The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

1944-10

Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

19 - 30 May 2008

Heavy Water Reactors:
1. Physics, Concepts and History
(Appendix)

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Canada

Heavy Water Reactors:
1. Physics, Concepts and History
(Appendix)

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AECL – Chalk River Laboratories

Joint ICTP-IAEA Workshop on

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May 26/27, 2008

AECL EACL

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Additional Information

- Alternative 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.

Deuterium-Based Moderators

- Heavy Water, D_2O
  - – Conventional, extracted from water (0.015 at%)
  - – Cost of purification to > 99.75 wt%D_2O
- Zirconium Deuteride, $ZrD_{1.6}$
  - – Chemically similar to $ZrH_{1.6}$, more expensive.
  - – High-temp operation with Na or gas coolant.
- Lithium-7 Deuteride, ^7LiD
  - – Similar to LiH, but reduced neutron absorption.
  - – Li-7 separation more costly.

Deuterium-Based Moderators

- **Deuterated Diphenyl/Terphenyl, C_xD_y**
  - Reduced neutron absorption.
  - More resistant to radiation and thermal decomposition.
  - Less corrosive.
  - High-temperature operation at low pressure feasible.
  - Expensive to produce.

Alternative Uses for D_2O

- Coolant for fast reactors (1990's to present, Japan)
  - Low moderator-to-fuel ratio ensures hard spectrum.
  - 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.

Alternative Coolant Options (Past & Future)

- Boiling H_2O at 5 to 7 MPa
  - SGHWR, FUGEN, Gentilly-1, CIRENE, AHWR
- Boiling D_2O at 3 to 7 MPa
  - Marviken, Halden
- Gas coolant at 5 MPa to 10 MPa (400°C to 800°C)
  - CO_2, He/Ne, N_2O_4 (dissociating coolant)
  - EL-4, KKN, KS-150, Lucens, GNEC Proposal(1961)

Alternative Coolant Options (Past & Future)

- 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.

Alternative Coolant Features

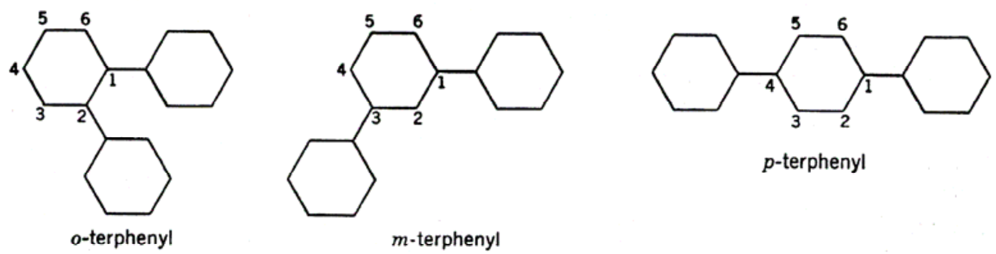
- Gas coolant at 5 MPa to 10 MPa (400°C to 800°C)
  - Reduced D_2O inventory – cost savings.
  - Potential for direct cycle – gas turbine.
  - High efficiencies possible, ~40% to 45%. (Eg. AGR ~ 41%)
  - Hydriding and coolant-voiding non-issues.
  - Lower heat transfer coefficient / conductivity.
    - 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.
  - Costs for coolant replenishment; filtering to remove crud.
  - Increased fire hazard.

Organic Coolants

- Diphenyl $(C_6H_5)_2C_6H_4$
- 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

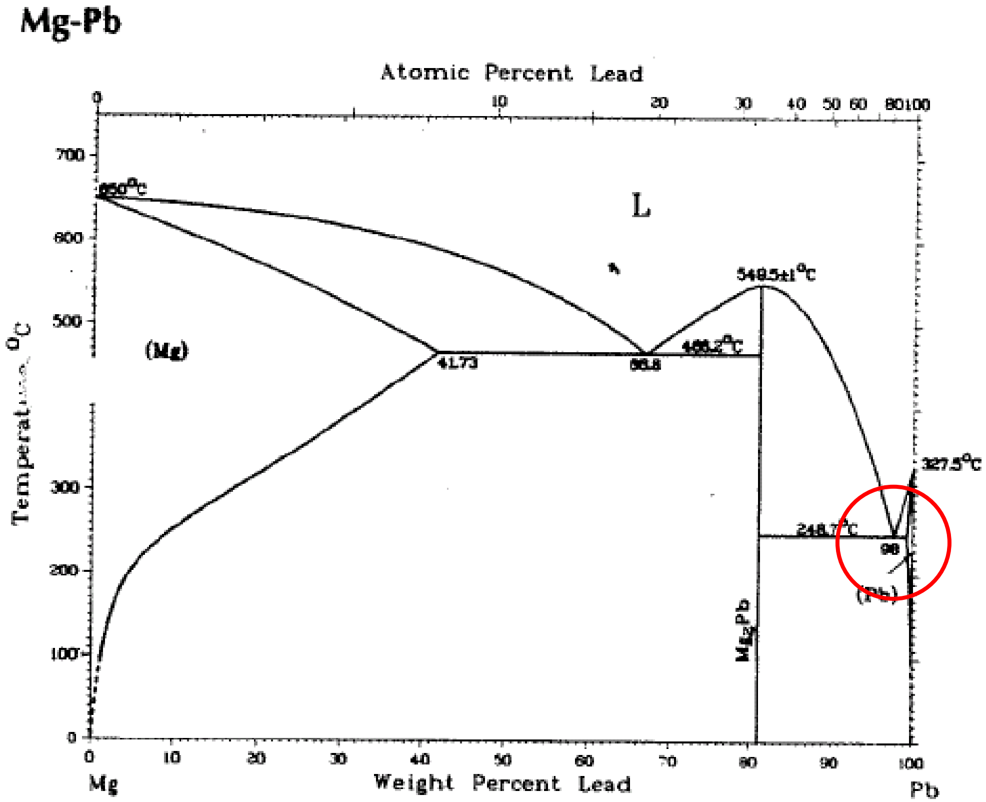


Alternative Coolant Features

- 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.
    - Safety concerns for ^{7}Li and Na

Lead-Magnesium (Future?)

- 2 wt% Mg, 98 wt% Pb
  - T_{melt} ~ 249°C



International Participation in HWR Technology

- **Canada**
  - ZEEP, NRU, NRX, WR-1, ZED-2
  - NPD-2, Douglas Point, Gentilly-I
  - Pickering, Bruce, Darlington, Point Lepreau, Gentilly-2
  - CANDU-6, 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.

International Participation in HWR Technology

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

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, 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) (~200 MWe)
  - Development of larger PHWR's and AHWR (using thorium)

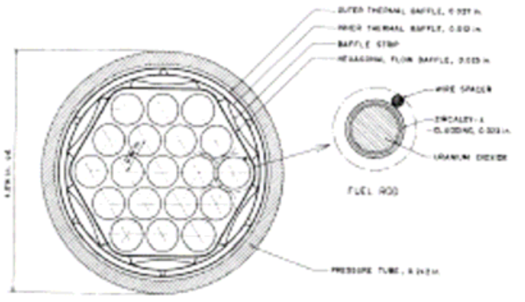
International Participation in HWR Technology

- Focus on power reactors.
- Organize by coolant type, chronology.
- Some projects were in advanced stage of design and development before cancellation.
  - Competing technologies performing well.
  - Reduced concerns about long-term uranium supplies.
  - Difficult to support several parallel programs.

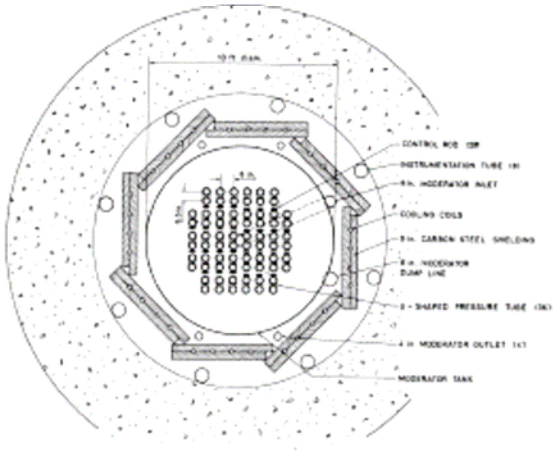
CVTR (USA)

- First and only HWR power reactor in U.S.A.
- Prototype operated 1963-1967.
- 65 MW_{th}, 17 MW_e, 26%, 15 kW/litre
  - 56 MWth from reactor, 9 MWth from oil-fired super-heater
- Vertical pressure tube reactor (HW mod+cool)
  - 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

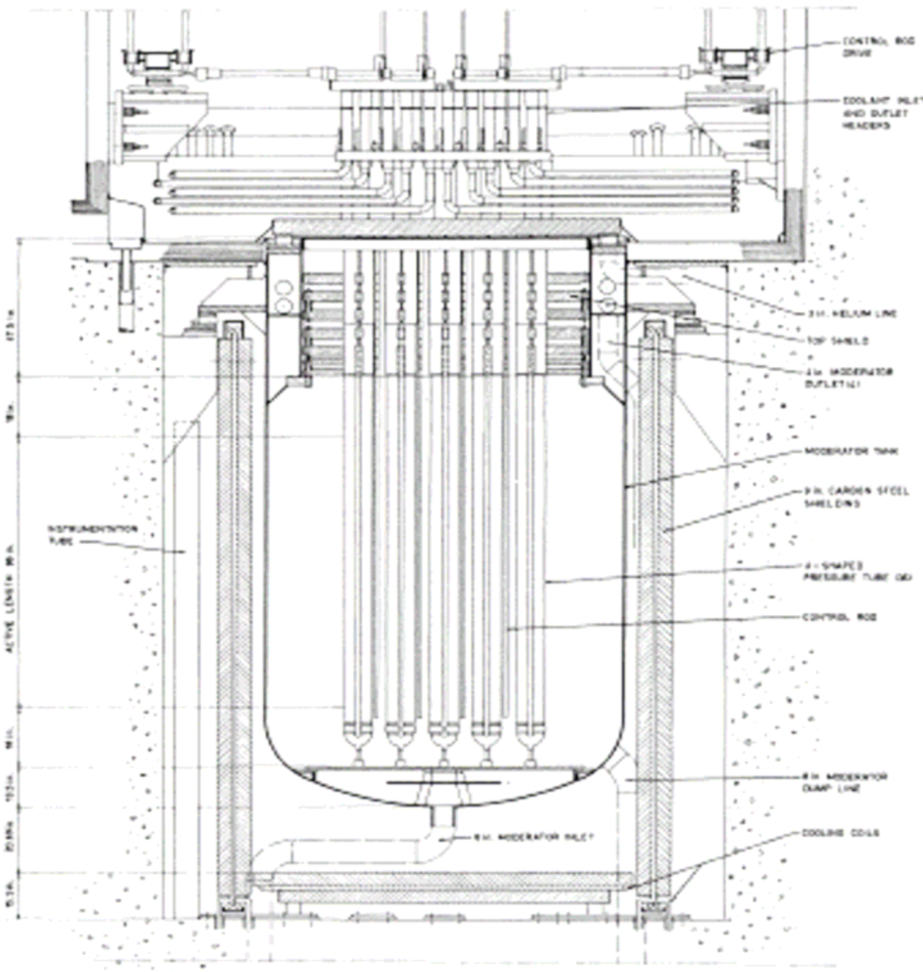
CVTR (U.S.A)



FUEL ELEMENT



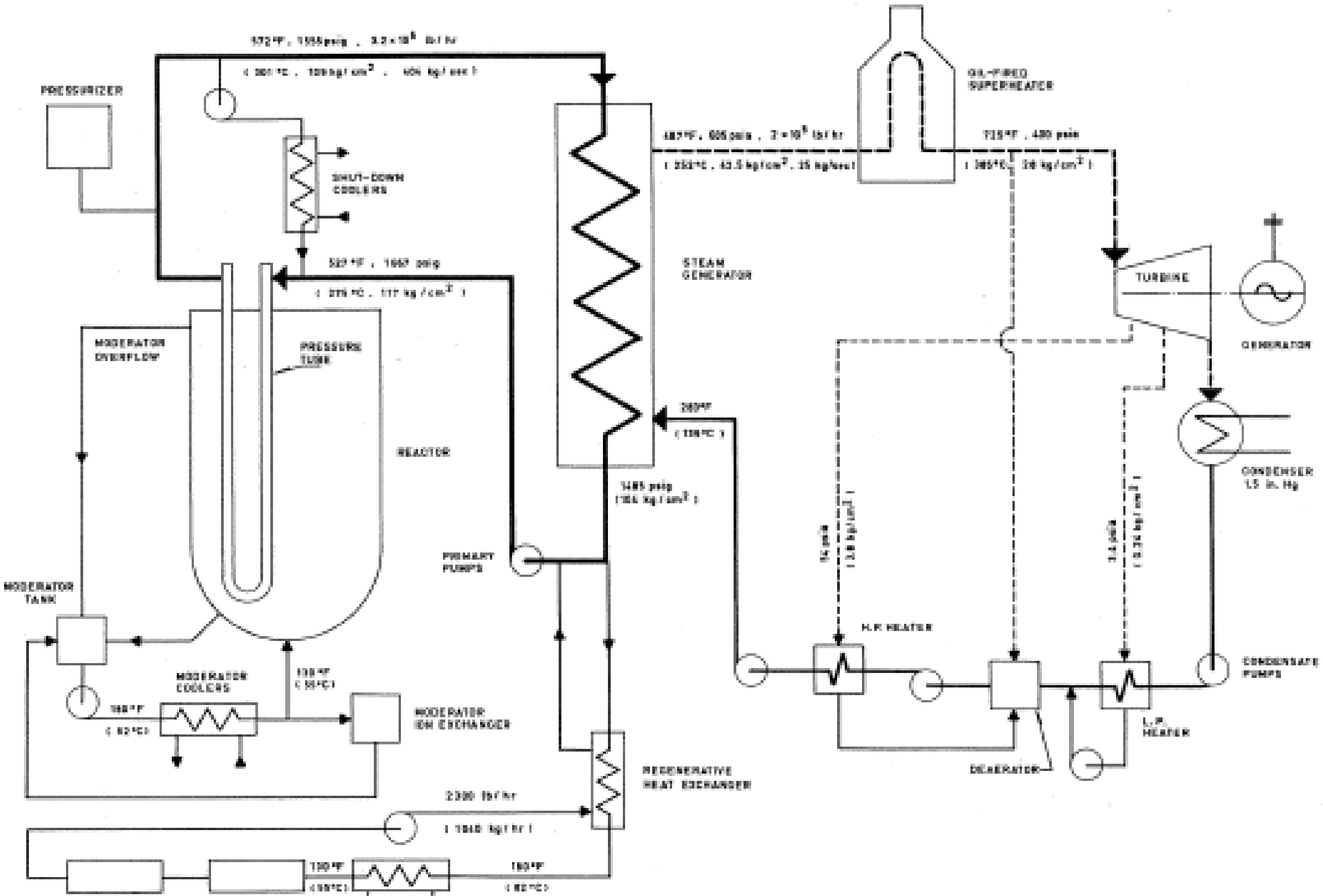
HORIZONTAL SECTION REACTOR CVTR



VERTICAL SECTION REACTOR CVTR

CVTR (U.S.A)

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

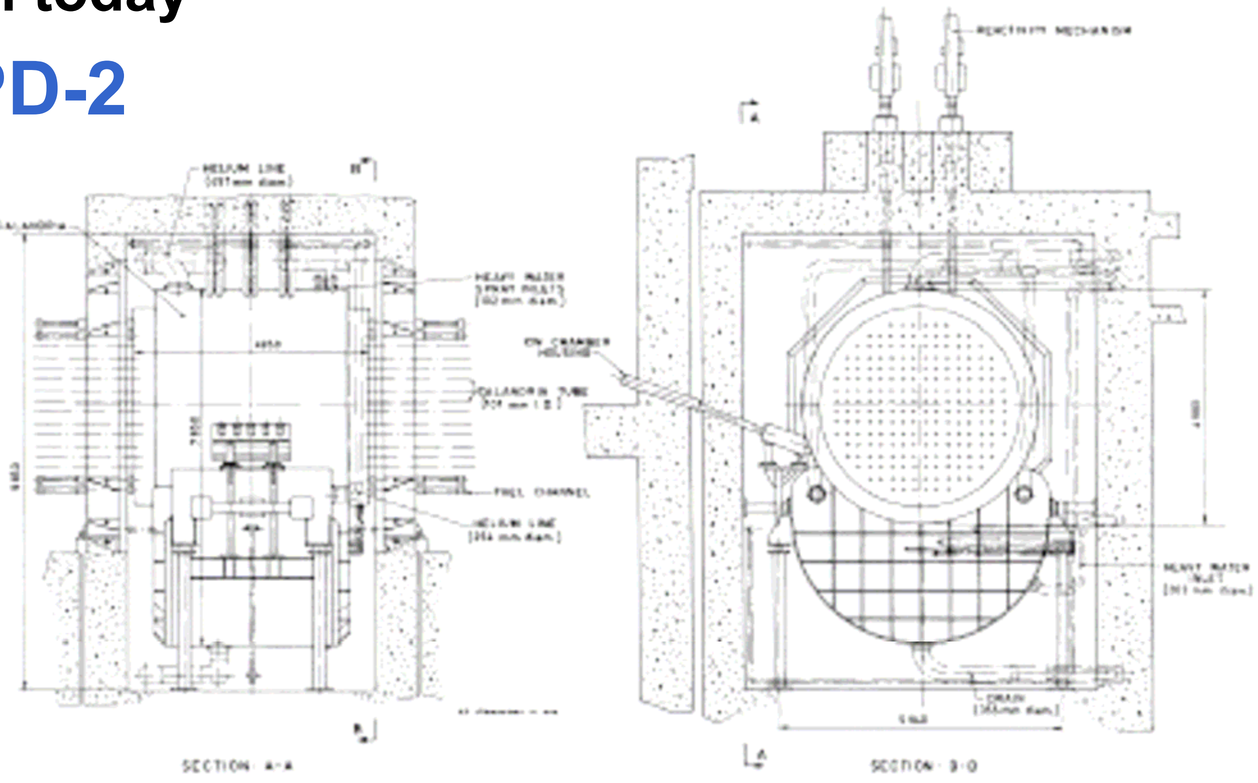


FLOW DIAGRAM REACTOR CVTR

UNRESTRICTED

KANUPP (Pakistan)

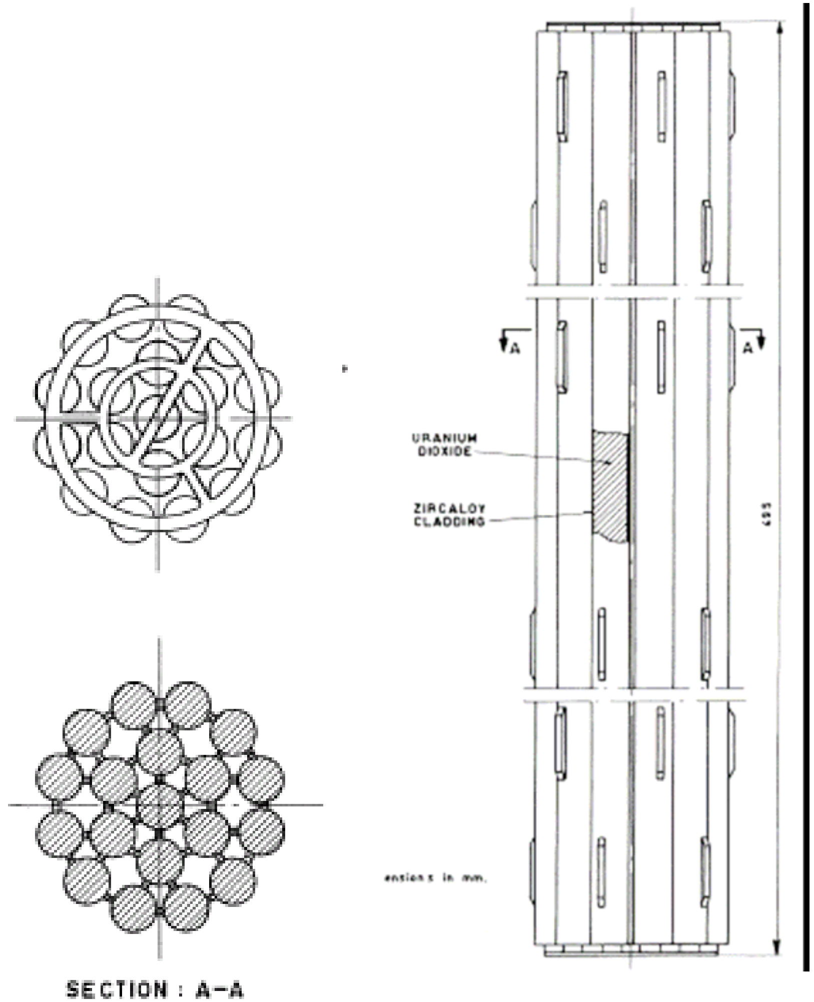
- 432 MW_{th} / 125 MW_e (1971)
  - Still in operation today
- Scale up of NPD-2
- 208 Channels
- 10.4-cm PT's
- 23.5-cm pitch
- 7.7 kW/litre
- On-line refuel
  - 4 bundles / day



VERTICAL SECTIONS REACTOR KANUPP

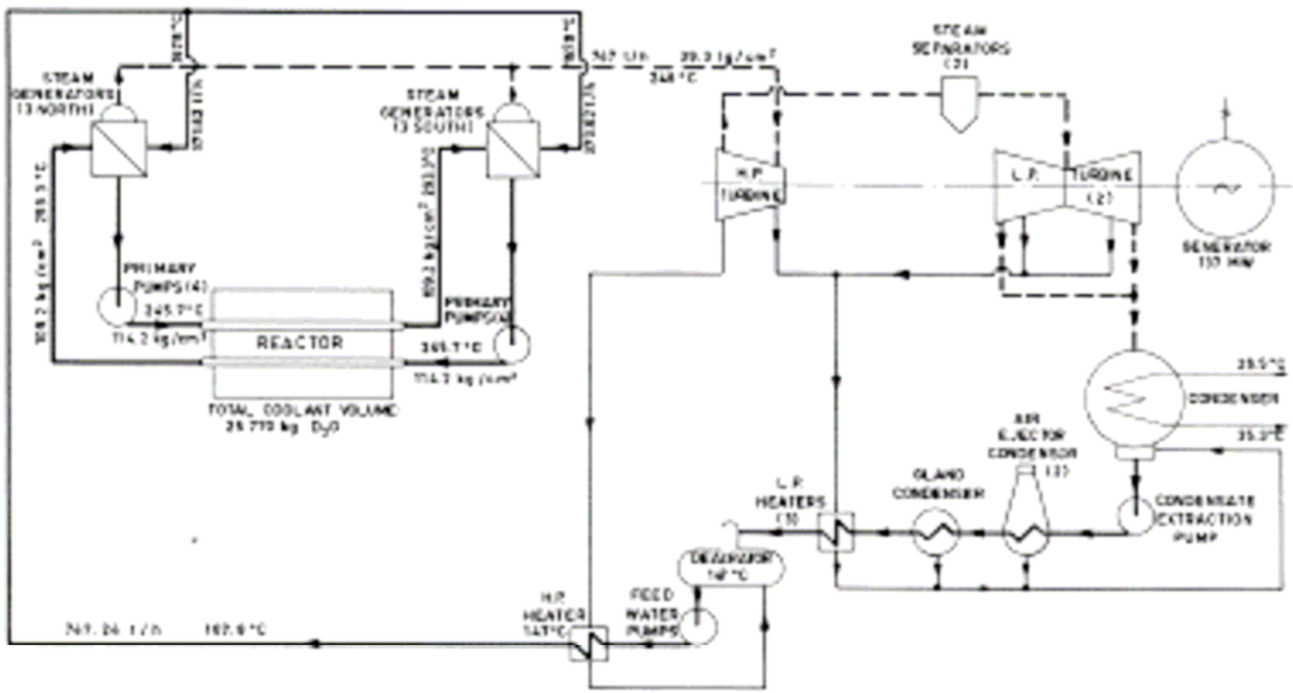
KANUPP (Pakistan)

- 19-element bundles
  - NPD-2, Douglas Point
  - Natural UO_2
  - Zr-4 clad
  - bearing pads (new)
  - 0.5-m length
- C=0.81
- 8,650 MWd/t (ave.)



KANUPP

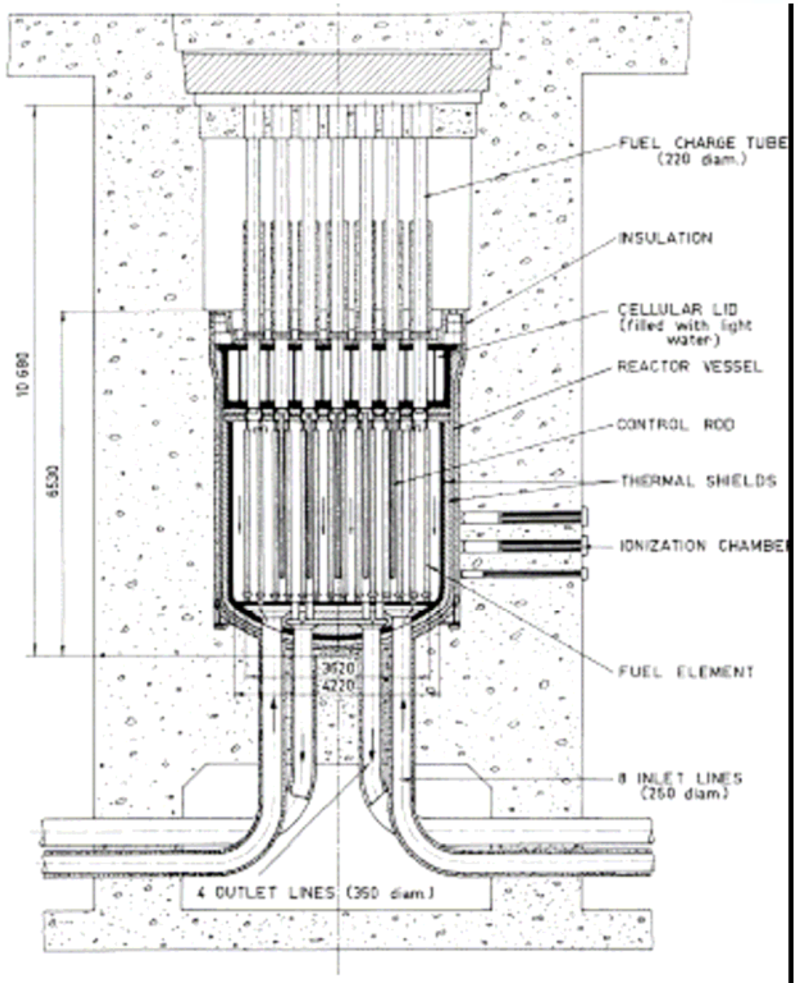
- 11.4 MPa, 293°C
- Steam at 4 MPa, 250°C (U-shaped shell/tube)
- Control: 4 rods, moderator level, boron shim



FLOW DIAGRAM REACTOR KANUPP

R3/Adam (Sweden)

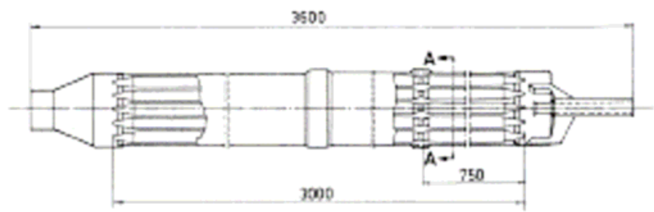
- First pressure-vessel HWR
- Operated 1964-1974.
- 65 MW_{th} / 10 MW_e
  - waste heat for district heating
- Coolant at 3.3 MPa, 220°C
- Steam at 1.37 MPa, 215°C



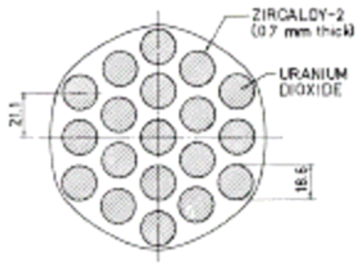
VERTICAL SECTION
REACTOR R-3/ADAM

R3/Adam (Sweden)

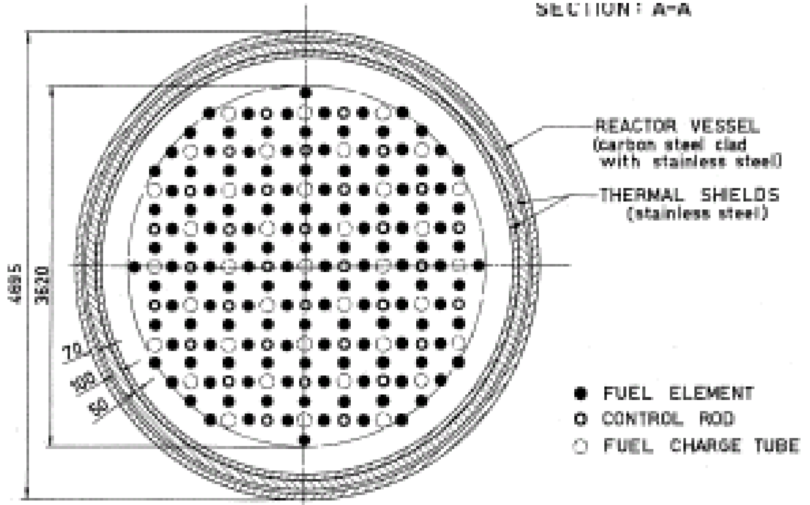
- **140 Channels**
- **Natural UO_2**
  - Zr-2 clad
  - 19-element clusters
  - 2,800 MWd/t burnup



FUEL ELEMENT



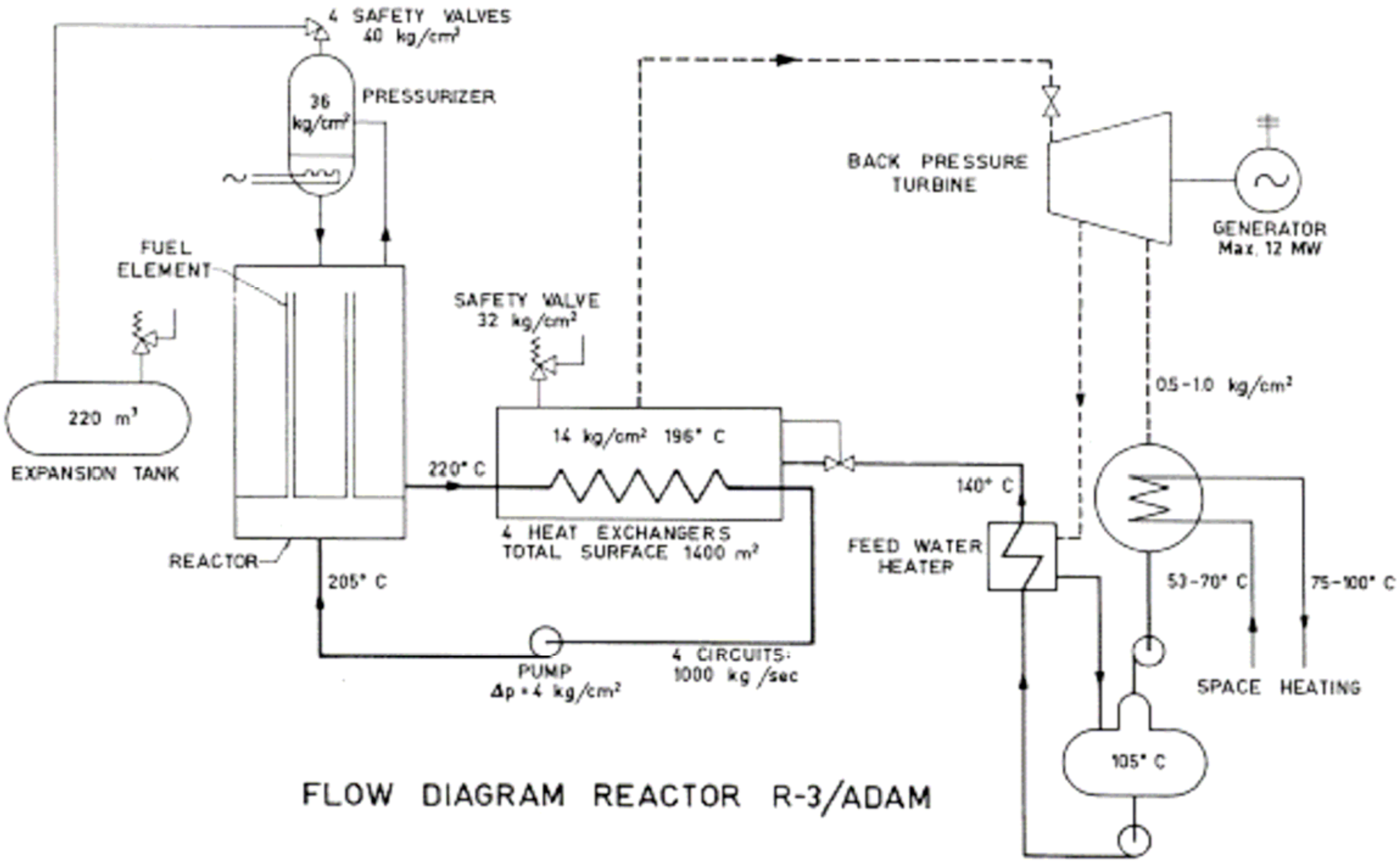
SECTION: A-A



HORIZONTAL SECTION
REACTOR R-3/ADAM

all dimensions in mm

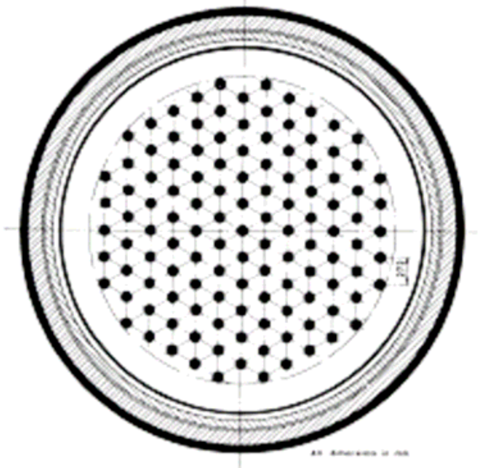
R-3 / Adam



FLOW DIAGRAM REACTOR R-3/ADAM

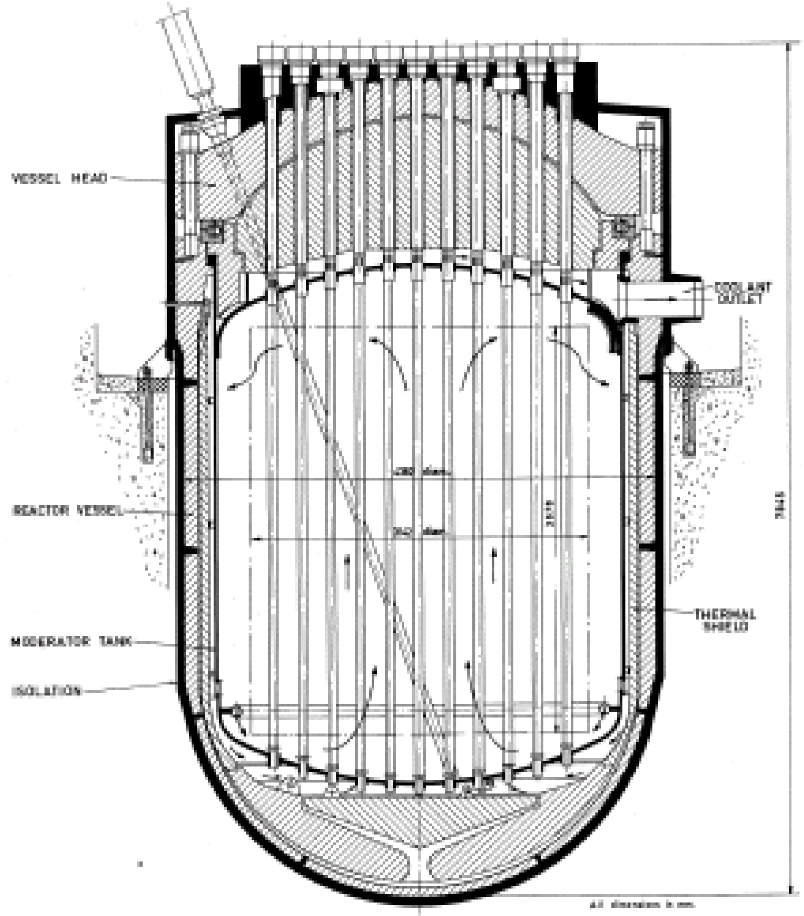
MZFR (Germany)

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



HORIZONTAL SECTION

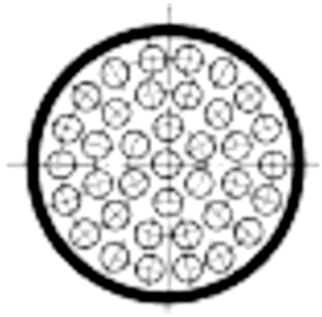
REACTOR MZFR



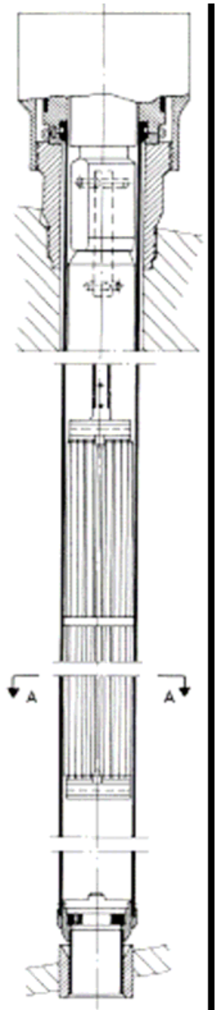
VERTICAL SECTION REACTOR MZFR

MZFR (Germany)

- **37-element fuel strings**
  - 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**



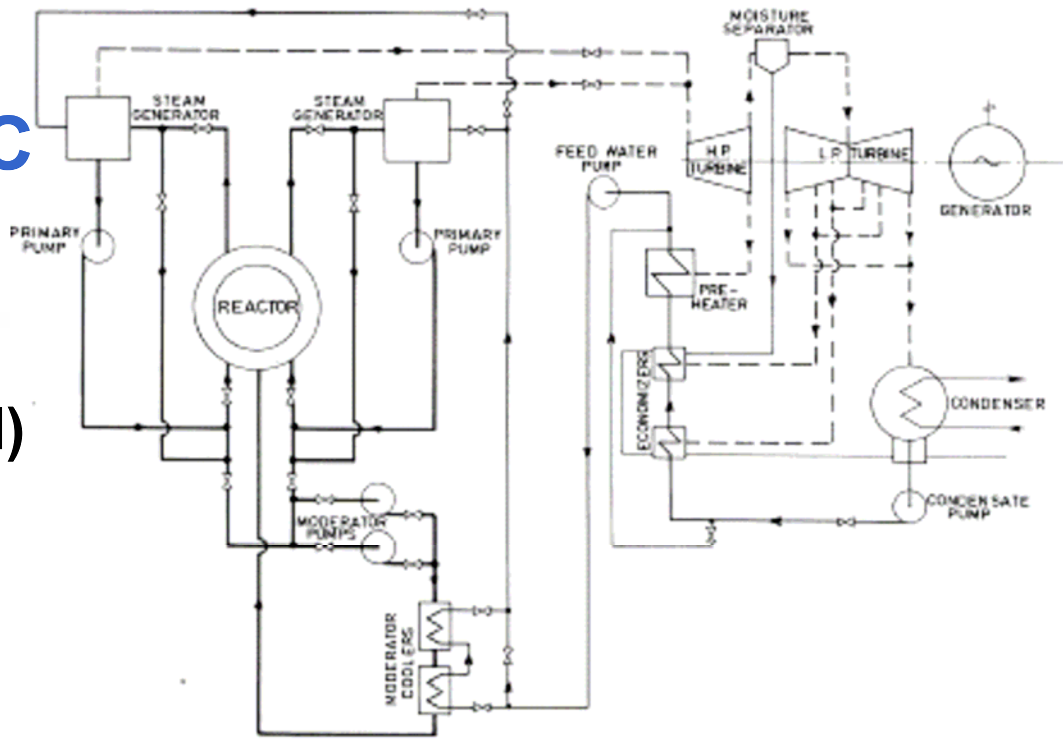
SECTION A–A



FUEL CHANNEL

MZFR

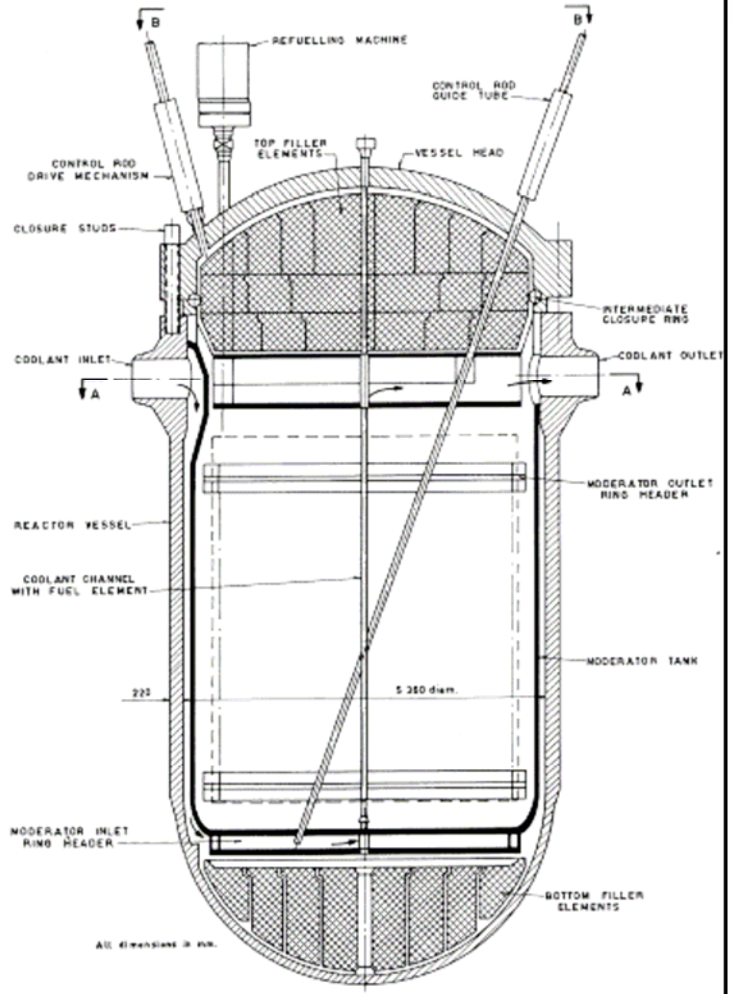
- Operated 1966 – 1984 (Seimens)
- Prototype for commercial reactor – Atucha
- 7 kW/litre
- 8.45 MPa, 280°C
- Steam at
  - 3.11 MPa
  - 236°C (Saturated)



FLOW DIAGRAM REACTOR MZFR

Atucha 1 (Argentina)

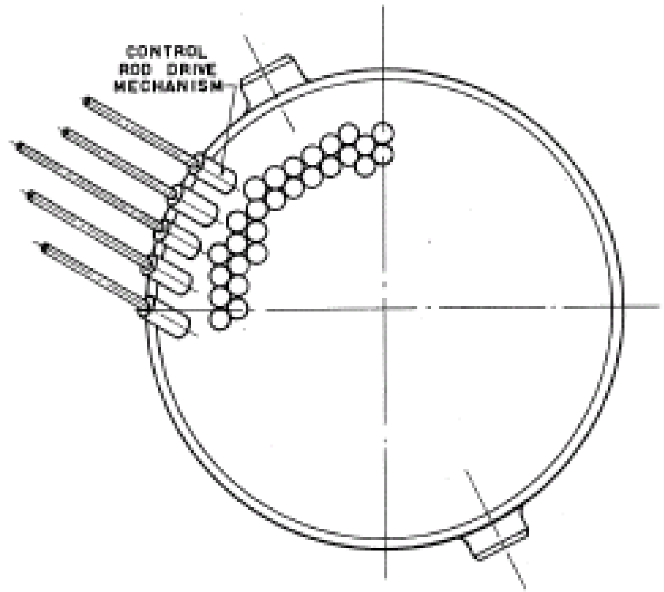
- First, and only PV-PHWR
- Scale-up of MZFR
- 1179 MW_{th} / 345 MW_e
- 37-element fuel string
  - Zr-4 clad
  - Natural UO_2 (early), C~0.81
    - ~6,000 MWd/t burnup
  - 0.9 wt% enriched (recent)
    - ~13,000 MWd/t burnup
- CARA Fuel (52 rod)
  - Under development



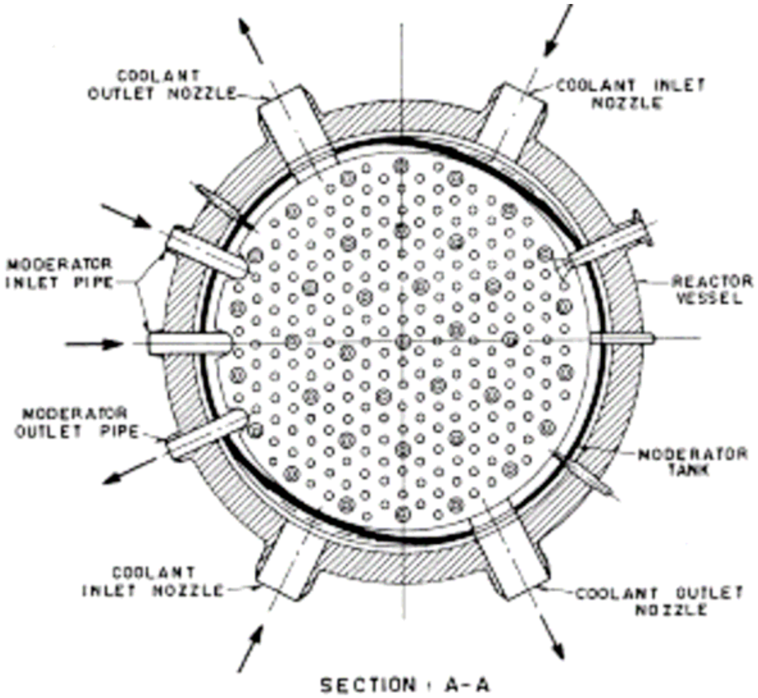
VERTICAL SECTION REACTOR ATUCHA

Atucha 1 (Argentina)

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



SECTION : B-B



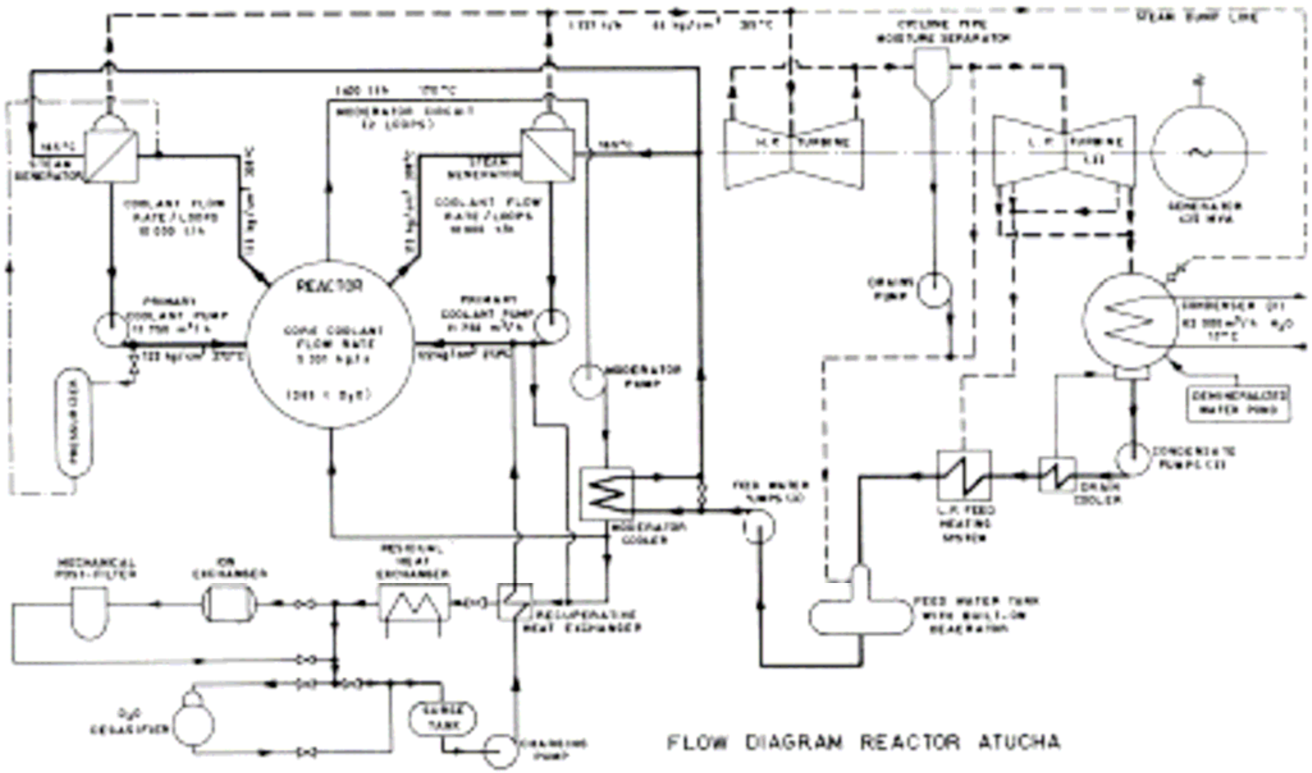
SECTION : A-A

HORIZONTAL SECTIONS REACTOR ATUCHA

UNRESTRICTED

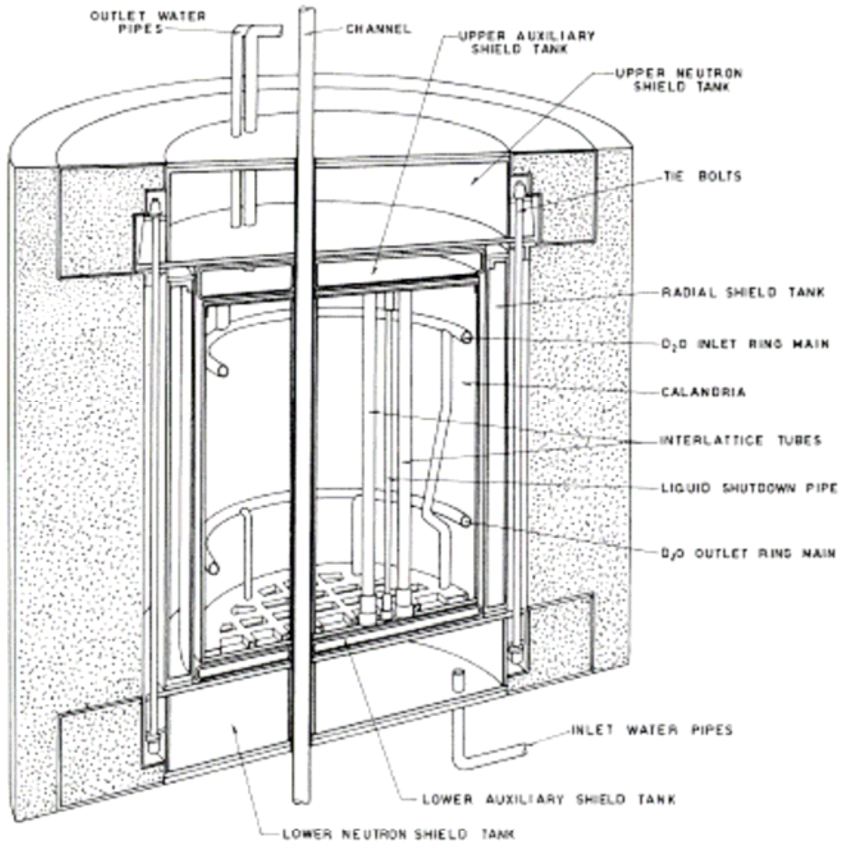
Atucha 1 / Atucha 2

- **Coolant at 11.3 MPa / 299°C**
- **Steam at 4.2 MPa / 253°C**
- **Atucha 2 (693 MW$_e$) on hold since 1980's**



SGHWR (Winfrith, U.K.)

- First HWBLW (1968-1990)
- 308 MW_{th} / 94 MW_e
- 103 PT's, Zr-2
  - 26-cm lattice pitch
- Mod. Displacer Tubes
- Void/Power Coefficients
  - Slightly negative
- On-line refuel feasible.
  - multi-batch offline preferred

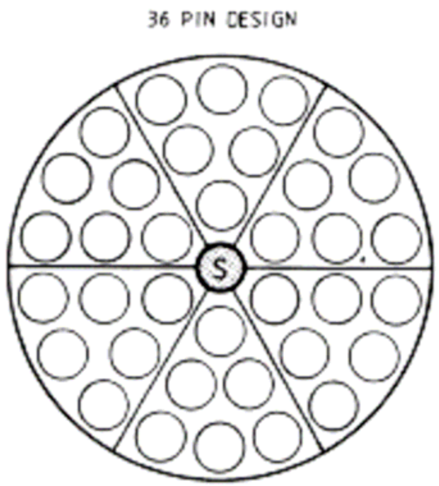


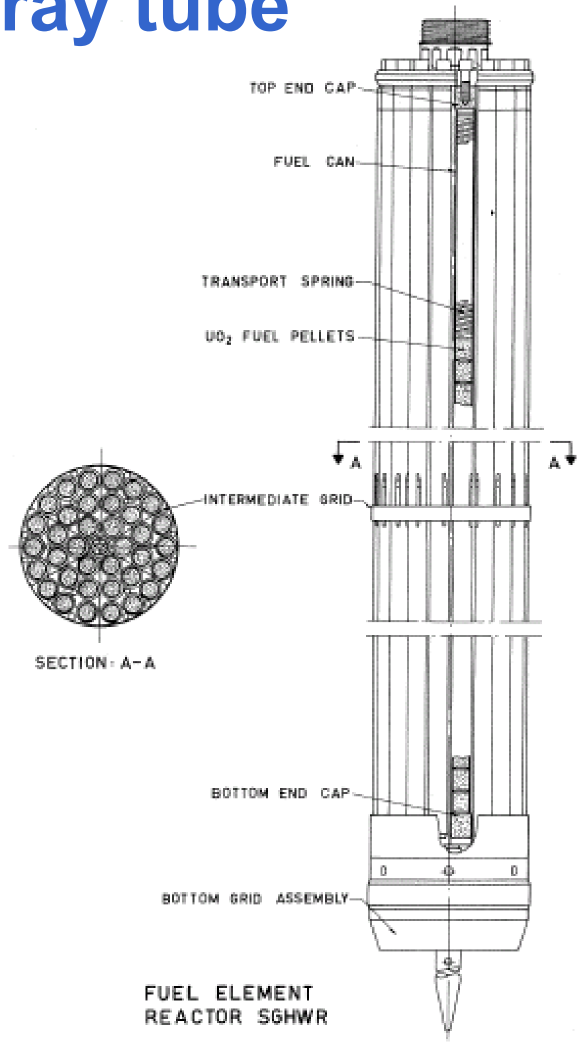
SCHEMATIC DIAGRAM OF CALANDRIA AND SHIELD TANKS

REACTOR SGHWR

SGHWR

- **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**





SGHWR

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

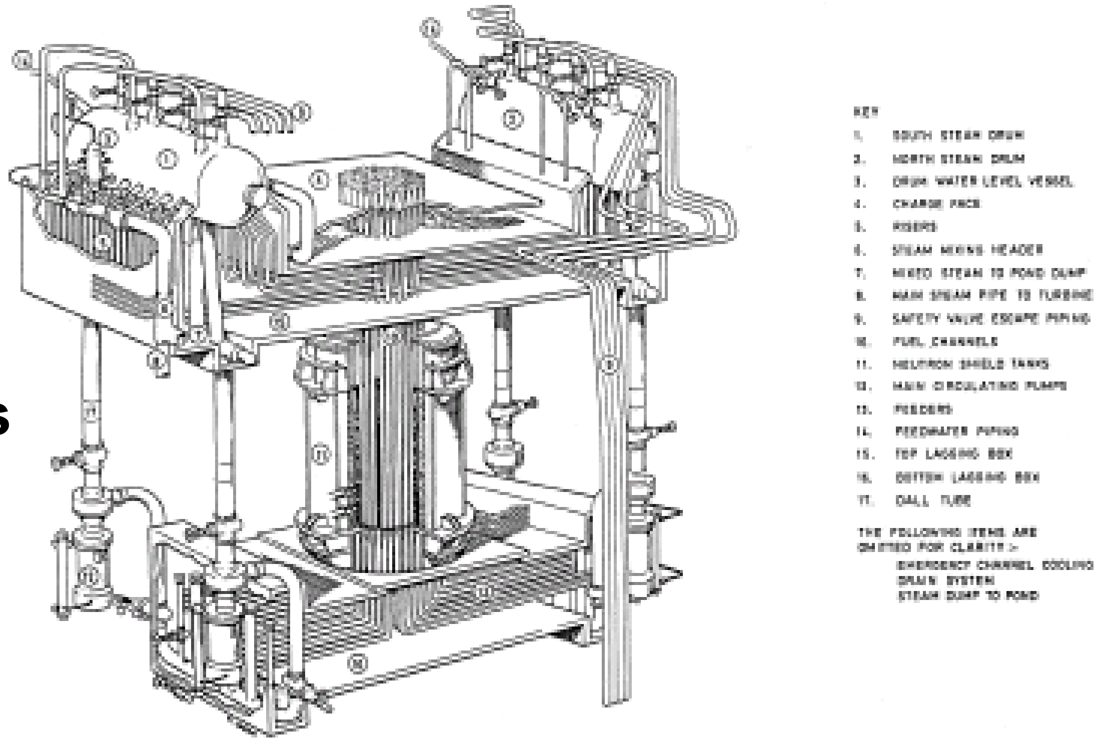
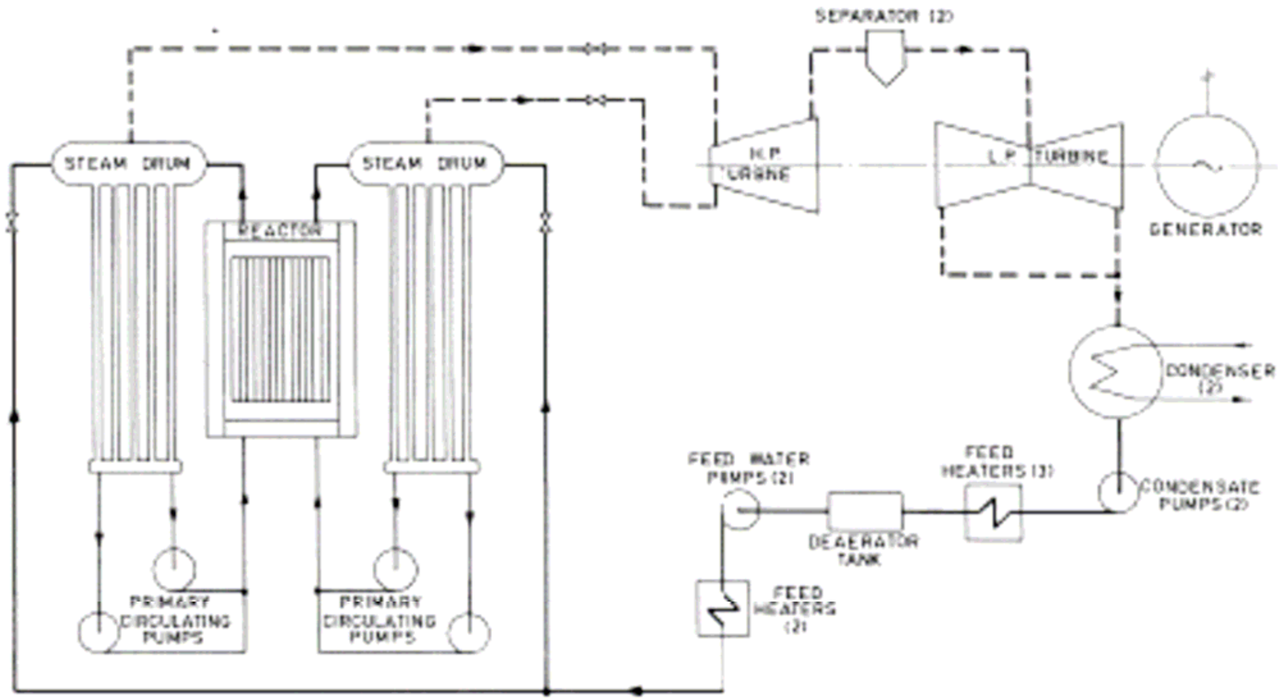


FIG. 1 PLANT IN PRIMARY CONTAINMENT

SGHWR

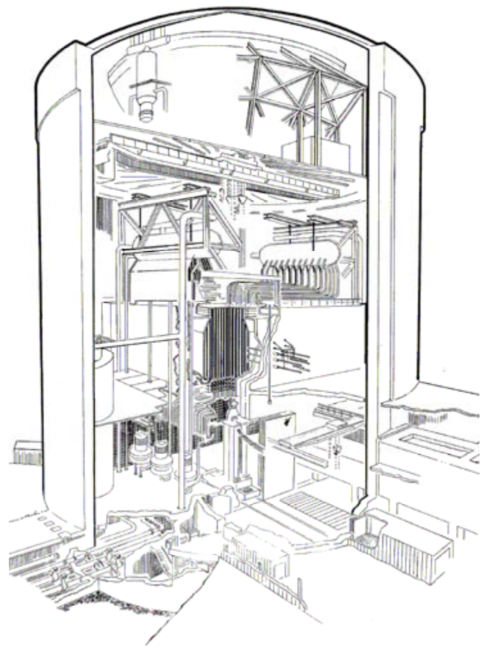
- Steam at 6.5 to 6.1 MPa, 279°C
- 31% efficiency, 11 kW/liter
- Successful technology demonstration.



FLOW DIAGRAM REACTOR SGHWR

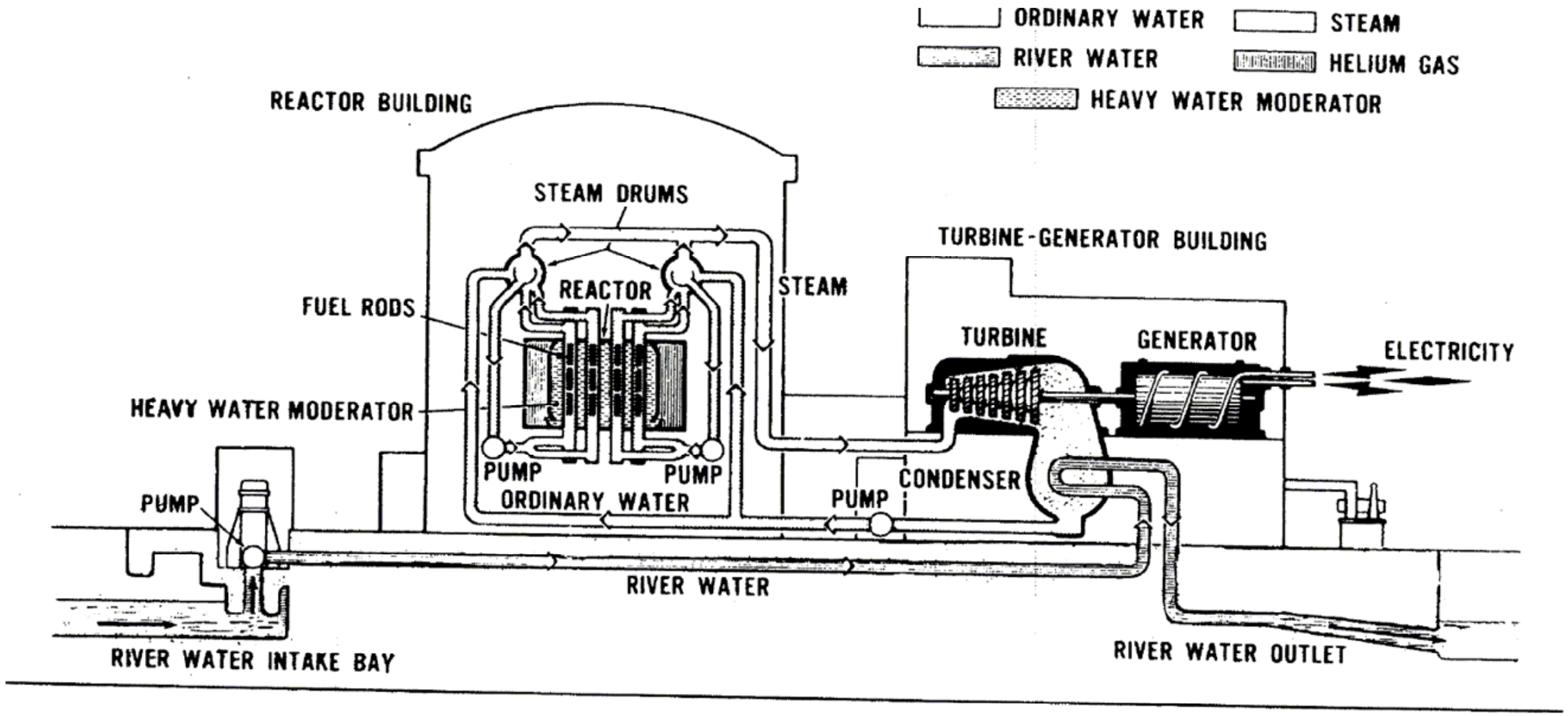
Gentilly-1 (1972-1977)

- Prototype
- 830 MW_{th} / 250 MW_e (net)
- 308 vertical channels / 10 bundles
- 18-element NU fuel bundles
  - 7,000 MWd/t burnup
- Boiling light water, 5.6 MPa, 270°C
- Shutdown in 1979
  - Debugging reactor control.
  - Consolidation in nuclear industry.
  - Focus on CANDU-PHWR only.



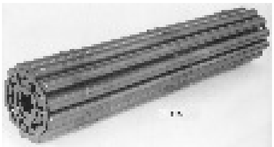
Gentilly-1

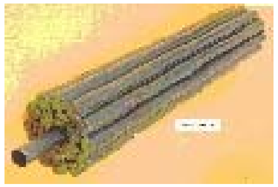
- **Steam drums; direct cycle.**

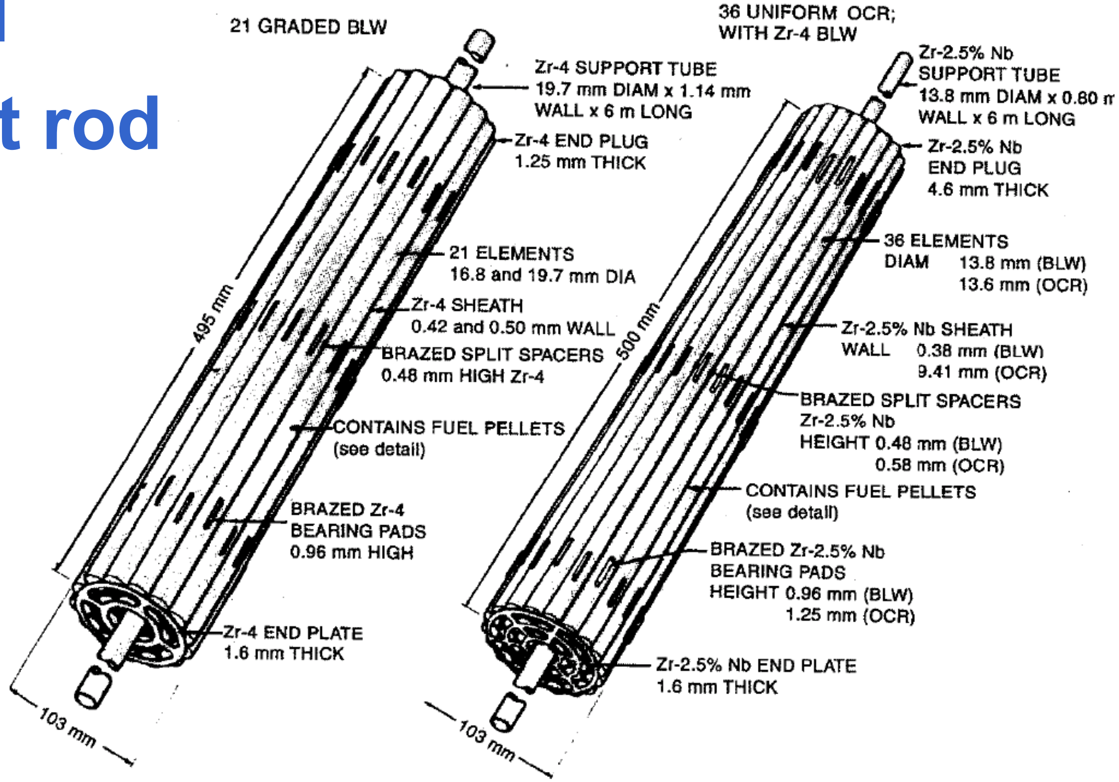


Gentilly-1

- 18-element fuel
- Central support rod

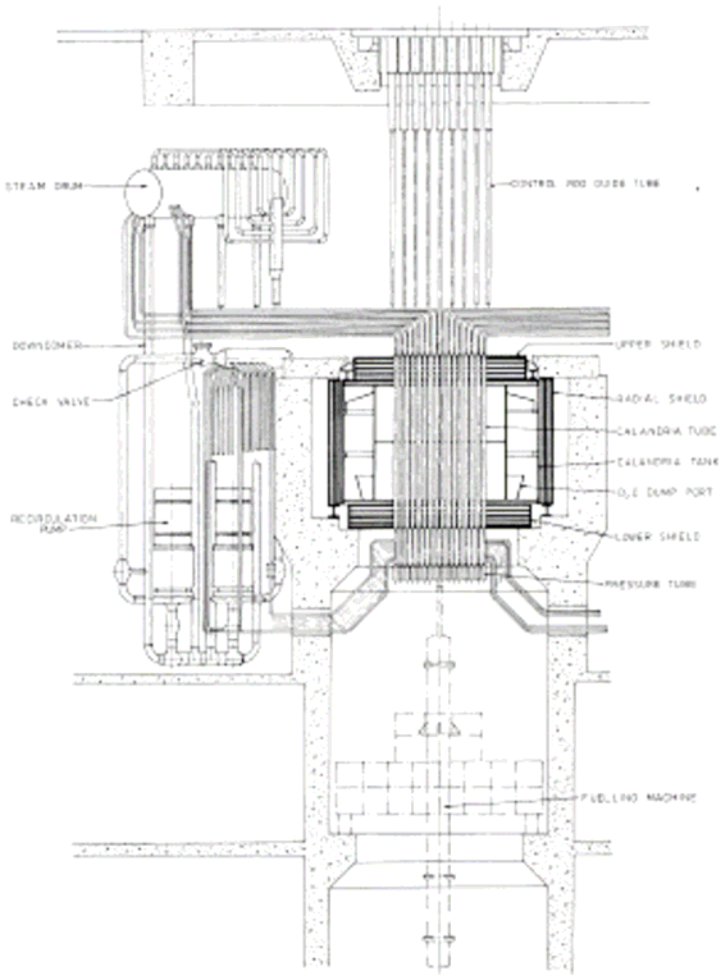






FUGEN (Japan)

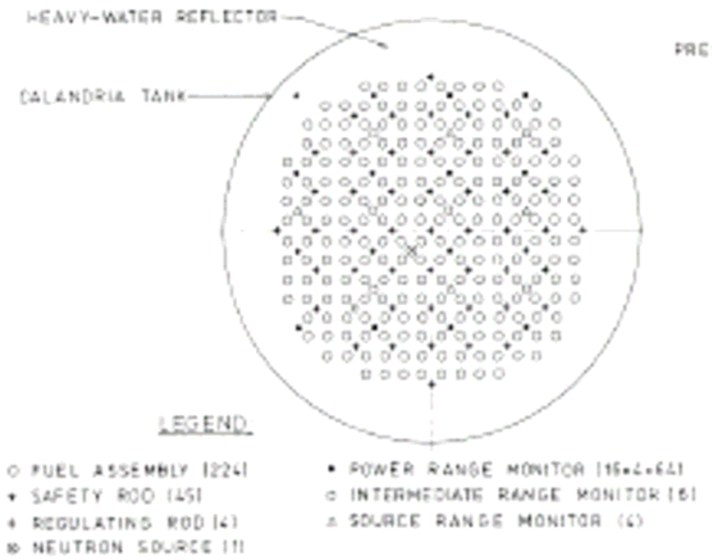
- HWBLW Reactor
- Operated 1979-2003
- Similarities to:
  - SGHWR, Gentilly-1
- 557 MW_{th} / 148 MW_e
- Void/Power Coefficients
  - Negative (MOX fuel)
- First for HW power reactor
  - Use recycled Pu in MOX
- Burnup
  - 10 GWd/t to 17 GWd/t



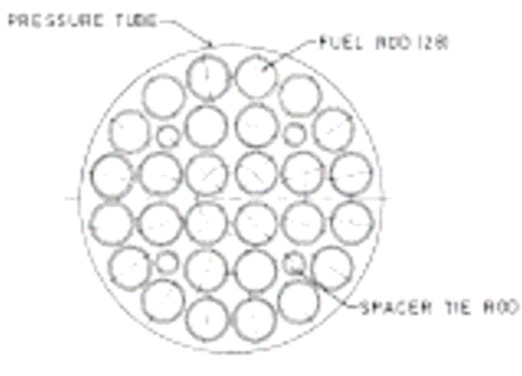
VERTICAL SECTION REACTOR FUGEN

FUGEN

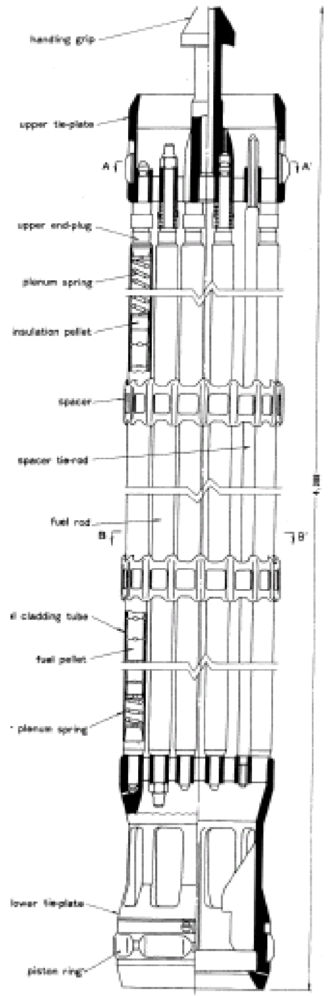
- **224 Channels, 24-cm pitch**
  - Zr-2.5%Nb PT, Zr-2 CT
- **28-element assemblies, 4.4 m long**
  - 1.5 to 2 wt% fissile in UO_2 or MOX
  - Zr-2 clad



CORE ARRANGEMENT

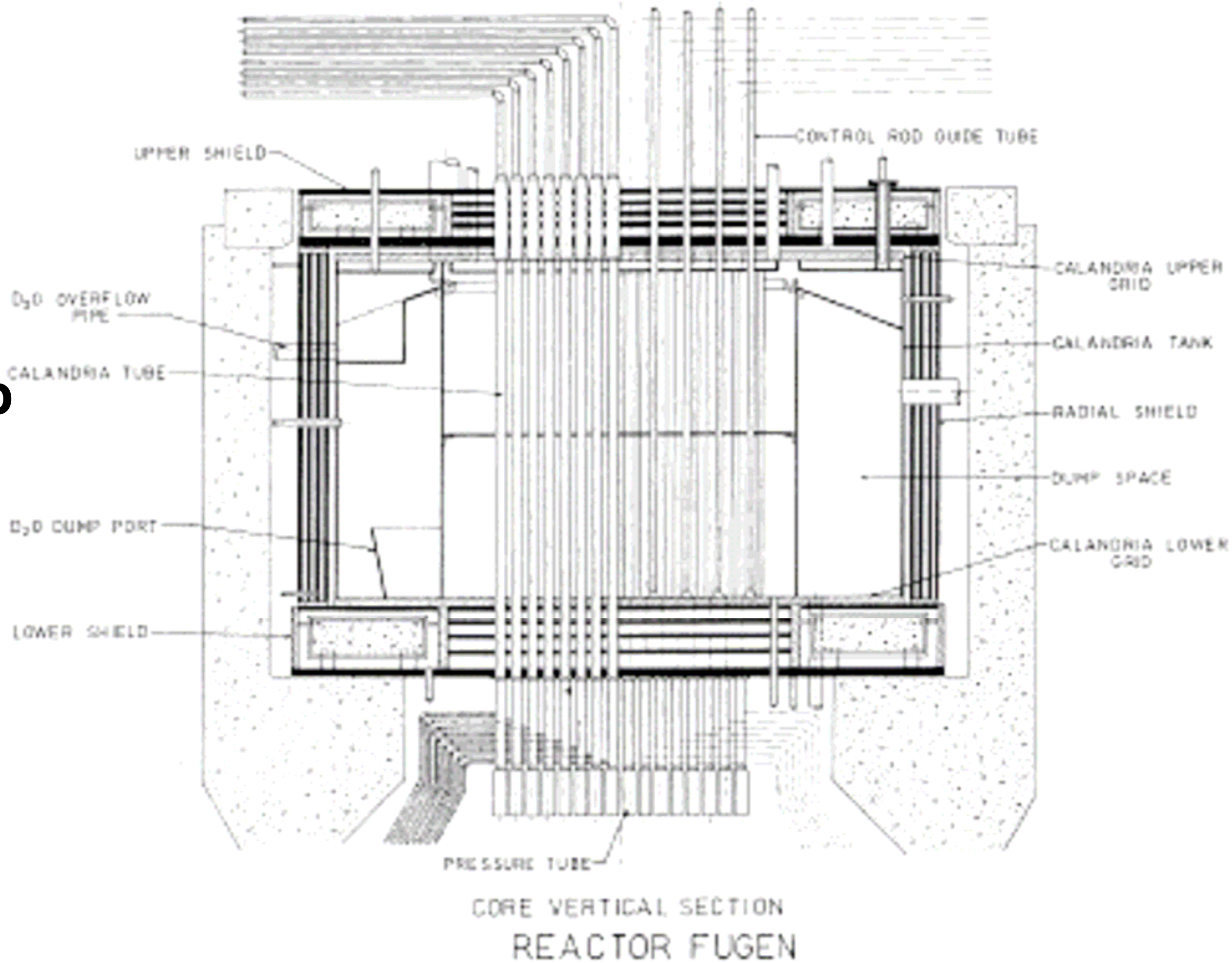


FUEL ELEMENT



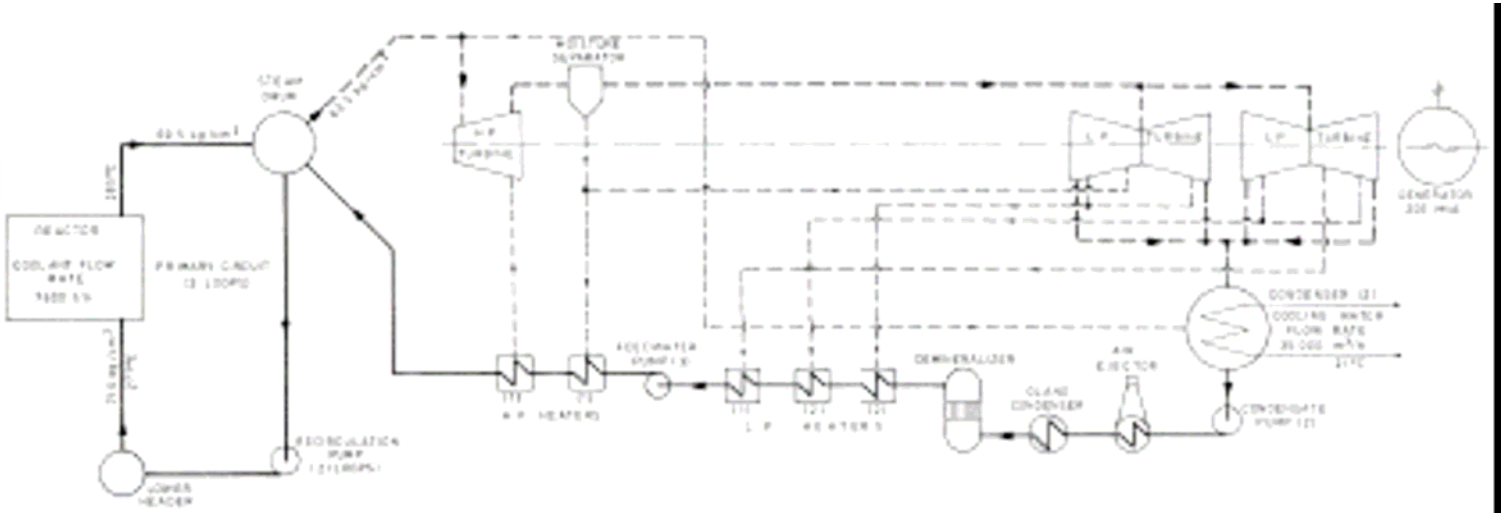
FUGEN

- On-load refuel
  - ~1 cluster / wk
- Control
  - B_4C rods
  - Moderator dump
  - Chemical shim
    - Boron



FUGEN

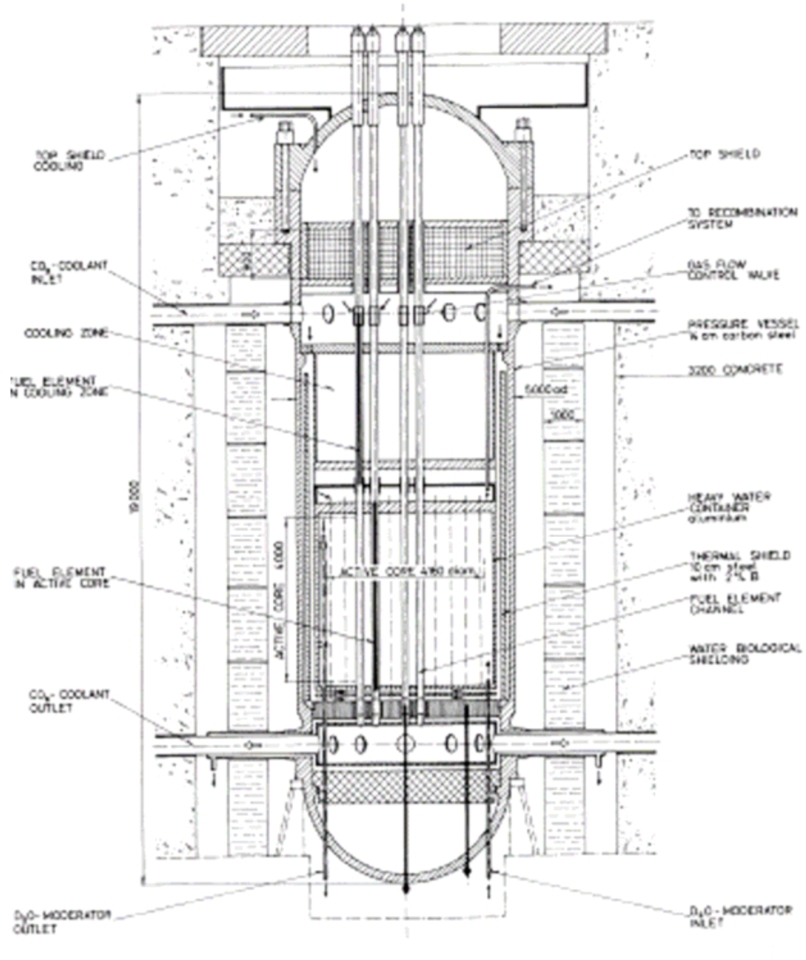
- **7.1 MPa, 283.5°C**
- **Steam at 6.4 MPa, 279°C**
- **Successful technology demonstration.**



FLOW DIAGRAM REACTOR FUGEN

KS-150 / A-1 (1972-1979)

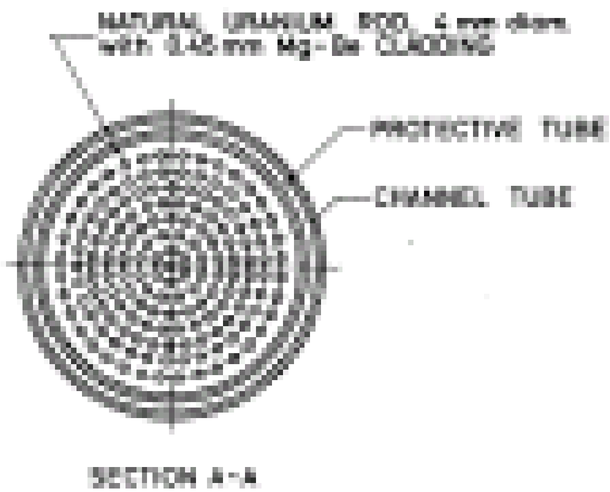
- Pressure vessel-type
  - Mod. at 90°C
- 590 MW_{th} / 150 MW_e
  - Blowers use ~15%
  - Net efficiency ~20%
- CO_2-cooled
- 11 kW/litre
  - CO_2 at 6.5 MPa
- 156 Fuel Channels
  - Mg-alloy PT, Al-alloy CT
- 40 Control rods

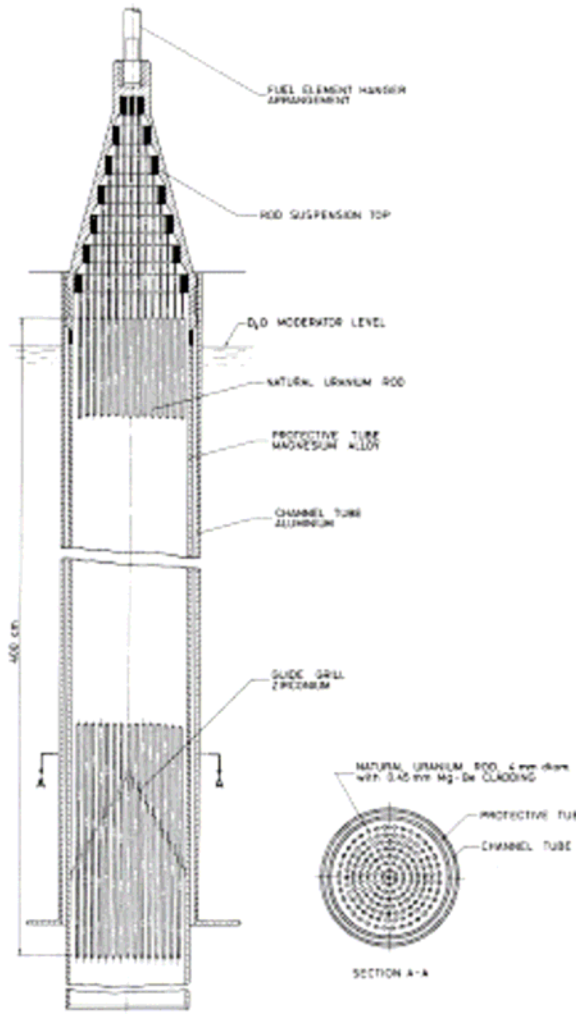


VERTICAL SECTION REACTOR HWGCR

KS150 / A-1 Bohunice (Slovakia)

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

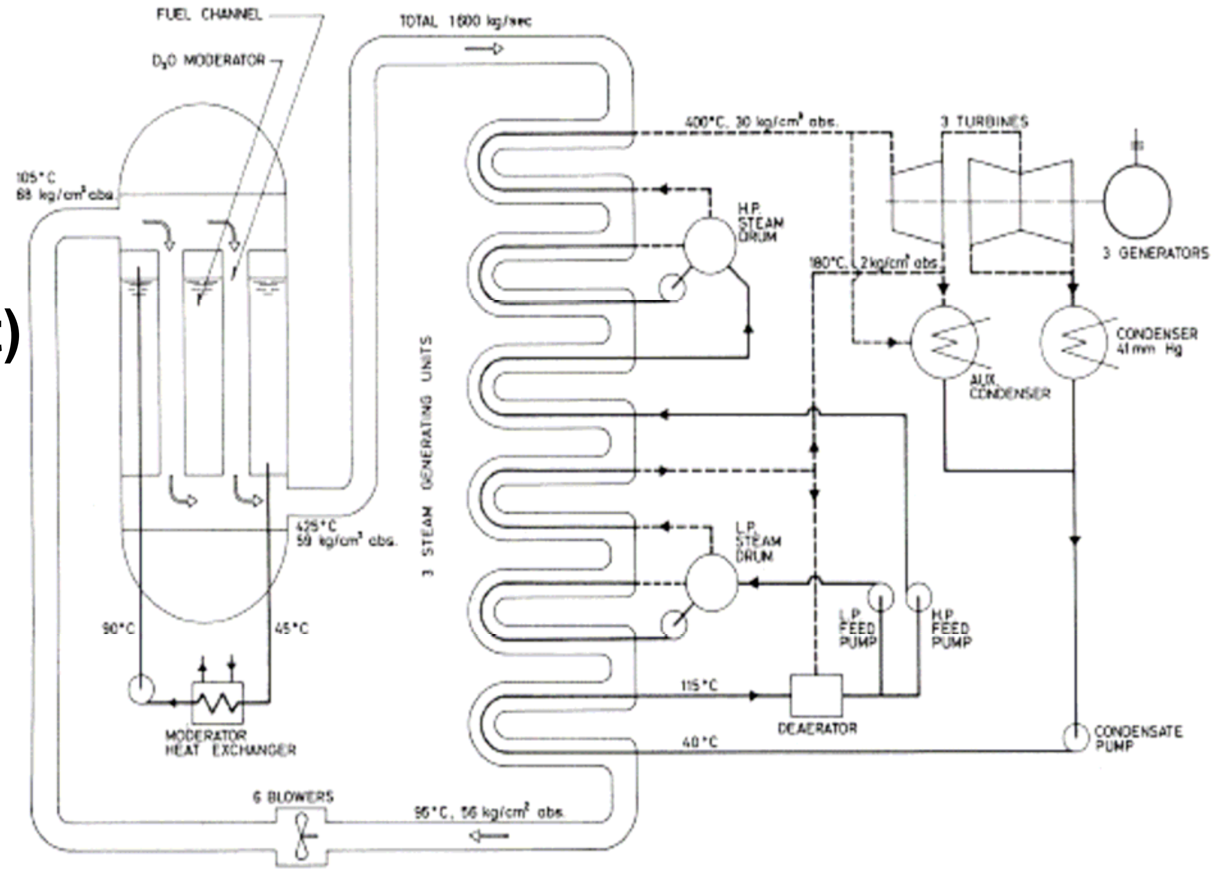




FUEL ELEMENT REACTOR HWGCR

KS-150 / A-1 Bohunice (Slovakia)

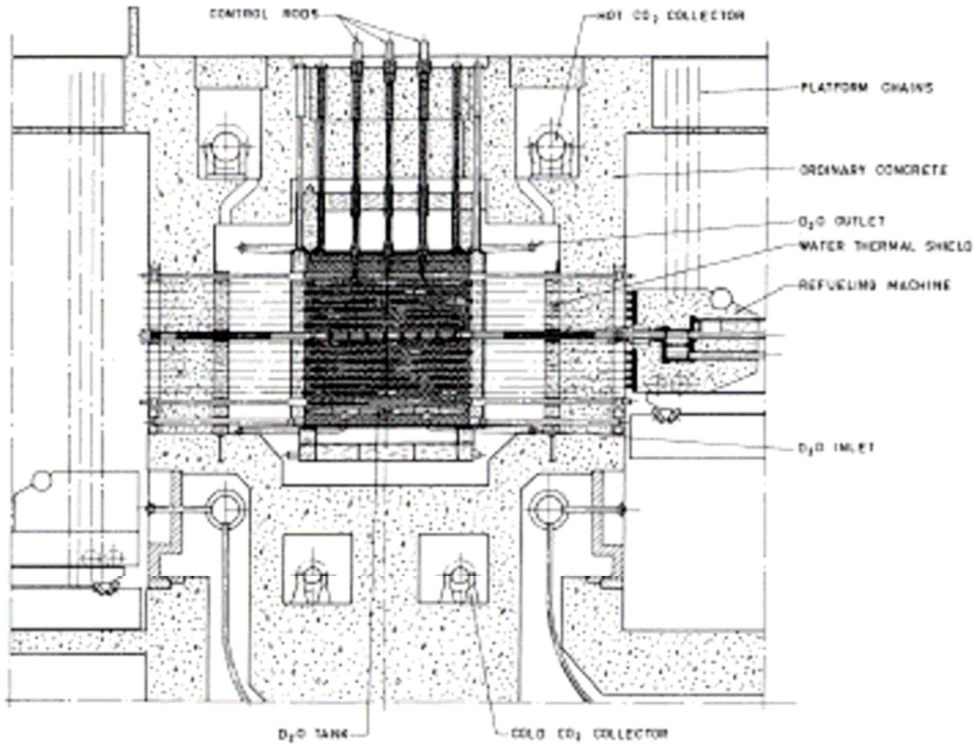
- CO_2 at 425°C
- Steam at
  - 2.8 MPa
  - 400°C (superheat)
- Shutdown
  - 1979
  - Partial fuel melt



FLOW DIAGRAM REACTOR HWGCR

EL-4 (France)

- GCHWR – Pressure Tube
- 250 MW_{th} / 70 MW_e
  - 28% efficient
  - 4.4 kW/litre
- CO_2 at 5.9 MPa, 500°C
- Zr-2 Channels
- Control
  - B_4C and SS rods

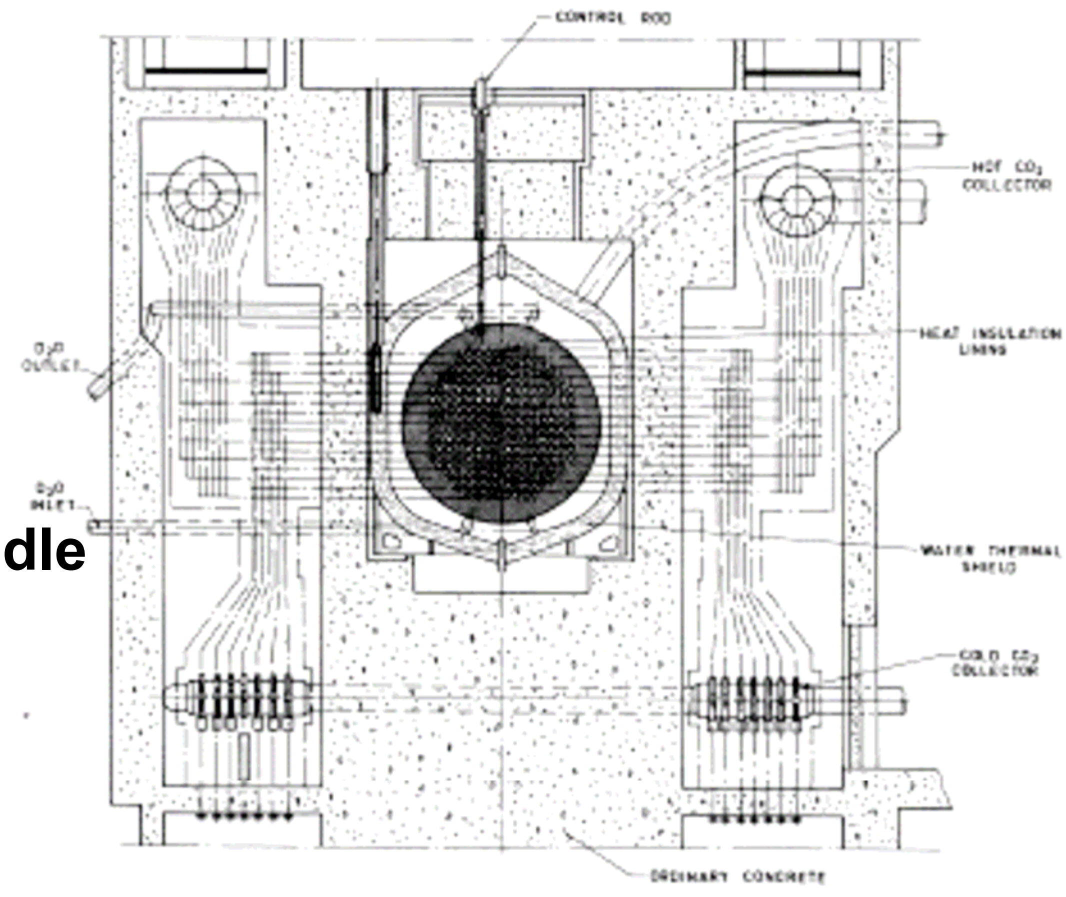


LONGITUDINAL SECTION

REACTOR EL-4

EL-4 (Monts d'Arree)

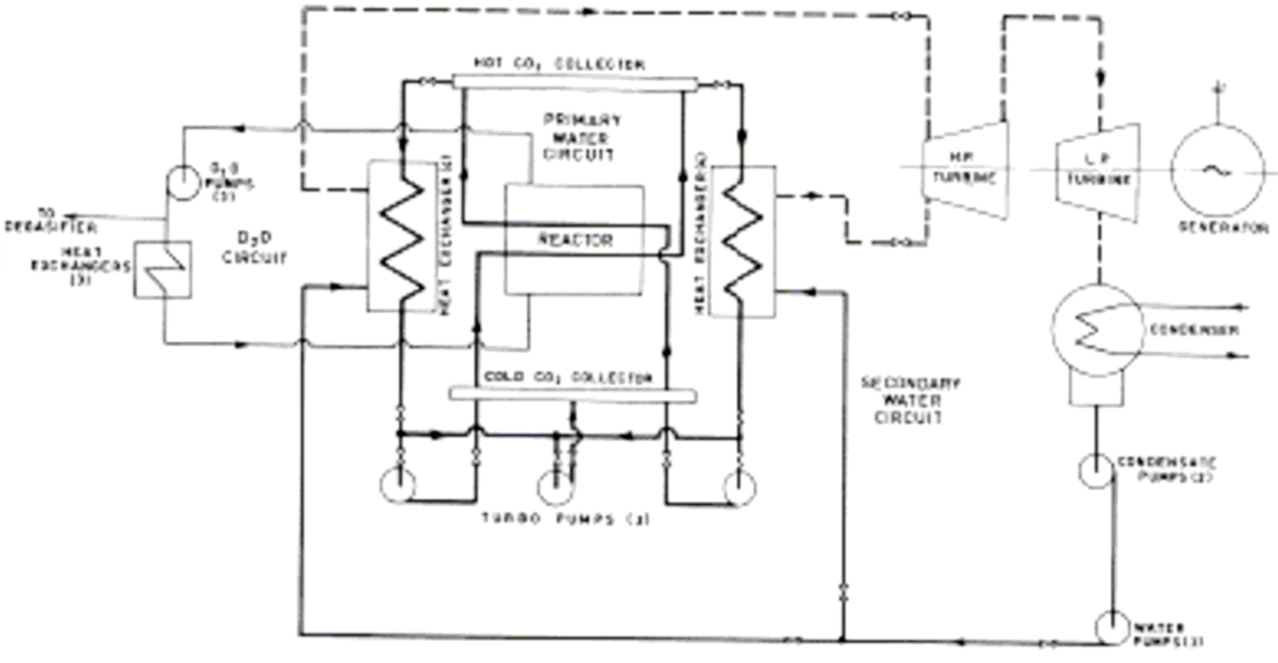
- 23.5-cm Pitch
- 19-rod bundles
  - – 0.5-m long
  - – 1.37 wt% UO_2
  - – 1.65 wt% UO_2
  - – SS clad (or Zr/Cu)
  - – graphite liner for bundle
  - – 9 bundles / channel
- 12,000 MWd/t



VERTICAL SECTION REACTOR EL-4

EL-4

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



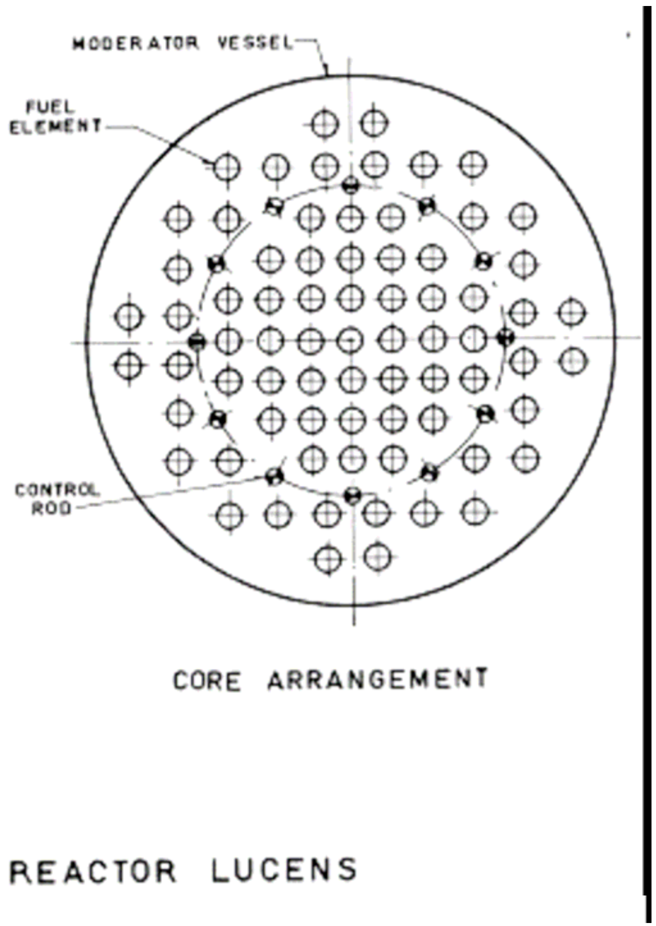
FLOW DIAGRAM REACTOR EL-4

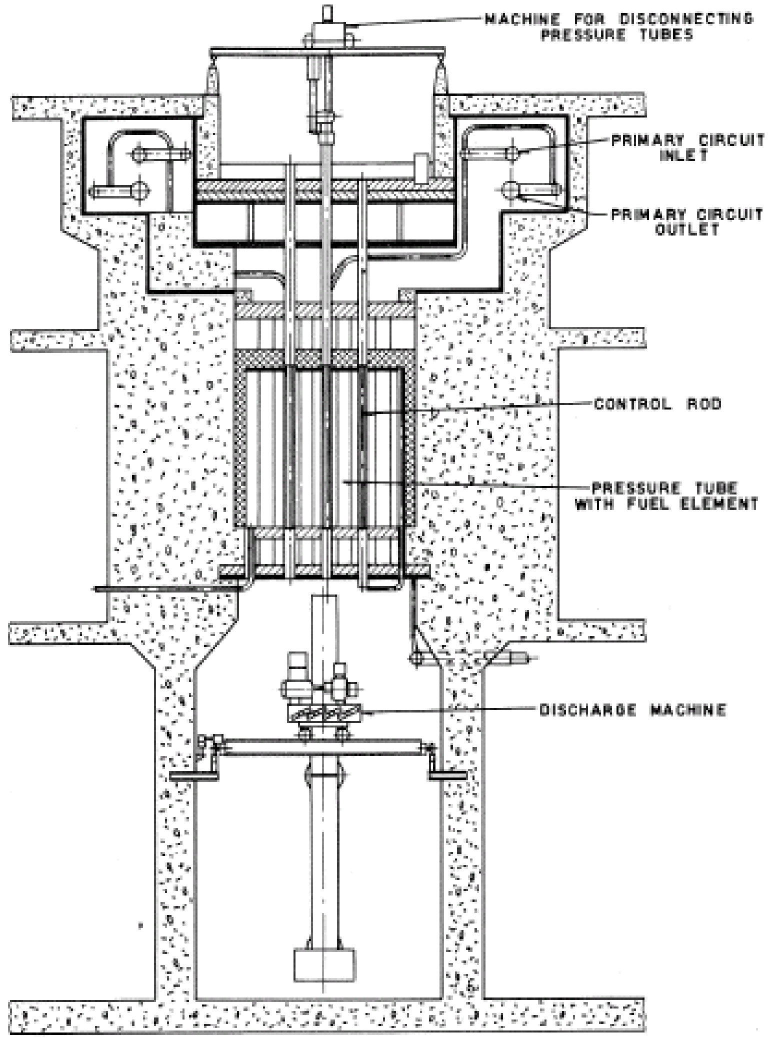
Lucens (Switzerland)

- GCHWR – pressure tube, small-scale experiment
- 30 MW_{th} / 7.6 MW_e, 25.3% efficiency.
- 73 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
- CO_2 at 6.2 MPa, 378°C outlet
- Steam at 2.2 MPa, 367°C

Lucens (1968-1969)

- 24-cm & 29-cm pitches





Lucens (Switzerland)

- **Off-load refuelling**
- **Shutdown 1969**
  - flow blockage from corrosion products
  - fuel damage at bottom at startup
- **Converted to test facility.**

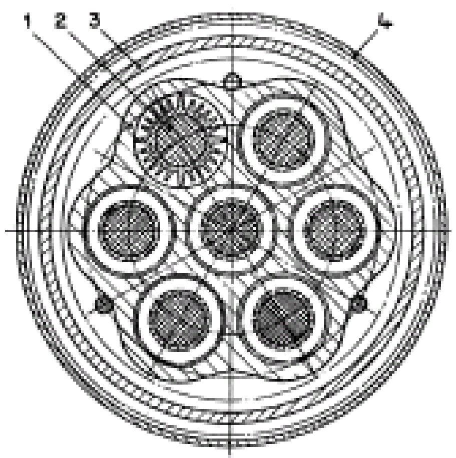
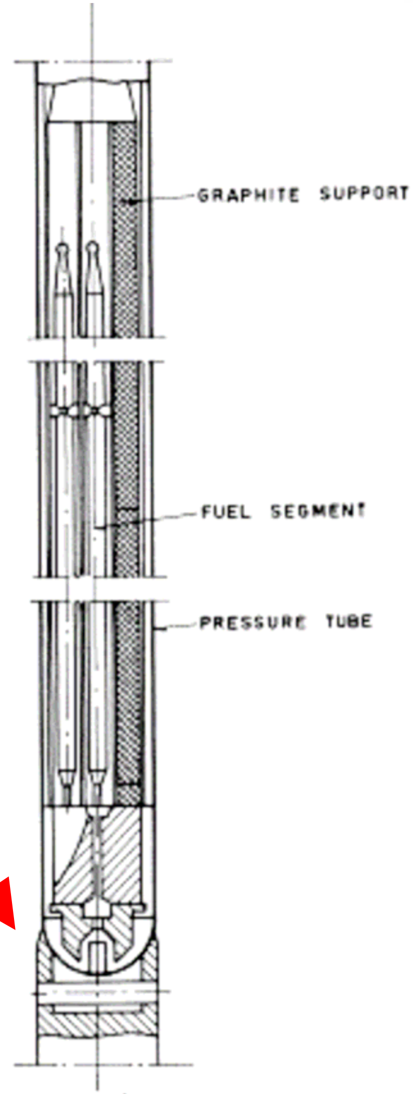


Figure 4. Fuel element, radial section
1: Graphite structure; 2: Uranium and cladding; 3: Pressure tube; 4: Calandria tube

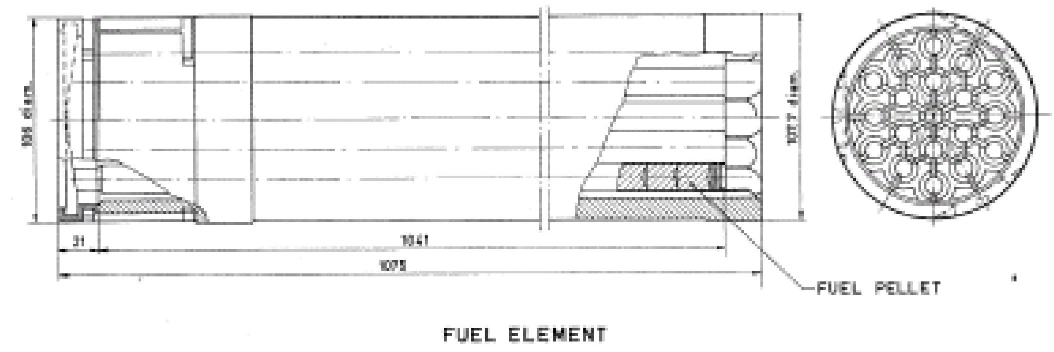


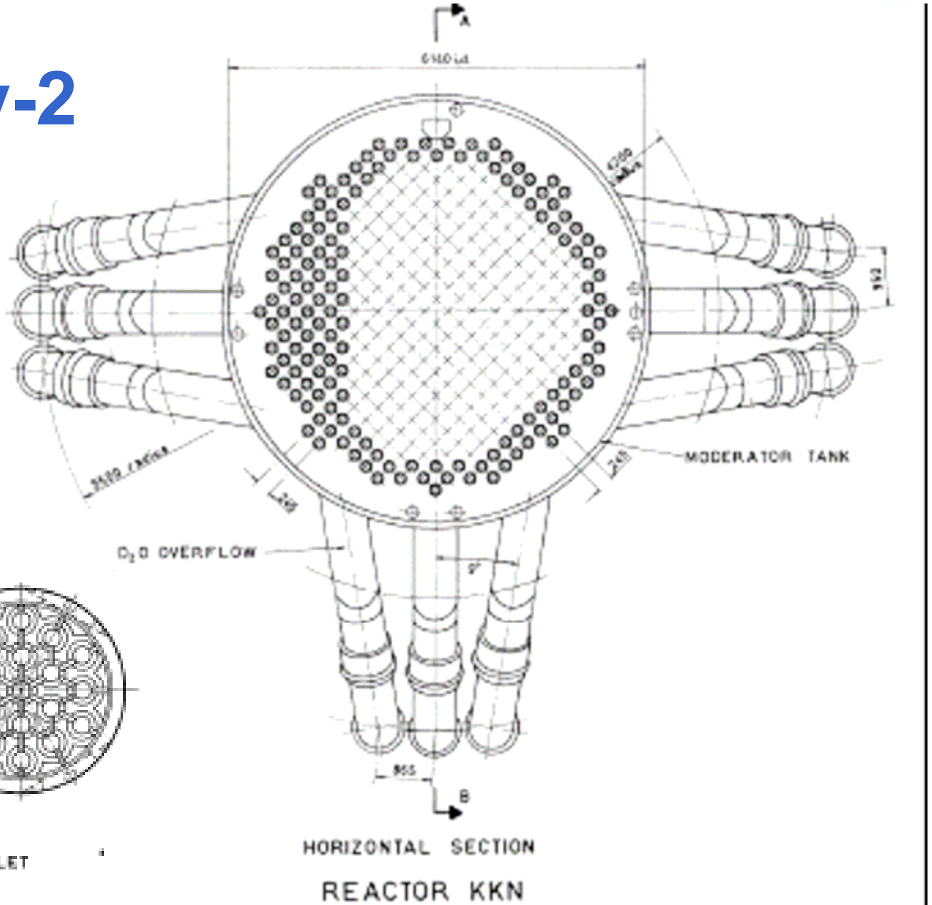
KKN – Niederaichbach (Germany)

- GCHWR – pressure tube, vertical
- 316 MW_{th} / 100 MW_e
- 31.6% efficient, 3.5 kW/litre
- 19-element bundles, 107-cm long, 4 per channel
  - 1.15 wt% UO_2, stainless steel clad
  - 11,600 MWd/t burnup
- On-load refuelling capability, 1 bundle/day

KKN – Niederaichbach (Germany)

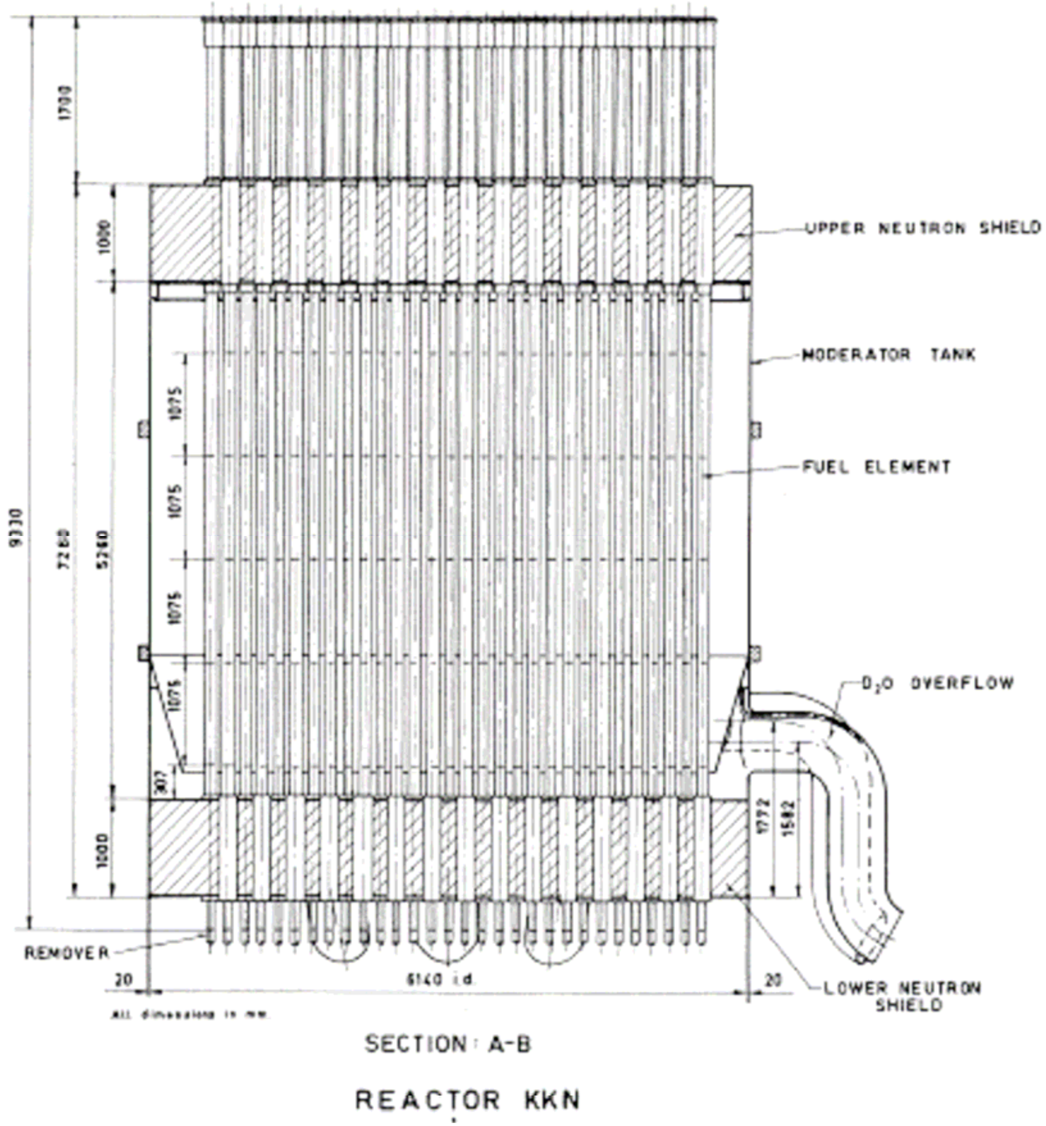
- 351 channels, Zircaloy-2
- 24.5-cm pitch





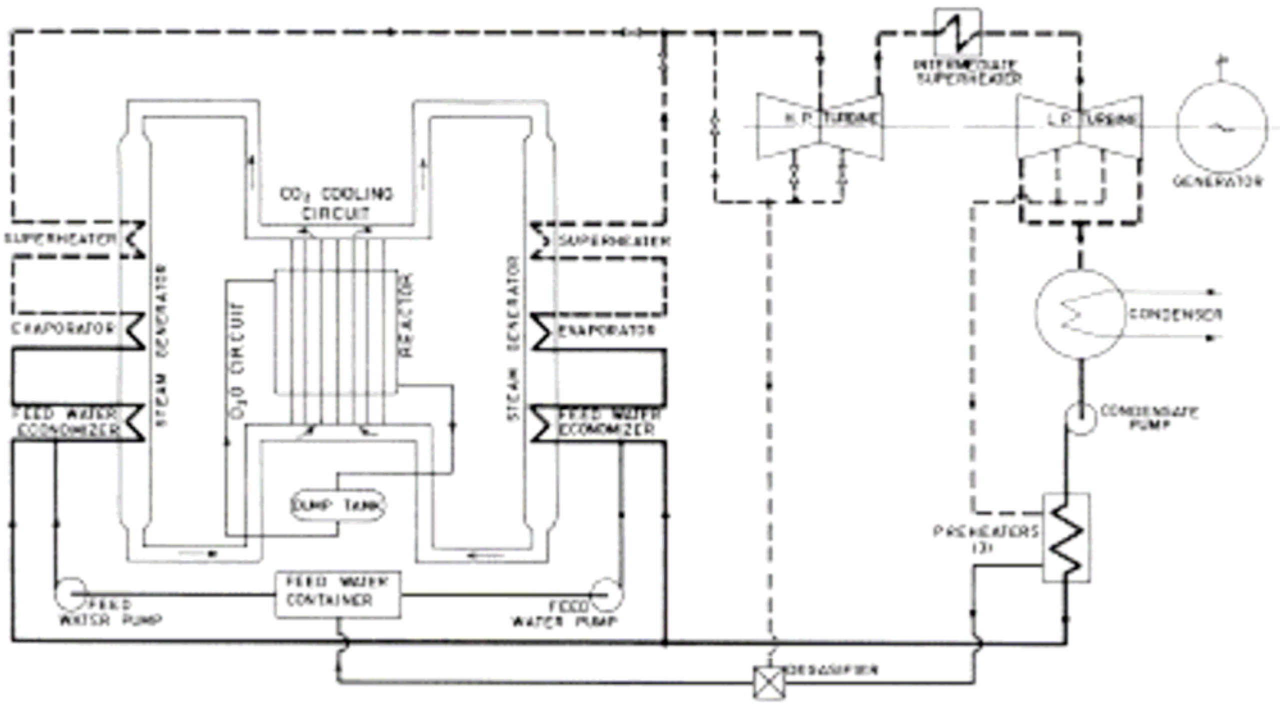
KKN - Niederaichbach

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



KKN - Niederaichbach

- CO_2 at 6 MPa, 550°C; steam at 10 MPa, 527°C
- Operated 1973-1974
  - Difficulties encountered with steam generators



FLOW DIAGRAM REACTOR KKN

Projects That Never Materialized

- Scale up of HWBLWR to Commercial Size
  - FUGEN (600 MWe)
    - MOX recycling in LWR's improved.
  - SGHWR (350 to 660 MWe)
    - Government decision to favor AGR's.
  - Gentilly-1 (600 MWe)
    - CANDU-PHWR's performing well.
  - 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 project cancelled during 1970's (focus on BWR's).

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.

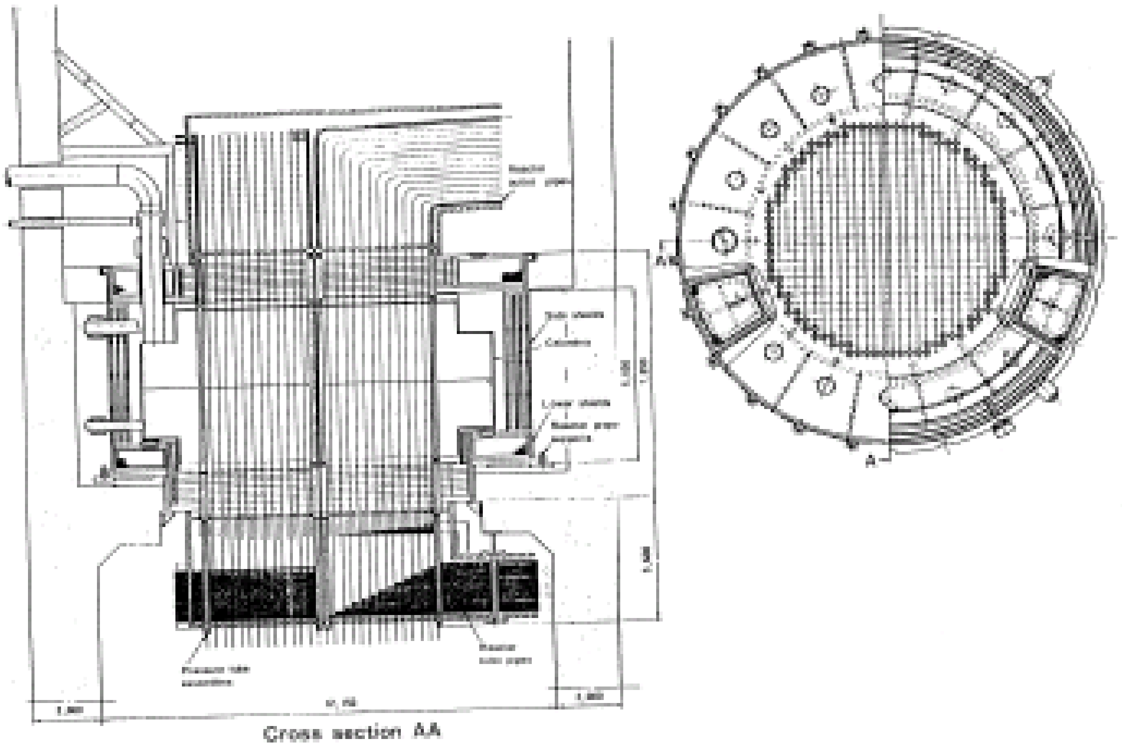
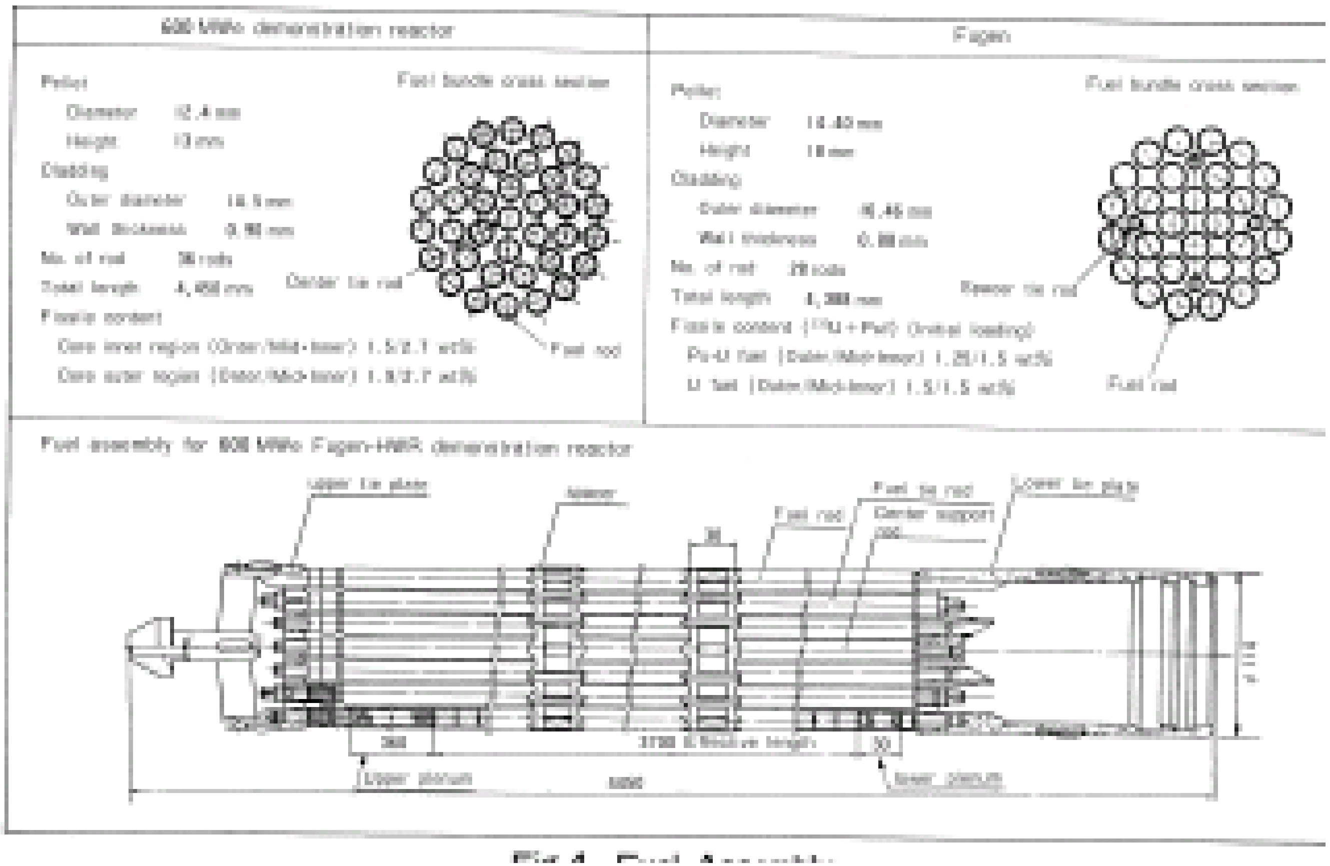


Fig.3 600 MWe Demonstration Plant

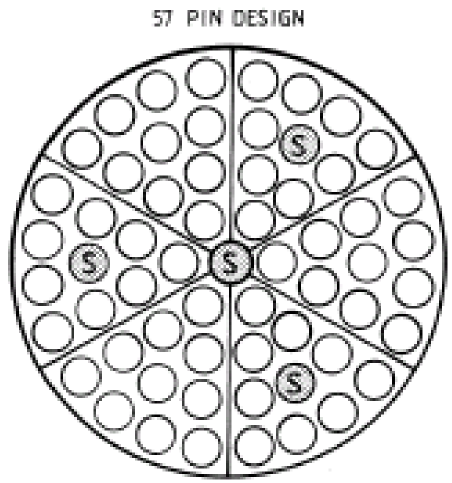
FUGEN - Commercial

- **36-element fuel assemblies**
  - **3.2 wt% fissile (UO_2 + MOX)**



SGHWR - 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



CIRENE (Italy)

- **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**
  - **19-rod assemblies**
  - **8,500 MWd/t**
  - **Off-load refuelling.**

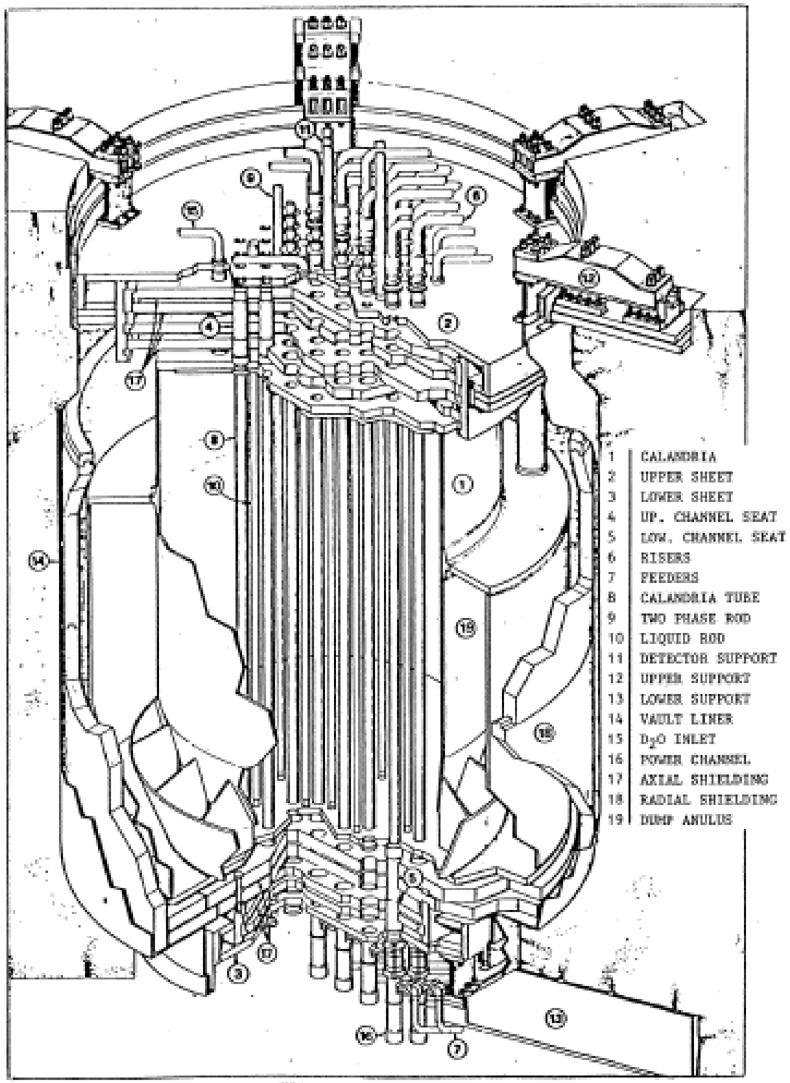
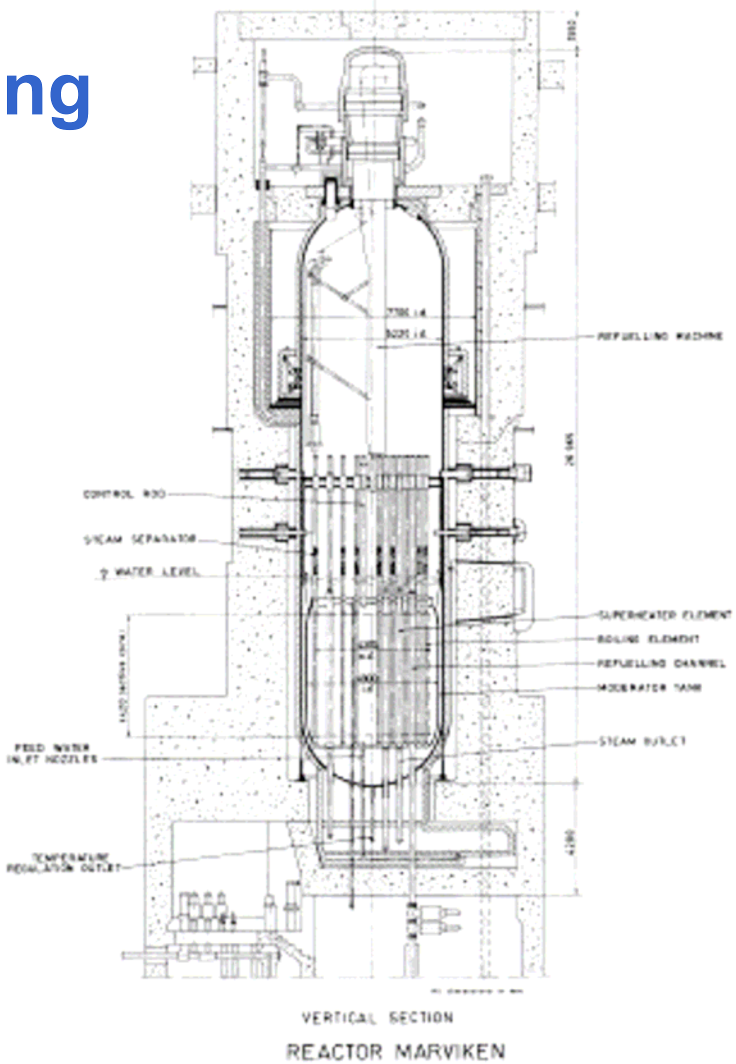


FIG. 1 REACTOR ASSEMBLY

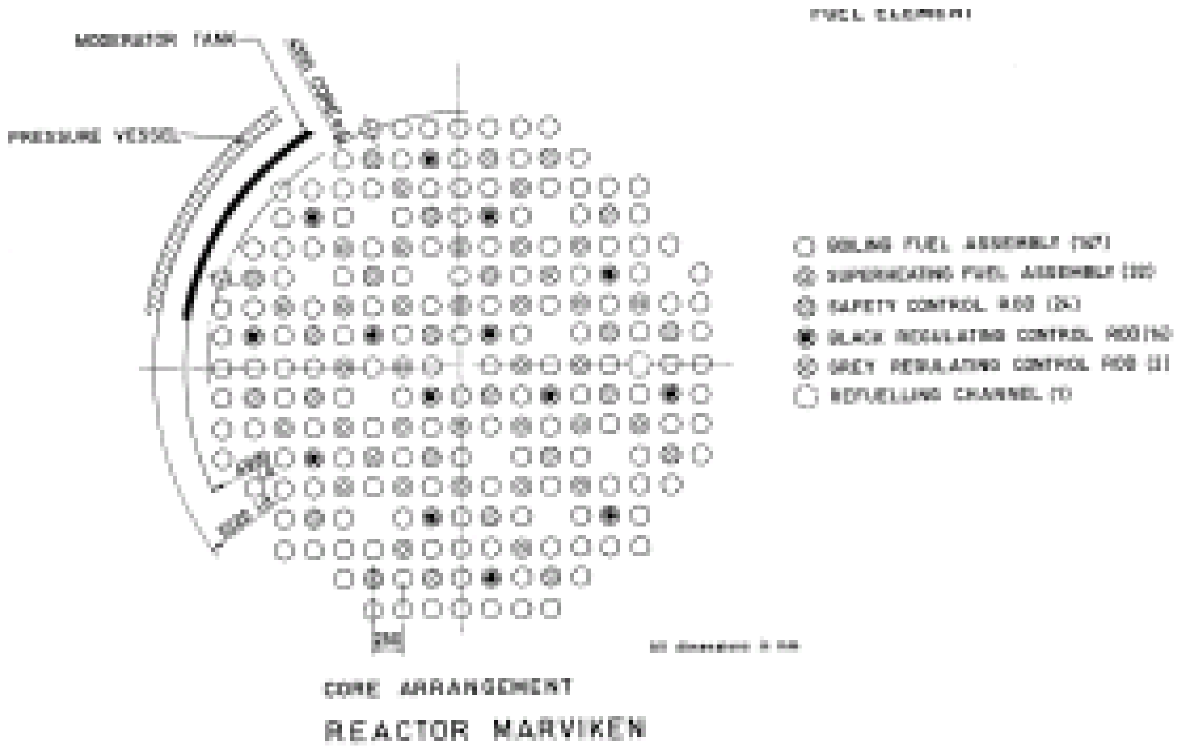
Marviken (Sweden)

- Boiling D_2O with superheating
- Pressure-vessel type.
- 593 MW_{th} / 193 MW_e
- 33% efficiency
- 147 boiler channels
- 32 superheat channels
- 4.85 MPa, 259°C/472°C
- 13,000 MWd/t burnup.



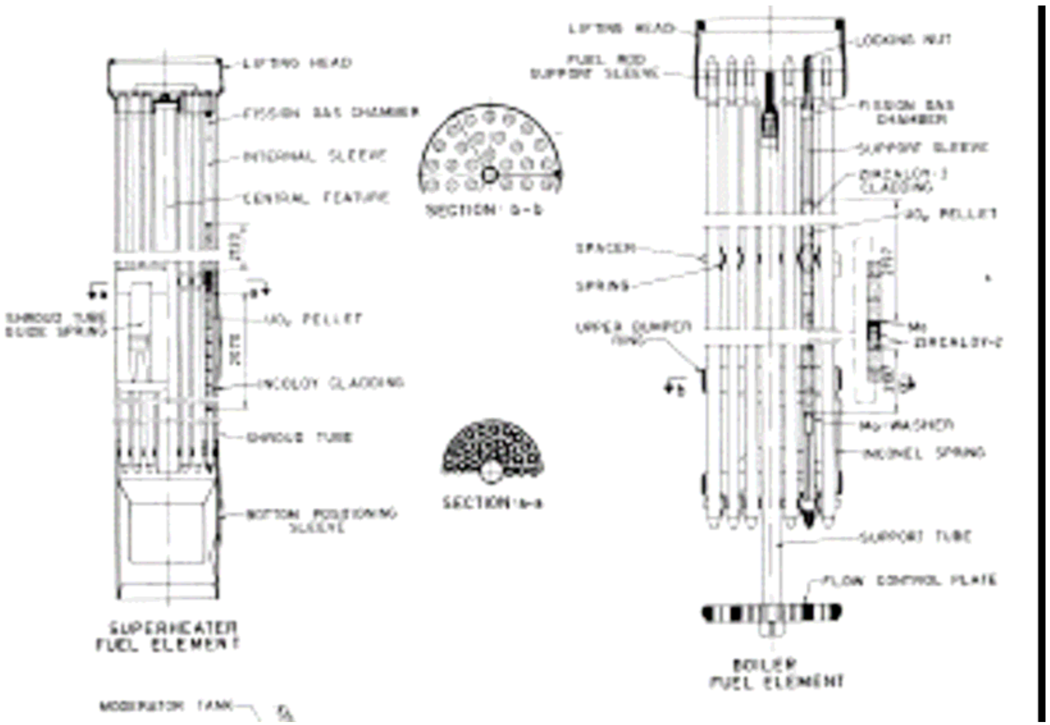
Marviken

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



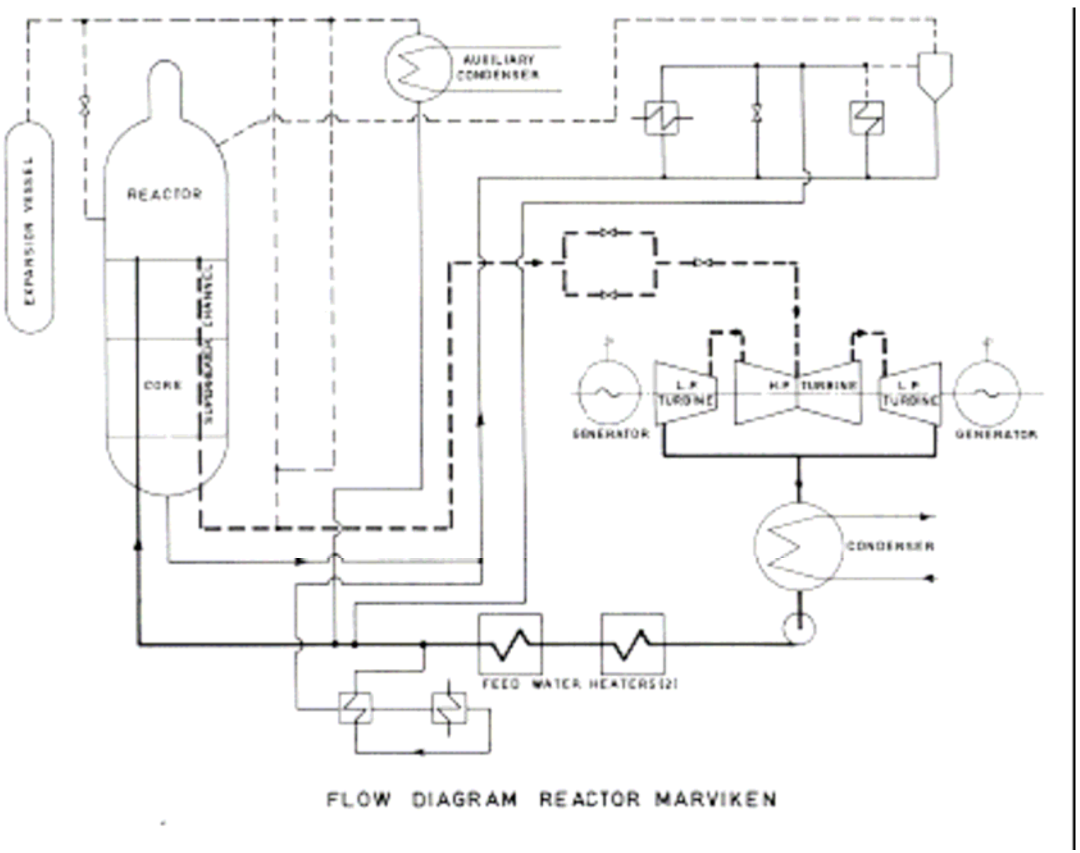
Marviken

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



Marviken

- 1963 to early 1970's
- Advanced stage of development
- Plans for 600-MW$_e$ commercial unit
  - Pre-stressed concrete
  - Natural uranium
  - 37-element assemblies
  - 9,900 MWd/t burnup
  - 7 MPa, ~284°C



Marviken

- Use of BHWR
  - Motivated by concerns of long-term uranium supply.
- Times change.
  - Project cancelled during 1970's.
  - Focus on BWR's.

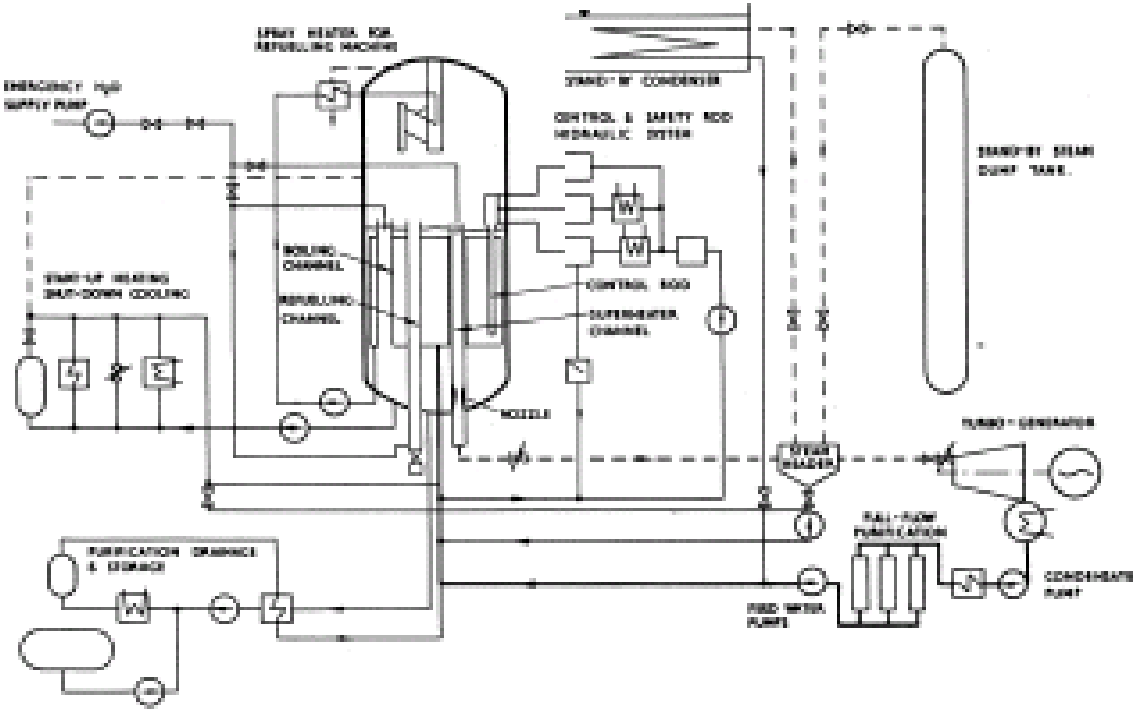


Fig. 4: Marviken BHWR. Simplified flow diagram

Abandoned Projects / Proposals

- Gas-cooled Heavy Water Reactors
  - EL-250, EL-500 (CO_2) (250 MW_e, 500 MW_e)
    - 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%

. Assemblage combustible.

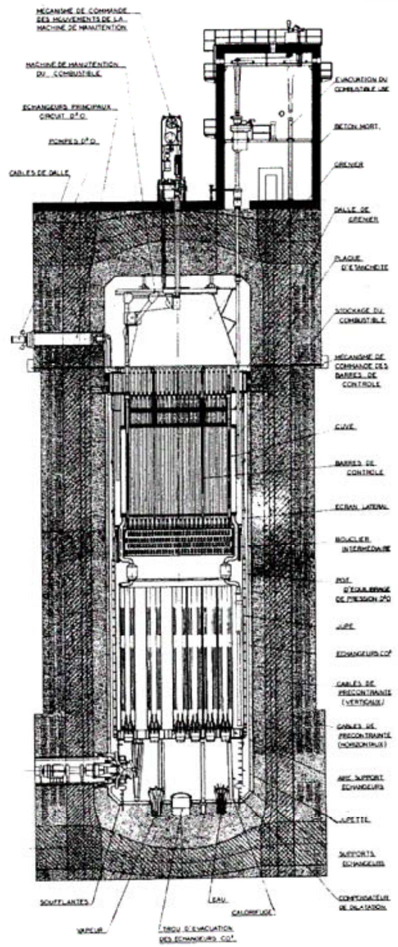
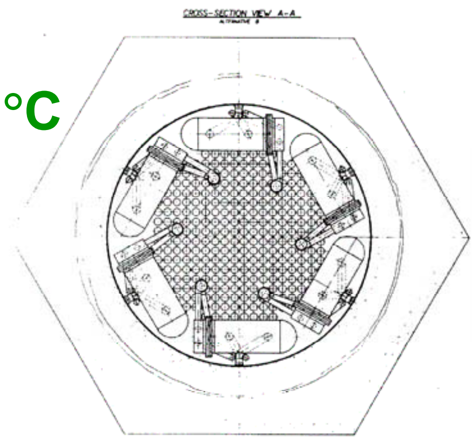
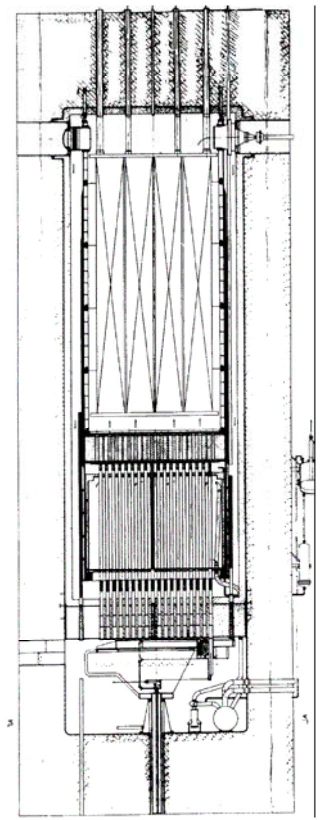


FIG.1. Ensemble du réacteur.

Abandoned Projects / Proposals

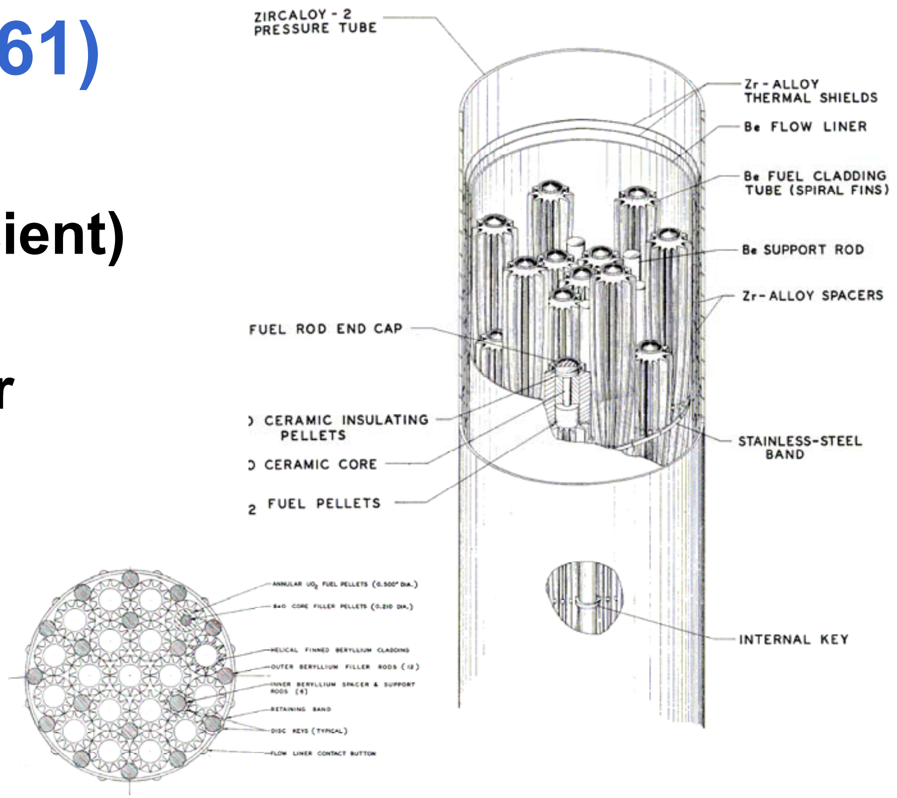
- **Gas-cooled Heavy Water Reactors**
  - **Czechoslovakia – 500 MW$_e$ gas-cooled HWR's.**
    - **Pre-stressed concrete as pressure boundary.**
    - **553 channels**
    - **U-metal or UO_2, natural**
    - **Mg-Be or Zr-alloy cladding**
    - **5,000 to 8,000 MWd/t burnup.**
    - **CO_2 at 8 to 9 MPa, 470°C to 510°C**
    - **Integral steam generators.**
    - **η_{th} > 31%**





Abandoned Projects / Proposals

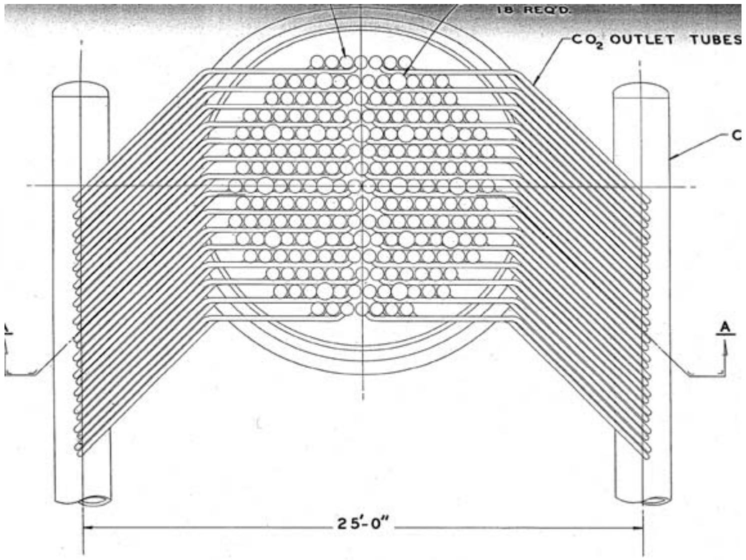
- General Nuclear Engineering Corporation
- GNEC – Florida (1958-1961)
- GCHWR Prototype
  - 175 MW_{th} / 58 MW_e (33% efficient)
  - CO_2 at 3.5 MPa, 540° C
  - Zircaloy-2 PT's with insulator
  - 19-element fuel bundles
  - Finned fuel pins
  - 1.2 to 1.9 wt% enriched UO_2
  - Be or stainless steel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

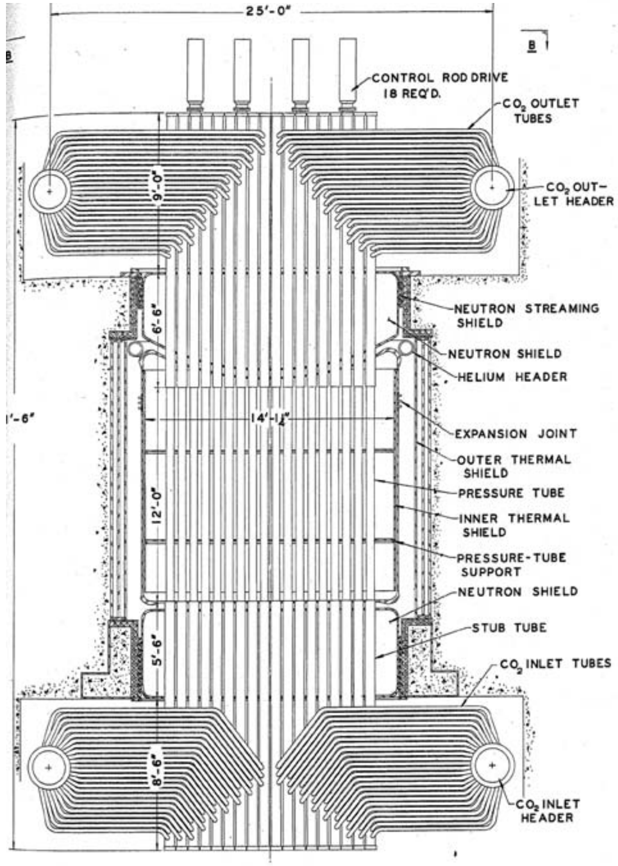


- Proposal for 300-MW_e Unit

GNEC – GCHWR (1958-1961)

- Horizontal PT's





SECTION A-A

Abandoned Projects / Proposals

- Organically-cooled Heavy Water Reactors
  - Cancelled in late 1960's and 1970's.
  - ORGEL (Euratom)
  - DON (Spain)
  - DOR (Denmark)
  - HWOCR (USA) – Cancelled 1967
    - 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
    - Most of major technical issues worked out.
    - But, CANDU-PHWR was working well.

DOR (Denmark)

- 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

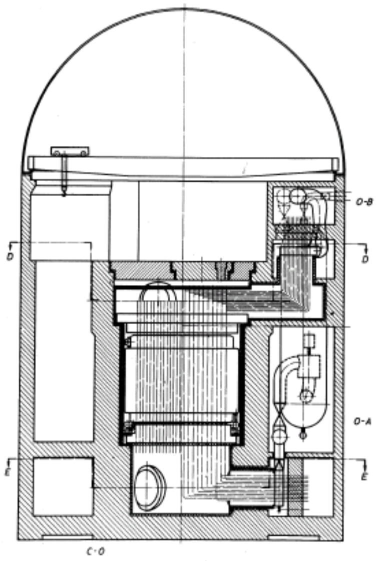


Figure 1. DOR, vertical cross section

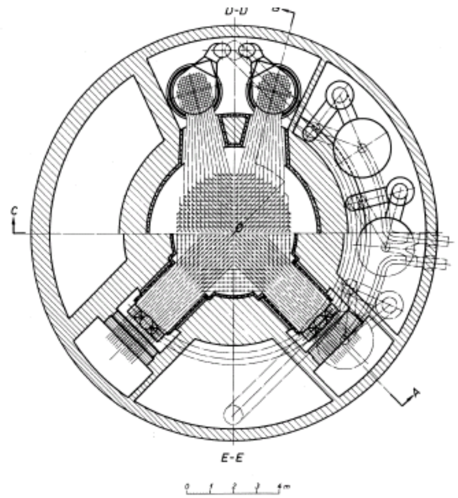


Figure 2. DOR, horizontal cross section

DON (Spain)

- 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

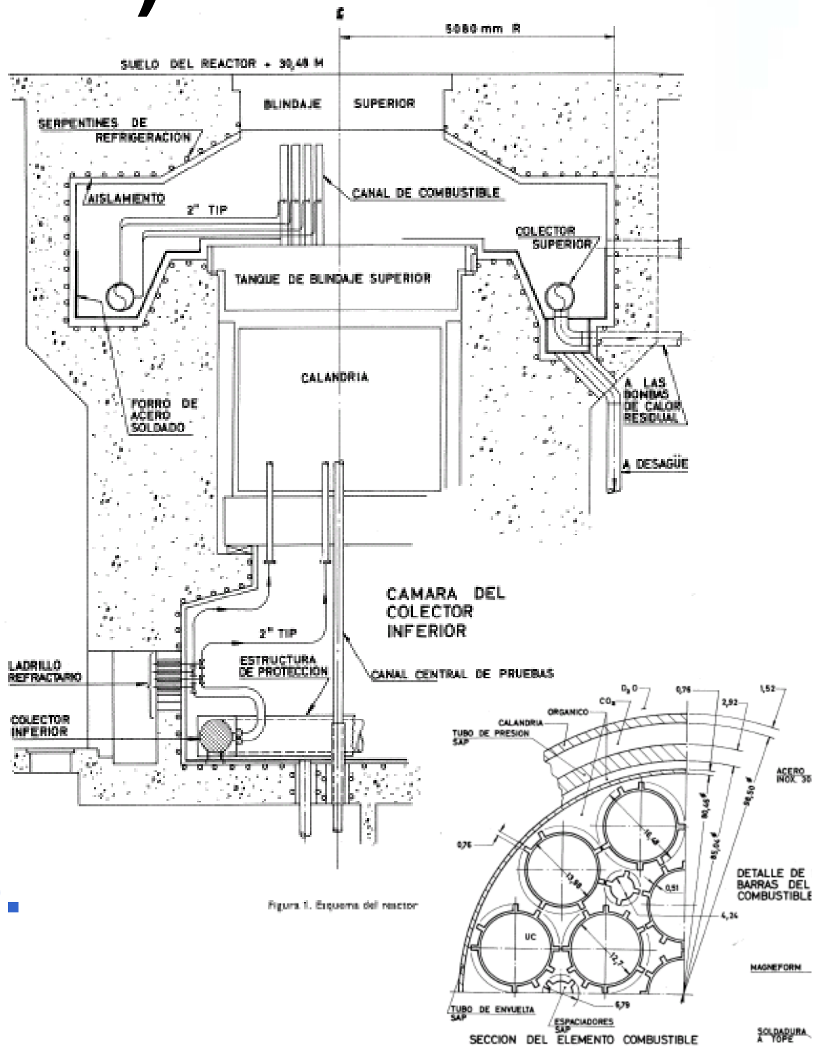
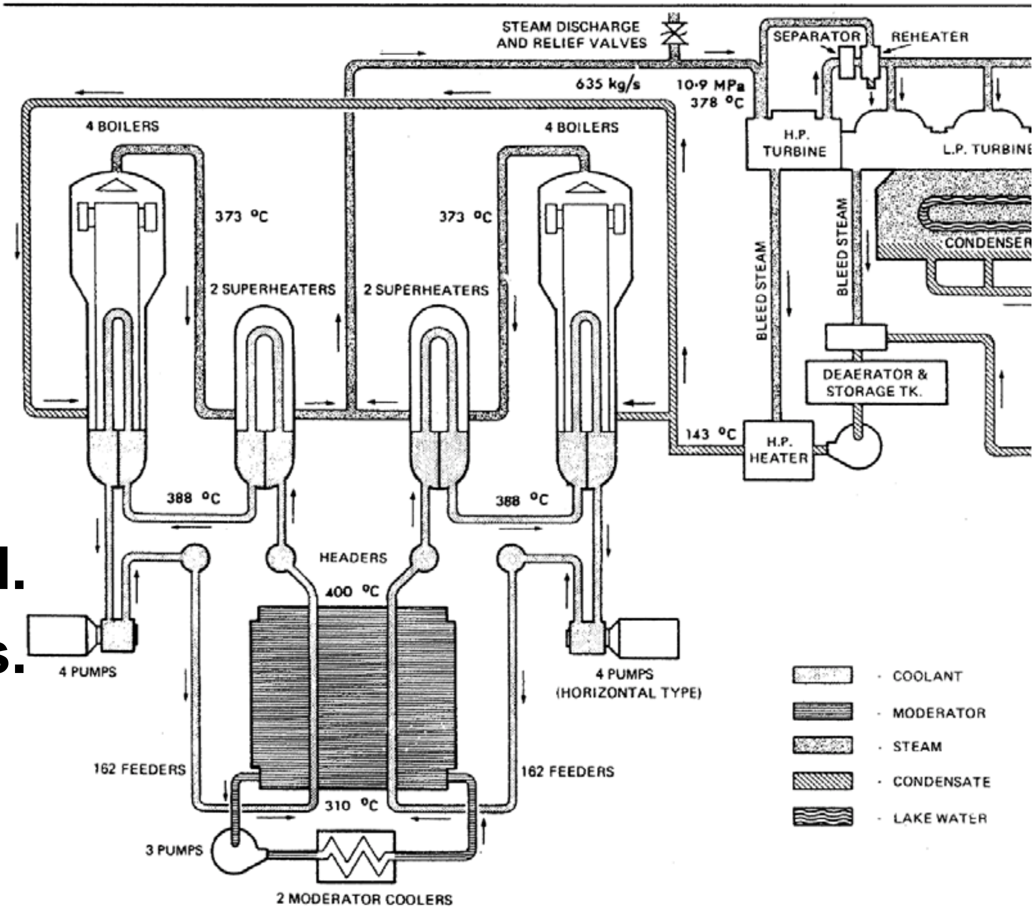


Figura 1. Esquema del reactor

CANDU-OCR

- $500\ MW_e$ station
- HB-40 coolant
  - mix of terphenyls
- 400°C outlet
- 34% efficiency
- Cancelled 1973
  - Pickering working well.
  - Consolidate resources.

FIGURE 16.5
Schematic Diagram of a CANDU-OCR Power Station



CANDU-OCR

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

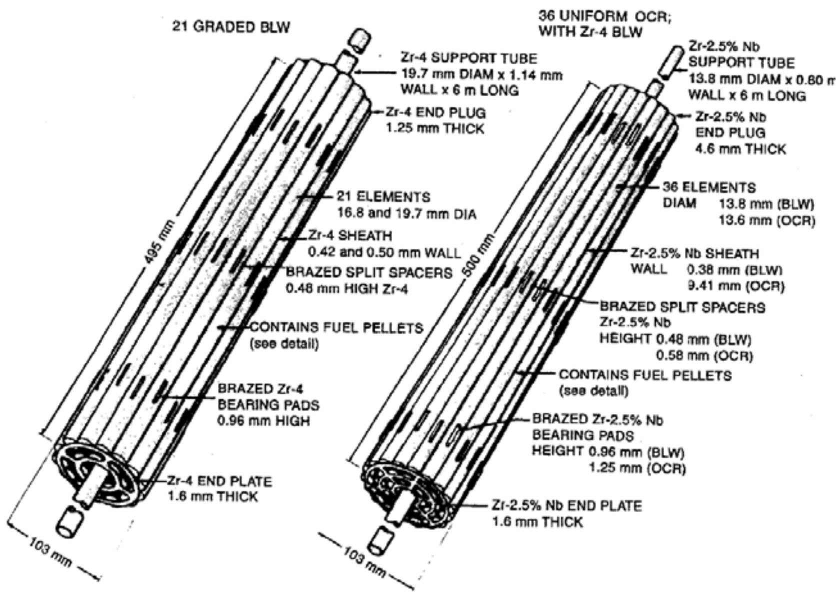
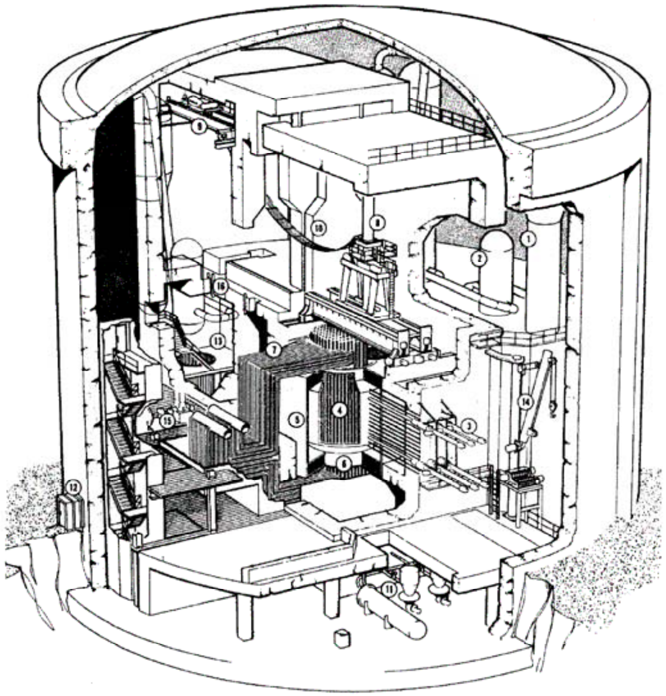


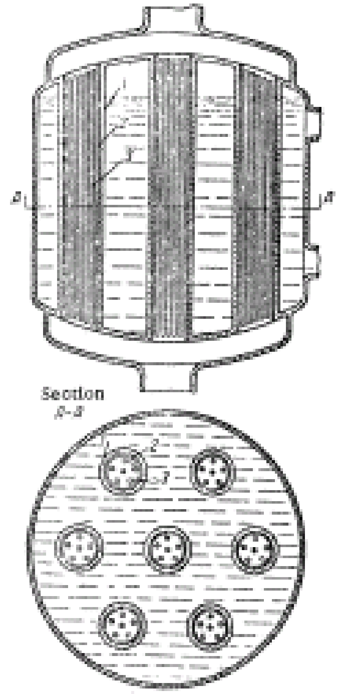
FIGURE 16.6
Cutaway of a CANDU-OCR Reactor Building



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

Abandoned Projects / Proposals

- SDR (Sodium Deuterium Reactor) - 1959
- 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.



Sodium Deuterium Reactor (SDR)

- **128 to 155 vertical channels**
  - Depending on fuel type

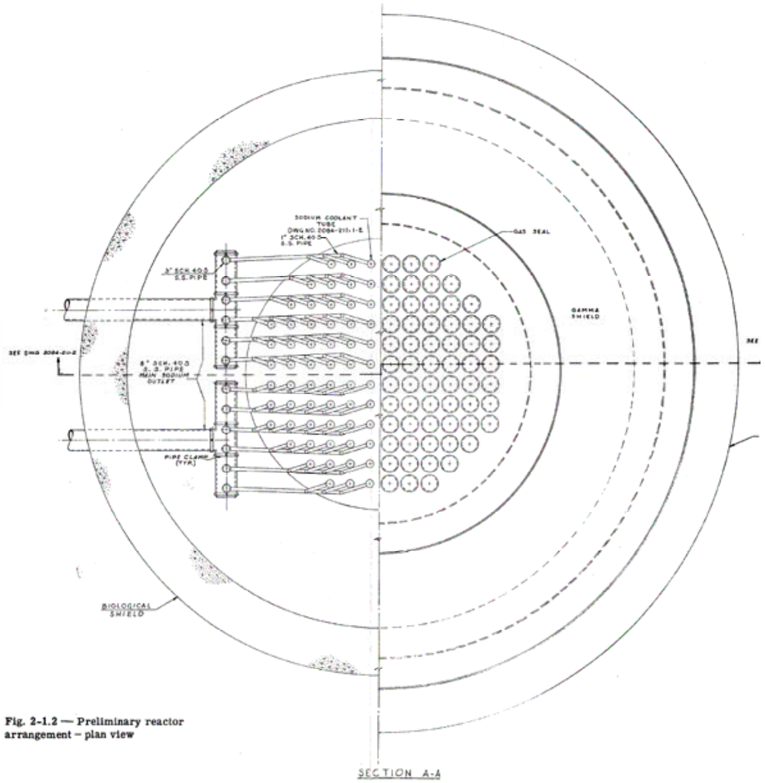


Fig. 2-1.2 — Preliminary reactor arrangement – plan view

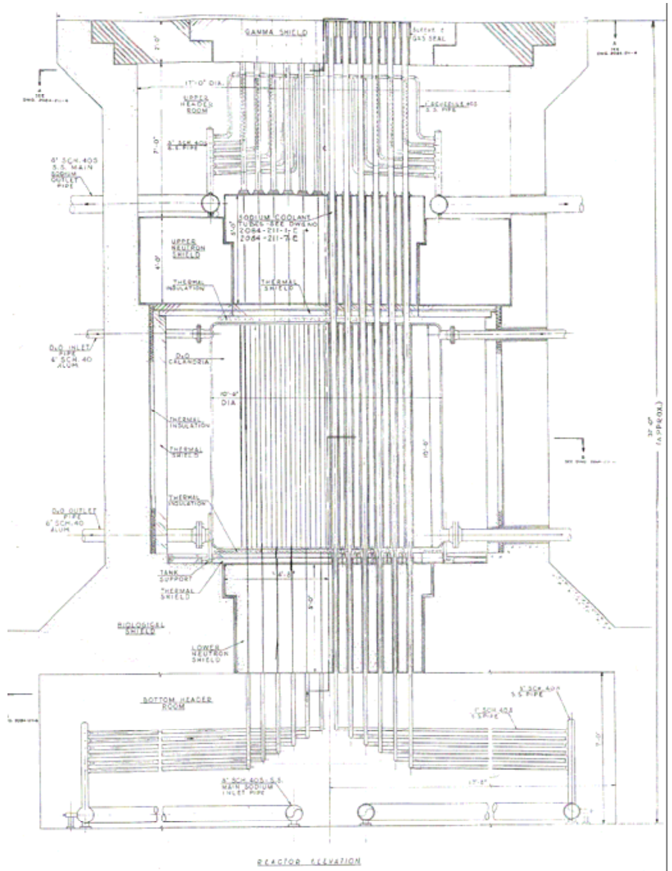


Fig. 2-1.1 — Preliminary reactor arrangement – elevation view

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