More resistant to radiation and thermal decomposition.
  - Less corrosive.
  - High-temperature (>400°C) operation at low pressure feasible.
    - No heavy pressure vessel or thick pressure tubes.
  - Could use as both a moderator and a coolant.
  - But, expensive to produce.
    - More expensive than D_2O.
    - Large-scale production facilities to get economies.

Alternative Uses for D_2O

- Coolant for fast reactors (1990's to present, Japan)
  - Low moderator-to-fuel ratio ensures hard spectrum.
  - Better neutron economy than using H_2O or liquid metal.
  - Permits conventional technology for secondary side.
- Spectral Shift Reactors (1960's, Belgium, U.S.A.)
  - PWR with D_2O/H_2O moderator/coolant.
  - Beginning of cycle: D_2O (faster spectrum)
  - As burnup progresses, dilute with H_2O
  - End of cycle: H_2O (thermal spectrum)
  - Reduce use of control rods, burnable poisons, and moderator poison.
    - Improved neutron economy, higher burnup.
    - But, costly to re-upgrade D_2O, unless alternative design can be implemented to maintain physical separation of H_2O and D_2O.

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Alternative Coolant Options

- Boiling H_2O at 5 to 7 MPa
  - Successfully demonstrated in a number of prototypes.
  - SGHWR, FUGEN, Gentilly-1, CIRENE, AHWR (new)
- Boiling D_2O at 3 to 7 MPa
  - Marviken (Sweden)
  - BHWR (Halden, Norway) – research reactor.

- Gas coolant at 5 MPa to 10 MPa (400 C to 800 C)
  - CO_2, He/Ne, N_2O_4 (dissociating coolant)
  - Demonstrated in prototypes:
    - EL-4, KKN, KS-150, Lucens
  - Proposed in early concepts
    - GNEC Proposal (1961)

Alternative Coolant Options

- Organic coolant at 0.6 to 2 MPa
  - Diphenyl, terphenyl, HB-40, Santowax
  - WR-1, ORGEL, ESSOR, etc.

- Liquid Metal at ~ 0.1 MPa (1 atm)
  - Pb, Pb-Bi, Pb-2wt%Mg, Na, ^{7}Li
  - Early patents by Leo Szilard (1940's)
  - Chugach/Alaska SDR Project (NDA study, 1950's)

- Molten Salt at ~ 0.1 MPa (1 atm)
  - ^{7}LiF-BeF_2-ZrF_4; Conceptual studies
  - Could also be used for fuel carrier (UF_4, ThF_4)

Alternative Coolant Features

- Boiling D_2O at 3 to 7 MPa
  - Similarities to boiling H_2O.
  - Reduced neutron absorption; better neutron economy.
  - Higher capital costs because of D_2O.
  - Extra tritium production.
  - Lattice physics design considerations
    - To ensure low or negative coolant void reactivity.

Alternative Coolant Features

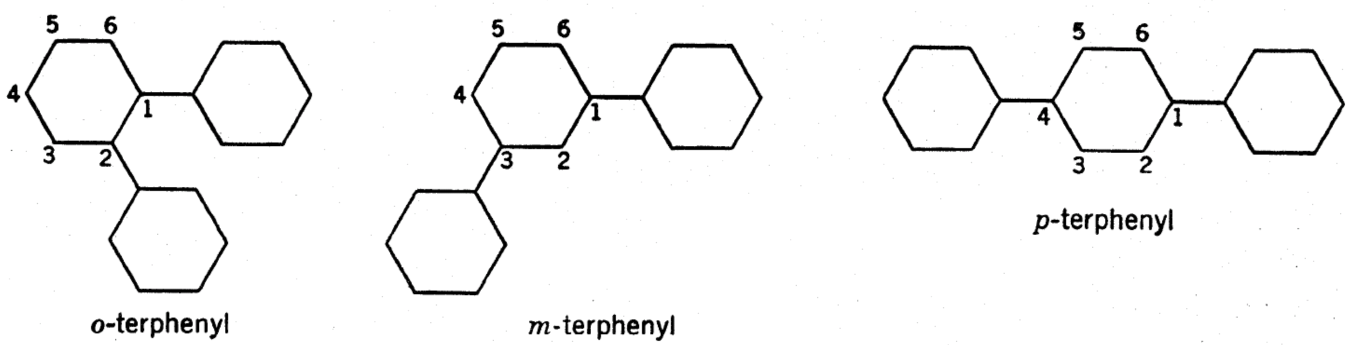
- Gas coolant at 5 MPa to 10 MPa (400 C to 800 C)
  - Reduced D_2O inventory – cost savings.
  - Potential for direct cycle – compact gas turbine.
  - High efficiencies possible, ~40% to 45%. (Eg. AGR ~ 41%)
  - Hydriding and coolant-voiding non-issues.
  - Lower heat transfer coefficient / conductivity.
    - Finned or roughened fuel pins; larger steam generators required.
  - More pumping power required (5% to 10% of power).
  - High-temperature materials required
    - Stainless steel, or graphite cladding.
    - Insulated liner (ZrO_2, MgO, or graphite) for PT.
  - Careful design for postulated accidents
    - Loss of pressure.

Alternative Coolant Features

- Organic coolant at 0.6 to 2.0 MPa (300 C to 400 C)
  - Reduced D_2O inventory (20%) – cost savings.
  - Higher efficiencies possible, ~34% to 38%.
  - Low-pressure coolant
    - Thinner PT’s; neutron economy improvements.
    - Safer operations; lower capital costs.
  - Low activity in primary circuit.
  - Lower heat transfer coefficient / conductivity for organics.
    - Finned or roughened fuel pins may be used to enhance heat transfer
  - Higher density fuel required (UC or U_3Si in SAP tubes)
    - Sintered Aluminum Product (SAP) – Al + 15% Al_2O_3
  - Higher-temperature materials required.
  - Hydriding still a concern, but less so.
  - Costs for coolant replenishment; filtering to remove crud.
  - Increased fire hazard (manageable).

Organic Coolants

- Diphenyl $(C_6H_5)_2C_6H_4$ (2 benzene rings)
- Terphenyl (3 benzene rings)
  - o-terphenyl (Tm = 57°C, Tb = 332°C)
  - m-terphenyl (Tm = 87°C, Tb = 365°C)
  - p-terphenyl (Tm = 213°C, Tb = 376°C)
- Santowax-R, Santowax-O-M, HB-40
  - Mixtures of diphenyl and terphenyl



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Alternative Coolant Features

❑ Liquid Metal at ~ 0.1 MPa (1 atm)

- Pb, Pb-Bi, Pb-2wt%Mg, Na, ^{7}Li
- High thermal conductivity; compact steam-generators.
- Low pressure operation
  - Thin-walled PT's; reduced neutron absorption
  - Enhanced safety; reduced capital costs.
- High boiling point (800 C - 1700 C); high melt (100 C - 330 C)
  - Efficiencies of 40% to 50% possible.
- Liquid metals absorb more high-energy gamma's.
- Materials issues (high temp; corrosion issues)
  - Ceramics, niobium alloys, stainless steel (reduced neutron economy).
- Neutron activation of coolant. (Bi is a problem).
- Separation of moderator, coolant, secondary side.
  - Fire safety / corrosion concerns for ^{7}Li and Na
    - o Maybe use $ZrD_{1.6}$ or ^{7}LiD as moderators instead.

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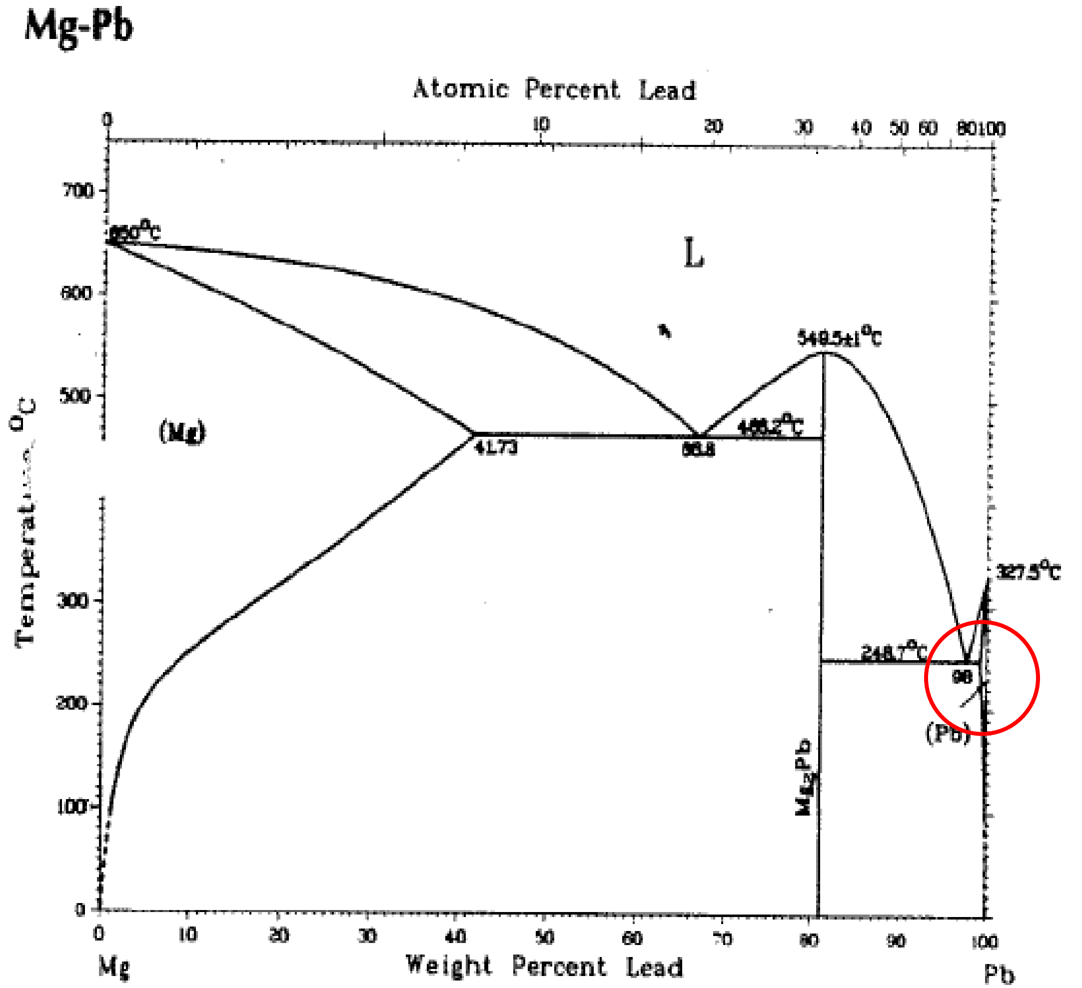
Lead-Magnesium (Future?)

- Eutectic
- 2 wt% Mg, 98 wt% Pb
  - T_{melt} ~ 249°C
  - Lower than pure Pb.



International Participation in HWR Technology

- Canada
  - ZEEP, NRU, NRX, WR-1, ZED-2
  - NPD-2, Douglas Point, Gentilly-I
  - Pickering A/B, Bruce A/B, Darlington, Point Lepreau, Gentilly-2
  - CANDU-6, EC6, ACR-1000
- U.S.A.
  - CP3, HWCTR, PRTR, Savannah River (Pu production)
  - CVTR prototype; HWOCR program (1967)
  - Many concepts investigated and proposed.
  - Emphasis on research reactors and Pu production.

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International Participation in HWR Technology

- U.K.
  - DIMPLE, SGHWR (Boiling light water)
- Japan
  - DCA, FUGEN (Boiling light water, MOX)
- Sweden
  - R3/Adam/Agesta (PHWR), Marviken (BHWR)
- Italy
  - CIRENE (Boiling light water)
  - ORGEL (organically cooled)
- Pakistan
  - KANUPP (CANDU)

International Participation in HWR Technology

- Germany
  - MZFR (pressure vessel)→ Atucha I (Argentina)
  - KKN (Niederaichbach) (CO_2-cooled)
- France
  - Aquilon, EL-1, EL-2, EL-3
  - EL-4 (CO_2-cooled)
- Czechoslovakia
  - KS-150 / A-1 Bohunice (pressure vessel, CO_2-cooled)
- Switzerland
  - Lucens (Magnox-type fuel, CO_2-cooled)

International Participation in HWR Technology

- Belgium
  - Vulcain / spectral shift reactors.
- Norway
  - Halden (BHWR) ; research only.
- Euratom, Italy, Spain, Denmark
  - Organically-cooled HWR’s (ORGEL, DON, DOR)
- India
  - CIRRUS, Rajasthan (RAPP - 1973); early Canadian assistance.
  - Norora, Kakrapar, Kaiga, Kalpakkam, Tarapur
  - Designs similar to Douglas Point (Canada) (~220 MWe)
  - Development of larger PHWR’s (~540 MWe)
    - Similar to Pickering A/B, CANDU-6
  - AHWR (variants using thorium, Pu, LEU)

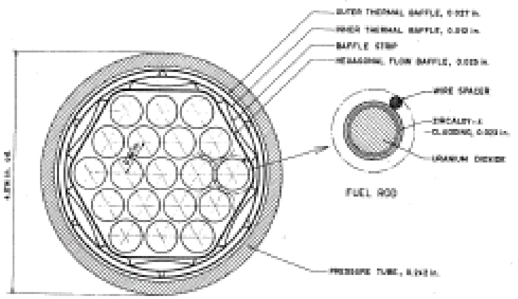
International Participation in HWR Technology

- Focus on power reactors.
  - Descriptions are for various prototypes.
  - Several constructed, several proposed.
- Organized by coolant type, chronology.
- Some projects were in advanced stage of design and development before cancellation.
  - Technical issues that needed more time and effort to address.
  - Competing technologies performing well.
  - Reduced concerns about long-term uranium supplies.
    - Achieving high neutron economy and conversion ratios lower priority.
  - Difficult to support several parallel programs.

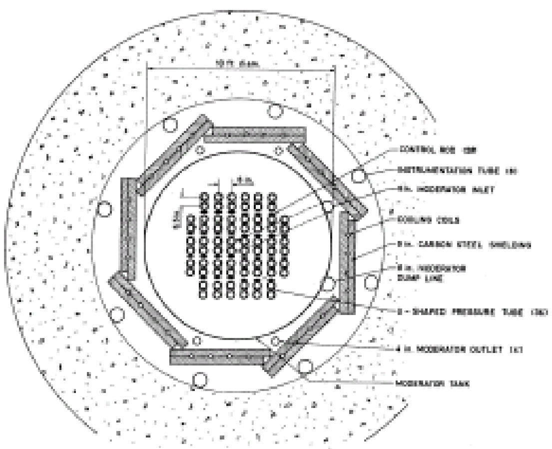
CVTR (U.S.A., 1963)

- Carolinas Virginia Tube Reactor (CVTR)
- First and only HWR power reactor in U.S.A.
- Prototype operated 1963-1967.
- 65 MW_{th}, 17 MW_e, η_{th}~ 26%, 15 kW/litre
  - 56 MWth from reactor, 9 MWth from oil-fired super-heater
- Vertical pressure tube reactor (D_2O moderated and cooled)
  - U-tube connections for pairs of PT's
  - 72 PT's, 36 pairs joined at bottom by U-tube
- 19-element assemblies
  - 1.5 to 2.0 wt% enriched UO_2; offline refuelling.
  - 12,500 MWd/t burnup
- Control: 32 boron-steel rods

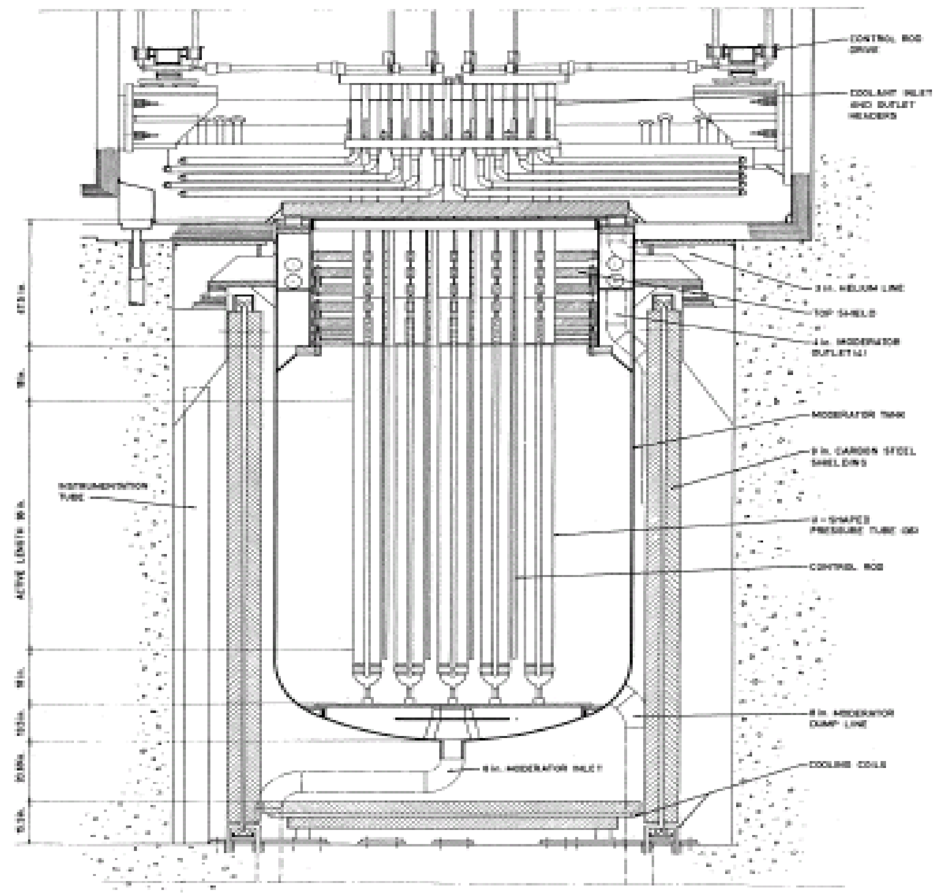
CVTR (U.S.A., 1963)



FUEL ELEMENT



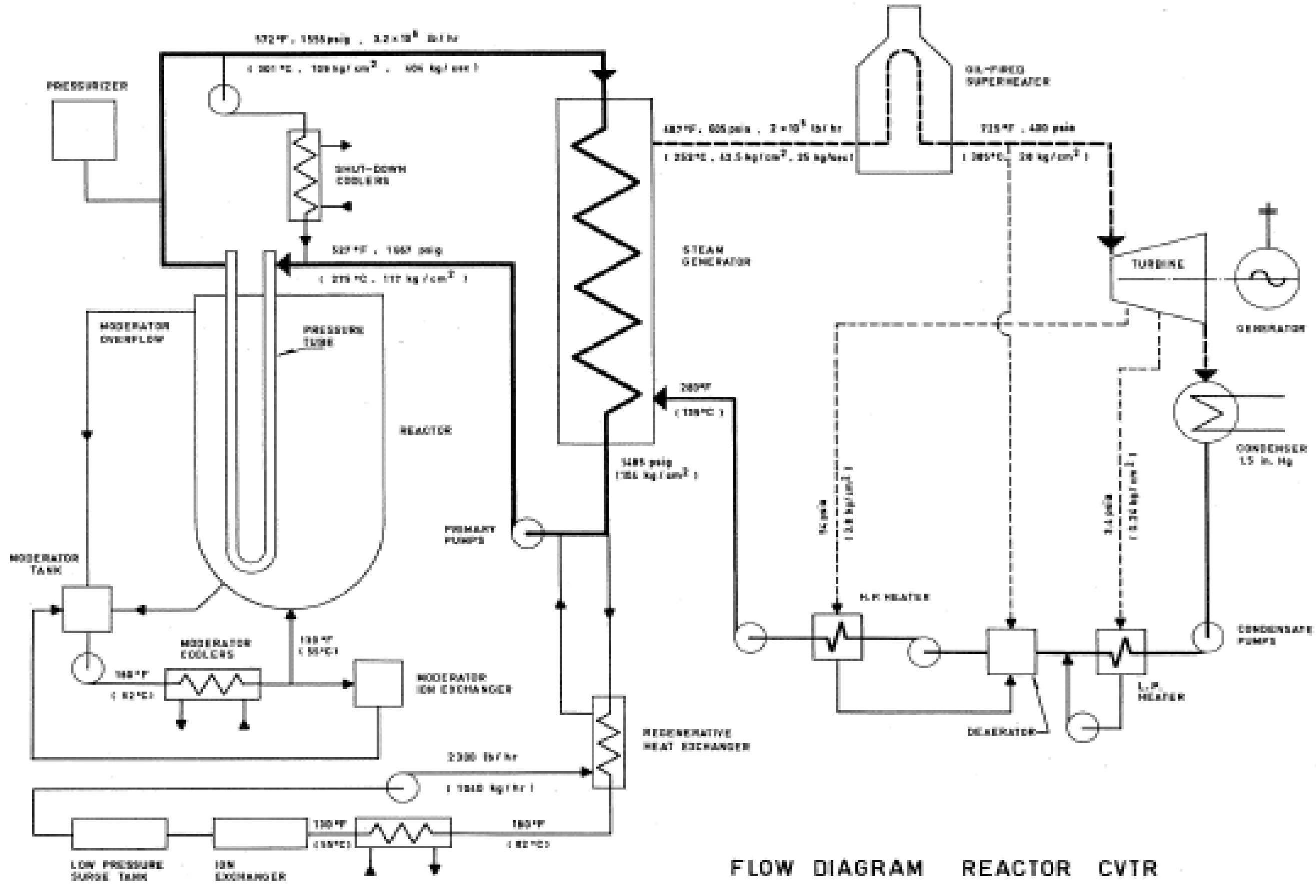
HORIZONTAL SECTION REACTOR CVTR



VERTICAL SECTION REACTOR CVTR

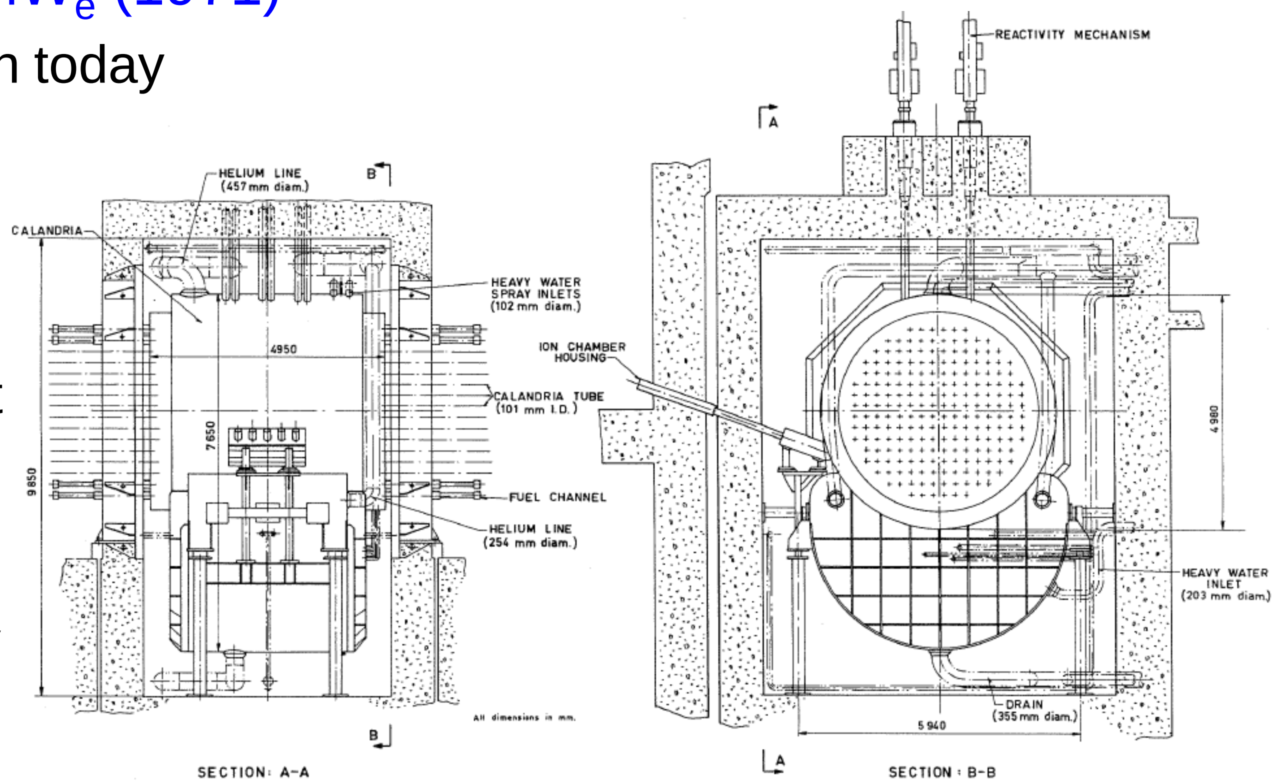
CVTR (U.S.A., 1963)

- Coolant
  - 10 MPa
  - 301 C
- Steam
  - 2.7 MPa
  - 385 C



KANUPP (Pakistan, 1971)

- **K**Arachi **NU**clear **P**ower **P**lant
- Similar to scale up of NPD-2
- 432 MW_{th} / 125 MW_e (1971)
  - Still in operation today
- 208 Channels
- 10.4-cm PT's
- 23.5-cm pitch
  - >Douglas Point
- 7.7 kW/litre
- On-line refuel
  - 4 bundles / day



VERTICAL SECTIONS REACTOR KANUPP

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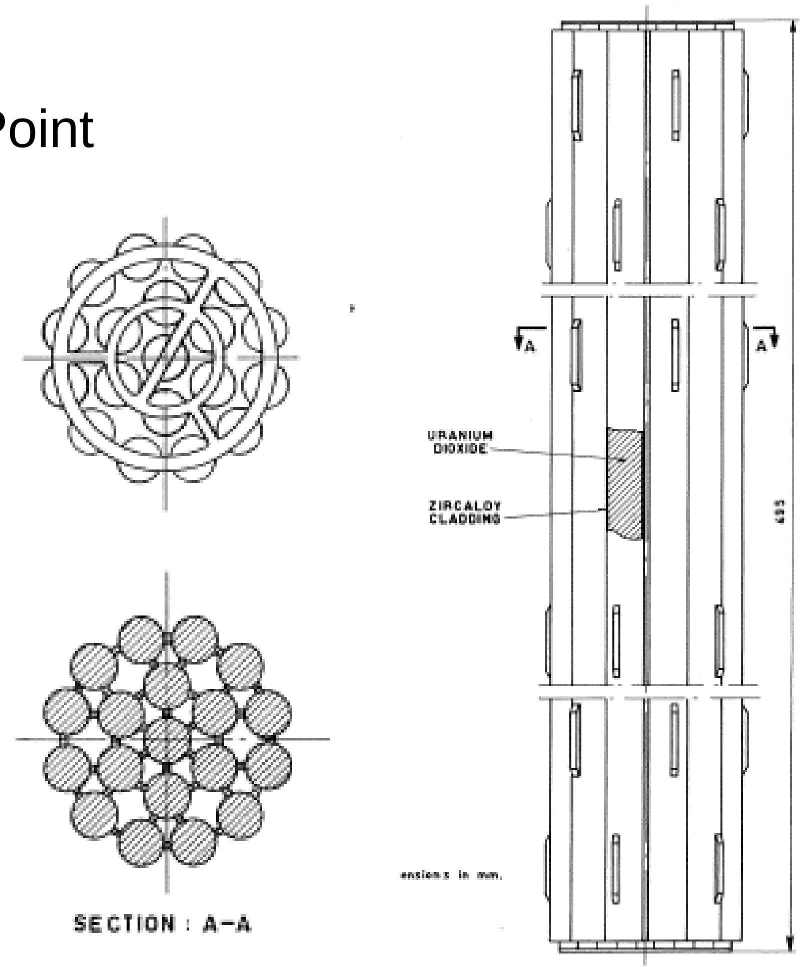
KANUPP (Pakistan, 1971)

- 19-element bundles
  - Similar to NPD-2, Douglas Point
  - Natural UO_2
  - Zr-4 clad
  - Bearing pads (new)
    - Not wire wraps
  - 0.5-m length
- C=0.81
- 8,650 MWd/t (ave.)



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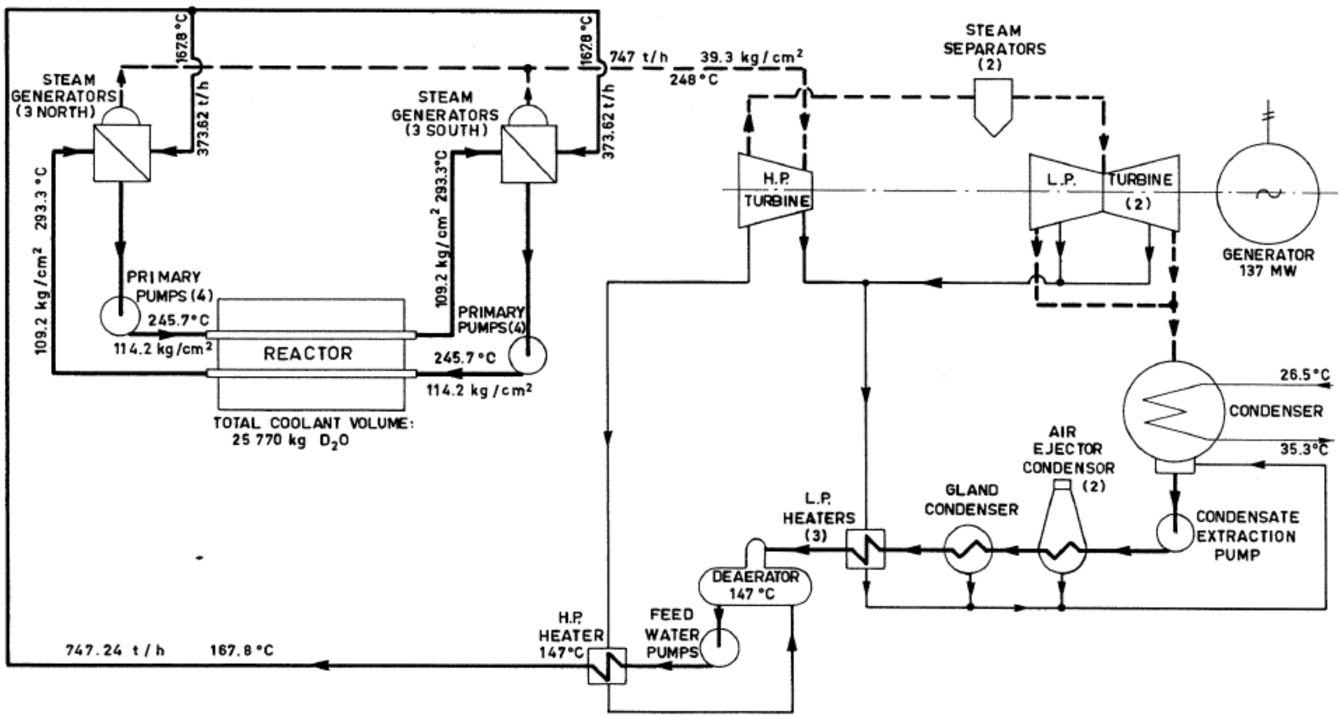
KANUPP (Pakistan, 1971)

- Coolant at 11.4 MPa, 293 C
- Steam at 4 MPa, 250 C (U-shaped shell/tube)
- Control: 4 rods, moderator level, boron shim



FLOW DIAGRAM REACTOR KANUPP

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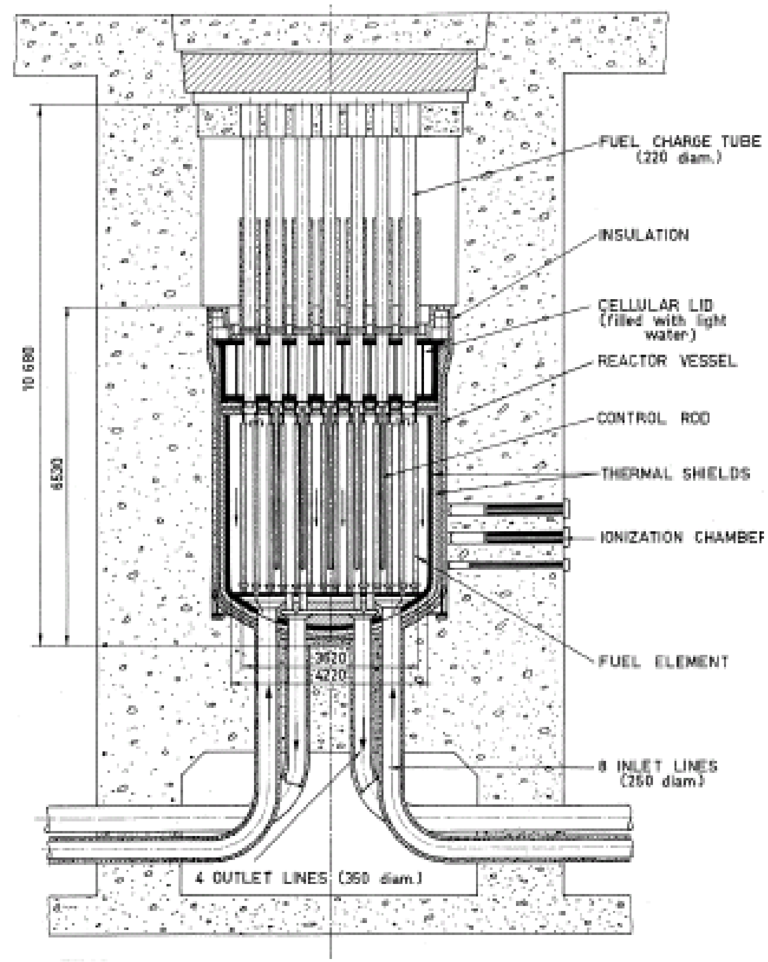
R3/Adam/Agesta (Sweden, 1964)

- World's first pressure-vessel HWR
- Operated 1964-1974.
- 65 MW_{th} / 10 MW_e
  - η_{th} ~ 15%, but,
  - Waste heat used for district heating
- Coolant at 3.3 MPa, 220 C
- Steam at 1.37 MPa, 215 C
- 2.1 kW/litre
- C.R. ~ 0.83
- Burnup:
  - 2,800 MWd/t to 4,000 MWd/t (max)

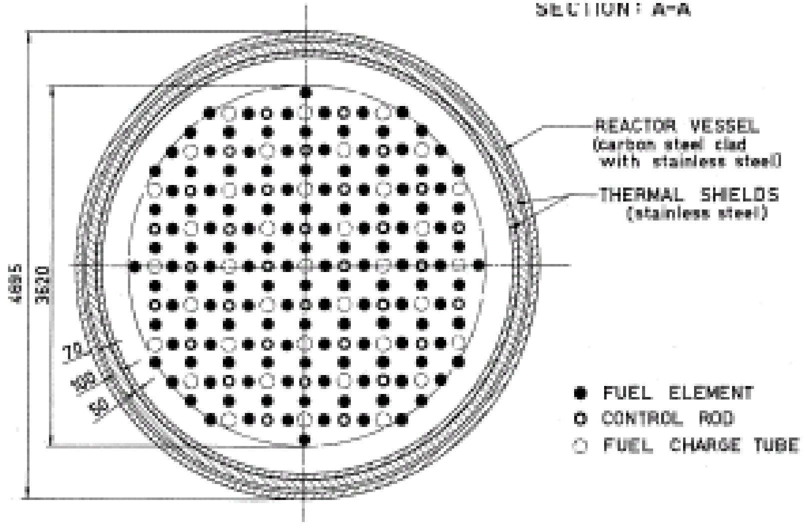


VERTICAL SECTION
REACTOR R-3/ADAM

all dimensions in mm

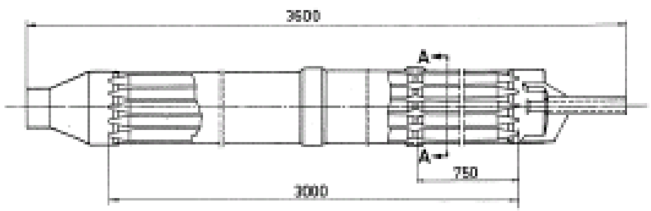
R3/Adam/Agesta (Sweden, 1964)

- 140 Channels
  - 27-cm pitch, Zr-2 flow tubes
- Natural UO_2
  - Zr-2 clad,19-element clusters
  - 4 bundles / fuel assembly
  - ~360 cm long

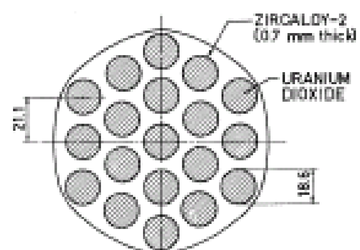


HORIZONTAL SECTION
REACTOR R-3/ADAM

all dimensions in mm



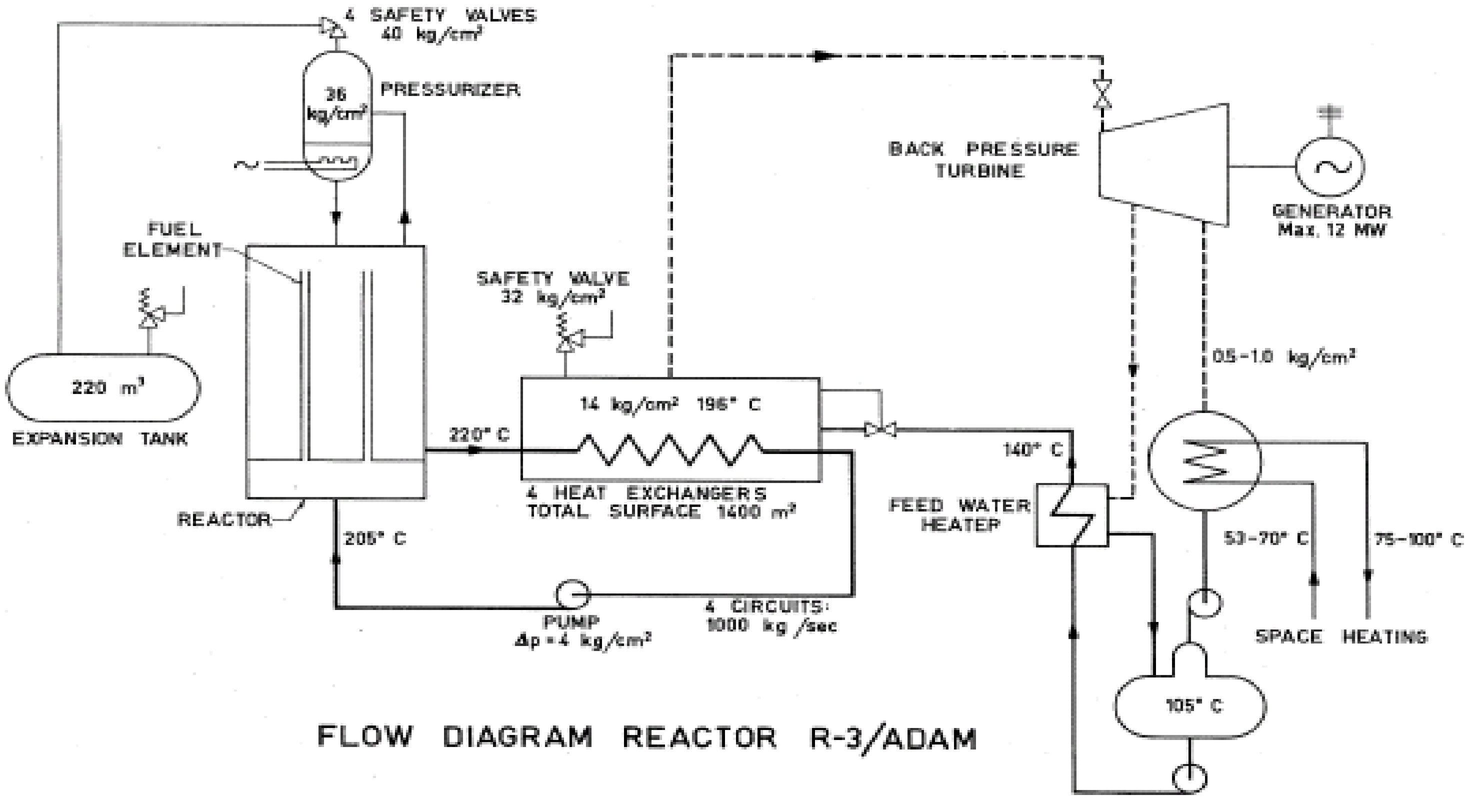
FUEL ELEMENT



SECTION: A-A

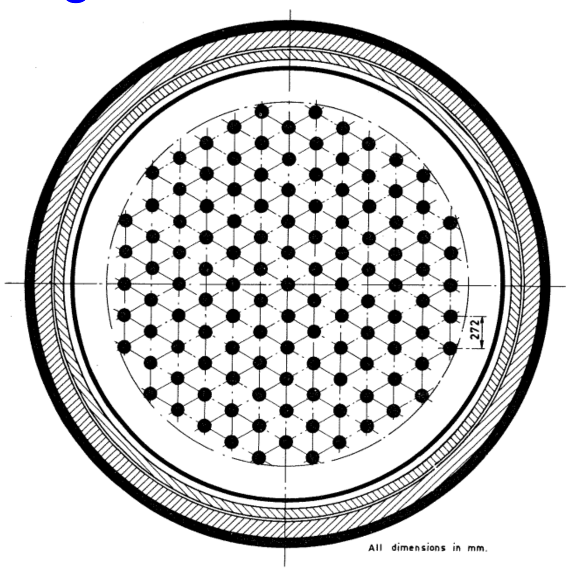
R3/Adam/Agesta (Sweden, 1964)

- Dual-purpose electricity and district heating

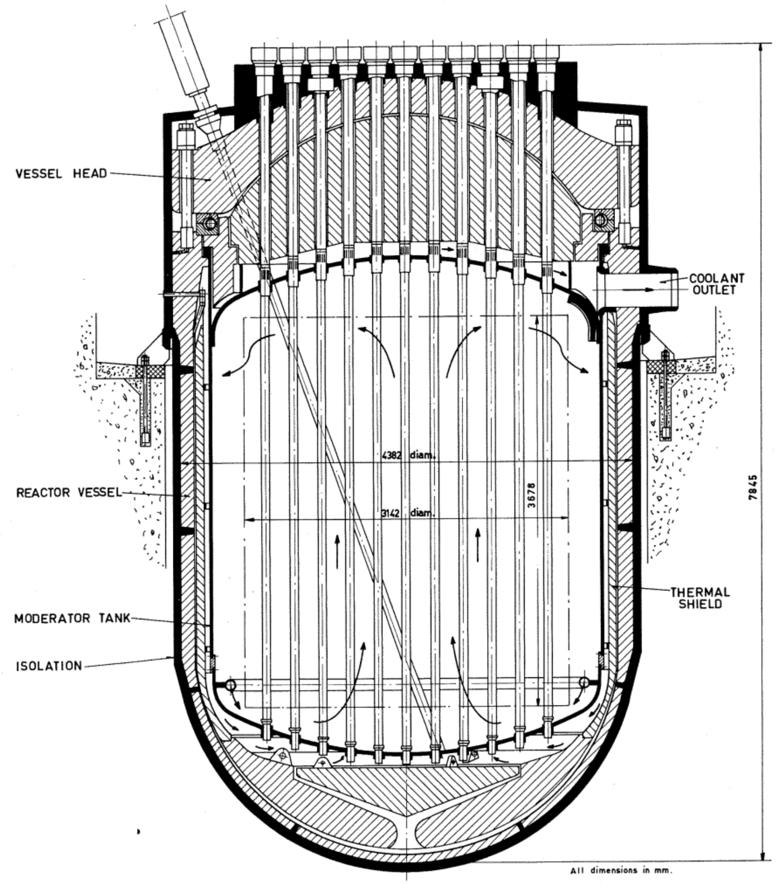


MZFR (W. Germany, 1966)

- Pressure vessel; vertical.
- 200 MW_{th} / 50 MW_e
- Hex. Pitch (27.2 cm)
- 121 Channels
- Diagonal control rods



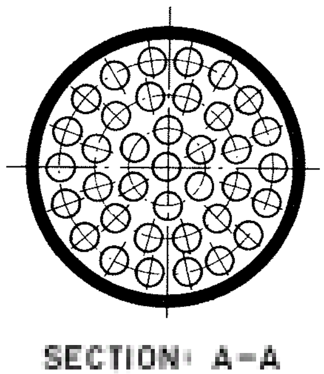
HORIZONTAL SECTION

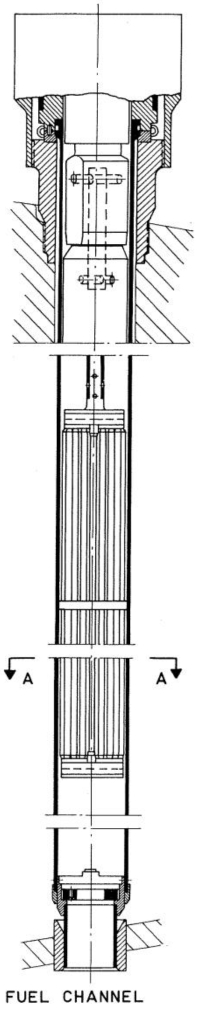


VERTICAL SECTION REACTOR MZFR

MZFR (W. Germany, 1966)

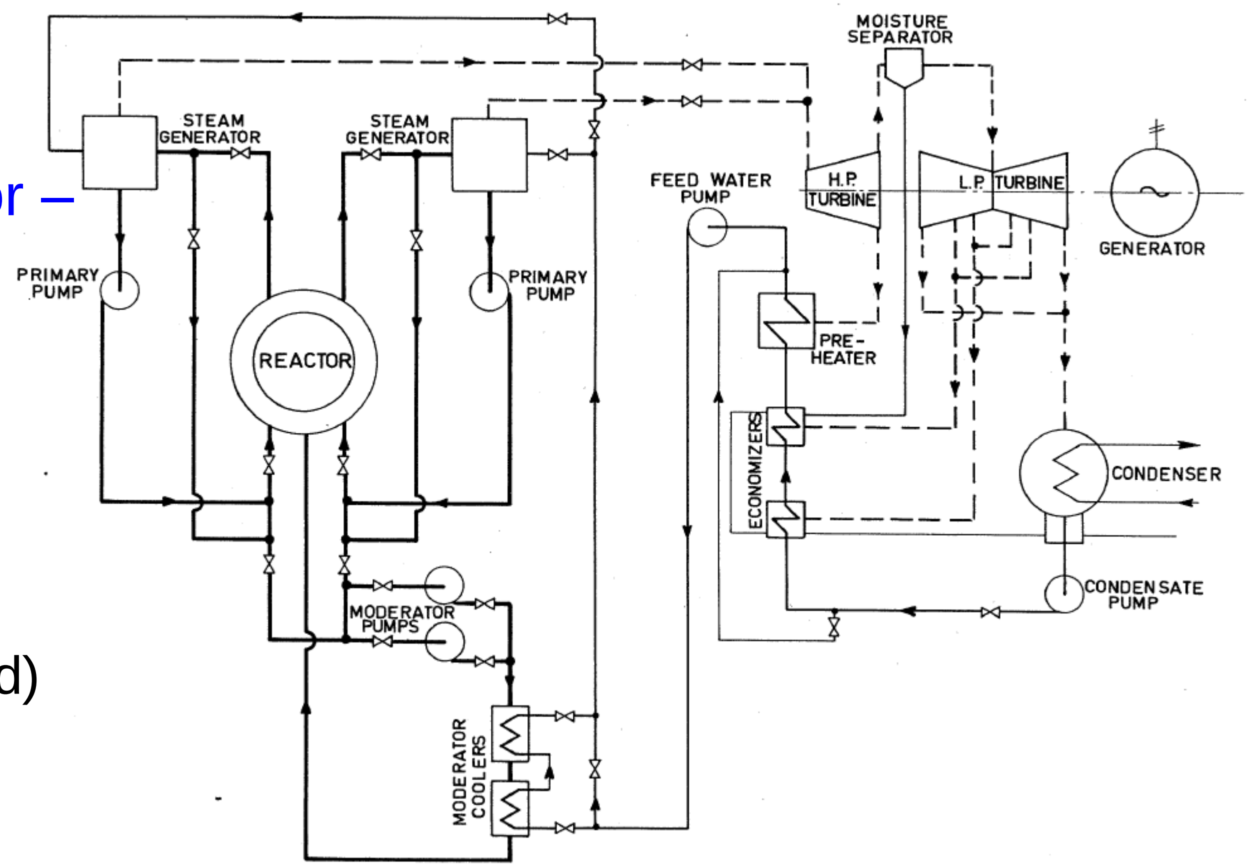
- ❑ 37-element fuel strings
  - ➢ First HWR to use 37 elements.
  - ➢ two per channel
  - ➢ 3.67-m core height
- ❑ UO_2, natural.
  - ➢ Zircaloy-2 clad
  - ➢ C~0.79
  - ➢ 5,000 MWd/t burnup
- ❑ On-line refuelling
  - ➢ Whole fuel string removed.





MZFR (W. Germany, 1966)

- Operated 1966 – 1984 (Seimens)
- Prototype for commercial reactor – Atucha I
- 7 kW/litre
- 8.45 MPa, 280 C
- Steam at
  - 3.11 MPa
  - 236 C (Saturated)



FLOW DIAGRAM REACTOR MZFR

Atucha 1 (Argentina, 1974)

- First and only
  - Large-scale commercial pressure vessel (PV) HWR
  - Atucha 2 (to follow in 2010)
- Scale-up of MZFR from Germany.
- 1179 MW_{th} / 345 MW_e
- 37-element fuel string
  - Zr-4 clad
  - Natural UO_2 (early), C~0.81
    - ~6,000 MWd/t burnup
  - 0.9 wt% enriched (recent)
    - ~13,000 MWd/t burnup
- CARA Fuel (52 rod)
  - Under development

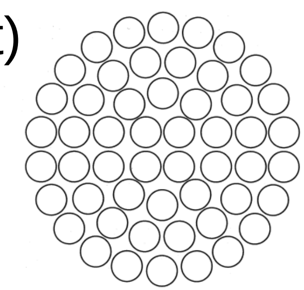
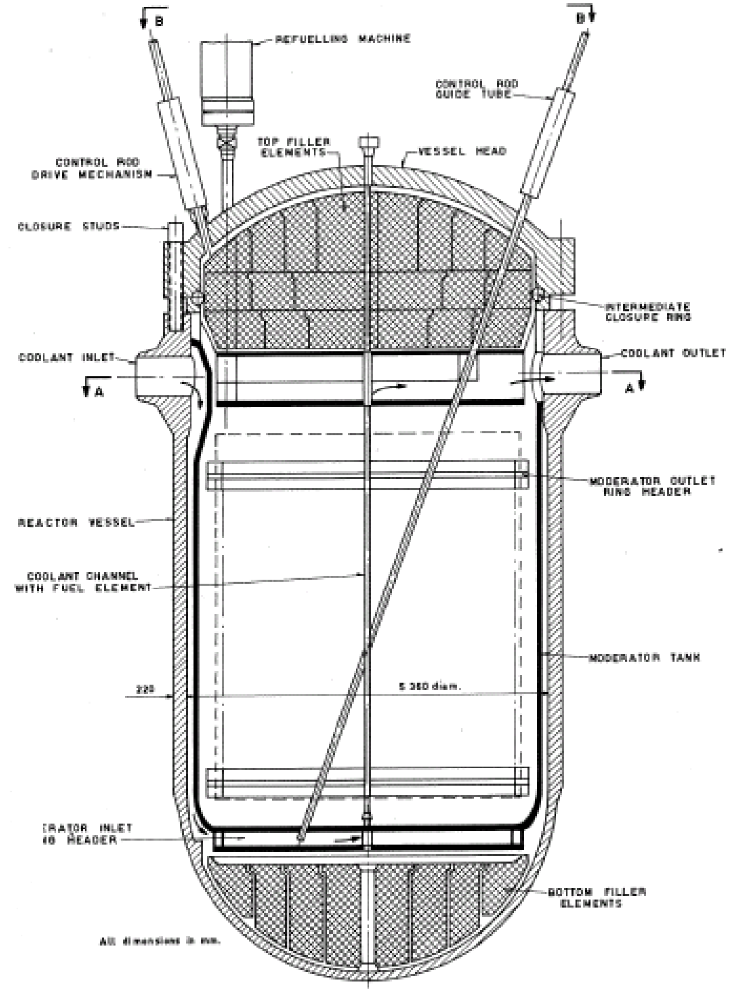


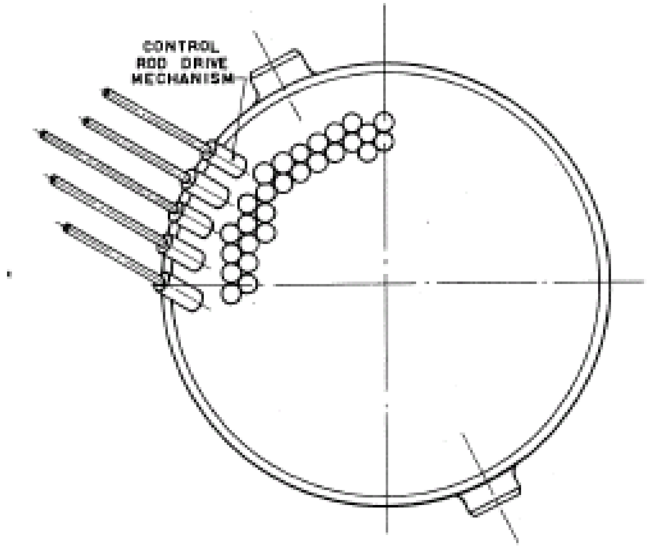
FIG. 159. Geometry of the CARA bundle with 52 fuel rods.

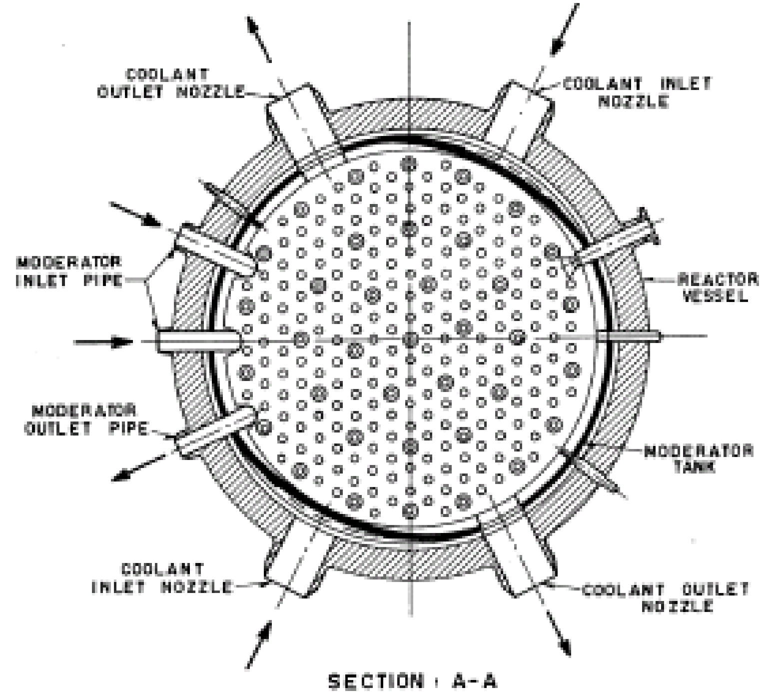


VERTICAL SECTION REACTOR ATUCHA

Atucha 1 (Argentina, 1974)

- Argentina's first power reactor.
- In operation since 1974.
- 27.2 cm hex pitch, 252 channels; on-line refuel.
- 22-cm thick PV wall.
- 20-degree diagonal CR





HORIZONTAL SECTIONS REACTOR ATUCHA

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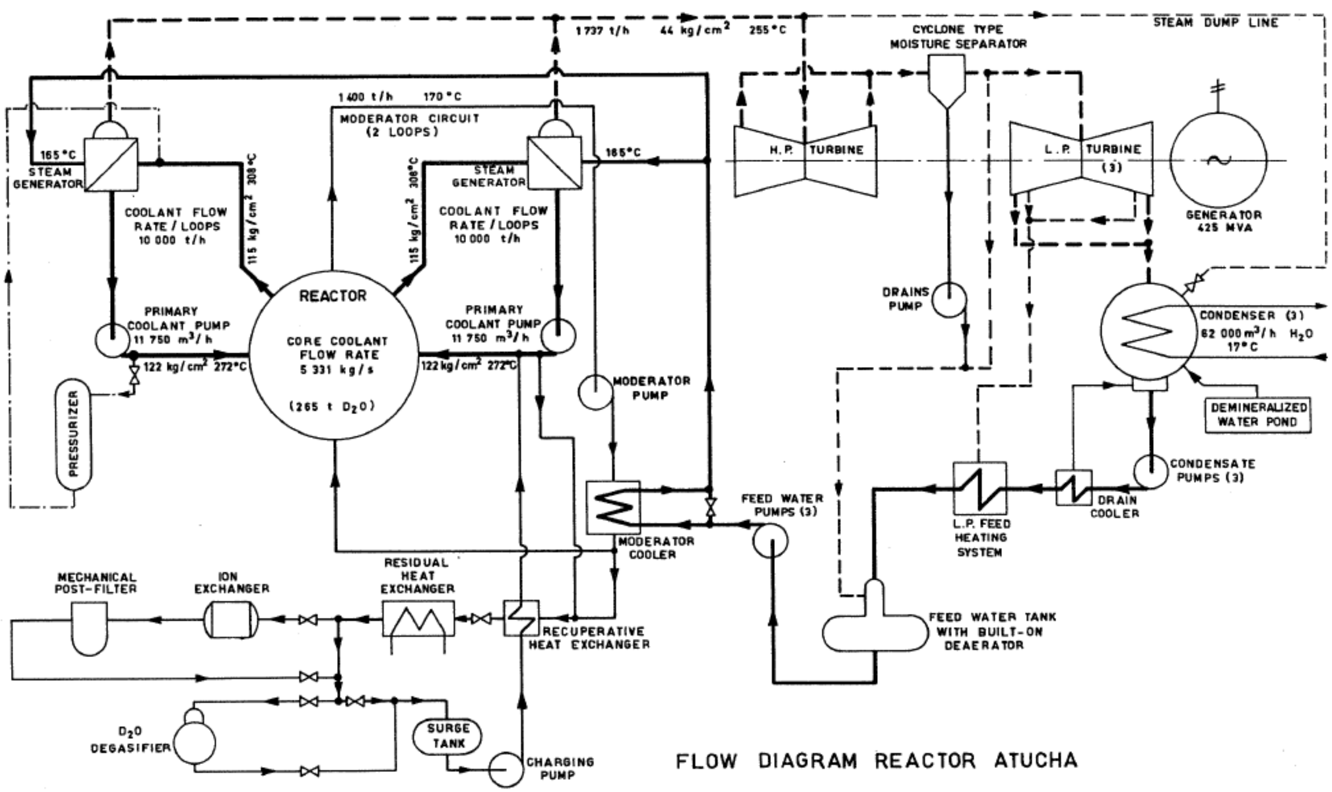
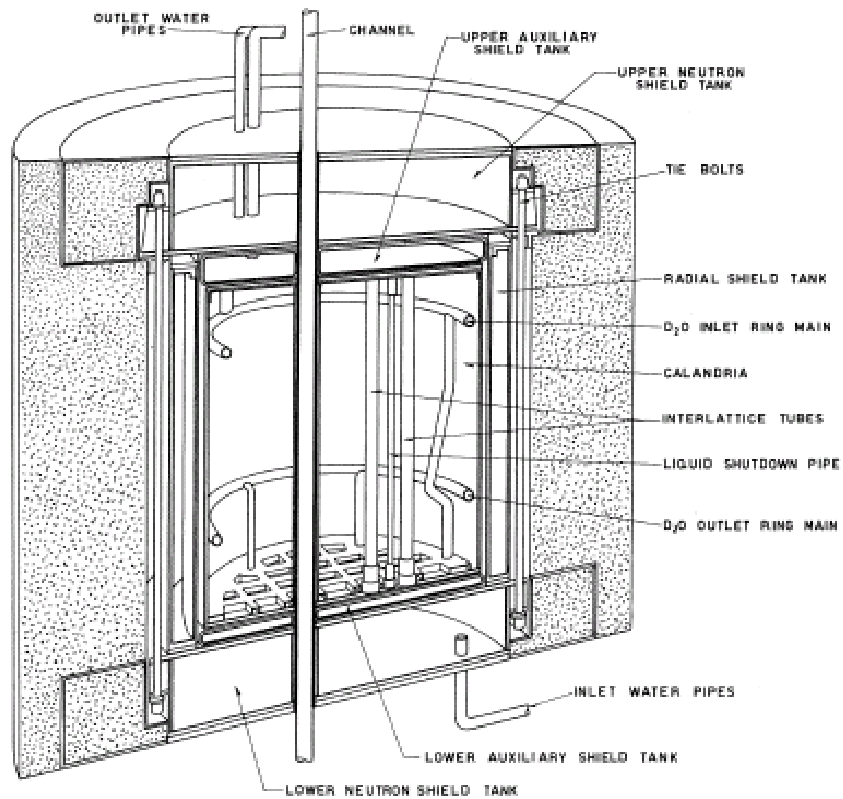
Atucha 1 / Atucha 2

- Coolant at 11.3 MPa / 299 C, stteam at 4.2 MPa / 253 C
- Atucha 2 (693 MW_e) on hold since 1980's (partially complete)
  - Work resumed in 2006, to start in 2010/2011.



SGHWR (U.K., 1968)

- Steam Generating Heavy Water Reactor (SGHWR)
- At Winfrith site in U.K.
- First HWBLW (1968-1990)
  - Direct production of steam.
  - No steam generators.
- 308 MW_{th} / 94 MW_e
- 103 PT's, Zr-2
  - 26-cm square lattice pitch
- Mod. Displacer Tubes
- Void/Power Coefficients
  - Slightly negative
- On-line refuel feasible.
  - multi-batch offline preferred



SCHEMATIC DIAGRAM OF CALANDRIA AND SHIELD TANKS

REACTOR SGHWR

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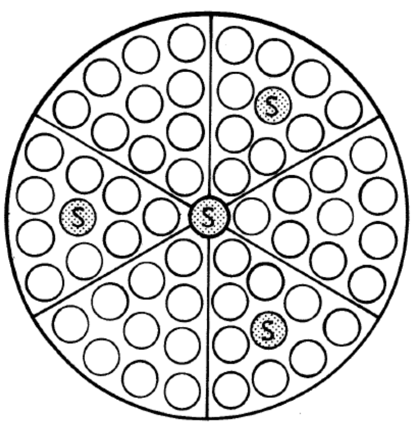
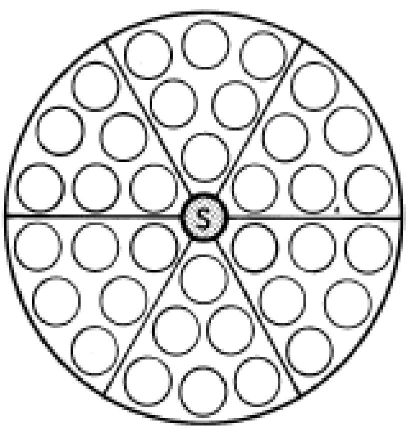
SGHWR (U.K., 1968)

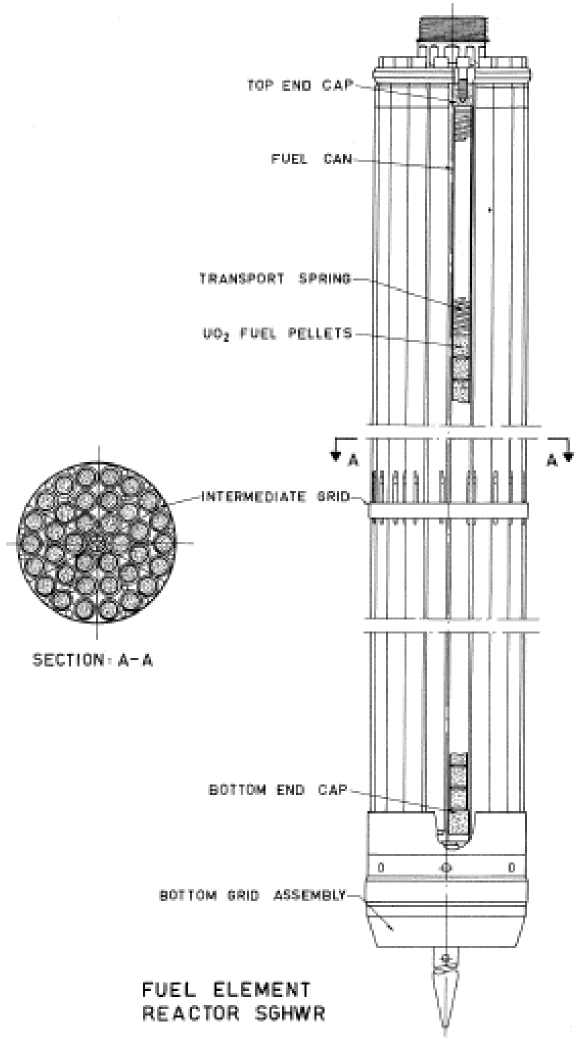
- 36-element bundle, central spray tube
  - 2.28 wt% enriched UO_2
  - Zircaloy-2 clad, 3.66 m long
  - 21,000 MWd/t burnup
- 57-element bundles tested
  - Smaller pins, lower element rating.
  - Enhanced heat transfer.

57 PIN DESIGN



36 PIN DESIGN





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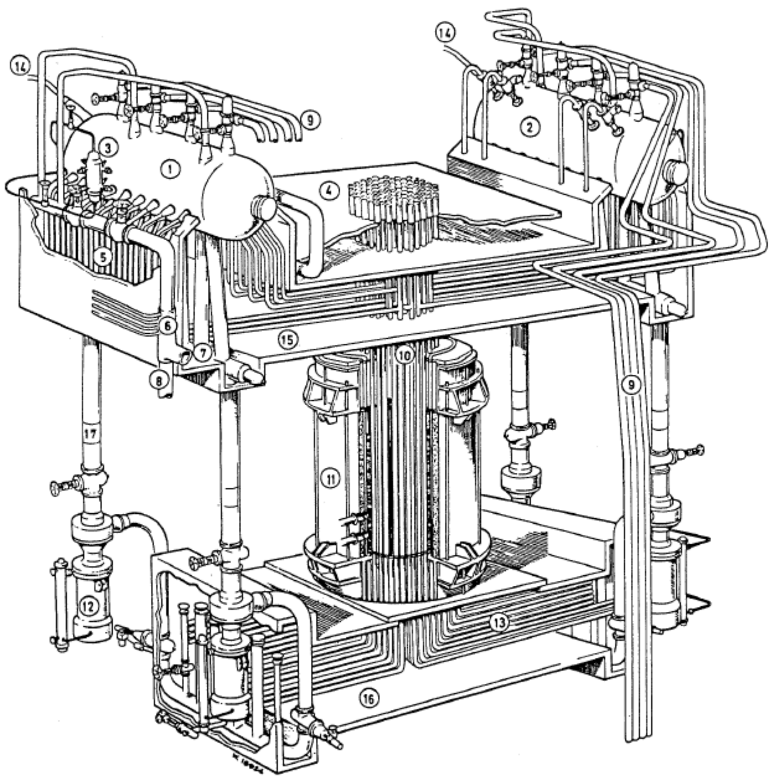
SGHWR (U.K., 1968)

- 5-batch refuelling established later
  - Off-line.
  - 28,000 MWd/t burnup
- Control
  - Boron in mod. tubes
  - Mod. dump
  - Liquid absorber tubes
  - Moderator height
  - Solid rods
  - Moderator boron.



KEY
1. SOUTH STEAM DRUM
2. NORTH STEAM DRUM
3. DRUM WATER LEVEL VESSEL
4. CHARGE FACE
5. RISERS
6. STEAM MIXING HEADER
7. MIXED STEAM TO POND DUMP
8. MAIN STEAM PIPE TO TURBINE
9. SAFETY VALVE ESCAPE PIPING
10. FUEL CHANNELS
11. NEUTRON SHIELD TANKS
12. MAIN CIRCULATING PUMPS
13. FEEDERS
14. FEEDWATER PIPING
15. TOP LAGGING BOX
16. BOTTOM LAGGING BOX
17. DALL TUBE

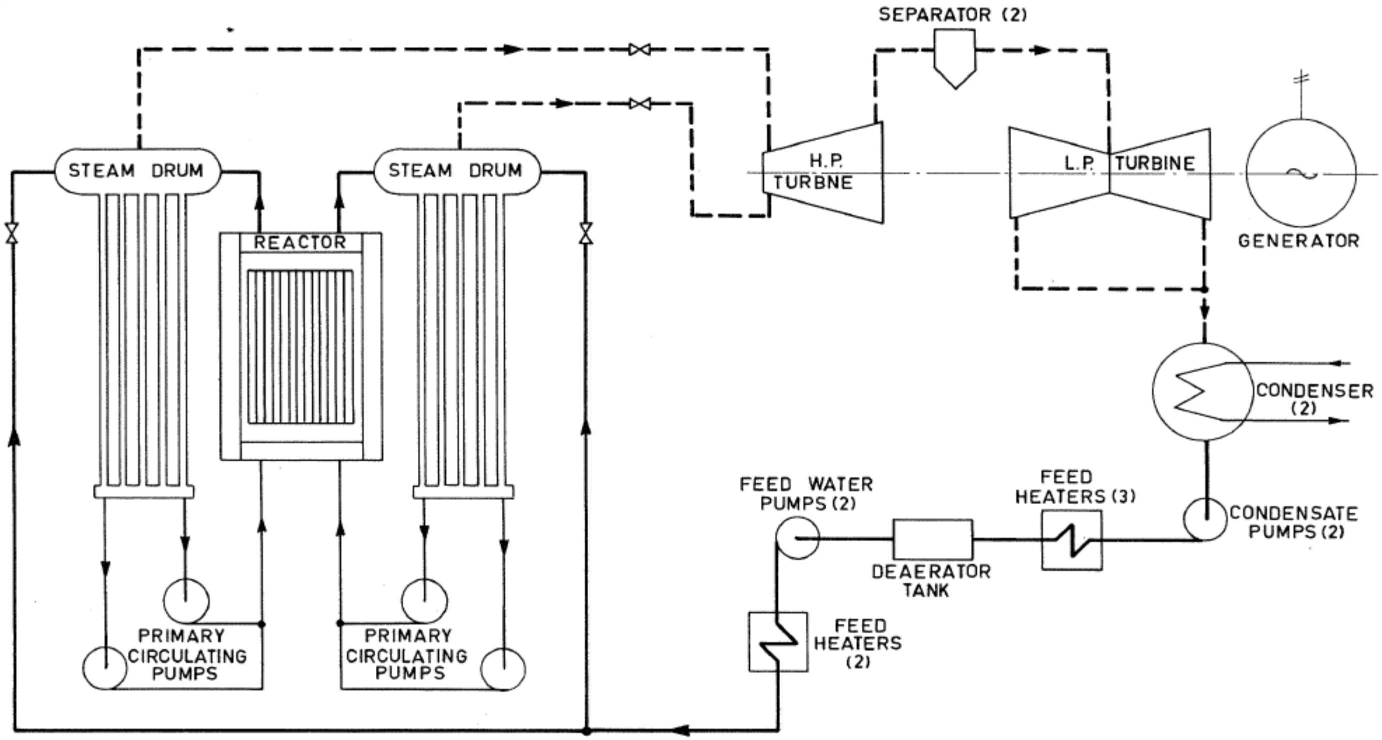
THE FOLLOWING ITEMS ARE OMITTED FOR CLARITY :-
EMERGENCY CHANNEL COOLING
DRAIN SYSTEM
STEAM DUMP TO POND

FIG. 1 PLANT IN PRIMARY CONTAINMENT

FJOH 2010

SGHWR (U.K., 1968)

- Steam at 6.5 to 6.1 MPa, 279 C
- 31% efficiency, 11 kW/liter
- Successful technology demonstration.

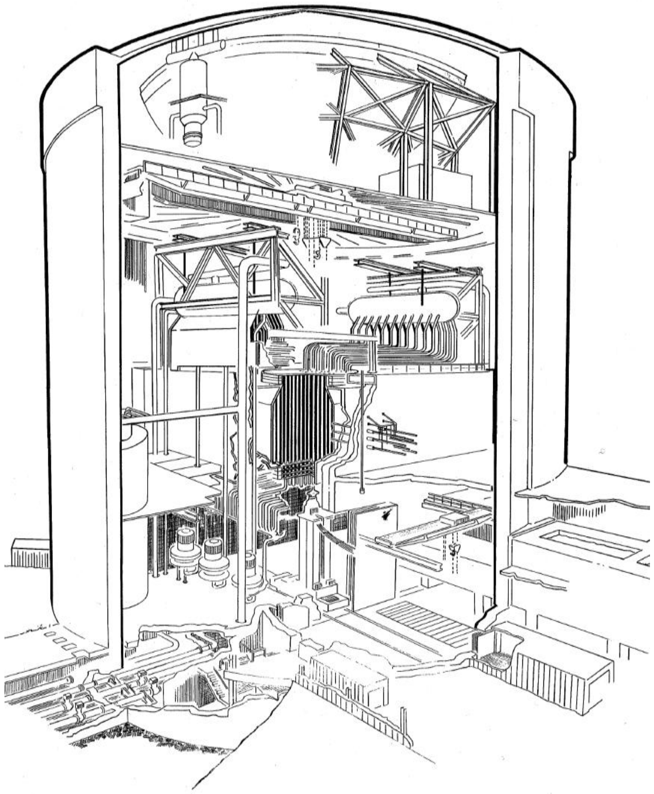


FLOW DIAGRAM REACTOR SGHWR

FJOH 2010

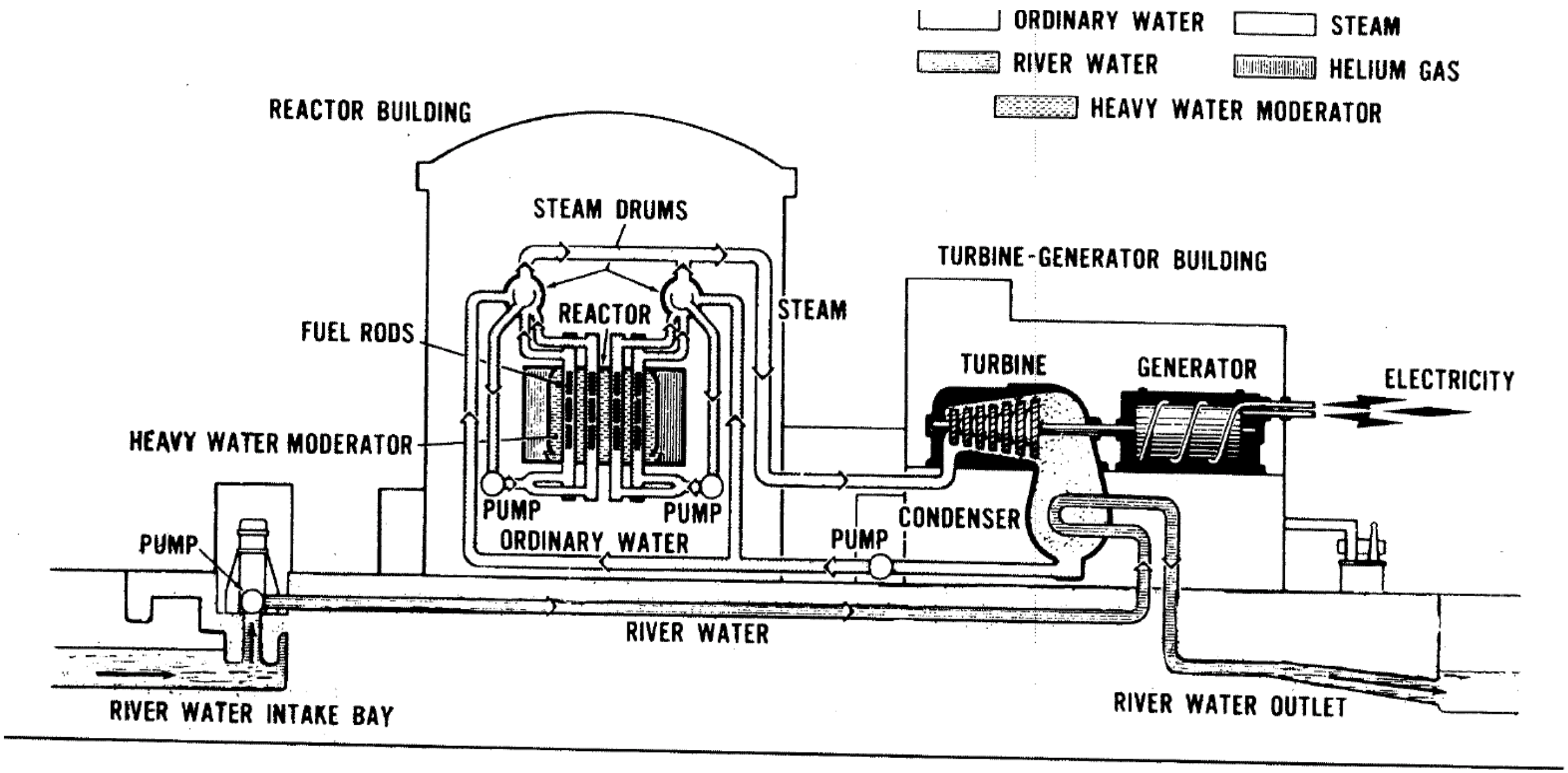
Gentilly-1 (Canada, 1972)

- Prototype for boiling light water in HWR.
- 830 MW_{th} / 250 MW_e (net)
- 308 vertical channels / 10 bundles
- 18-element Natural UO_2 fuel bundles
  - 7,000 MWd/t burnup.
- Boiling light water, 5.6 MPa, 270 C
- Shutdown in 1979
  - Operated 1972-1977.
  - Debugging reactor control.
    - Xenon (Xe-135) oscillations.
    - Larger, more positive void coefficient.
  - Consolidation in nuclear industry.
  - Focus on CANDU-PHWR only.



Gentilly-1 (Canada, 1972)

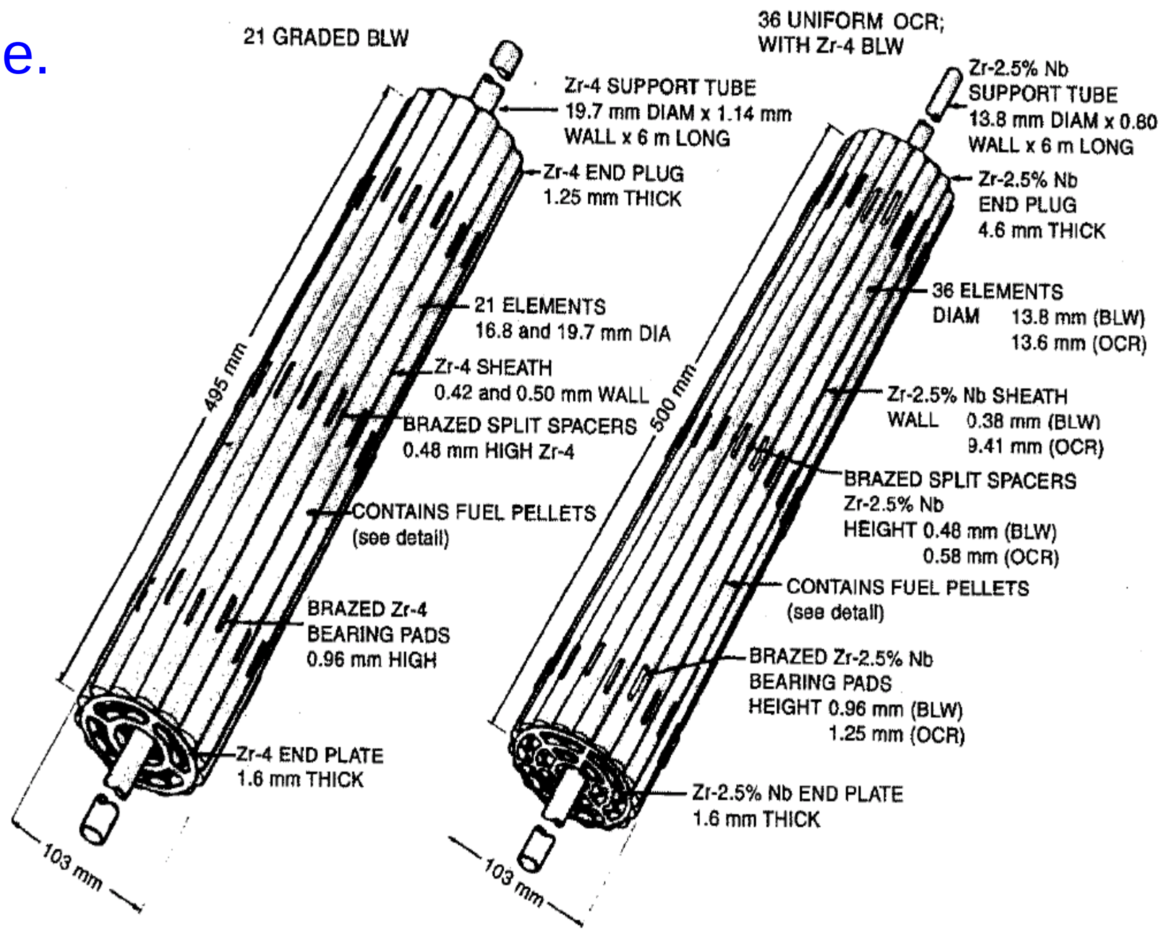
- Similar to SGHWR.
- Steam drums; direct cycle.



FJOH 2010

Gentilly-1 (Canada, 1972)

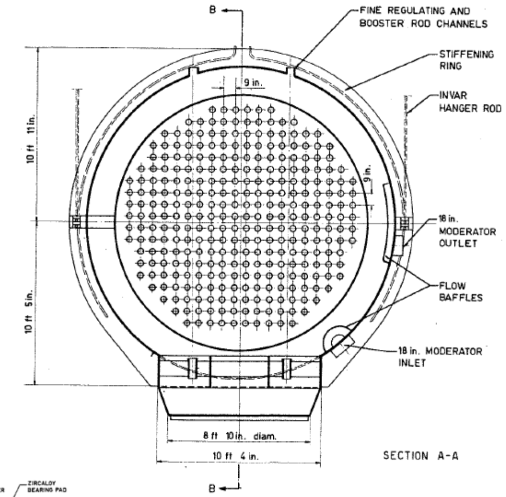
- 18-element fuel bundle.
  - ~50 cm long.
  - Natural UO_2.
- Central support rod.
- Anticipated designs.
  - 22-element.
  - 36-element.

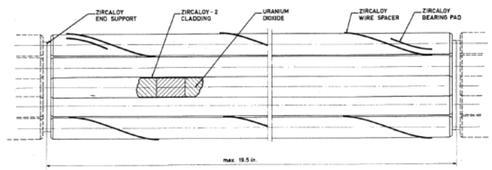


FJOH 2010

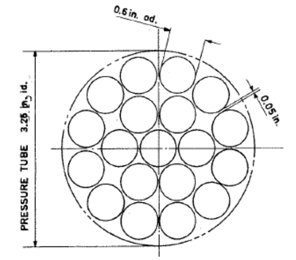
Rajasthan (India, 1973)

- Two CANDU reactors built at Rajasthan Atomic Power Station (RAPS)
  - Unit 1: 90-MWe CANDU (1973)
  - Unit 2: 187-MWe CANDU (1981)
  - Both based on Douglas Point CANDU design.
    - 694 MWth output (nominal, maximum).
    - 306 channels, 22.86-cm square lattice pitch.
    - Zircaloy-2 PT/CT
      - o PT later replaced with Zr-2.5%Nb
    - 19-element fuel bundles.
      - o Natural UO_2 oxide
      - o Zircaloy-2 sheath.
      - o Wire wrap for spacing (similar to NPD-2, Douglas Point)
    - Coolant at 9.2 MPa, 293°C (reactor exit conditions).
  - Indigenous Indian R&D program for PHWR's grew.
    - Evolution and improvement over RAPS-1 and RAPS-2.





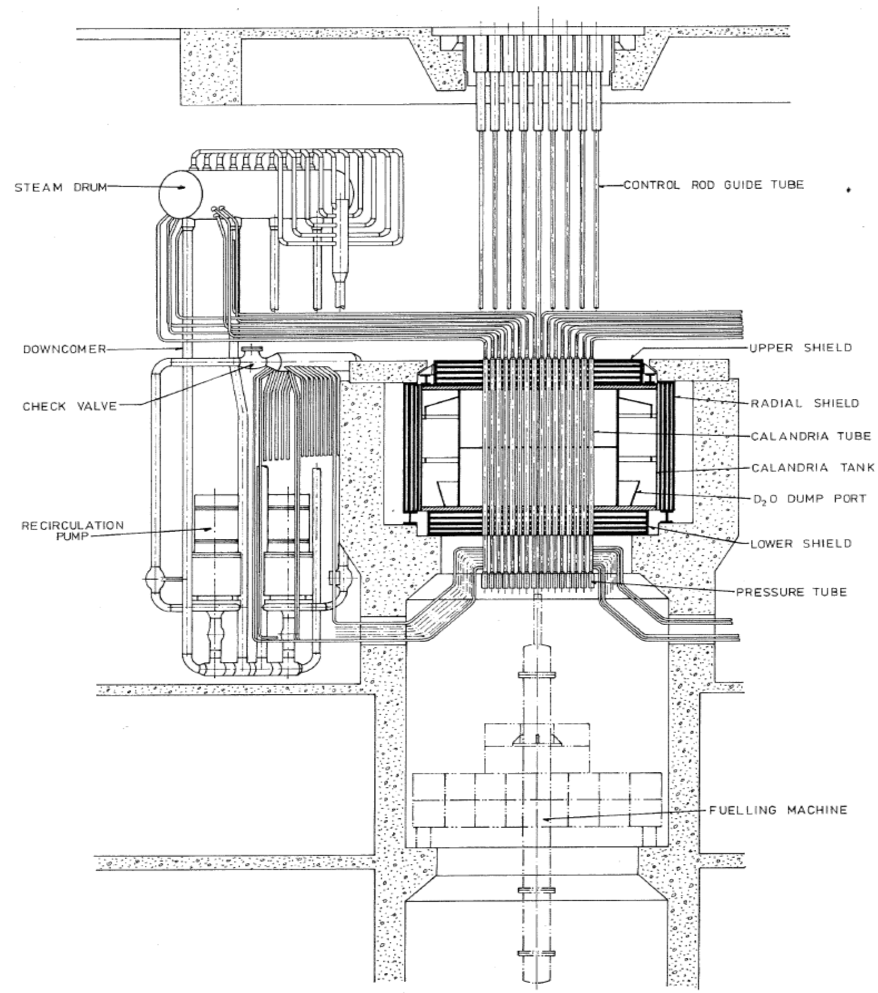
FUEL ELEMENT REACTOR CANDU



FJOH 2010

FUGEN (Japan, 1979)

- HW-BLW Reactor
- Operated 1979-2003
- Similarities to:
  - SGHWR, Gentilly-1
- 557 MW_{th} / 148 MW_e
- Void/Power Coefficients
  - Slightly negative.
  - Use of MOX fuel.
- First for HW power reactor
  - Use recycled Pu in MOX
- Burnup
  - 10 GWd/t to 17 GWd/t

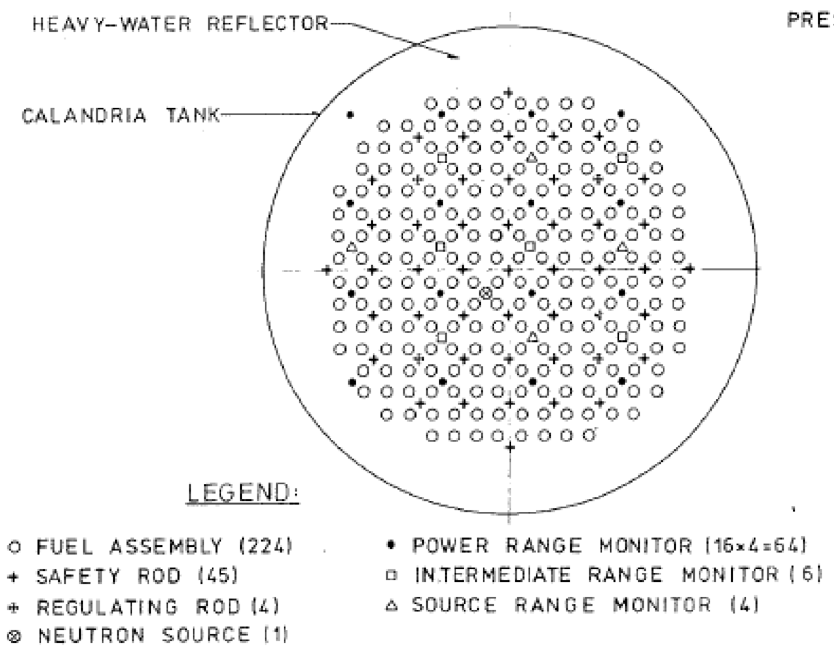


VERTICAL SECTION REACTOR FUGEN

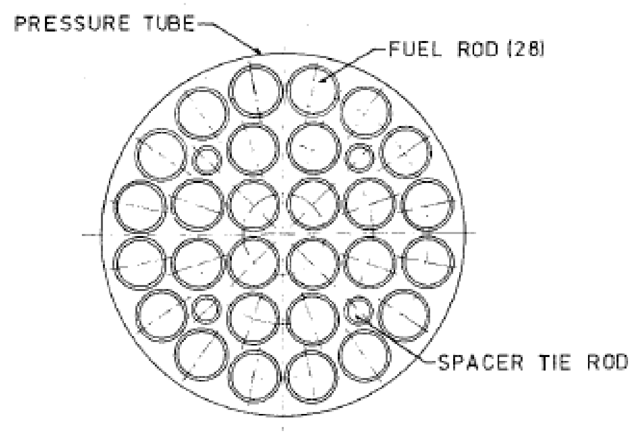
FJOH 2010

FUGEN (Japan, 1979)

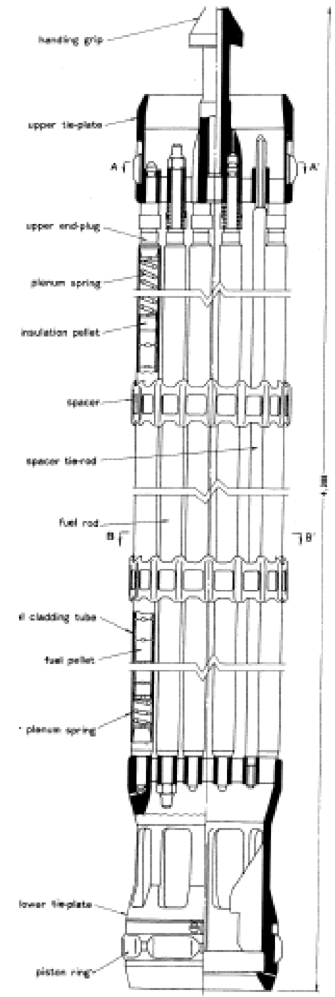
- ❑ 224 Channels, 24-cm pitch.
  - ➢ Zr-2.5%Nb PT, Zr-2 CT.
- ❑ 28-element assemblies, 4.4 m long.
  - ➢ 1.5 to 2 wt% fissile in UO_2 or MOX.



CORE ARRANGEMENT

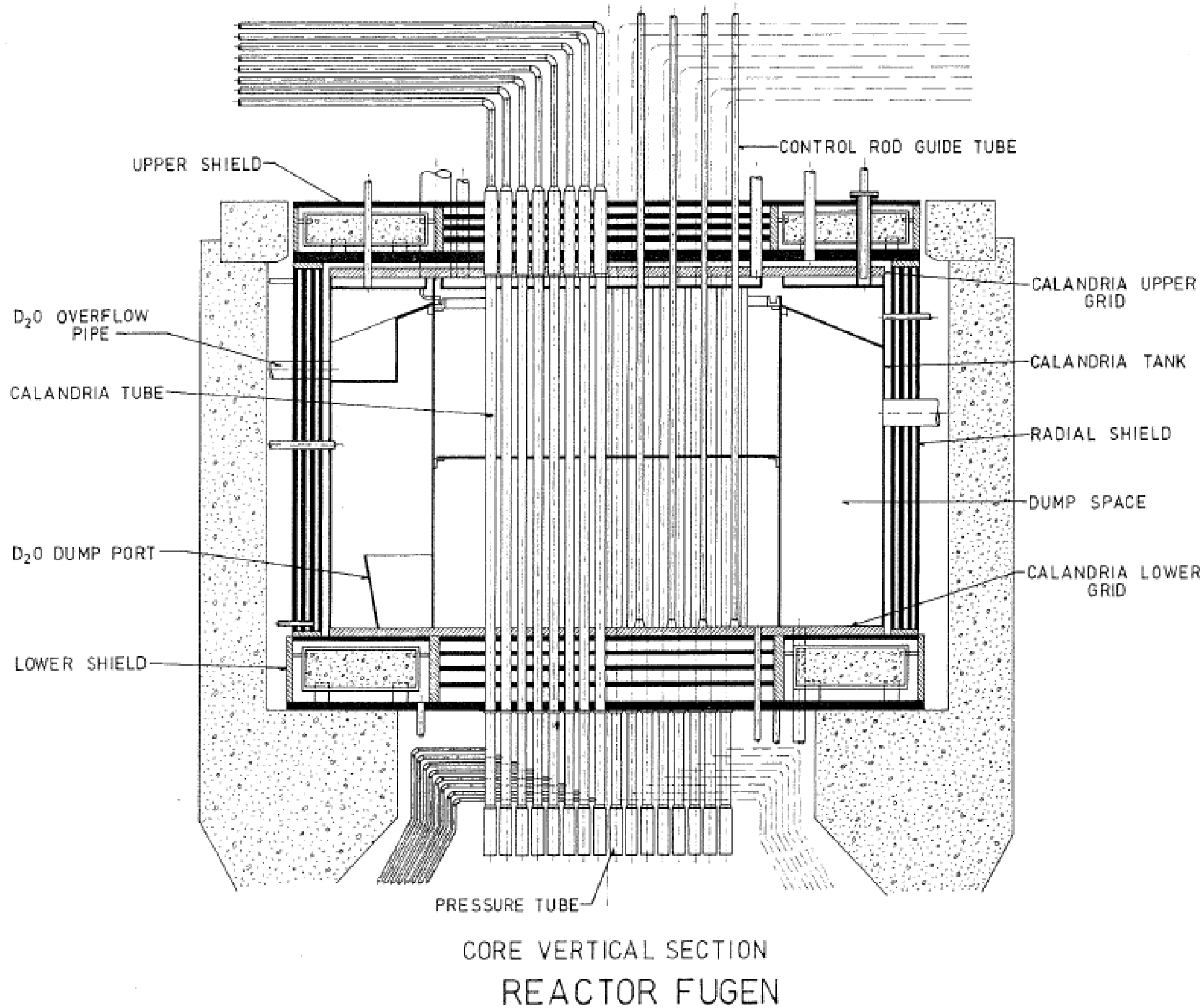


FUEL ELEMENT



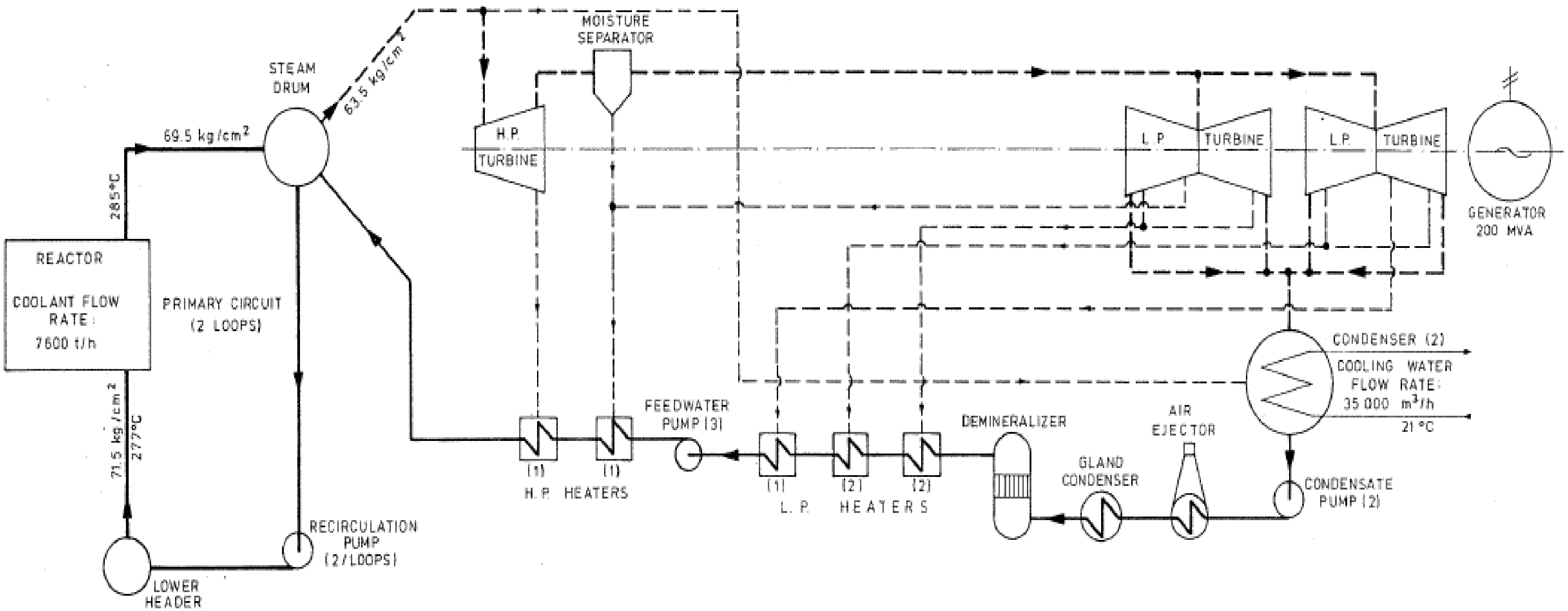
FUGEN (Japan, 1979)

- On-load refuelling
  - ~1 cluster / week
- Control
  - B_4C rods
  - Moderator dump
  - Chemical shim
    - Boron



FUGEN (Japan, 1979)

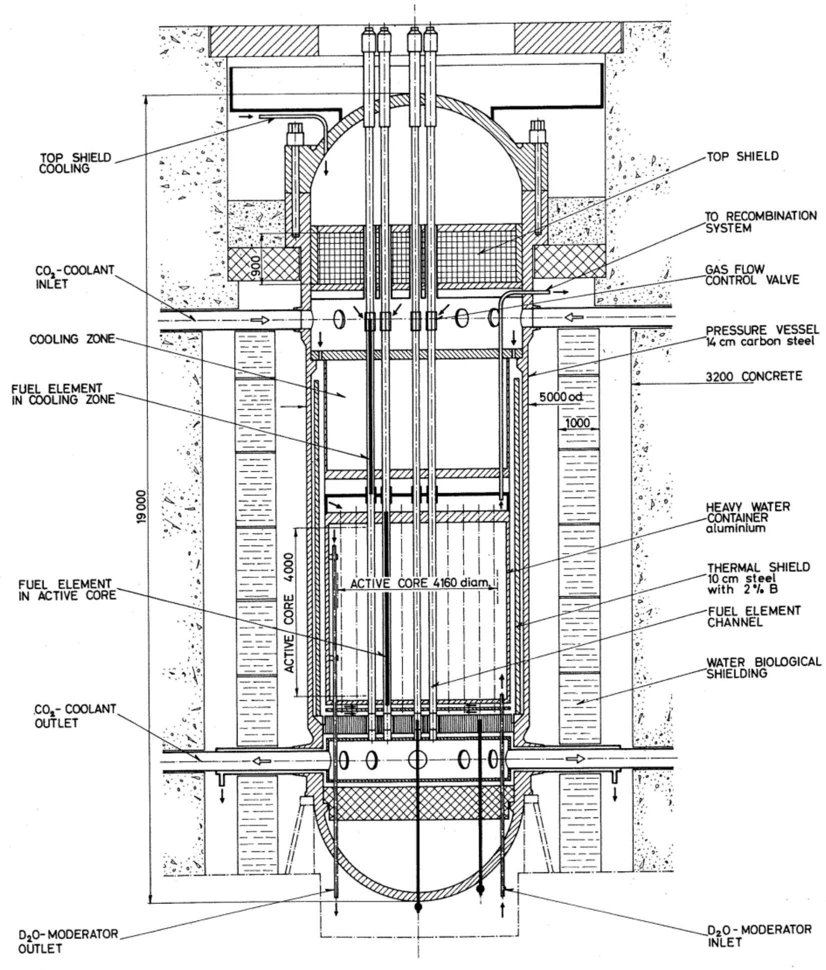
- Boiling coolant at 7.1 MPa, 283.5 C.
- Steam to turbines at 6.4 MPa, 279 C.
- Successful technology demonstration.



FLOW DIAGRAM REACTOR FUGEN

KS-150 / A-1 (Slovakia, 1972)

- Czechoslovakia (1972-1979)
  - Based on Russian design.
- Pressure vessel-type
  - Moderator at 90 C.
- 590 MW_{th} / 150 MW_e
  - Blowers use ~15%
  - Net efficiency ~20%
- CO_2-cooled.
- 11 kW/litre
  - CO_2 at 6.5 MPa .
- 156 Fuel Channels
  - Mg-alloy PT, Al-alloy CT.
- 40 Control rods

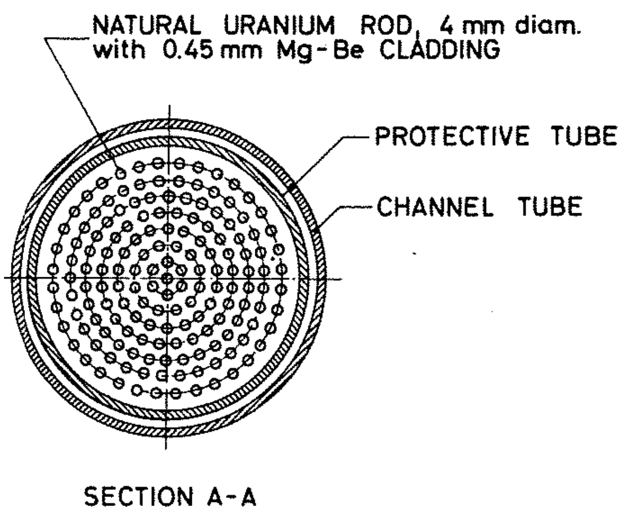


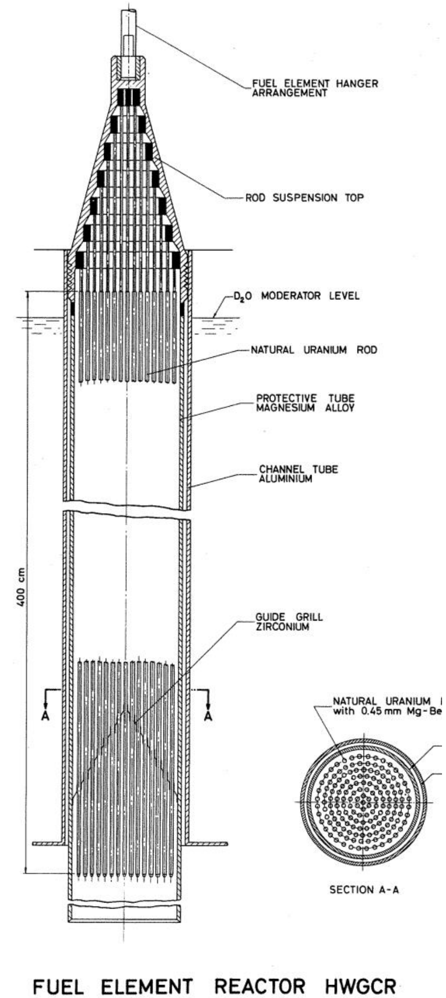
VERTICAL SECTION REACTOR HWGCR

FJOH 2010

KS150 / A-1 (Slovakia, 1972)

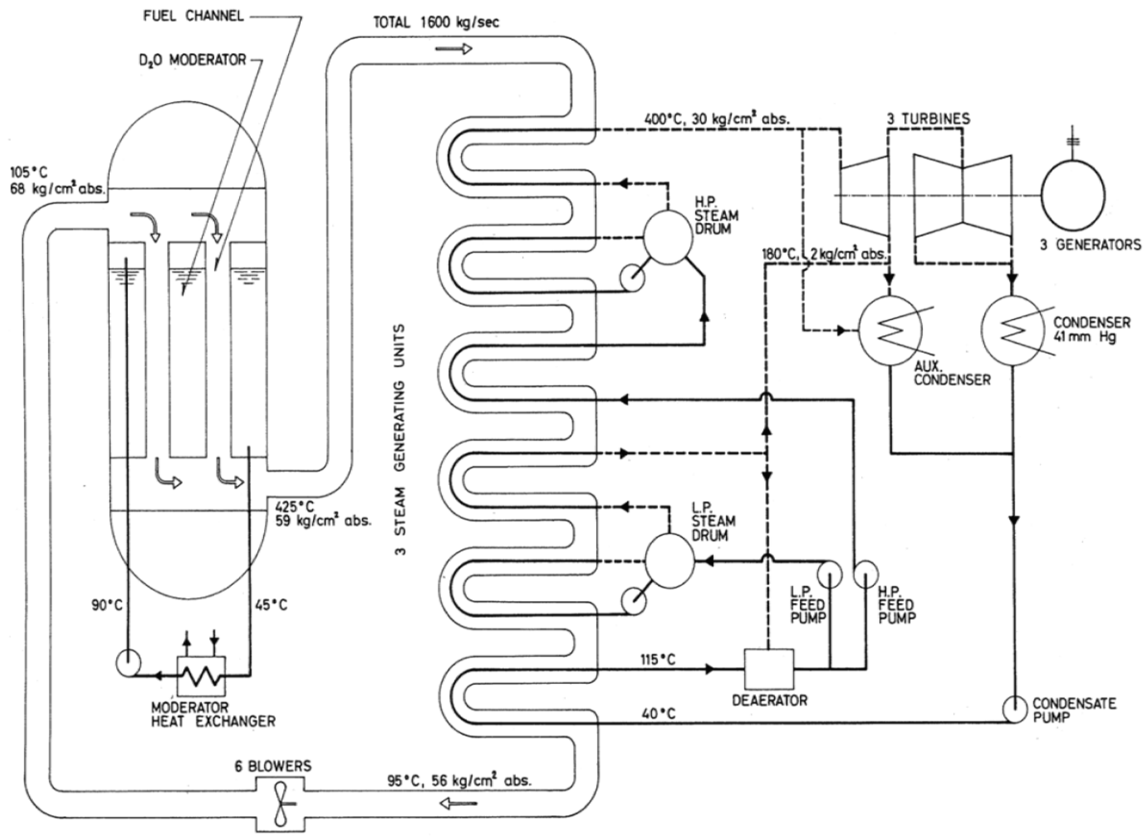
- Metallic fuel in cluster
  - 150 to 200 fuel pins
  - Nat. U metal clad in Mg/Be
  - Aluminum channels.
- 3,000 MWd/t to 5,000 MWd/t





KS-150 / A-1 (Slovakia, 1972)

- CO_2 at 425 C
- Steam at
  - 2.8 MPa
  - 400 C (superheat)
- Construction
  - Started in late 1950's
  - Startup in 1972.
- Shutdown
  - 1979.
  - Partial fuel melt.
  - Misc. tech. problems.

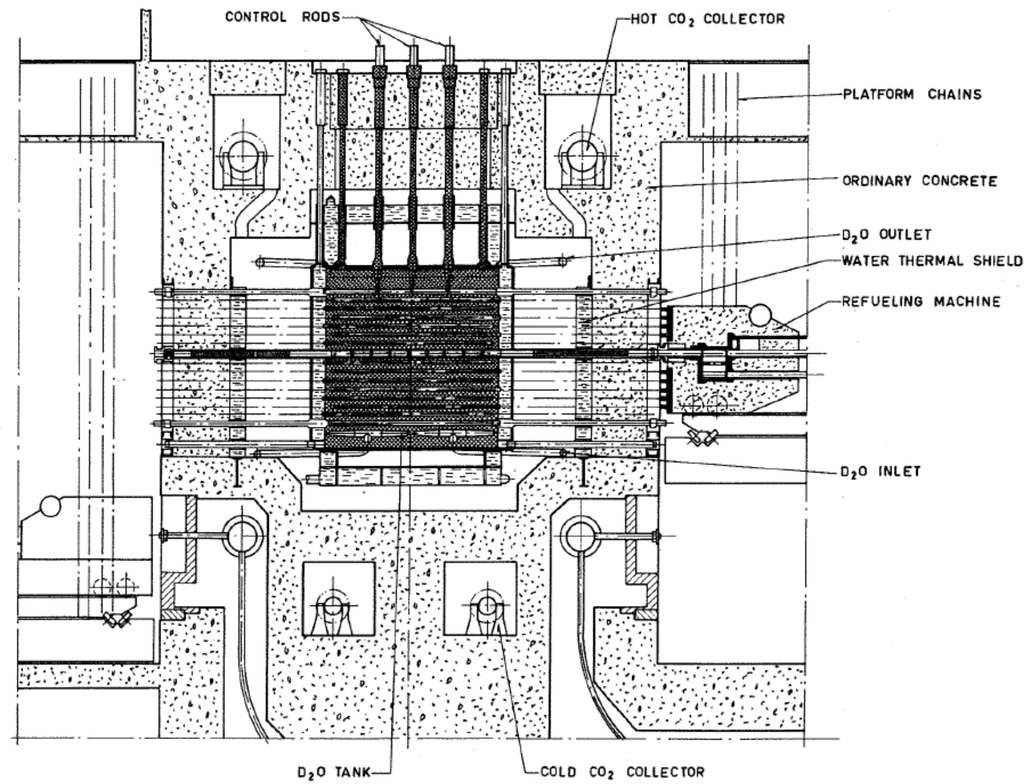


FLOW DIAGRAM REACTOR HWGCR

FJOH 2010

EL-4 (France, 1968)

- Monts d’Arree (Brennilis)
- GCHWR – Pressure Tube
- Very similar to CANDU
  - But gas-cooled.
- 250 MW_{th} / 70 MW_e
  - 28% efficient
  - 4.4 kW/litre
- CO_2 at 5.9 MPa, 500 C
- Zr-2 Channels
  - Horizontal
- Control
  - B_4C and SS rods

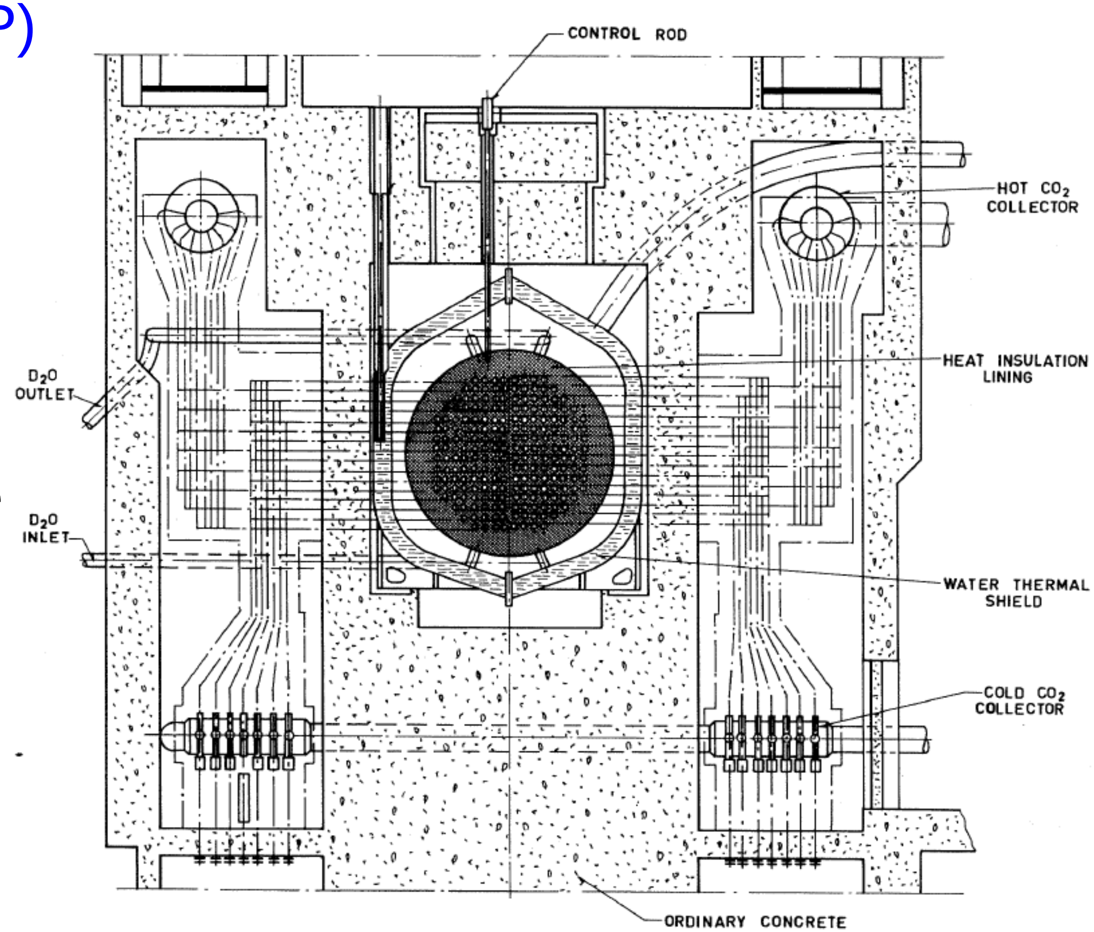


LONGITUDINAL SECTION

REACTOR EL-4

EL-4 (France, 1968)

- 23.5-cm Pitch (~KANUPP)
- 19-rod bundles
  - 0.5-m long
  - 1.37 wt% UO_2
  - 1.65 wt% UO_2
  - SS clad (or Zr/Cu)
  - Graphite liner for bundle
  - 9 bundles / channel
  - On-line refuelling.
- Burnup:
  - 12,000 MWd/t

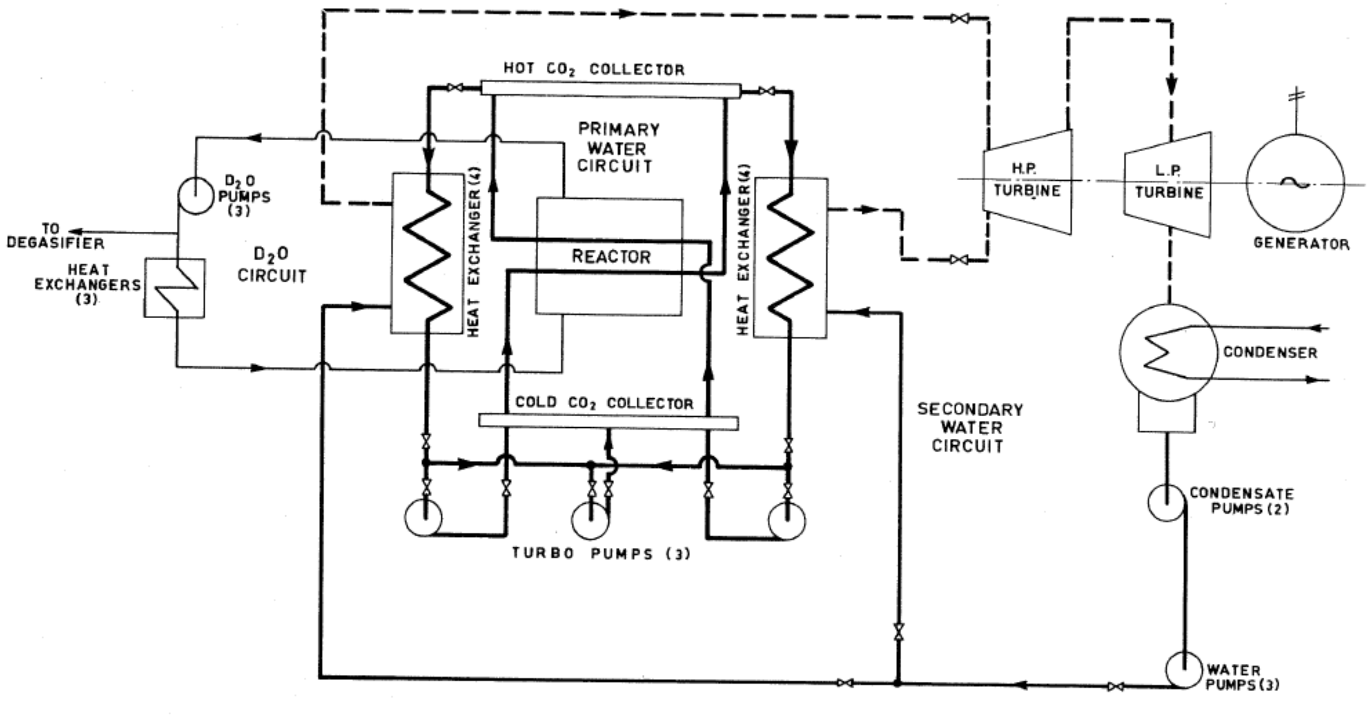


VERTICAL SECTION REACTOR EL-4

FJOH 2010

EL-4 (France, 1968)

- Steam at 6.7 MPa, 490 C
- Operated successfully 1968-1985 (17 years).
  - Demonstration successful.



FLOW DIAGRAM REACTOR EL-4

FJOH 2010

Lucens (Switzerland, 1968)

- GCHWR – pressure tube, small-scale experiment
- 30 MW_{th} / 7.6 MW_e, 25.3% efficiency.
- 73 vertical fuel channels, 10 control channels
  - Zircaloy pressure tubes, calandria tubes.
  - Cd/Ag alloy control rods
- 0.96 wt% enriched U-0.1%Cr metal alloy
  - 7-rod assemblies, Mg-Zr alloy finned clad (~Magnox)
  - Graphite liner / coolant tube around each fuel rod
  - Return flow (down outer annulus, up through fuel pins)
  - 3,000 MWd/t burnup
- Off-load refuelling.
- CO_2 at 6.2 MPa, 378 C outlet
- Steam at 2.2 MPa, 367 C

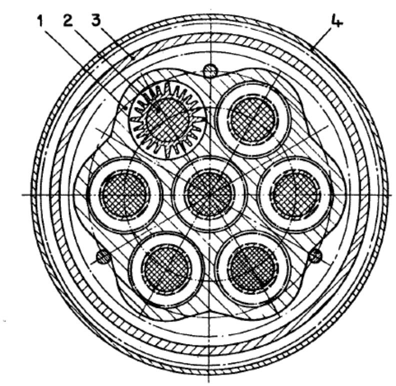
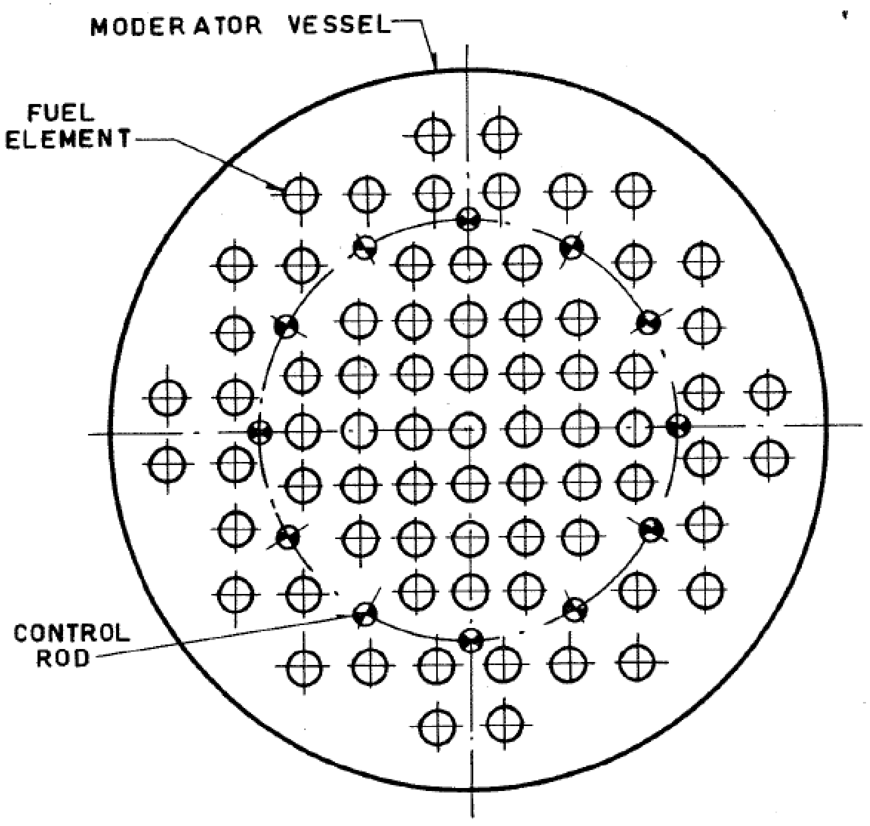


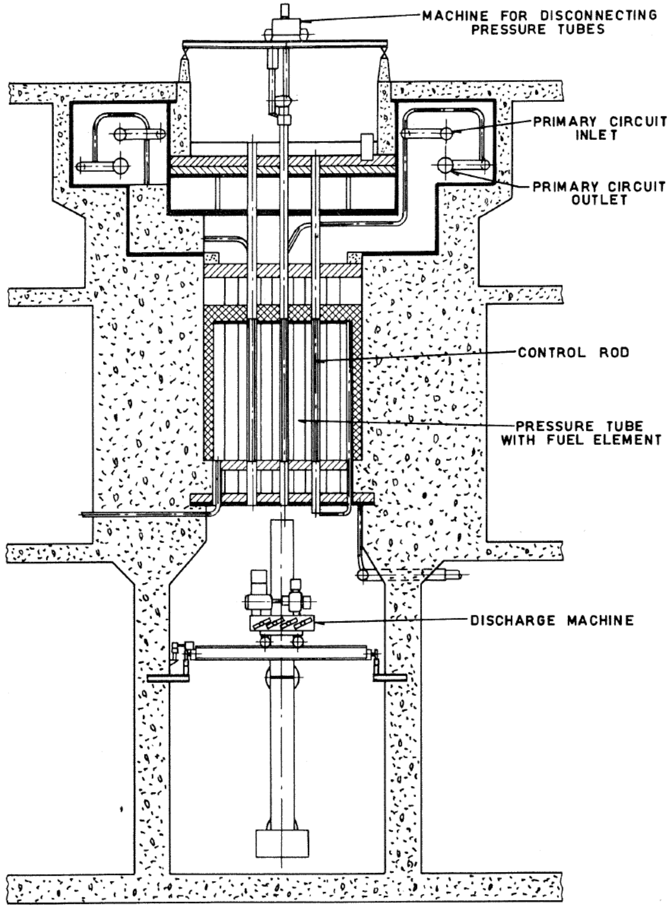
Figure 4. Fuel element, radial section
1: Graphite structure; 2: Uranium and cladding; 3: Pressure tube; 4: Calandria tube

Lucens (Switzerland, 1968)

- Two pitches: 24 cm & 29 cm



CORE ARRANGEMENT



VERTICAL SECTION REACTOR LUCENS

Lucens (Switzerland, 1968)

- Project started in early 1960's.
- Startup in 1968, but shutdown in 1969
  - Flow blockage formed from corrosion products
  - Fuel damage and partial melt
  - At bottom at startup
- Later converted to test facility.

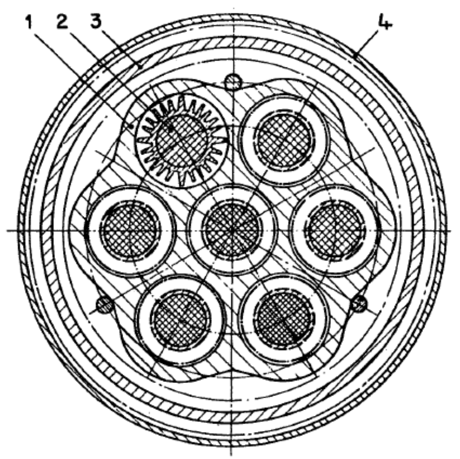
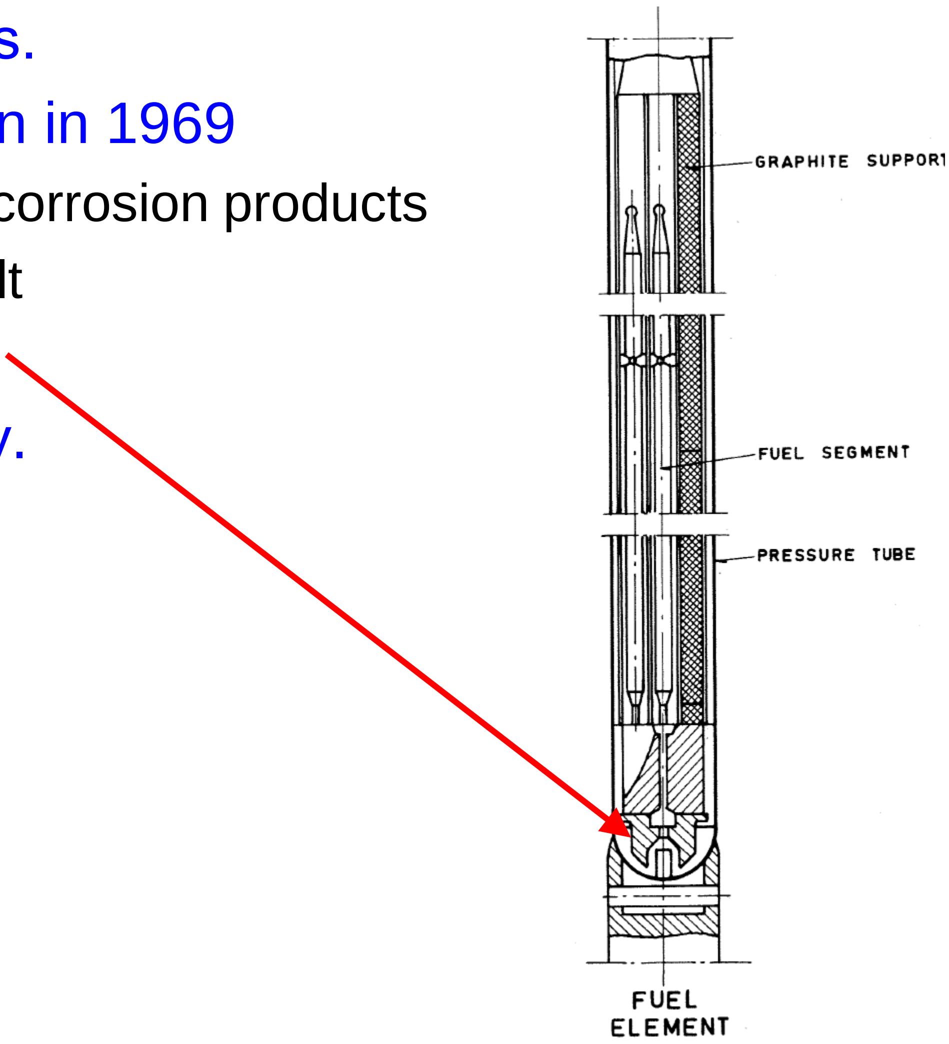
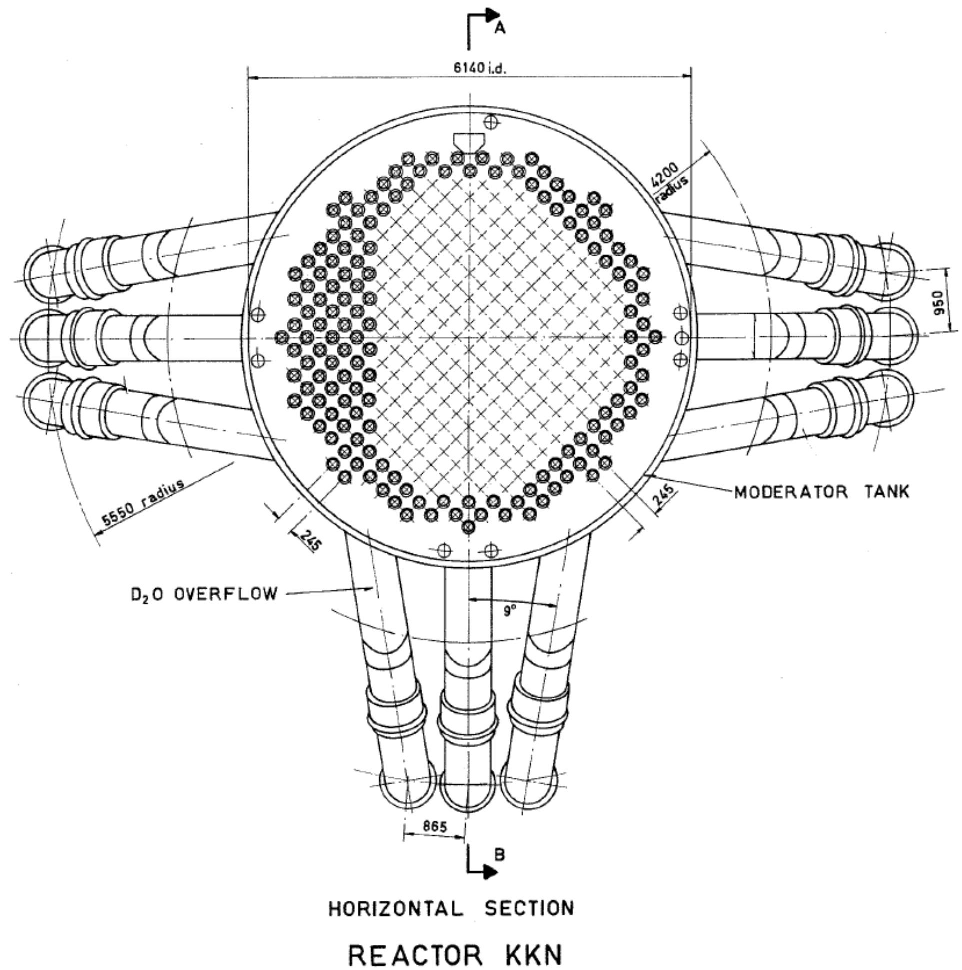


Figure 4. Fuel element, radial section
1: Graphite structure; 2: Uranium and cladding; 3: Pressure tube; 4: Calandria tube



KKN (W. Germany, 1970)

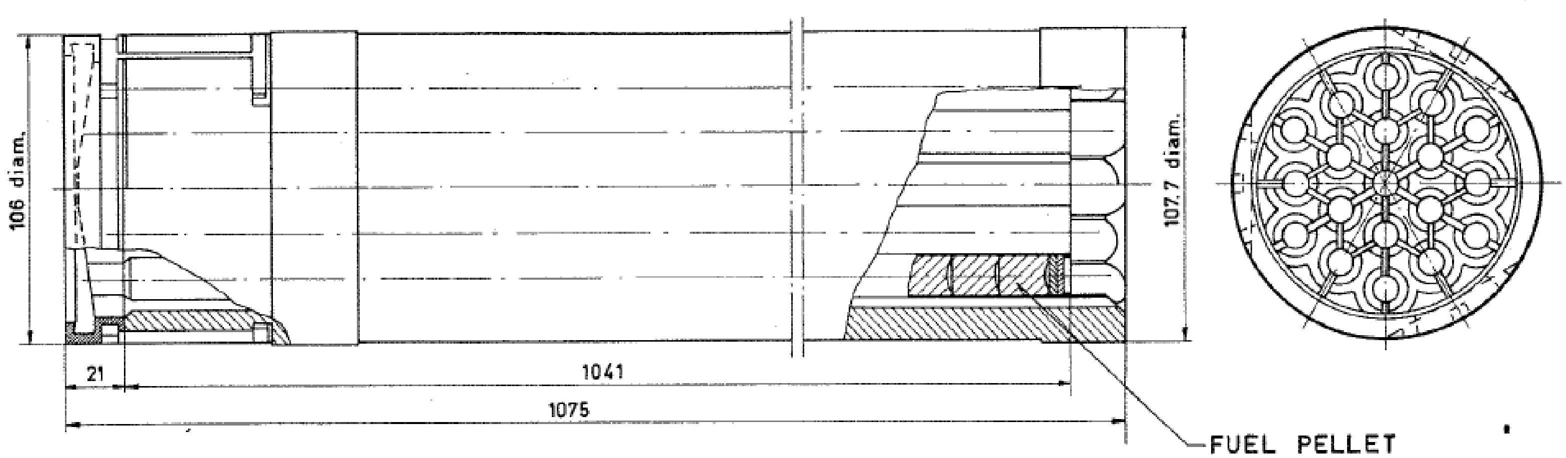
- Kernkraftwerk Niederaichbach (KKN)
  - Project began in early 1960's
  - Reached full power in 1970.
  - Connected to grid in 1973. Shutdown in 1974.
- GCHWR – pressure tube, vertical.
- 316 MW_{th} / 100 MW_e
- 31.6% efficient, 3.5 kW/litre.
- 351 channels, Zircaloy-2
- 24.5-cm pitch



FJOH 2010

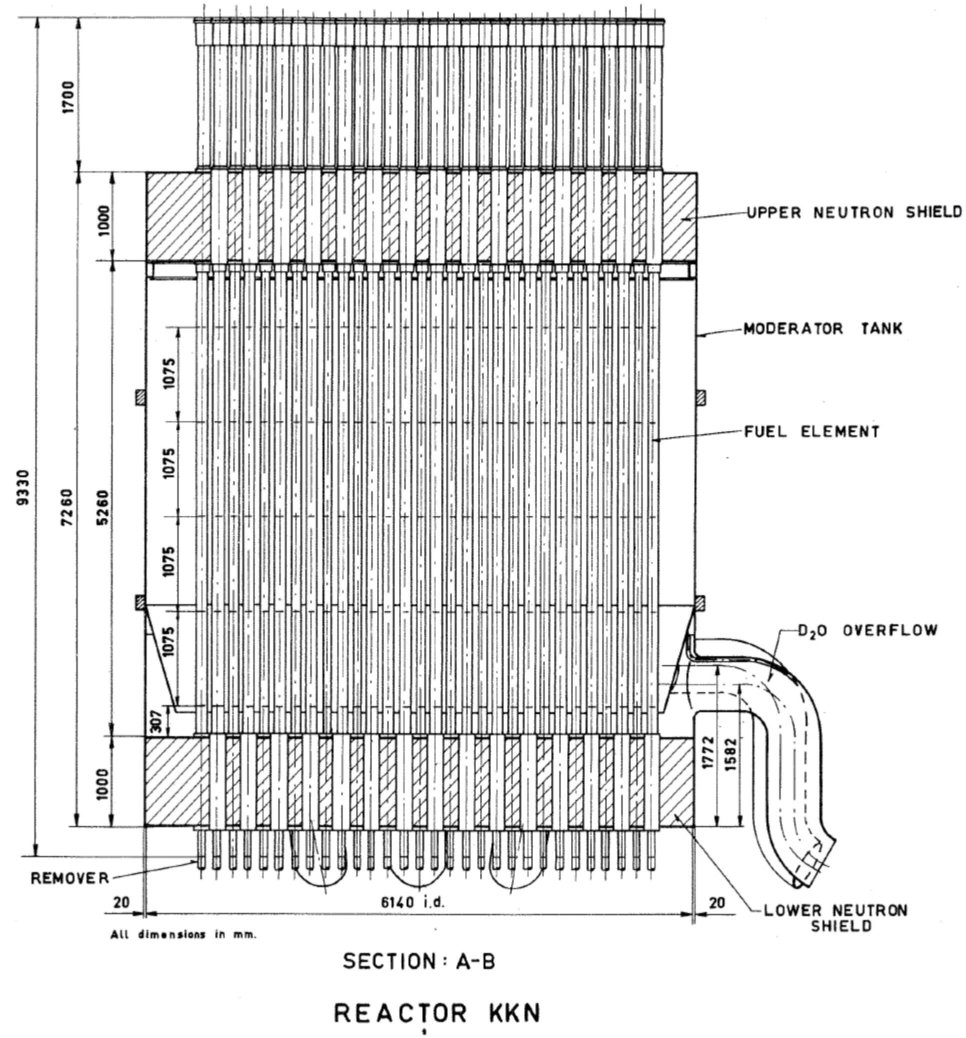
KKN (W. Germany, 1970)

- 19-element bundles, 107-cm long, 4 per channel.
  - 1.15 wt% UO_2, stainless steel clad.
  - 11,600 MWd/t burnup.
  - C.R. ~0.58 (at startup).
- On-load refuelling capability, 1 bundle/day.



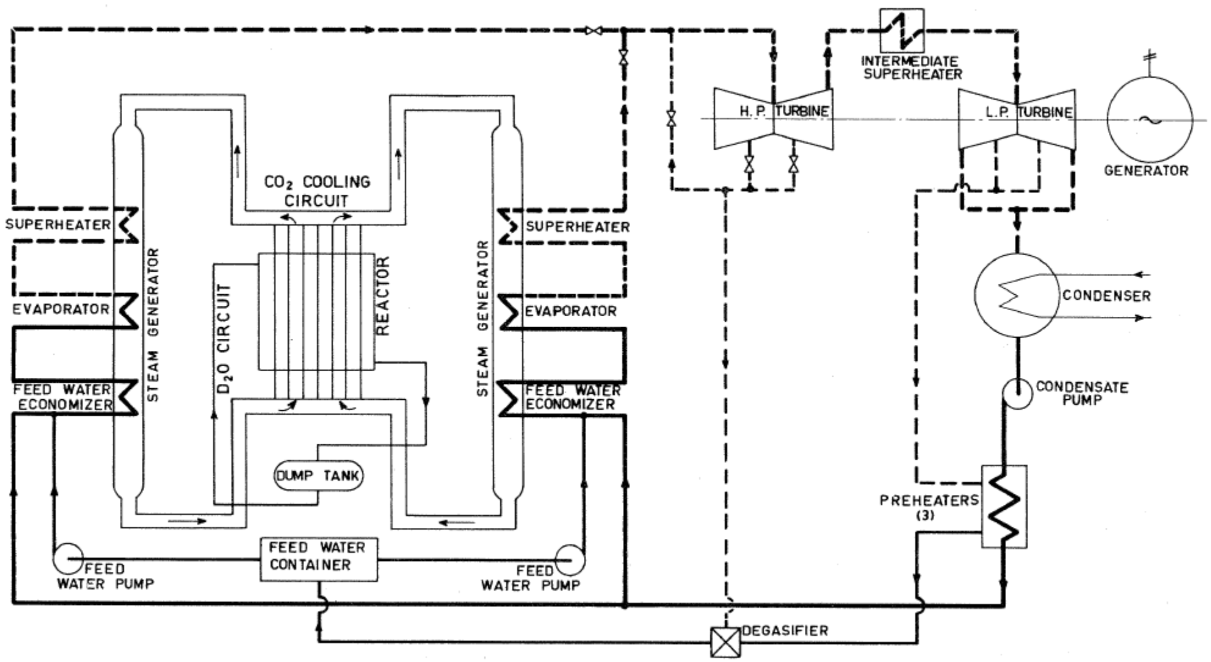
KKN (W. Germany, 1970)

- Vertical channels
- Control:
  - $CdSO_4$ in moderator
  - Moderator level
  - Moderator dump



KKN (W. Germany, 1970)

- CO_2 at 6 MPa, 550 C; steam at 10 MPa, 527 C
- Operated 1970-1974, but shutdown.
  - Difficulties encountered with steam generators.
  - Consolidation of efforts. Larger LWR's were doing well.



FLOW DIAGRAM REACTOR KKN

HWR Projects That Did Not Materialize

❑ Scale up of HWR-BLW to Commercial Size

- FUGEN (600 MWe)
  - MOX recycling in LWR's improved.
- SGHWR (350 to 660 MWe)
  - U.K. Government decision to favor AGR's.
- Gentilly-1 (600 MWe)
  - CANDU-PHWR's performing well, consolidation of efforts.
- Cirene (Italy) – 1968 (project shutdown 1988)
  - Prototype, with plans for commercial plant.
  - 1613 MWth / 500 MWe, 31% efficiency
  - 19-rod assemblies, natural UO_2, 8500 MWd/t, 5 MPa
  - Similarities to Gentilly-1

❑ Boiling Heavy Water

- Marviken (Sweden) project cancelled during 1970's.
- Focus on BWR's; take advantage of international LWR experience.

FUGEN (Japan) - Commercial

- 1930 MW_{th} / 600 MW_e
- 648 Channels
- Pu-recycling
- MOX and UO_2
  - 3.2 wt% fissile
  - 30,000 MWd/t burnup
- Void reactivity
  - Negative w/ MOX
- Power coefficient
  - Negative
- Poison injection.

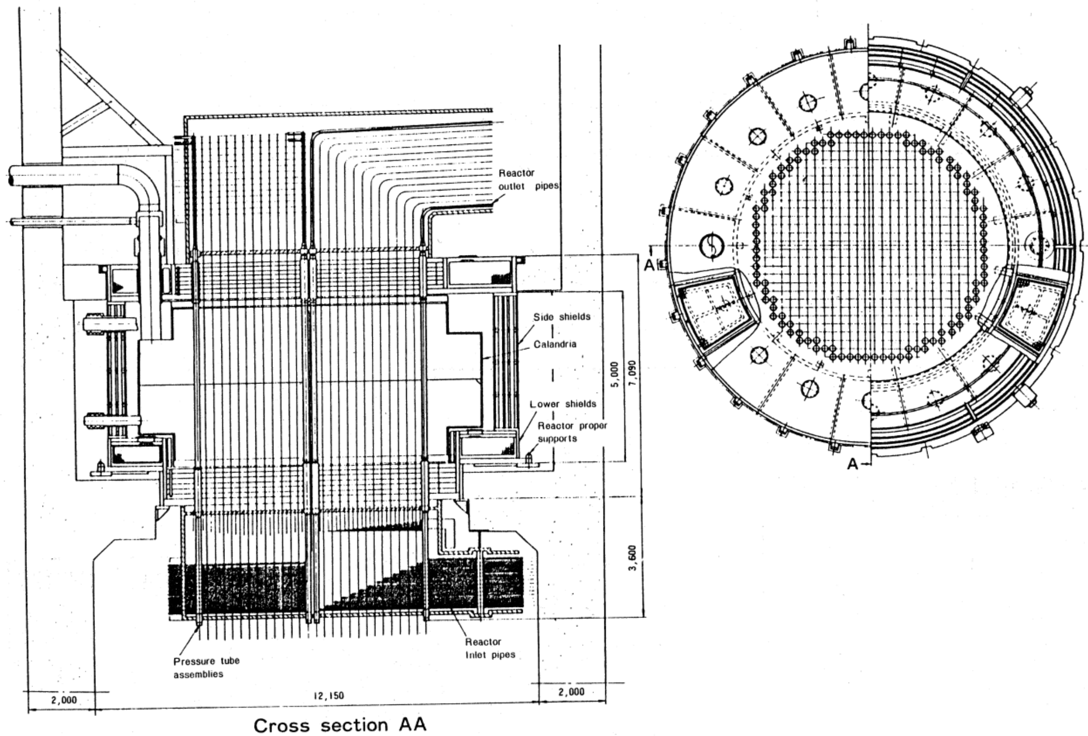


Fig.3 600 MWe Demonstration Plant

FUGEN (Japan) - Commercial

- 36-element fuel assemblies
  - 1.5 wt% to 2.7 wt%
  - 3.2 wt% fissile (UO_2 + MOX)

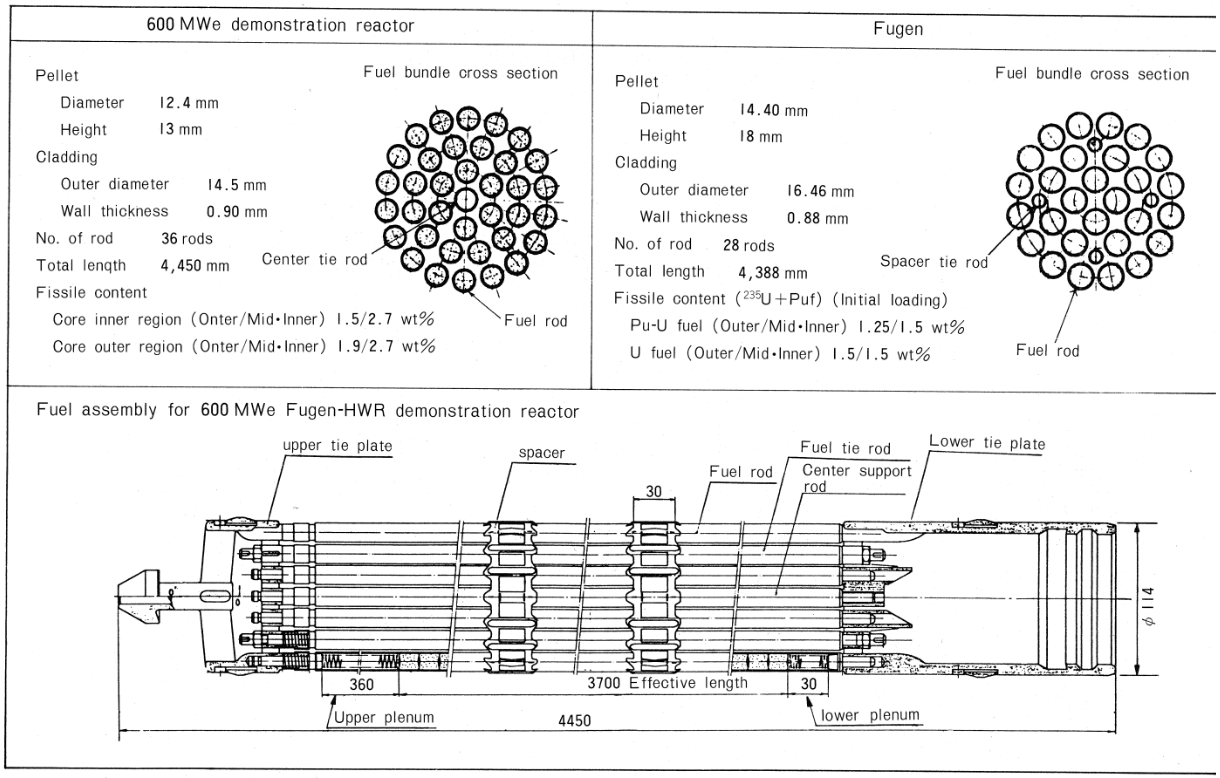
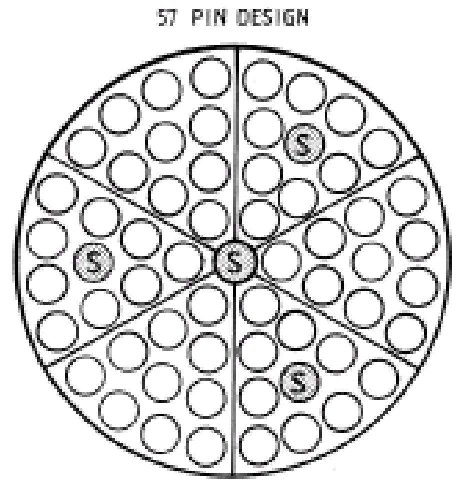


Fig.4 Fuel Assembly

FJOH 2010

SGHWR (U.K.) - Commercial



- Scale-up of Prototype
  - 350 MW_e, 660 MW_e reactors
  - 31% to 32% efficiencies
- 57-rod assemblies
  - upgrade from 36-rod bundles
  - 2.2 to 3 wt% enriched UO_2.
  - 25,000 MWd/t to 27,000 MWd/t
- Negative void, power coefficients
  - Enriched fuel, moderator displacer tubes, tight pitch
- On-load or off-load refuelling.
- 6.7 MPa, 284 C
  - 11% quality

FJOH 2010

CIRENE (Italy, 1976-1988)

- Prototype
  - 130 MW_{th} / 36 MW_e
  - Natural / enriched UO_2
- Commercial
  - 1613 MW_{th} / 500 MW_e
  - 600 vertical channels
  - Boiling H_2O
  - 5 MPa / 260-270 C
  - UO_2 natural
    - Positive void reactivity.
    - Reduced by using enriched.
  - 19-rod assemblies
  - 8,500 MWd/t
  - Off-load refuelling.
- Commissioning stopped in 1988.

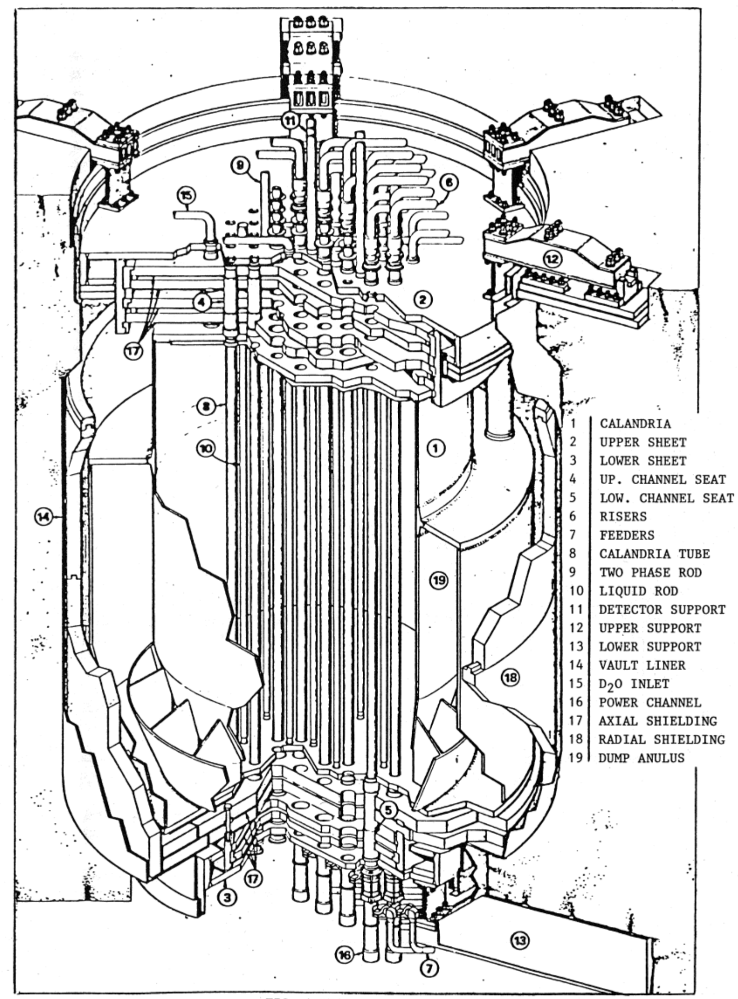
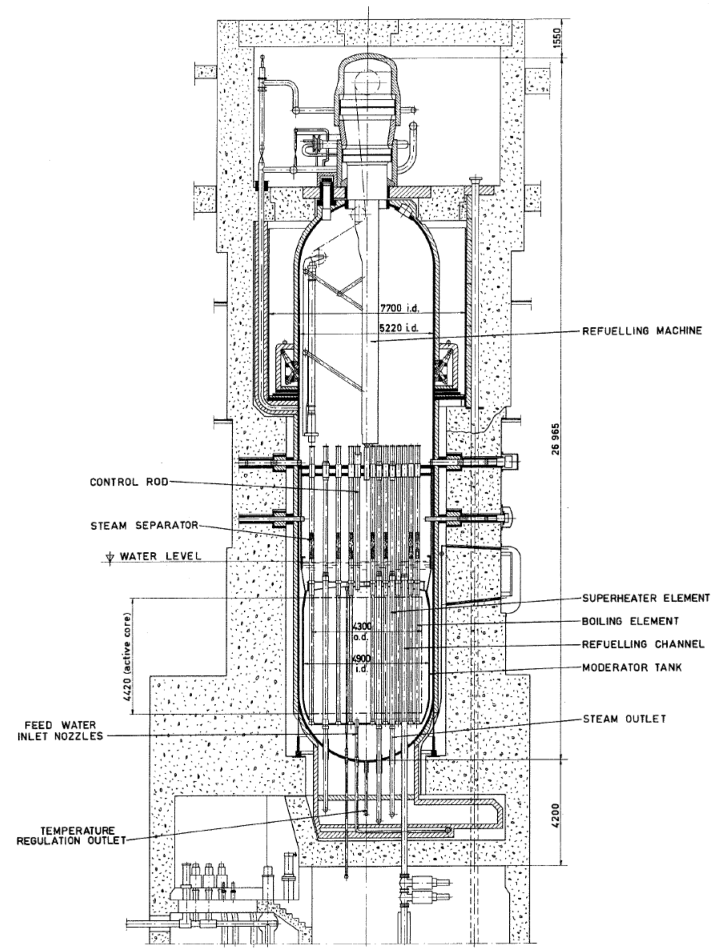


FIG. 1 REACTOR ASSEMBLY

FJOH 2010

Marviken (Sweden, 1960-1970)

- Boiling D_2O with superheating
- Pressure-vessel type.
- 593 MW_{th} / 193 MW_e
- ~34% efficiency
- 147 boiler channels
- 32 superheat channels
- 4.85 MPa, 259 C/472 C
- 13,000 MWd/t burnup.
- C.R.~ 0.40 to 0.47

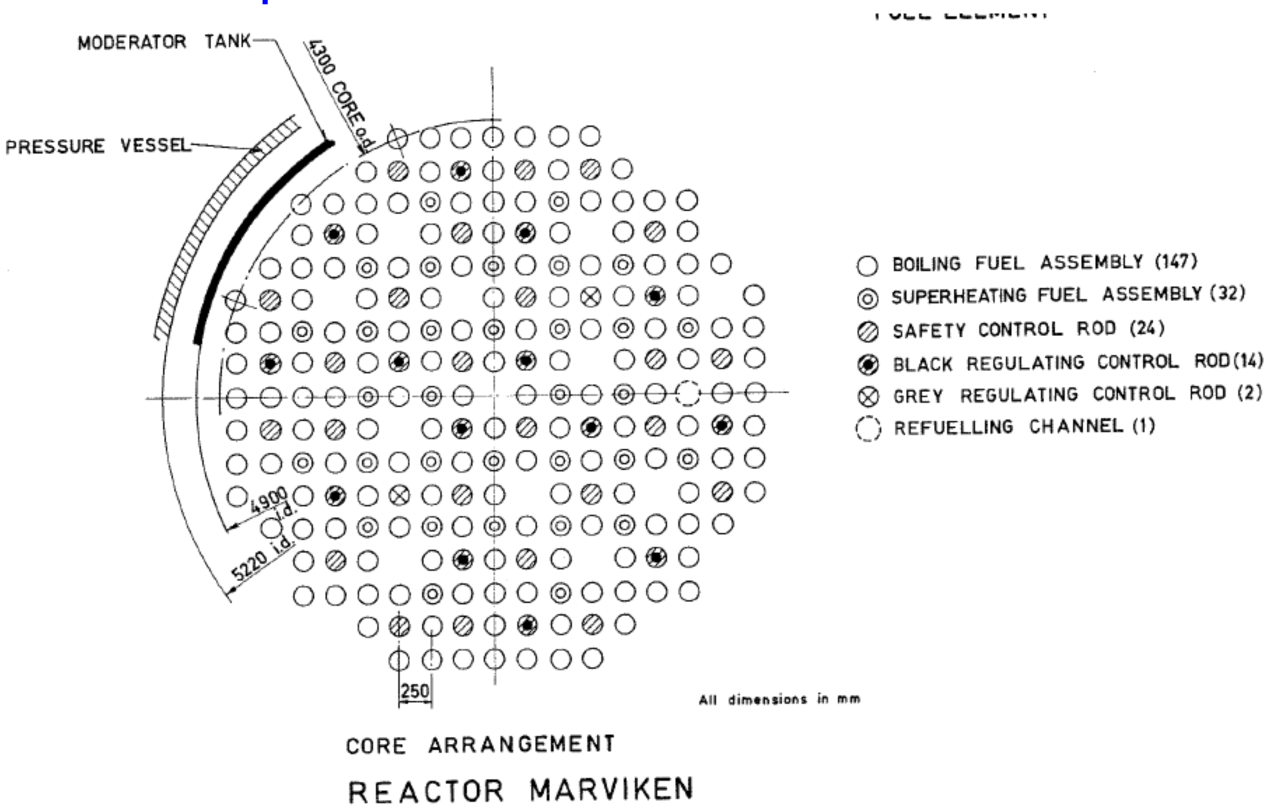


VERTICAL SECTION

REACTOR MARVIKEN

Marviken (Sweden, 1960-1970)

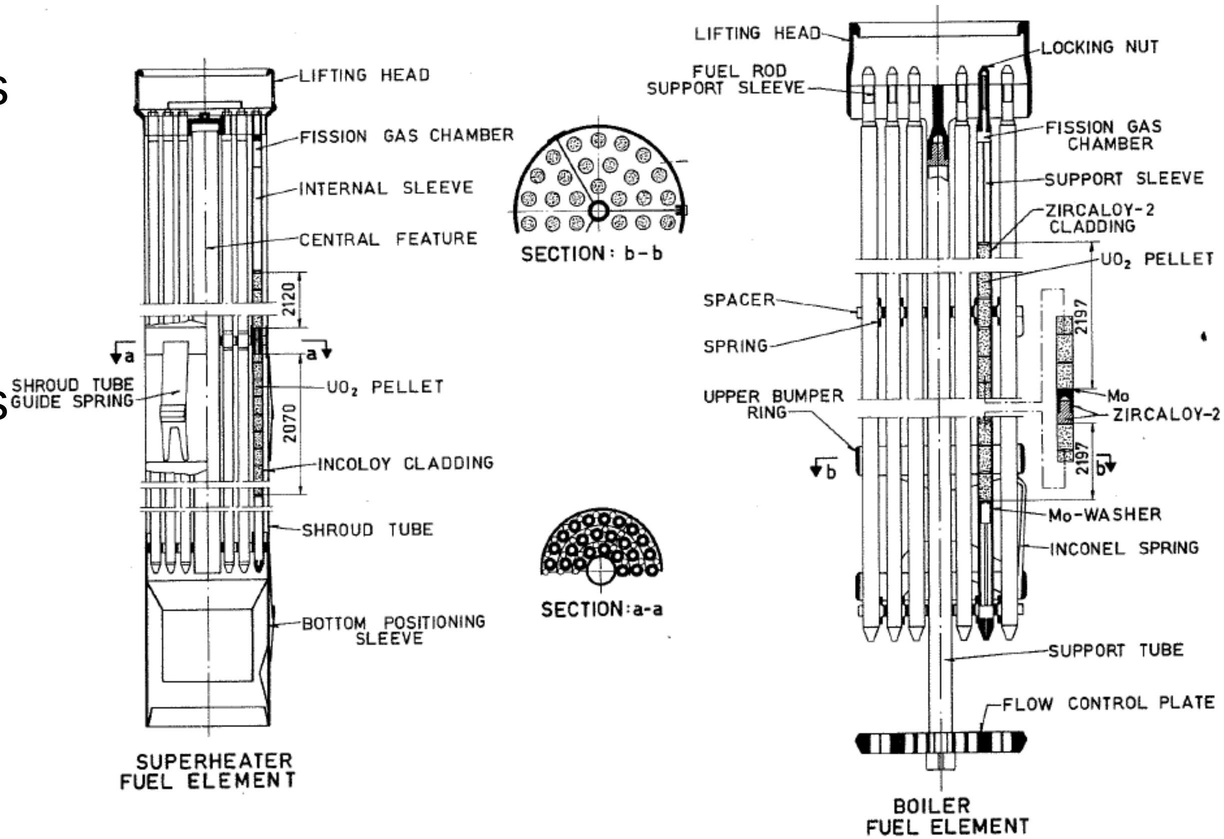
- 4.42 m core height, 4.3 m core diameter
- 25-cm lattice pitch
- 147 boiler; 32 superheat



FJOH 2010

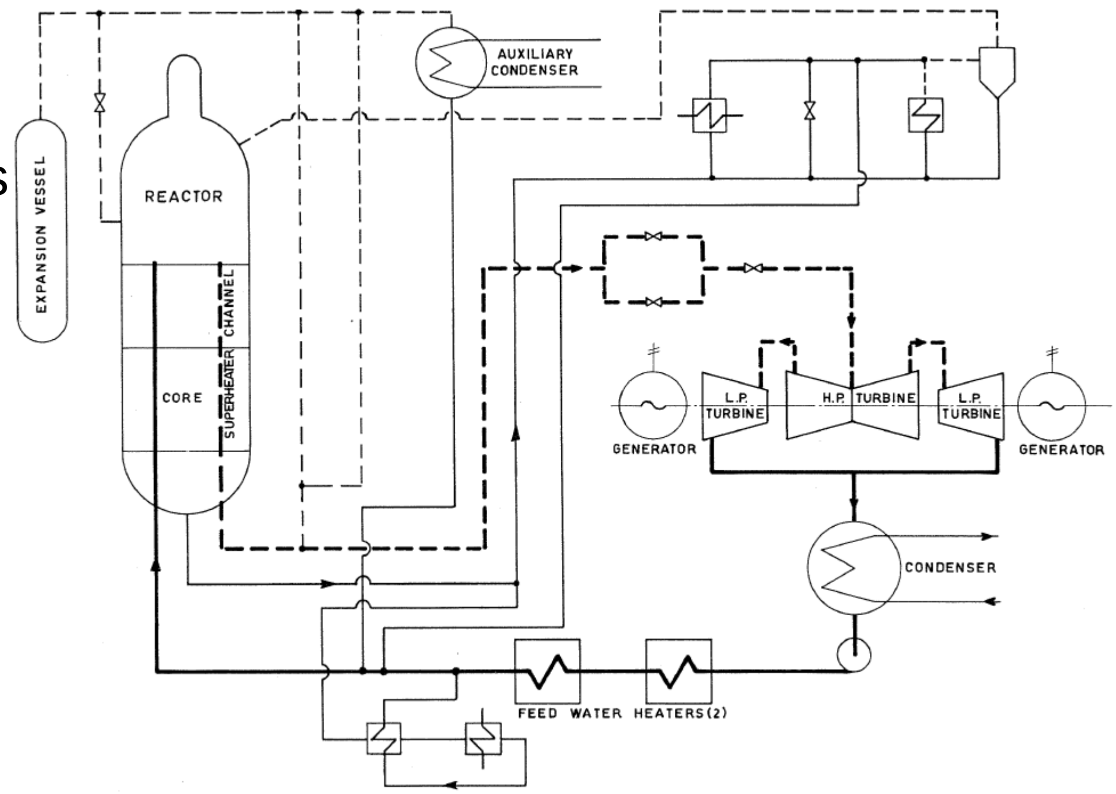
Marviken (Sweden, 1960-1970)

- Boiling
  - 36-rod assemblies
  - 1.35wt% UO_2
  - Zircaloy-2 clad
- Superheat
  - 45-rod assemblies
  - 1.75 wt% UO_2
  - Inconel alloy clad.



Marviken (Sweden, 1960-1970)

- Plans for 600-MW$_e$ commercial unit
  - Pre-stressed concrete
  - Natural uranium
  - 37-element assemblies
  - 9,900 MWd/t burnup
  - 7 MPa, ~284 C
- Stopped at advanced stage of development.
  - Loss of interest by utilities.
  - More work to be done.
  - Licensing issues.



FLOW DIAGRAM REACTOR MARVIKEN

FJOH 2010

Marviken (Sweden, 1960-1970)

- Motivation for use of BHWR
  - Concerns of long-term uranium supply.
- Times change.
  - Project cancelled during 1970's.
  - Focus on BWR's.

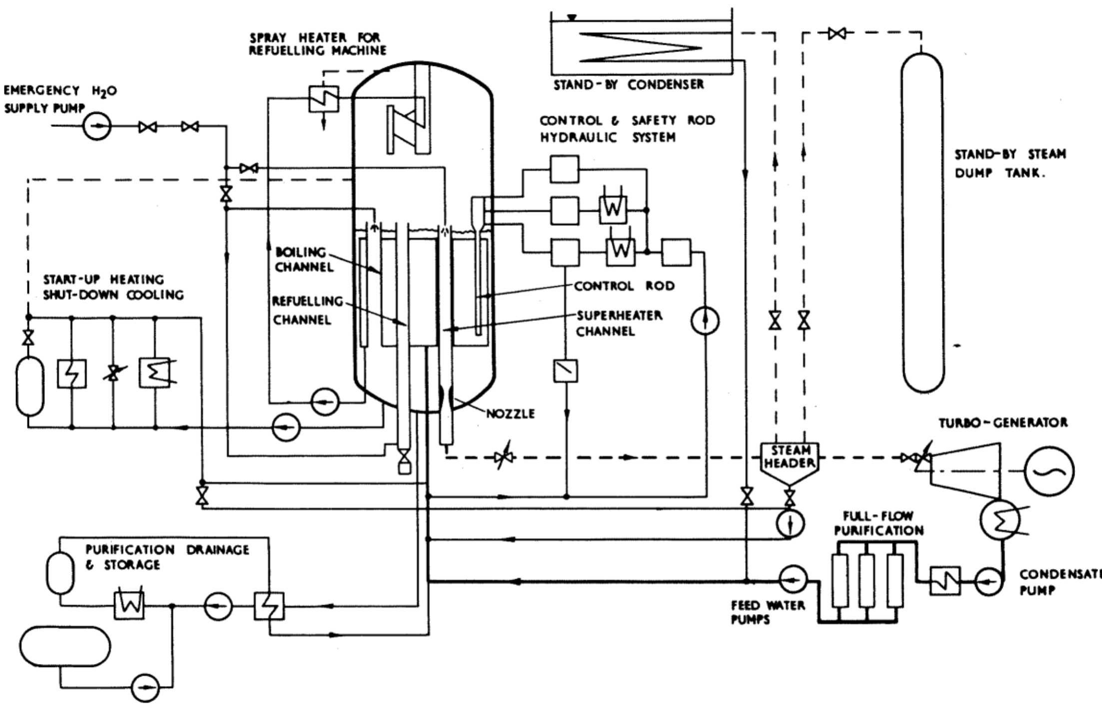


Fig. 4: Marviken BHWR. Simplified flow diagram

FJOH 2010

HWR Projects That Did Not Materialize

- Gas-Cooled Heavy Water Reactors (GCHWR)
  - EL-250 / EL-500 (France)
    - Scale up of EL-4.
    - Consolidation; LWR competition working well.
  - 500 MWe GCHWR (Czechoslovakia)
    - Scale up and improvements over KS-150 / A1 Bohunice
    - Orphaned technology; switch to VVER (Russian PWR).
  - GNEC Project (U.S.A.)
    - PT-GCHWR
    - 58 MWe Prototype, 300 MWe Prototype.
    - Competing priorities.
- Organically-cooled Heavy Water Reactors (OCHWR /HWOCR)
  - Canada, U.S.A., Italy, Spain, Denmark, Czechoslovakia, Russia.
- Sodium-cooled Heavy Water Reactor (SDR)
  - U.S.A.

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EL-250/EL-500 (France, 1960's)

- Gas-Cooled Heavy Water Reactors (GCHWR)
- EL-250, EL-500 (CO_2)
  - 250 MW_e, 500 MW_e designs.
  - Pre-stressed concrete as pressure boundary.
  - Be, Zr/Cu cladding with natural or enriched U.
  - 37-element bundles in PT with liner
  - 6,500 to 15,000 MWd/t burnup.
  - CO_2 at 8.5 MPa, 500°C
  - Integral steam generators.
  - η_{th} > 37%
- Project not pursued.
  - Government policy shift.
  - Focus on standardized PWR's

FIG.4. Assemblage combustible.

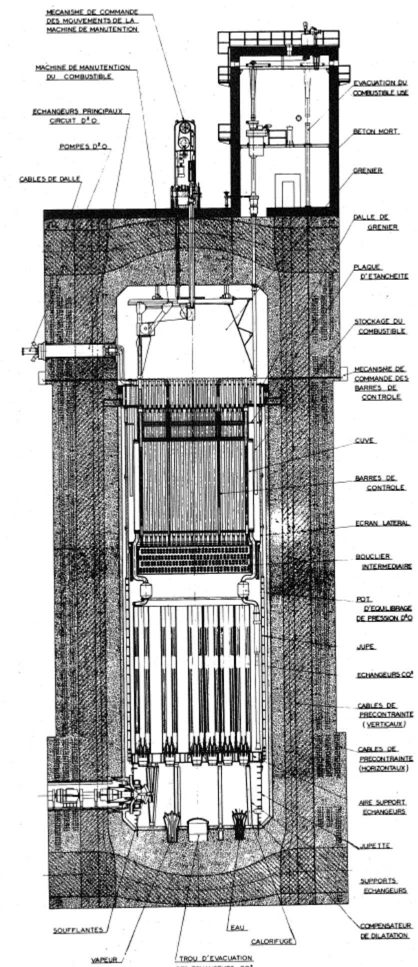

FIG.1. Ensemble du réacteur.

500 MWe GCHWR (Czechoslovakia)

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❑ Gas-cooled Heavy Water Reactors

- Czechoslovakia – 500 MW_e gas-cooled HWR's.
  - Pre-stressed concrete as pressure boundary.
  - 553 channels
  - U-metal or UO_2, natural
  - Mg-Be or Zr-alloy cladding
  - 5,000 to 8,000 MWd/t burnup.
  - CO_2 at 8 to 9 MPa, 470 C to 510°C
  - Integral steam generators.
  - η_{th} > 31%
- Consolidation
  - Conserve resources.
  - Shift to focus on VVER.

CROSS-SECTION VIEW A-A

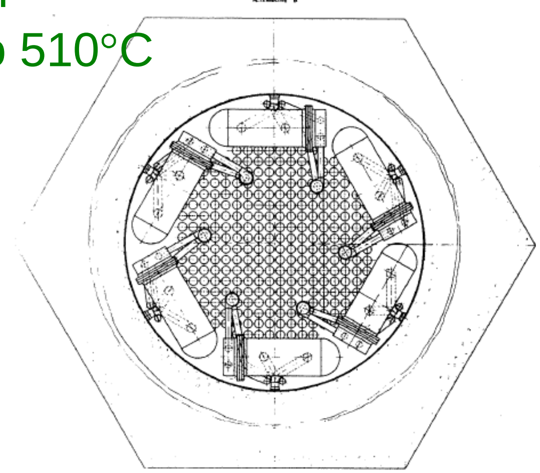
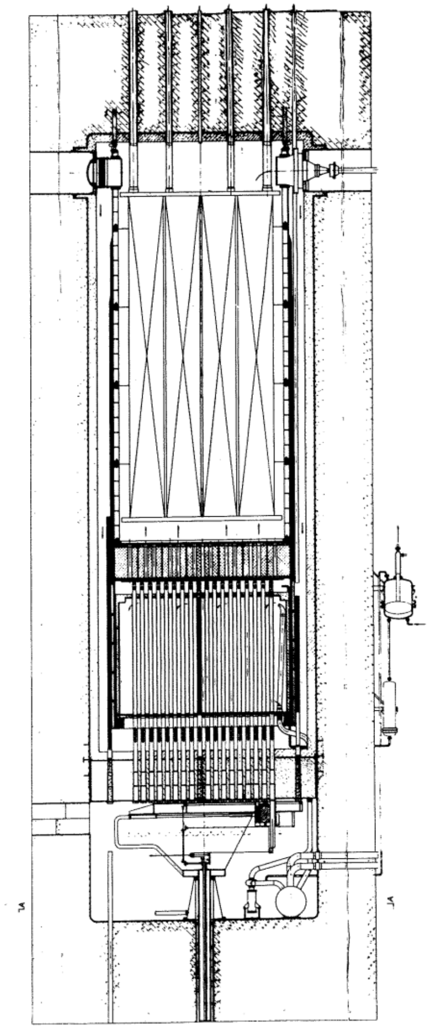


FIG. 2. Variant B.



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GNEC Proposal (U.S.A., 1958-1961)

- General Nuclear Engineering Corporation
- GNEC – Florida (1958-1961)
- GCHWR Prototype
  - 175 MW_{th} / 58 MW_e (33% efficient)
  - CO_2 at 3.5 MPa, 540 C
  - Zircaloy-2 PT's with insulator
  - 19-element fuel bundles
  - Finned fuel pins
  - 1.2 to 1.9 wt% enriched UO_2
  - Be or stainless steel clad
  - 10,000 MWd/t burnup.
  - Similar to EL-4.
- Proposal for 300-MW_e Unit

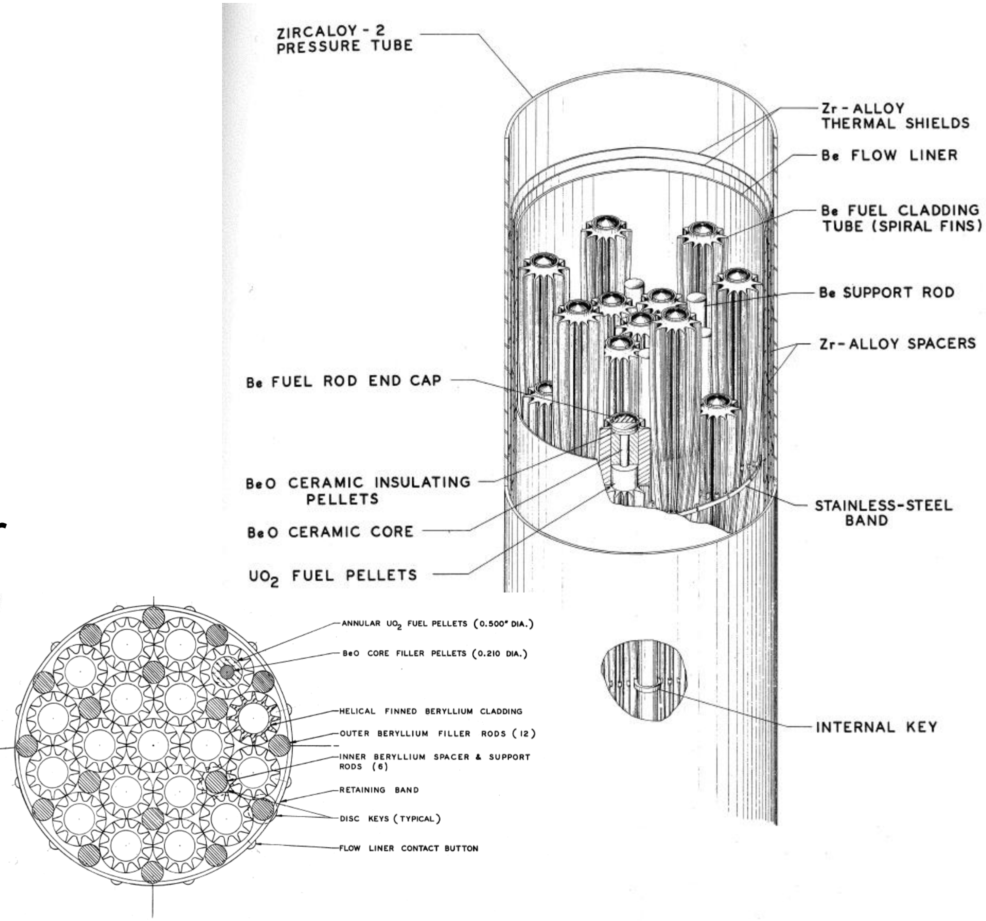
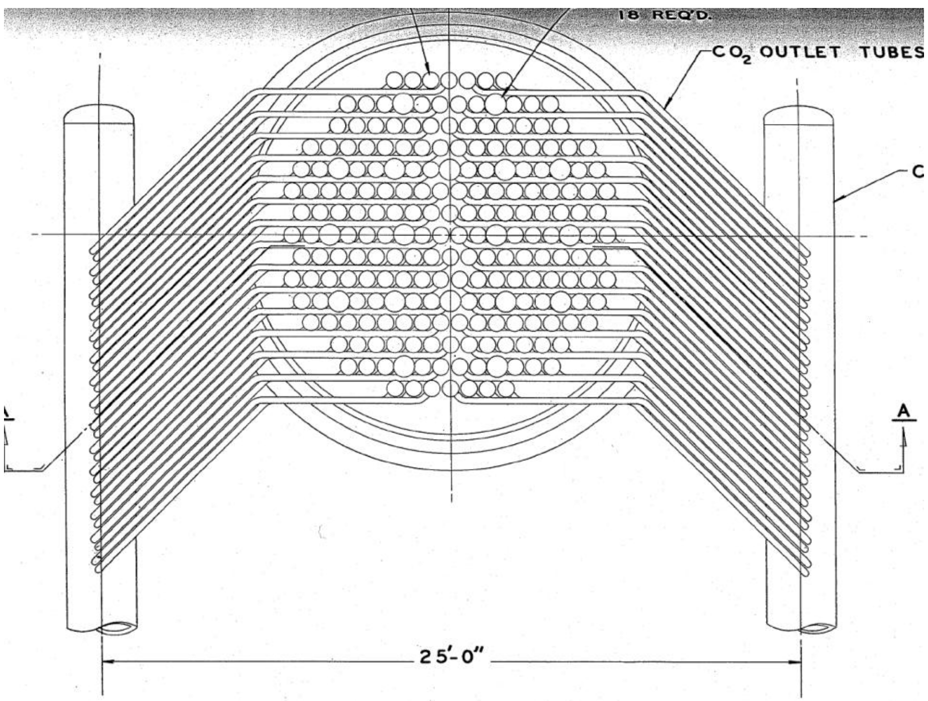


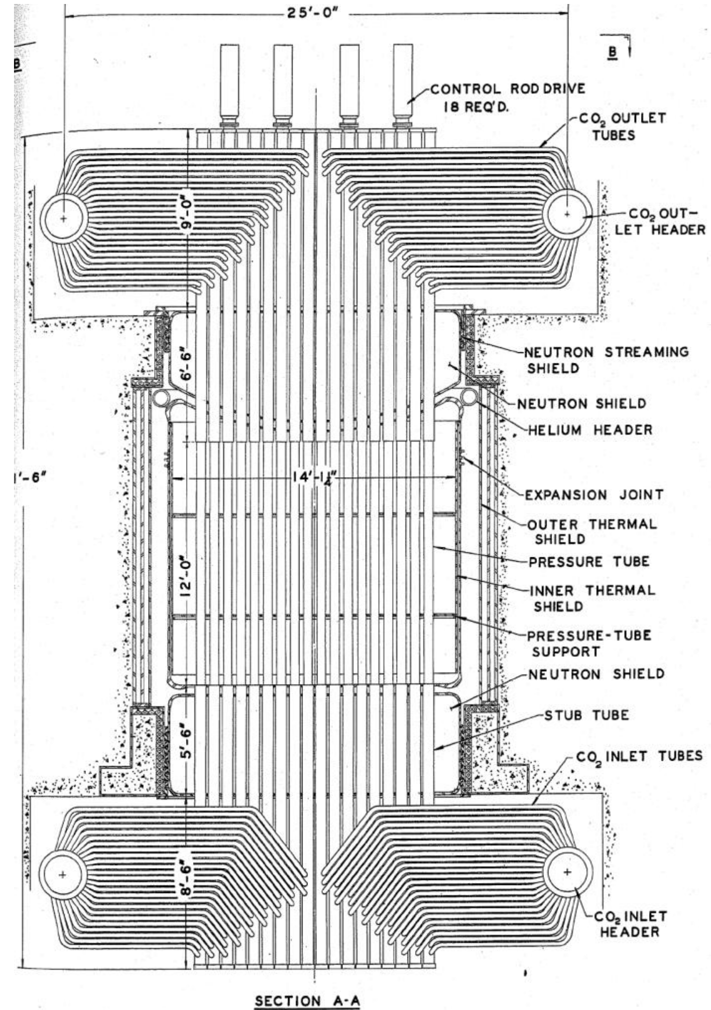
Figure 11. Cross Section of Beryllium-Clad Fuel Bundle

Figure 10. Perspective of Be Fuel Bundle and Pressure Tube — Staggered-Rod Alternate

GNEC Proposal (U.S.A., 1958-1961)

- Horizontal PT's
- Headers for CO2 coolant.





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Organically-cooled HWR Projects / Proposals

- Most projects cancelled in late 1960's and 1970's.
  - ORGEL (Italy/Euratom, 1959-1969)
  - DOR (Denmark)
  - DON (Spain)
  - HWOCR (U.S.A.) – Cancelled 1967
    - Walter Zinn / Trilling proponent.
    - Conceptual designs completed – 1000-MW_e .
    - Component testing and irradiations done in NRU reactor.
  - CANDU-OCR (500 MW_e size) – Cancelled 1973.
    - Successful technology demonstration in WR-1 research reactor.
    - Most of major technical issues worked out.
    - But, CANDU-PHWR was working well.
    - Consolidation of efforts in Canada.
  - Smaller-scale projects in Czechoslovakia, Russia.

ORGEL (Italy/Euratom, 1959-1969)

- 1,500 MW_{th} / 500 MW_e reactor concept.
- Intention to use thorium cycles.
  - Take advantage of HWR neutron economy.
  - Organic coolant for low-pressure operation.
- Metallic and oxide fuels considered.
- UO_2/ThO_2 fuel, clad in SAP.
- 37-element bundle.
- 2.92 wt% enrichment; 1.25 wt% makeup.
- Complete recycling of U with U-235 makeup.
- C.R. ~ 0.74
  - Higher with lower burnup, lower specific power (~0.9)
- Burnups
  - Ranging from 10,000 MWd/t to 60,000 MWd/t

DOR (Denmark, 1957)

- 1957 study, 235 MW_e
- 19-rod, cluster-type elements
- Enriched UC clad in SAP
  - Sintered Aluminum Product
- Terphenyl coolant
- 276 C / 371 C coolant temp.
- Steam at 6.7 MPa, 346 C

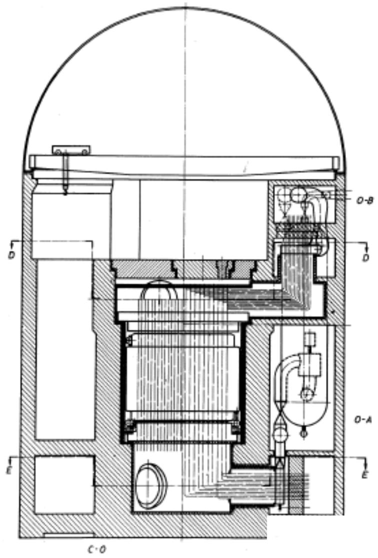

Figure 1. DOR, vertical cross section

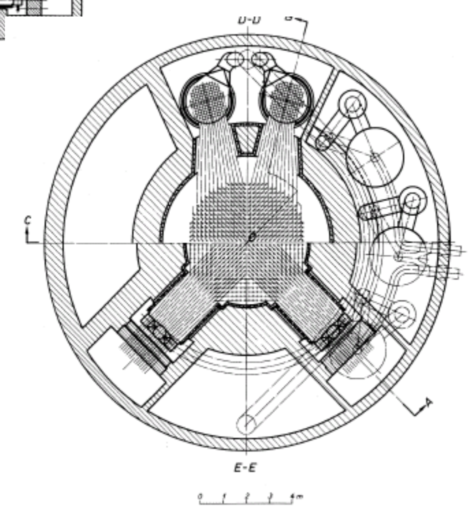

Figure 2. DOR, horizontal cross section

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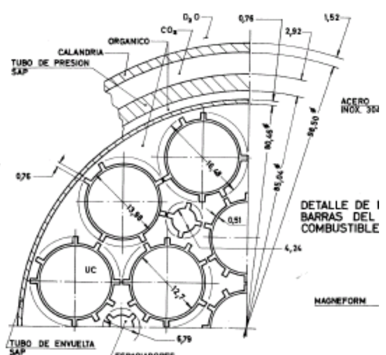
DON (Spain, 1960s)

- 107 MW_{th} / 30 MW_e (1960's)
- UC Fuel, Santowax coolant
- 1.1 wt% enriched UC fuel
- 19-element bundles, 138 channels
- B_4C control rods
- 8,000 MWd/t burnup
- 299 C to 343 C coolant temp.
- Steam at 6 MPa, 321 C



SECCION DEL ELEMENTO COMBUSTIBLE

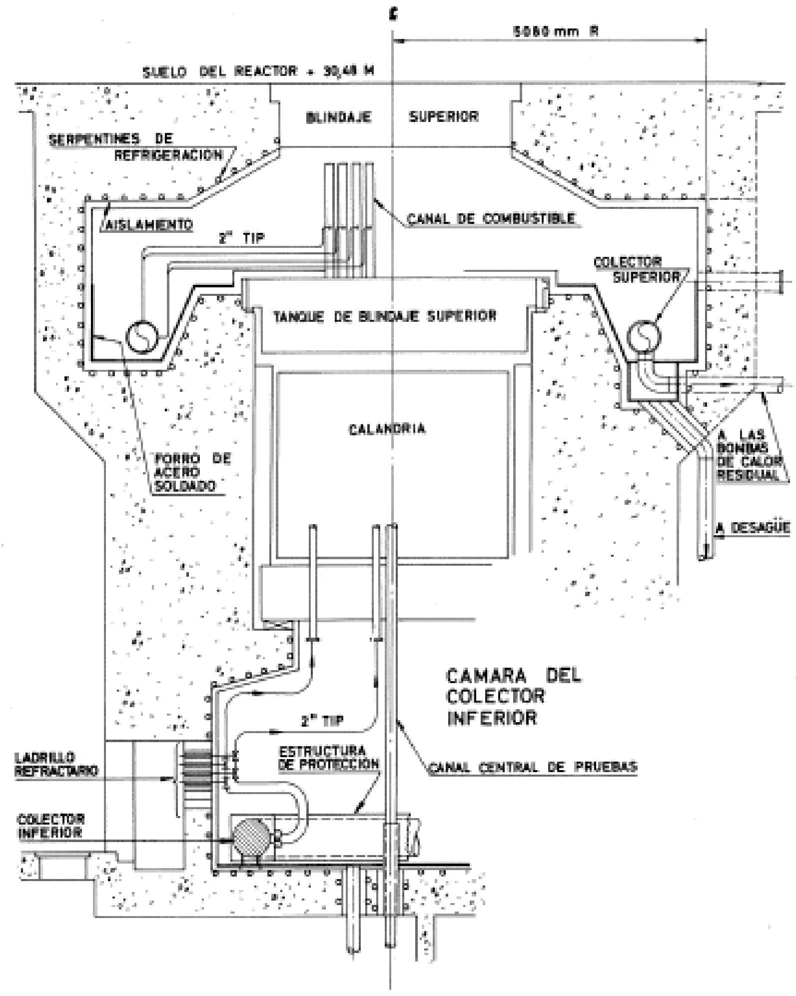


Figura 1. Esquema del reactor

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HWOCR (U.S.A., 1967)

- R&D during 1960's.
- Component test irradiations in Canada.
  - NRU, WR-1 research reactors.
- 1076 MW_e
- 34% to 36% efficiency.
- 492 Vertical Channels, PT made with SAP
  - Sintered Aluminum Product (SAP)
- Santowax OM Coolant
  - Coolant exit temp. ~ 400°C.
- Steam at 6.2 MPa, ~385°C

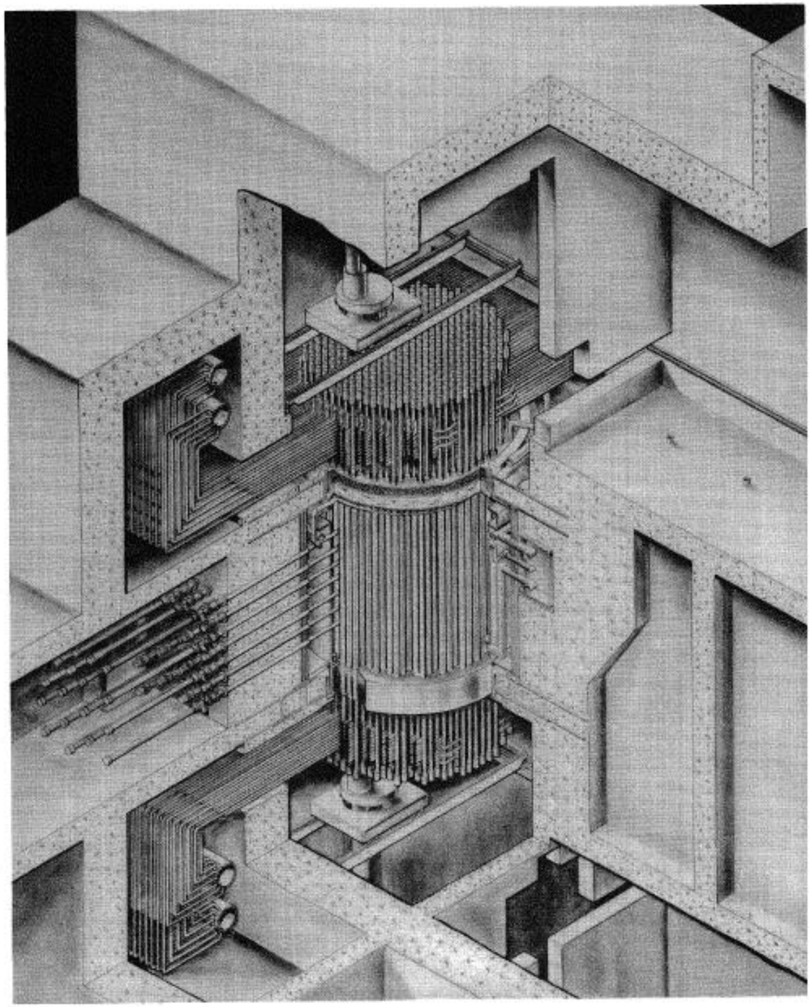

FIG.1. Perspective view of HWOCR.

HWOCR (U.S.A., 1967)

- 26.7 cm square lattice pitch.
- 37-rod bundles
  - 1.16 wt% U in UC form.
  - Clad with finned SAP.
- Burnup.
  - 15,000 to 20,000 MWd/t.
- Alternative fuel designs.
  - 55-rod bundles.
  - U-metal annular fuel.
  - Larger pitches (32.8 cm).
- Potential for using thorium.
- Project cancelled in 1967.
  - Competing priorities.

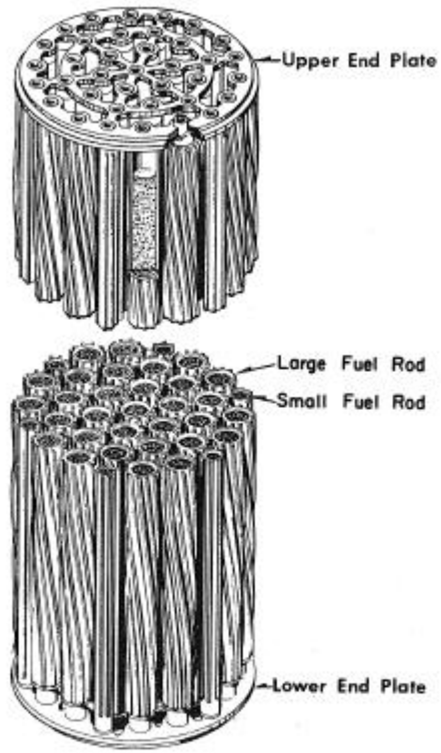

FIG. 4. HWOCR 37-rod fuel bundle.

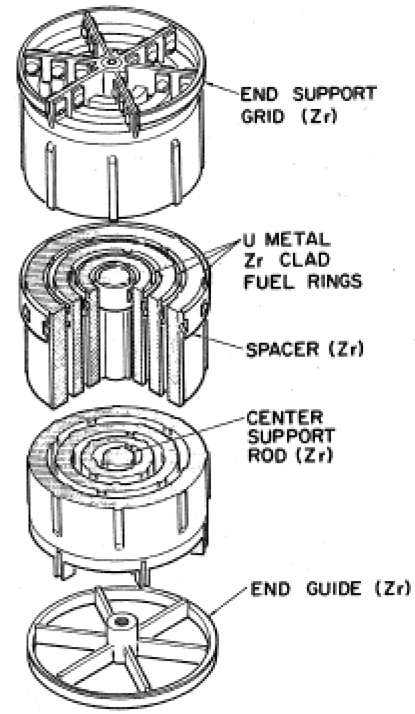

FIG. 3. Metal fuel element.

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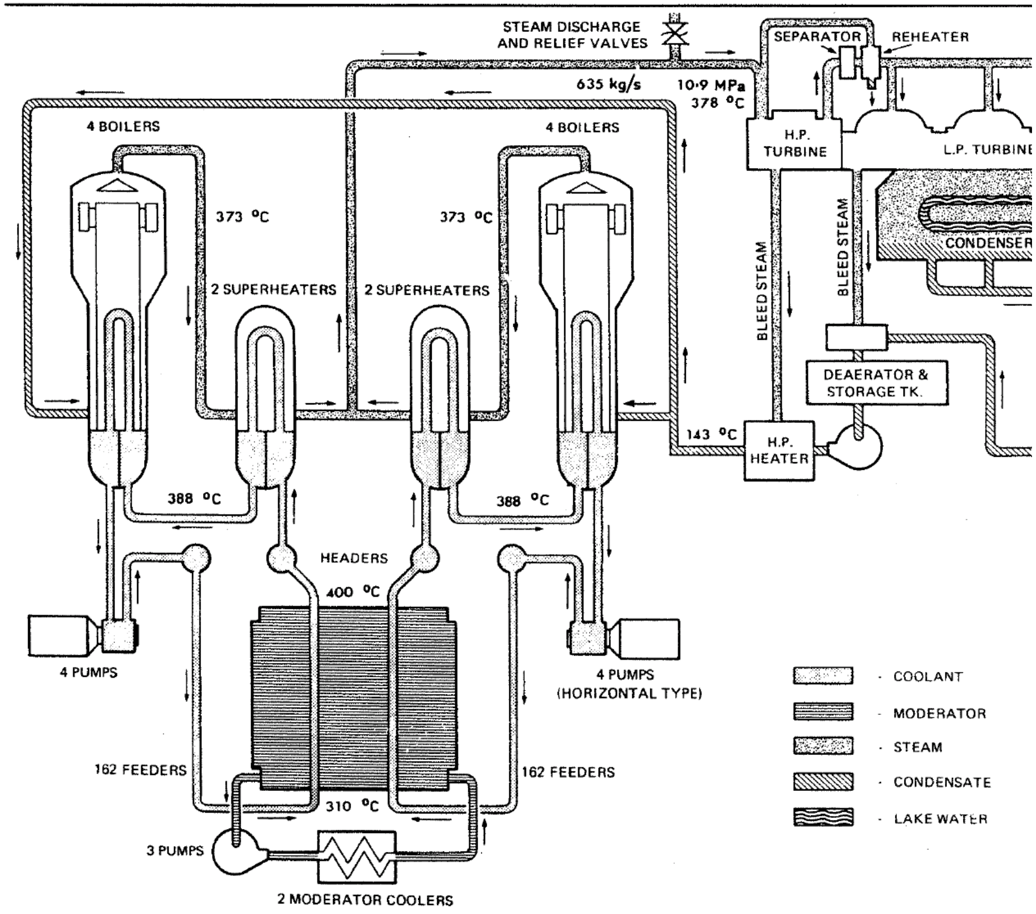
CANDU-OCR (Canada, 1960s)

- 500 MW_e station.
- HB-40 coolant.
  - Mix of terphenyls.
- 400 C outlet.
- 34% efficiency.
- Experimental database.
  - WR-1 working well.
  - Technical bugs solved.
- Cancelled 1973.
  - Pickering working well.
  - Consolidate resources.

FIGURE 16.5
Schematic Diagram of a CANDU-OCR Power Station



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CANDU-OCR (Canada, 1960s)

- 36-element bundles.
- UC-fuel, Zr-2.5%Nb clad.
- Natural uranium.
- Potential for use of thorium.

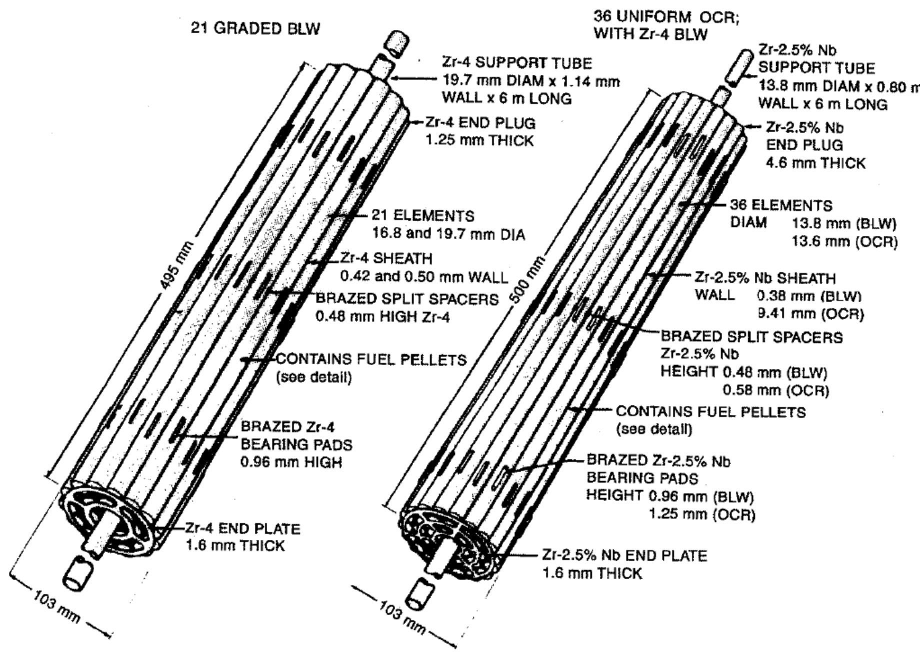
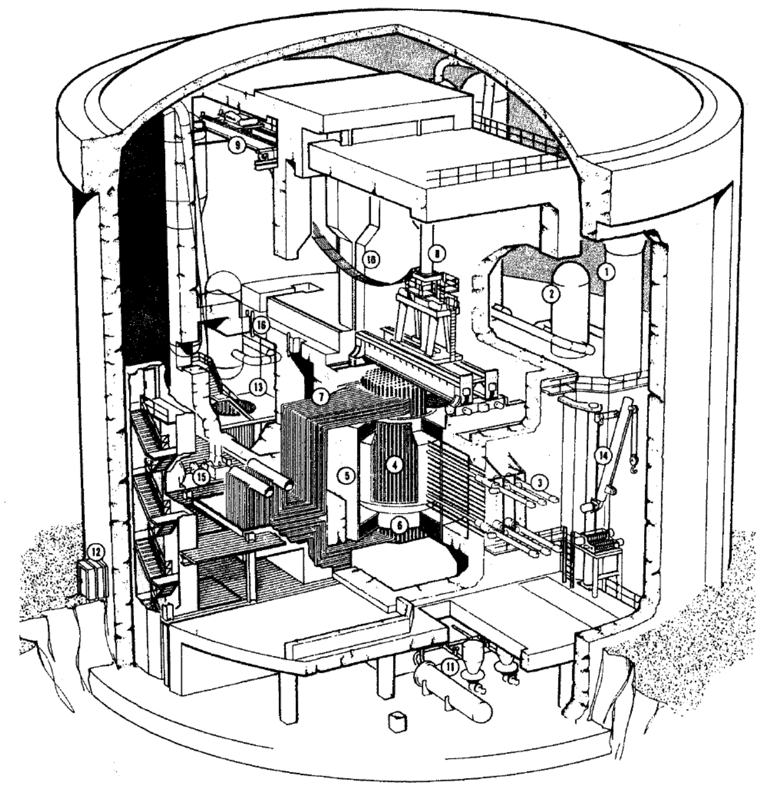


FIGURE 16.6
Cutaway of a CANDU-OCR Reactor Building



1. Boilers (8)
2. Superheaters (4)
3. Booster Rods
4. Calandria Assembly
5. Shield Tank
6. End Shield
7. Feeders
8. Fueling Machine
9. F/M Service Crane
10. F/M Vault Door
11. Moderator System
12. Emergency Airlock
13. Fuel Transfer Bay
14. Booster Flask Crane
15. Primary Pumps (4)
16. Fueling Machine Ports

SDR (U.S.A., 1956-1959)

- SDR (Sodium Deuterium Reactor) – 1959
  - Heavy water moderator.
  - Liquid sodium coolant.
- Nuclear Development Corp.
- 40 MW_{th} / 10 MW_e; Chugach, Alaska
  - Sodium at 510 C.
- Fuel:
  - 7 rods per assembly
  - 1.5 to 2 wt% UO_2 (or U-10wt%Mo)
  - Stainless steel clad
  - ~5,000 MWd/t burnup
- Potential
  - Larger reactor could run on NU.
  - Reduced neutron leakage.

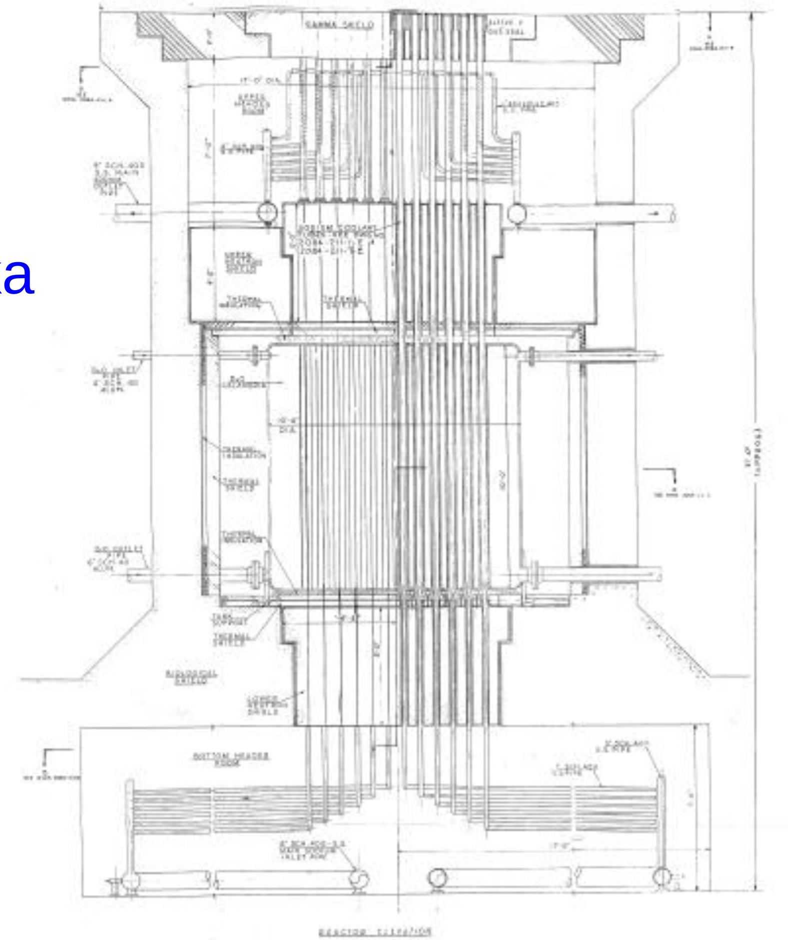


Fig. 2-1.1 — Preliminary reactor arrangement – elevation view

SDR (U.S.A., 1956-1959)

- 128 to 155 vertical channels
  - Depending on fuel type
- Initial development
  - 1957-1960.
- Technical issues to address
  - Separation Na, D_2O.
  - Barrier.
  - Safe operations.
  - Economics.
- Related experience:
  - Sodium Graphite reactors.
- Project stopped 1959.
  - Competing alternatives.

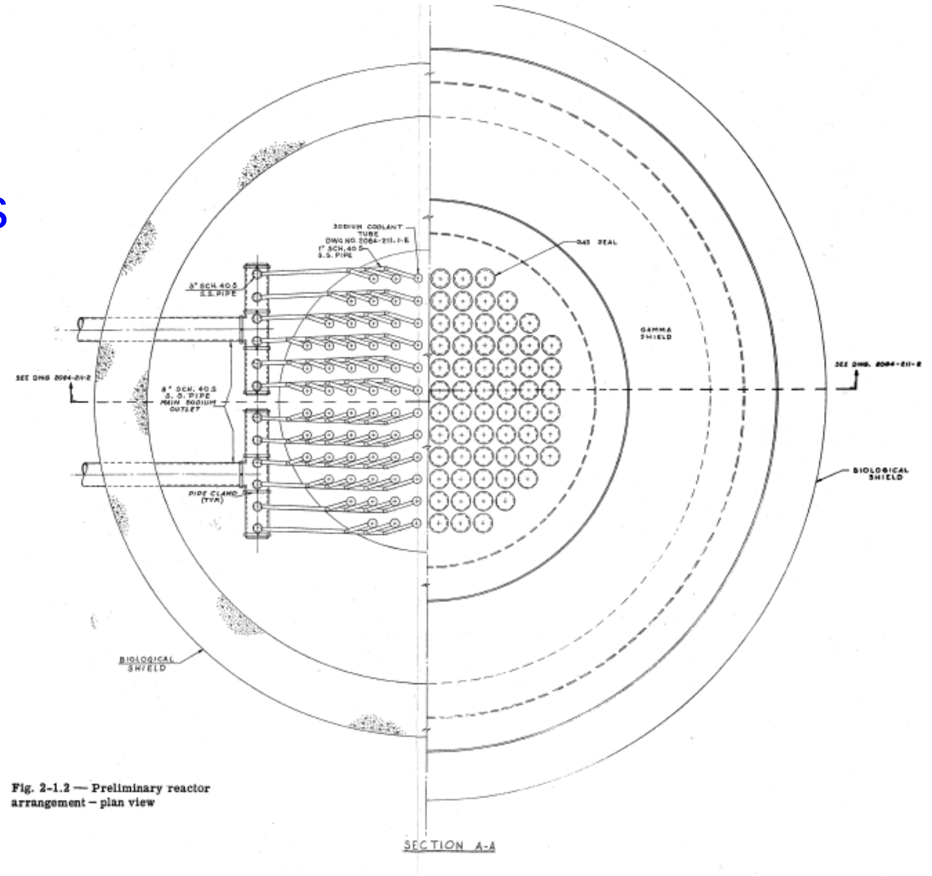


Fig. 2-1.2 — Preliminary reactor arrangement – plan view

Conclusions / Summary

- Deuterium is a light-weight, low-neutron-absorbing isotope.
  - Is most common in the form of heavy water (D_2O).
  - Alternative deuterium-based compounds could be developed and used as a moderator in alternative reactor designs.
    - Metal-deuterides, deuterated organics, etc.
    - May be preferable to D_2O in certain design applications.
      - Where chemical reactions or corrosion with D_2O is an issue.
      - Material compatibility, high temperature applications.
  - Alternative uses for D_2O
    - Coolant for fast reactors, use in spectral-shift reactors.
- Alternative coolants for HWR reactors
  - Boiling H_2O (or D_2O), organics, gas (CO_2, He, Ne, etc.), liquid metals (Pb, ^{7}Li, Na, Pb/Mg, etc.), molten salts.
    - Can help achieve higher thermal efficiencies.
    - Potentially reduce capital and operational costs.

Conclusions / Summary

- International involvement in HWR technology
  - Since 1950's, more than a dozen nations have built prototype HWR power reactors.
    - Many more have built HW research reactors.
  - Many prototypes successful demonstrations – proof of concept.
  - Others experienced a variety of technical difficulties.
    - Balance of plant, engineering issues, physics, materials.
    - But, LWR prototypes have experienced similar difficulties.
  - Cancellation and abandonment of HWR projects / proposals
    - Technical difficulties could eventually be overcome, but would require more time and investment (a longer-term commitment). Timing.
    - Difficult to maintain several reactor development projects in parallel.
      - Industry / utilities need standardization to reduce costs.
    - Competing technologies (e.g. LWR's) with a larger database of experience and supporting industrial infrastructure.
      - Experience and R&D from naval reactors.

Conclusions / Summary

- Long-term success stories – long-term commitment.
  - Canada: continuously developing, improving and deploying PHWR technology (CANDU, EC6, ACR-1000).
    - CANDU technology has been exported to several nations (e.g. India, Pakistan, Argentina, S. Korea, Romania, China).
  - India: since 1970's, pursuing parallel, independent path for PHWR's, and now innovation with AHWR, which has general similarities to SGHWR/FUGEN.
    - Motivated by long-term energy independence through exploitation of domestic resources of thorium.
- Future HWR development and deployment.
  - Re-visit and explore alternative technologies and designs.
    - Improve thermal efficiency, reduce capital/operational costs.
  - When price of uranium goes up, and availability goes down.
    - Strong motivator for using more HWR's.

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September 7, 2010
50th Anniversary of ZED-2

- **Z**ero **E**nergy **D**euterium – **2**
- Heavy Water Critical Facility at Chalk River Laboratories.
- 5 Watts – 200 Watts
- Fundamental lattice physics, core physics, kinetics tests.
- Calibration of flux detectors.
- Physics design verification.
- Validation data for physics codes.
- Support of many HWR concepts and designs.
  - Organic coolants (OCR), gas coolants (air, CO_2, He)
  - Boiling light water (e.g., CANDU-BLW, Gentilly-1)
  - CANDU (NPD, Douglas Point, Pickering A/B, Bruce A/B, Darlington)
  - CANDU-6, Enhanced CANDU-6 (EC6), ACR-1000
- http://www.cns-snc.ca/
  - Sign up for upcoming ZED-2 conference (Nov. 1-3, 2010).

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