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 1: R&D Activities for HWR Design and Safety Analysis

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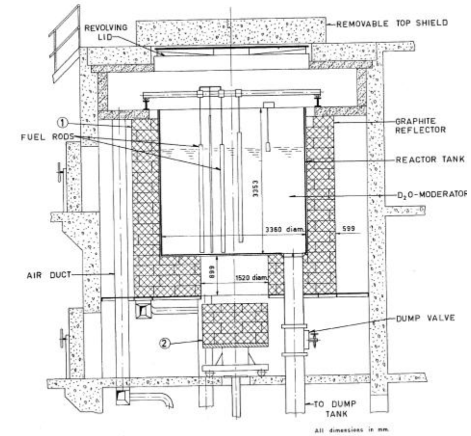
Outline

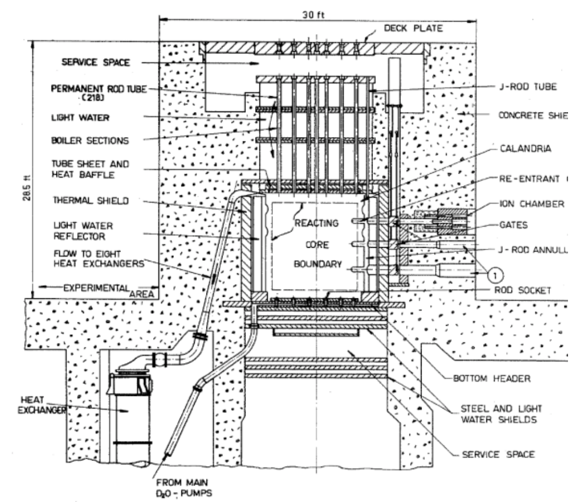
- Types of Measurements/Testing.
- Heavy Water Research Reactors.
  - Critical Facilities (< 1 kW).
    - Less shielding required.
  - High-power Facilities.
- International Participation.
  - Historical, Present Day.
- Present R&D Efforts and Needs for HWR's.
  - Canada (CANDU, EC6, ACR-1000).
  - India (AHWR, PHWR).
  - International.
    - Gen-III+, Gen-IV, Advanced Fuel Cycles.
- Emphasis on physics, but,
  - Fuel behavior and thermal-hydraulics equally important.

Types of Measurements/Testing

- Low-power (Critical Facility).
  - Critical height measurements.
  - Activation foil measurements.
  - Fine structure.
  - Transient / period measurements.
- High-power (Research Reactor)
  - Fuel bundle irradiations / performance
    - Testing of mechanical / material design.
    - Post Irradiation Examinations (PIE)
      - Fuel composition, burnup, depletion
  - Spectrum measurements.
  - High-power reactivity measurements.



VERTICAL SECTION REACTOR ZED-2



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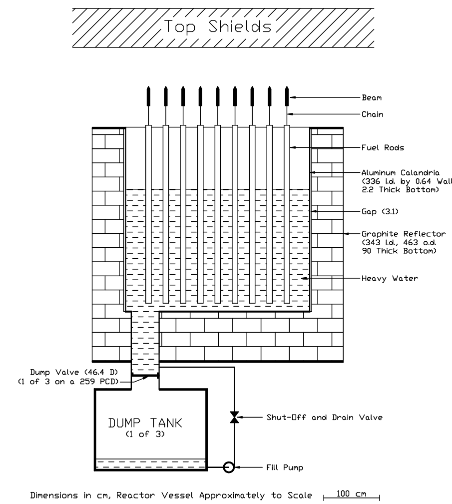
Types of Measurements/Testing

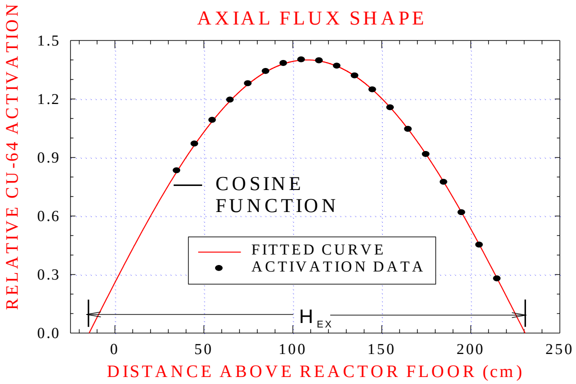
ZED-2 REACTOR



- Critical height measurements.
  - Vary one or more parameters in experiment.
    - Lattice geometry / material design.
      - Pitch, #pins, pin arrangement, size.
      - Enrichment, composition, PT/CT size, etc.
    - Coolant density, coolant distribution pattern.
    - Fuel / coolant temperature.
    - Moderator density, temperature, purity, poison concentration.
    - Presence / absence of a control device / fuel bundle.
    - Lattice distortions / eccentricity.
    - Core size (D, H).
  - Use critical height measurements to check core calculations.
    - Ideally, calculated k_{eff} = 1.000, or $H_{crit-calc} = H_{crit-exp.}$
    - For substitution experiments, infer bucklings from $\Delta H_{c.}$

Types of Measurements/Testing

❑ Activation Foil Distributions



- Global flux distributions $\phi(x,y,z)$
  - Cu-63 (thermal), In-115 (fast)
  - Mn-55, Au-197, etc.
  - Use for checking core code predictions.
- Curve-fitting in asymptotic region.
  - Neutron energy spectrum constant.
  - Infer material buckling from curve fit.
  - $\phi(r,z) = A_0 \times \cos(\alpha \times (z - z_{max}))\, J_0(\lambda \times r)$ $B^2 = \alpha^2 + \lambda^2$
  - Use B^2 for direct validation of lattice physics codes.
  - Measured lattice properties used directly in early reactor design.

$$k_{effective} = \frac{k_{infinity}}{1 + M^2 B^2}$$

Types of Measurements/Testing

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- Fine structure measurements.
  - Local flux distributions (radial and axial).
  - Activation foils / wires within lattice cell moderator.
    - Cu-63 (thermal), In-115 (fast), Mn-55, Au-197
    - Aluminum usually used for wrapping.

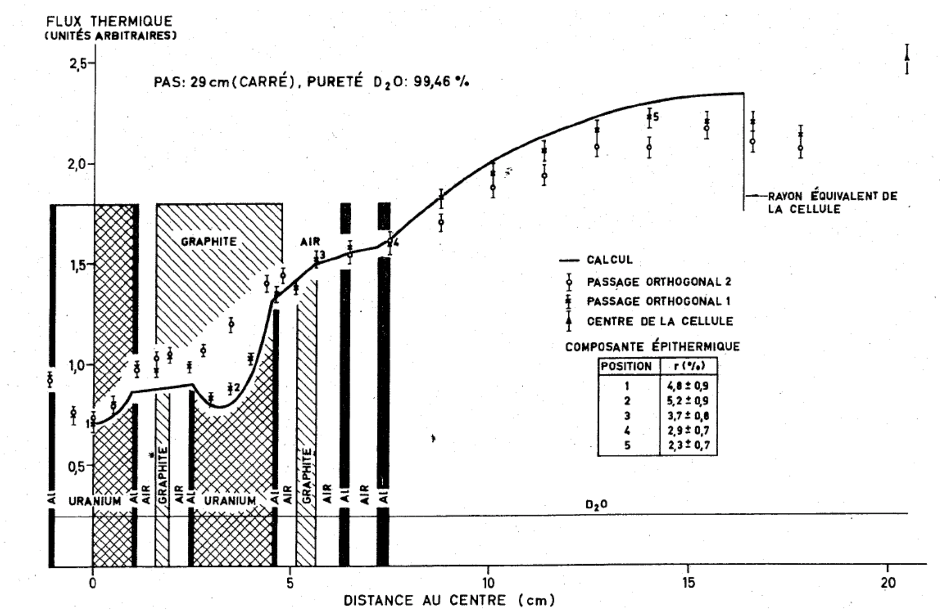
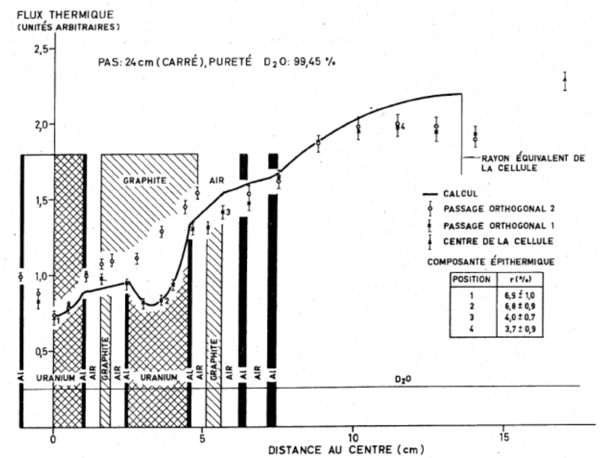


Figure 10

Types of Measurements/Testing

❑ Fine structure measurements

- Foils within fuel pellets (radial and axial)
  - U-235, U-238, Pu-239, U-nat
  - Cu-63, Mn-55, In-115, Lu-176, Au-197,
  - Dy-164, etc.
  - Cd foil wraps may be used to shield out thermal neutrons for fast activation only.
  - Normalized to foils in a well-thermalized spectrum.
  - Spectrum ratios, conversion ratios
  - Spectral index (r) can be inferred from Au/Cd activation
    - o Determine also effective neutron temperature, Tn



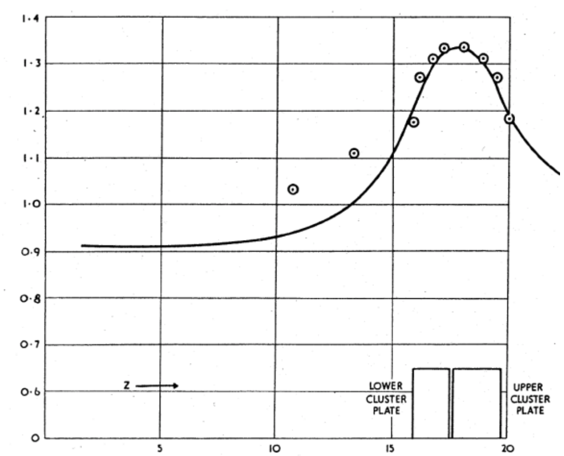


Fig. 14

Manganese axial reaction rate; Core 5002

Types of Measurements/Testing

Transient Measurements

- Ionization chamber for relative flux
  - Absolute flux value depends on core size / design
- Variation of flux with time, $\phi(t)$
  - Rapid rod insertion / removal, or increase/decrease moderator height.
    - Reactor stable period measurements
    - $\phi(t) = A_0 \times e^{t/T}$
    - Infer the dynamic reactivity, control rod worth, or level coefficients.
    - Works well for fuels with single fissile isotope (eg. U-235 in U)

$$\rho = \frac{l}{Tk_{\text{eff}}} + \frac{5.30 \times 10^{-4}}{0.62 + T} + \frac{5.30 \times 10^{-3}}{2.20 + T} + \frac{0.0138}{6.48 + T} + \frac{0.0526}{31.7 + T} + \frac{0.0200}{80.0 + T},$$

Types of Measurements/Testing

- Fuel bundle irradiations / fuel performance
  - Testing of mechanical and material design.
  - Post Irradiation Examinations (PIE) for fuel composition.
    - Burnup, depletion.
- Direct neutron spectrum measurements
    - Velocity selectors / choppers.
- “Pile oscillator” method
  - Total absorption cross section measurements.
- Neutron beams
  - Scattering experiments.
  - Structure of materials.

Heavy Water Critical Facilities

- Canada:
  - ZEEP (1945), ZED-2 (1960) – Operating today
- U.S.A.:
  - PDP (1 kW, 1953), Pawling (1958)
- France:
  - Aquilon (1956)
- Belgium:
  - VENUS (1964)
- U.K.:
  - DIMPLE (1954), DAPHNE (1962), JUNO (1964)

Heavy Water Critical Facilities

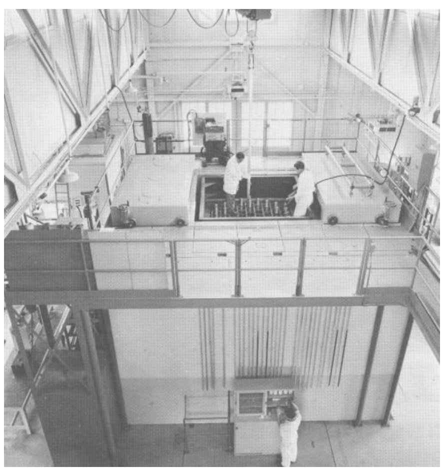
- Norway:
  - NORA (1961)
- Sweden:
  - R-O (1959)
- Italy:
  - ECO (1965), RB-3 (1971) – support for HWOCR
- Czech Republic:
  - TR-0 (1972)
- Serbia (Yugoslavia):
  - RB (1958) – Operating today
- Japan:
  - DCA (1969) – support for FUGEN design

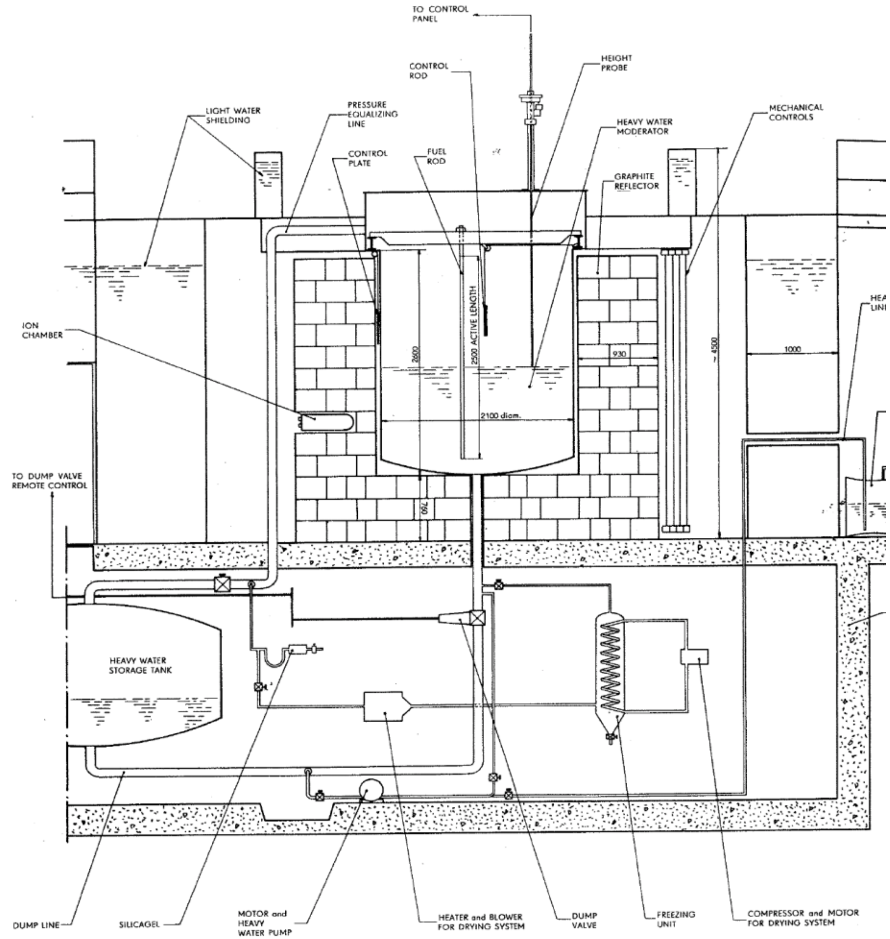
Heavy Water Critical Facilities

- India:
  - Zerlina (1961)
  - BARC – HWCF (2003) – new for PHWR, AHWR work
- Iran:
  - ENTC HWZPR (1995)
- South Africa:
  - Pelinduna Zero (1967)

ZEEP (Canada, 1945)

- **Z**ero **E**nergy **E**xperimental **P**ile
- Canada 2nd country to build critical facility
  - Lattice Physics tests to support design of:
    - NRX, NRU
    - NPD-2, CANDU

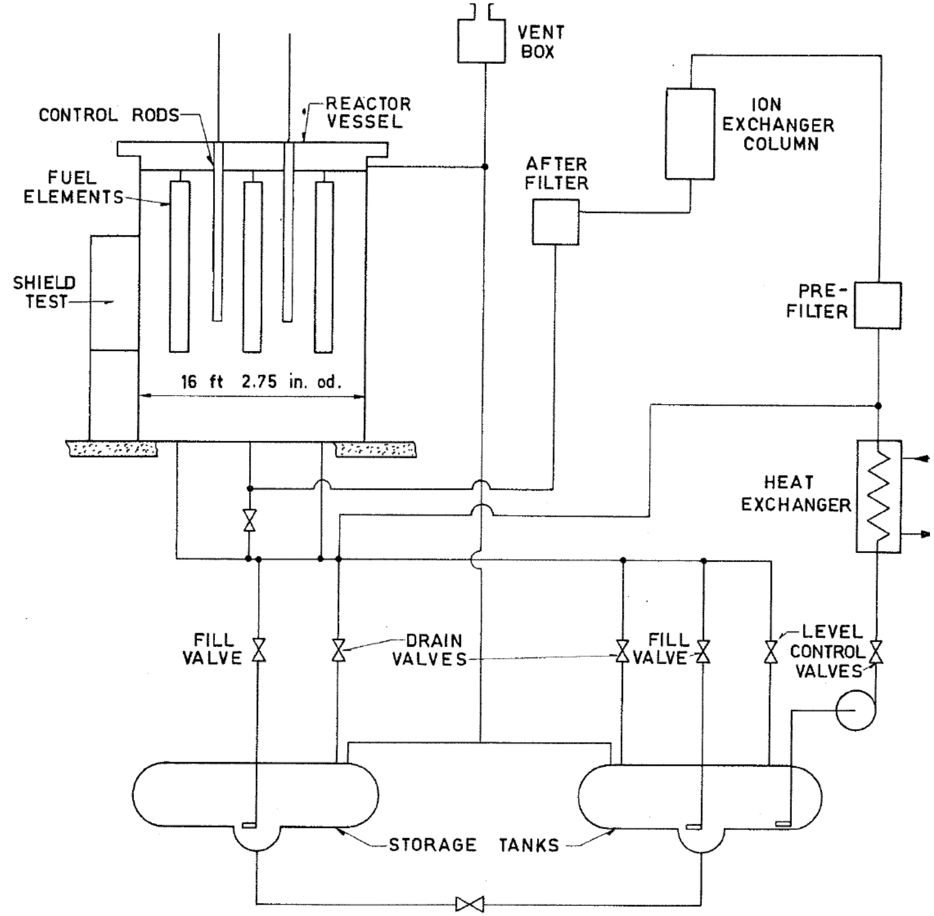




VERTICAL SECTION ZEEP

PDP (U.S.A, 1953)

- Process Development Pile
  - Lattice physics studies for heavy water reactors



FLOW DIAGRAM REACTOR PDP

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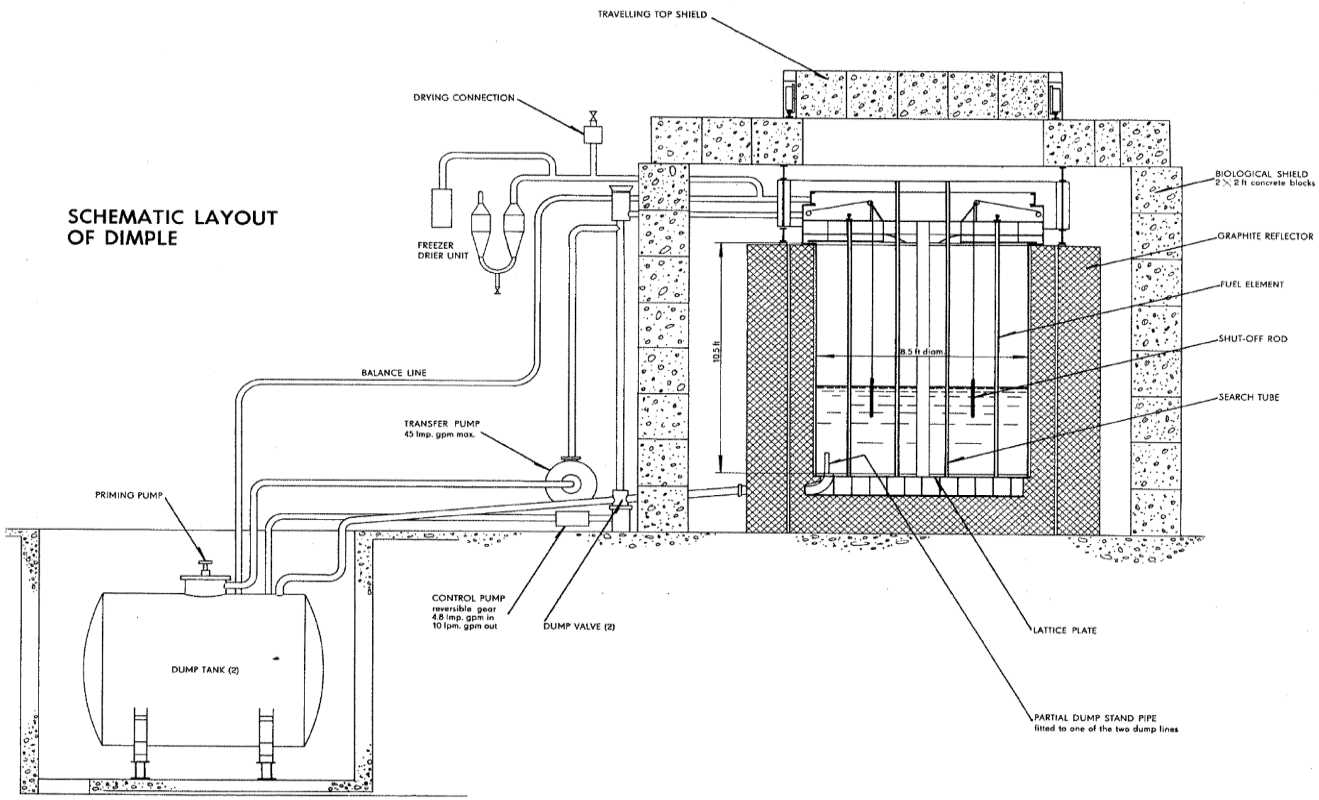
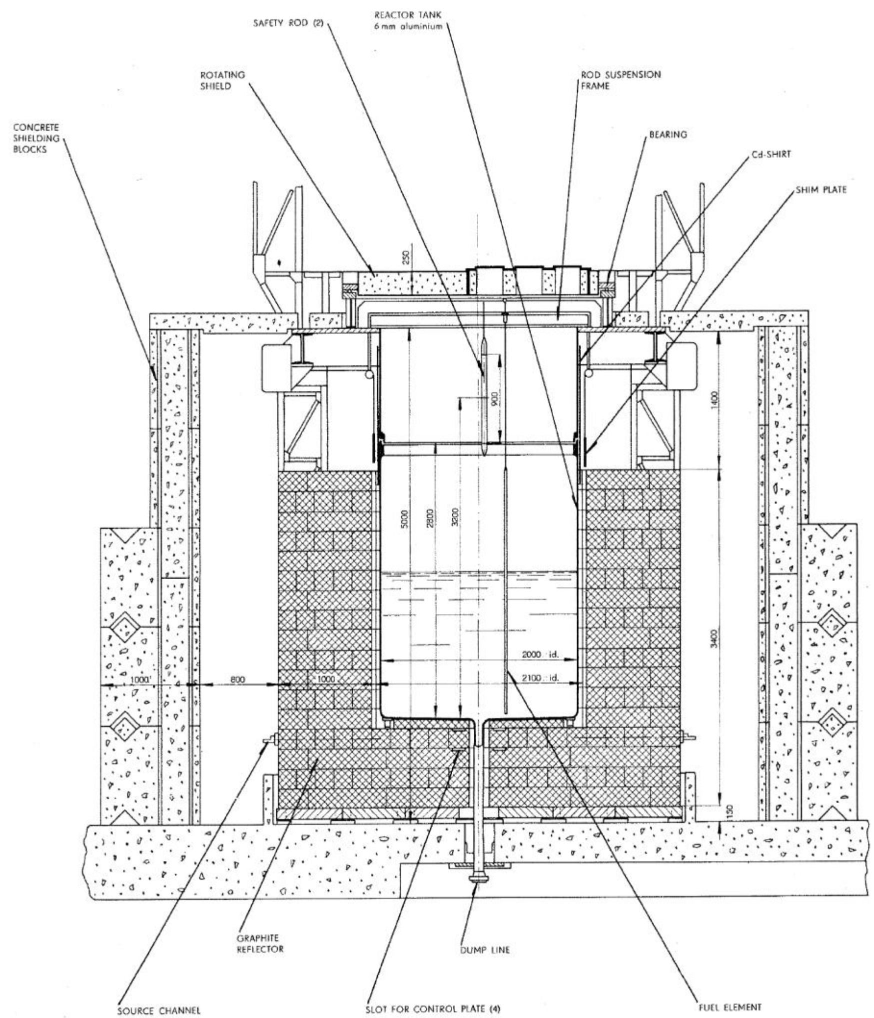
DIMPLE (U.K., 1954)

- Critical experiments supported SGHWR program, and others.



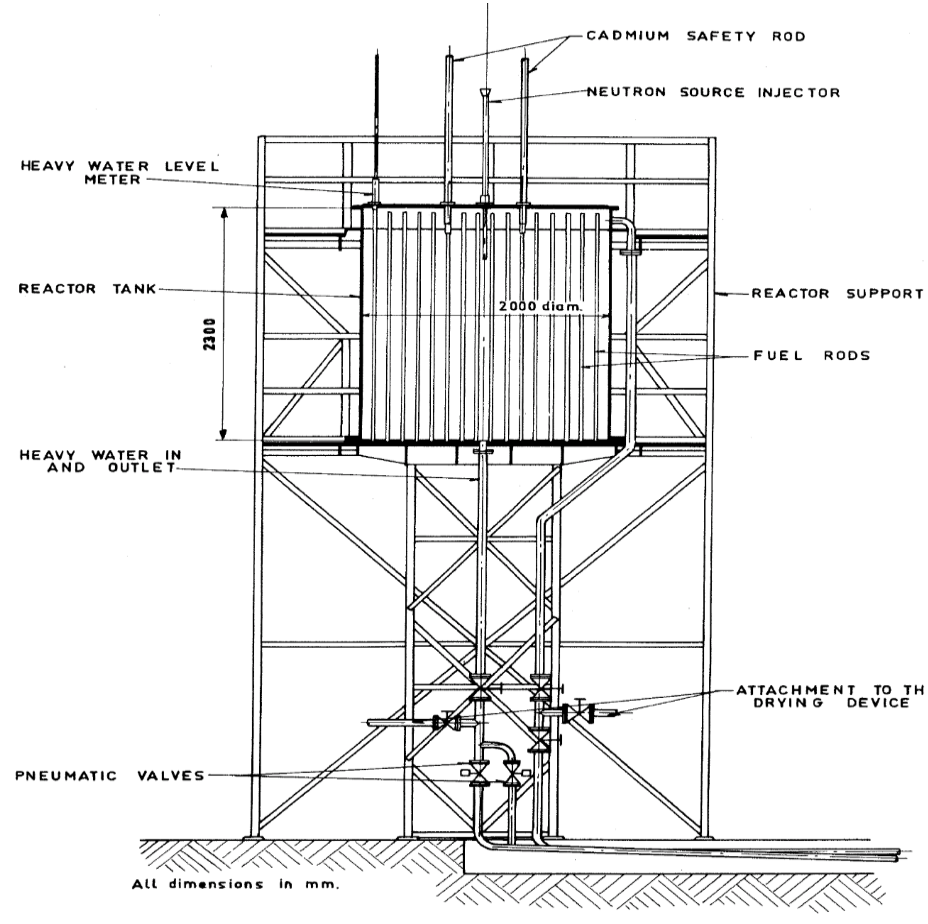
Aquilon (France, 1956)

- Supported work for French heavy water research reactors and prototypes:
  - EL-1 / ZOE
  - EL-2
  - EL-3
  - EL-4 (~70 MWe)
- Fundamental lattice physics measurements.
  - Critical heights.
  - Activation foils.



RB (Serbia/Yugoslavia, 1958)

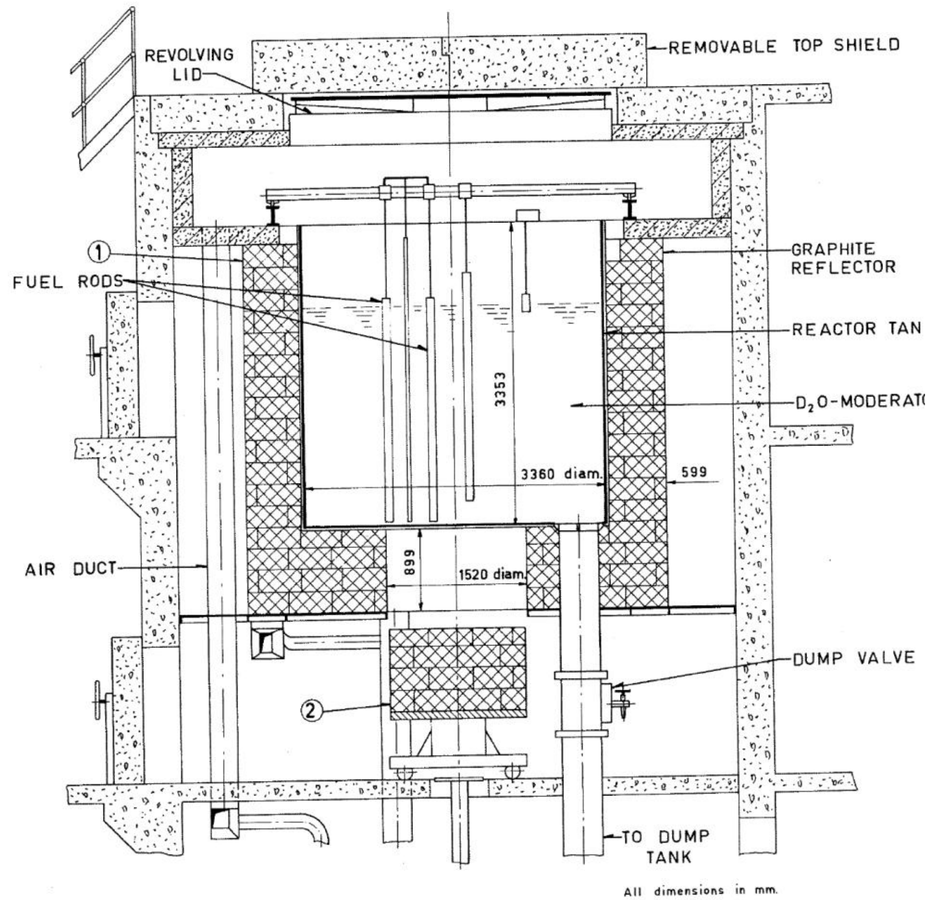
- Bare critical lattices
  - Teaching, training and basic research
  - In operation today.



VERTICAL SECTION BARE CRITICAL ASSEMBLY RB

ZED-2 (Canada, 1960)

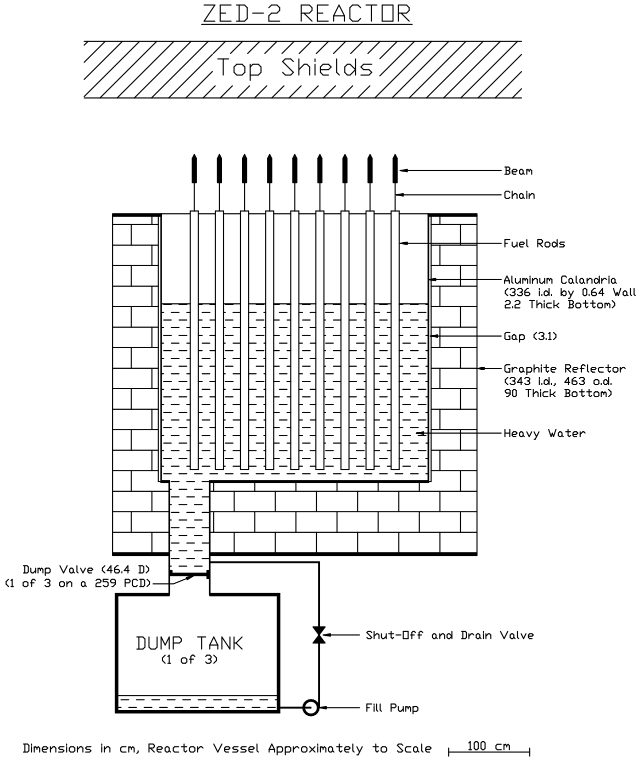
- Critical Facility, operating today.
  - Lattice experiments support CANDU and ACR
  - Heated channel experiments operate up to 300 C

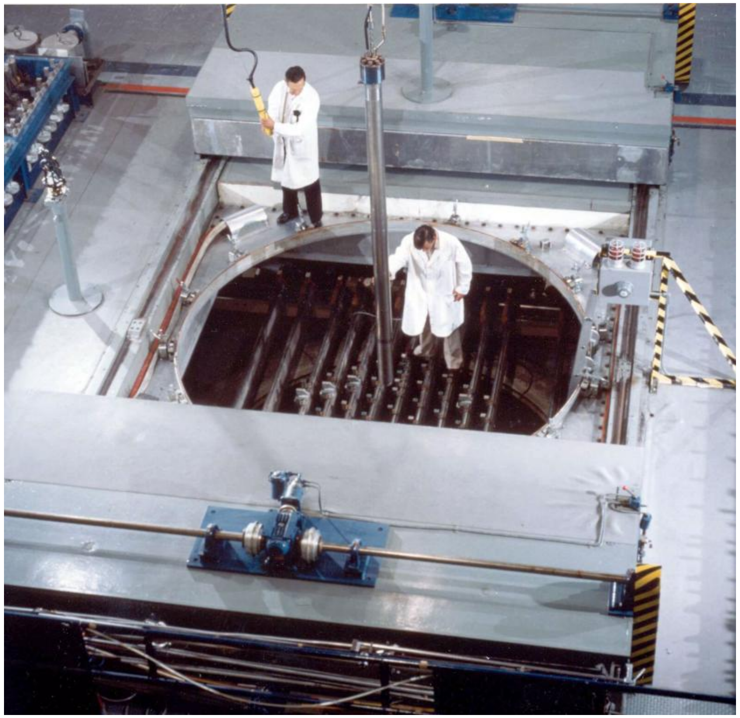


VERTICAL SECTION REACTOR ZED-2

ZED-2 Critical Facility

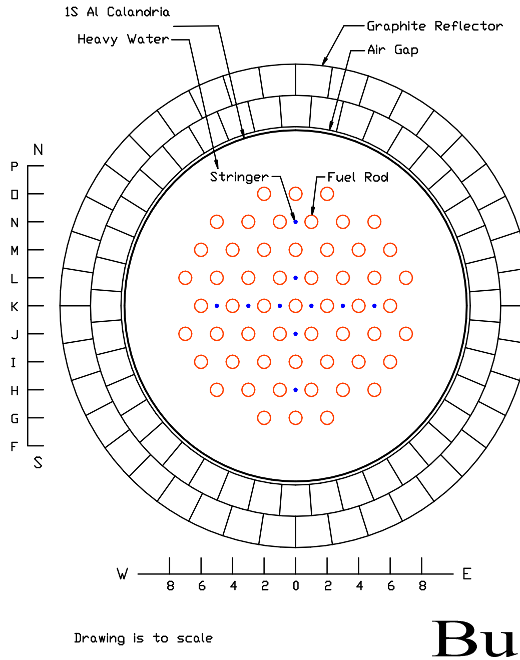
- Tank-type critical facility, 3.3 m diameter & depth
  - Moderator height adjusted to control criticality and power
  - Power level ~ 5 Watts to 200 Watts

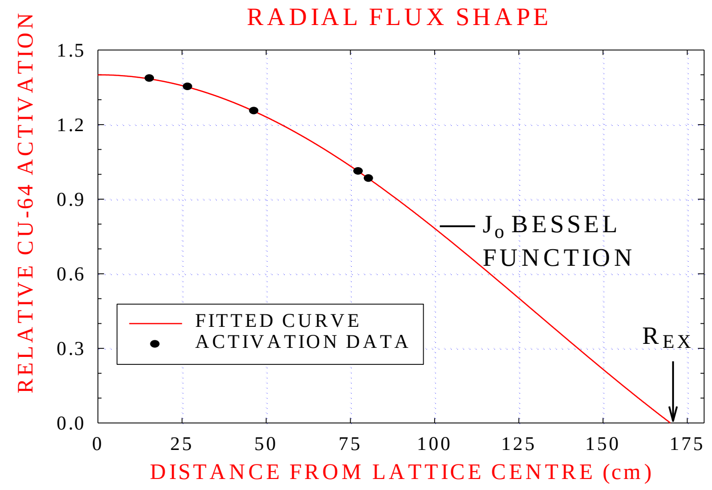


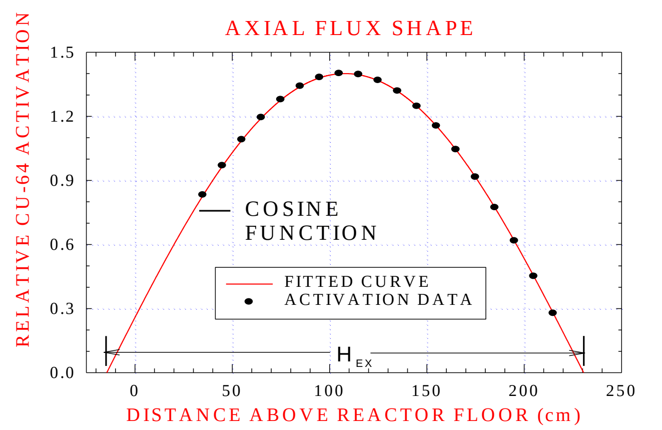


Example: Full-Core Flux Map

- Buckling determined from curve fits of Cu-foil flux maps



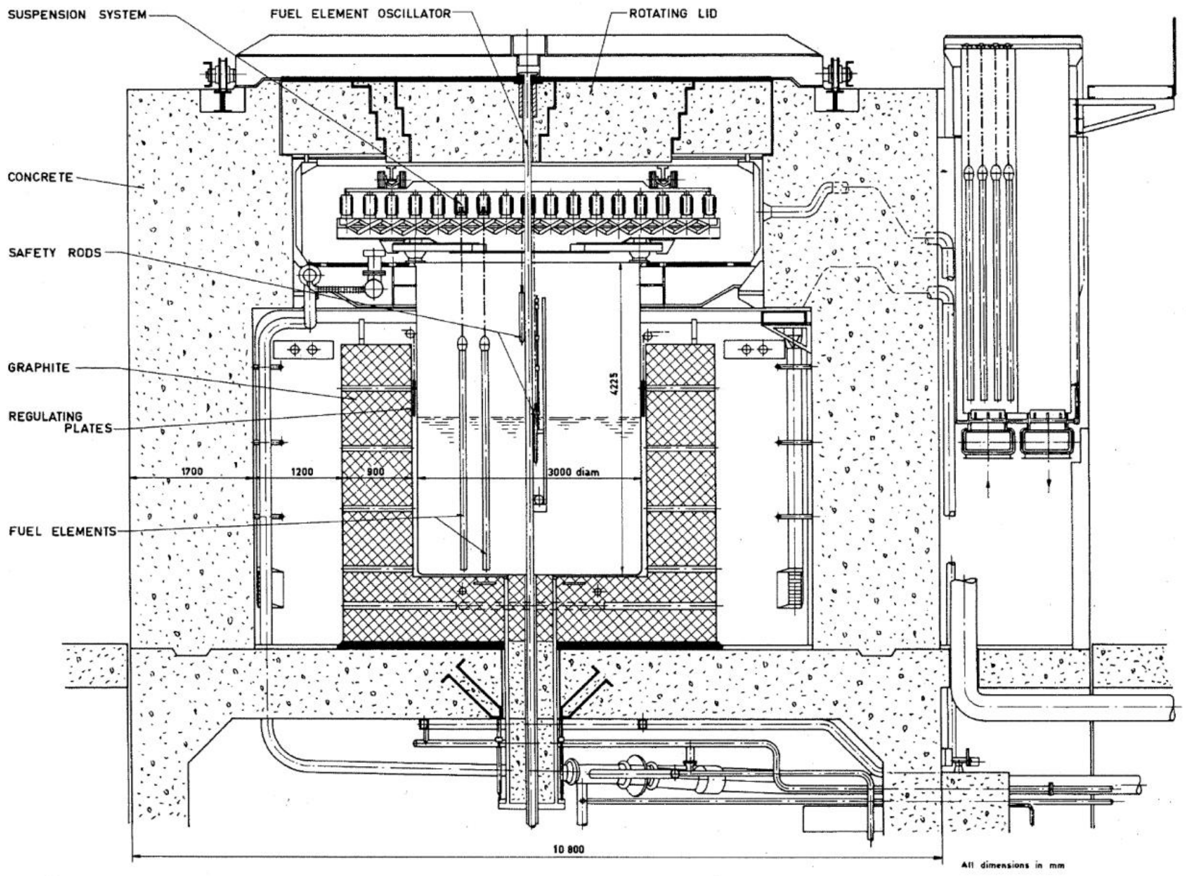




$$\text{Buckling} = (2.405/R_{EX})^2 + (\pi/H_{EX})^2$$

ORGEL (Italy, 1965)

- 1 kW, lattice studies with organic coolant



VERTICAL SECTION REACTOR ECO

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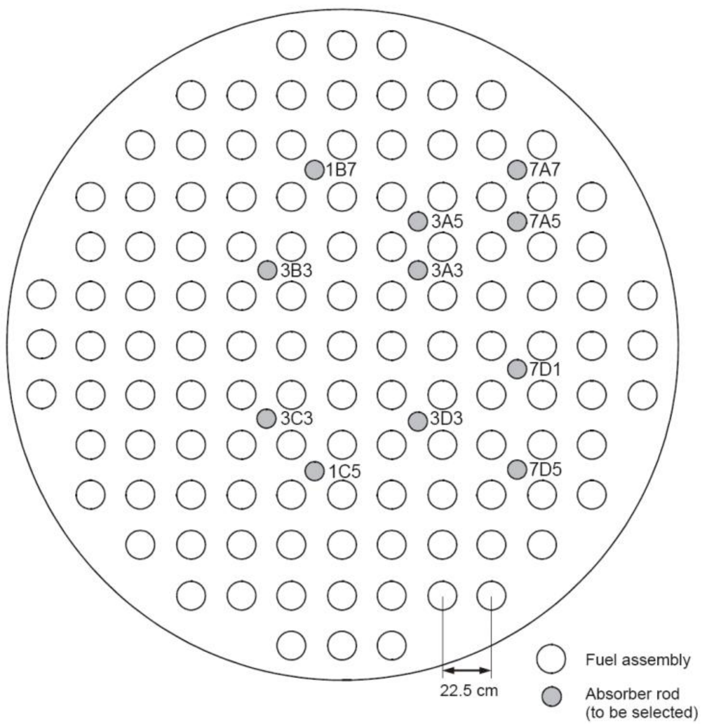
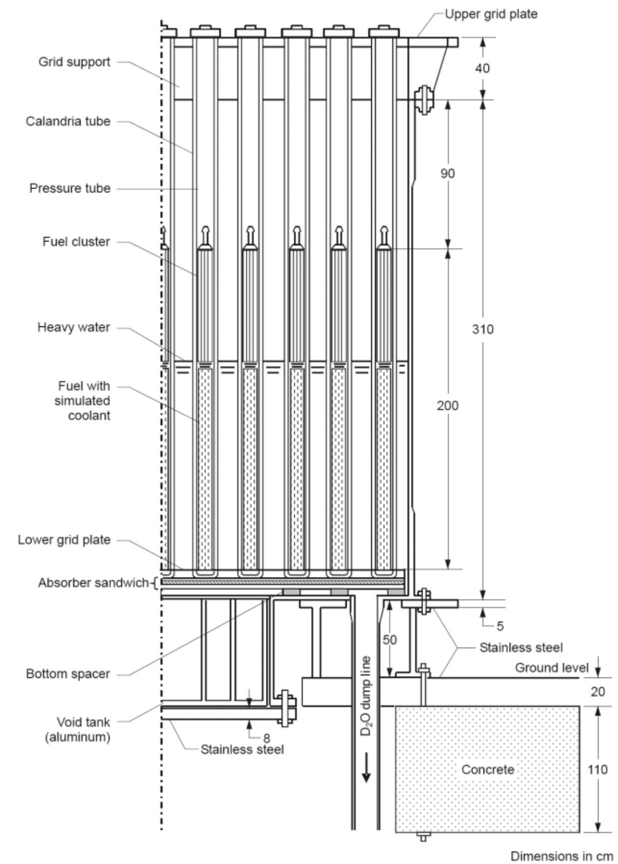
DCA (Japan, 1969)

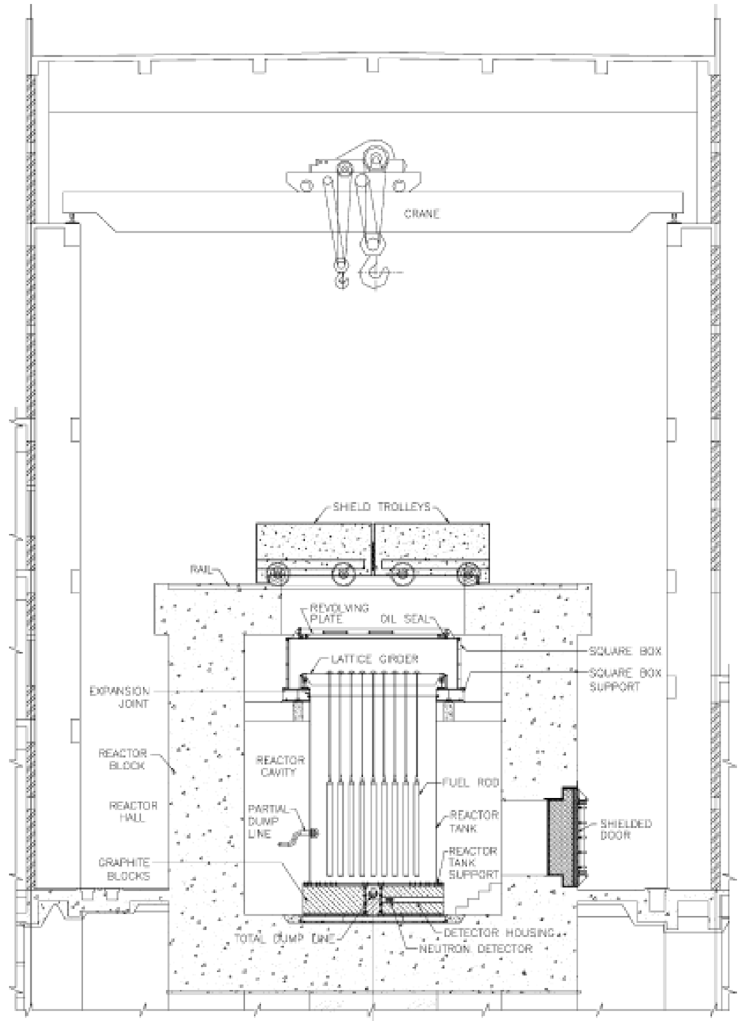
- Deuterium Critical Assembly (DCA)
  - Bare lattice experiments to support FUGEN project





BARC – HWCF (India, 2003)

- India's new heavy water critical facility (HWCF).
- Critical experiments in support of:
  - AHWR
  - PHWR (500 MWe)
  - Alternative fuel cycles.
  - Thorium-based fuels.



Heavy Water Research Reactors

- Canada:
  - NRX (40 MW, 1947)
  - NRU (135 MW (LEU),1957)
    - First to demonstrate on-line re-fuelling.
    - Operating today – >60% World's supplier of radioisotopes
  - WR-1 (40 MW, 1961) – organically cooled.
- Australia:
  - HIFAR (10 MW, 1958)
- U.K.:
  - DIDO (15 MW, 1956), PLUTO (22 MW, 1957)
  - Dounreay MTR (22 MW, 1958)

Heavy Water Research Reactors

- U.S.A.: Strong interest in Heavy Water for research purposes.
  - CP-3 (300 kW, 1944) – World's first HW reactor.
  - CP-5 (5 MW, 1954)
  - MITR (5 MW, 1958) – Operating today.
  - PRTR (85 MW, 1960) – demonstrate Pu recycling.
  - HWCTR (61 MW, 1962)
  - GTRR (1 MW, 1964)
  - Ames Laboratory (5 MW, 1965)
  - HFBR (BNL – 40 MW, 1965)
  - NBSR (10 MW, 1967) – Operating today

Heavy Water Research Reactors

- Belgium
  - BR-1 (4 MW, 1956)
  - BR-3/VN (41 MW, 1962) – spectral shift reactor
- France:
  - ZOE/EL-1 (150 kW, 1948)
  - EL-2 (2 MW, 1952) , EL-3 (20 MW, 1957)
  - EOLE (10 kW, 1965)
  - HFR (58 MW, 1971) – Operating today
- Germany:
  - FR-2 (44 MW, 1961), FRM-II (20 MW, 2004)
  - DIDO-JULICH (23 MW, 1962) – Operating today
- Switzerland:
  - DIORIT (30 MW, 1960)

Heavy Water Research Reactors

- Denmark:
  - DR-3 (10 MW, 1960).
- Norway:
  - JEEP-1 (450 kW, 1951).
  - JEEP-2 (2 MW, 1966) – Operating today.
  - Halden (BHWR, 20 MW, 1959) – Operating today.
- Sweden:
  - R-1 (1 MW, 1964) .

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Heavy Water Research Reactors

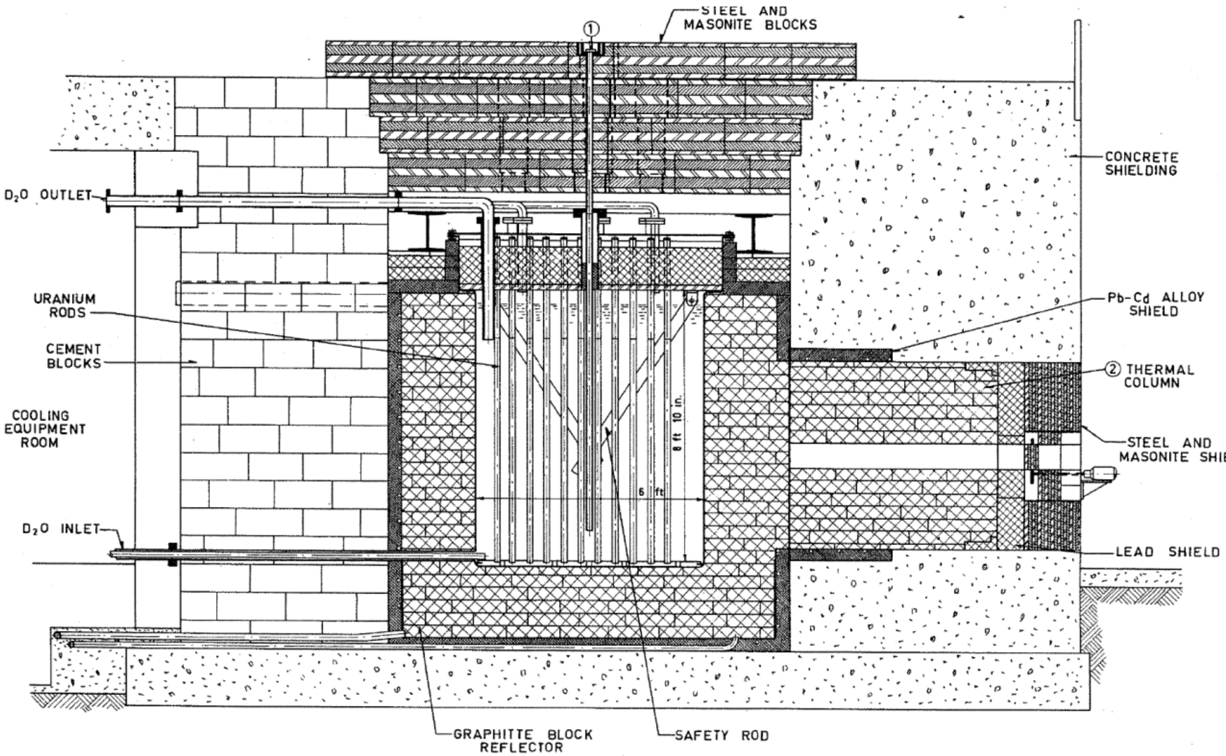
- Algeria:
  - ES-SALAM (15 MW, 1992) – Operating today
- Italy
  - ISPRA-1 (5 MW, 1959), ESSOR (43 MW, 1967)
- Israel:
  - IRR-2 (26 MW, 1963) – Operating today
- Serbia (Yugoslavia):
  - RA (6.5 MW, 1959)

Heavy Water Research Reactors

- China:
  - HWRR-II (15 MW, 1958) – Operating today
- India:
  - CIRUS (40 MW, 1960) – Operating today.
  - DHRUVA (100 MW, 1985) – Operating today.
- Japan:
  - JRR-2 (10 MW, 1960), JRR-3 (10 MW, 1962)
- Russia:
  - TR (2.5 MW, 1949)
- Taiwan:
  - TRR (40 MW, 1973)

CP-3 (U.S.A., 1944)

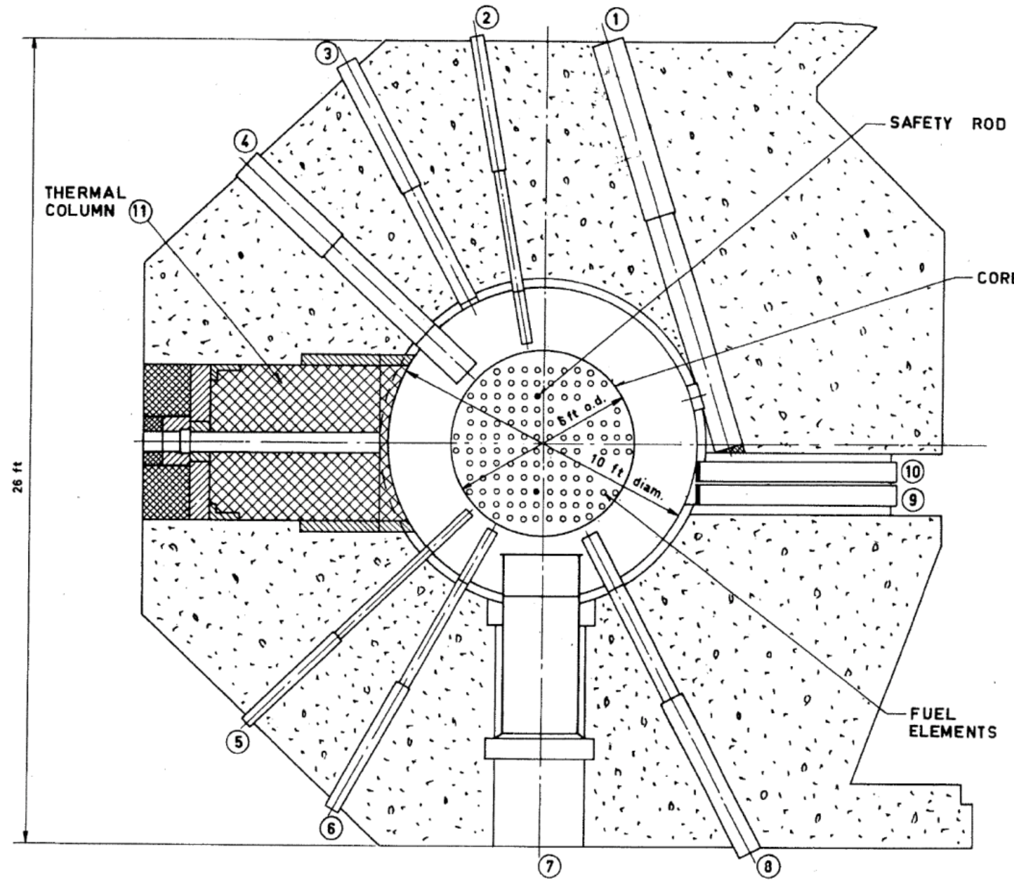
- Chicago Pile 3 (300 kW)
  - World's first critical heavy water reactor.
  - Absorption measurements; oscillator techniques.



VERTICAL SECTION REACTOR CP-3

CP-3' (U.S.A, 1950)

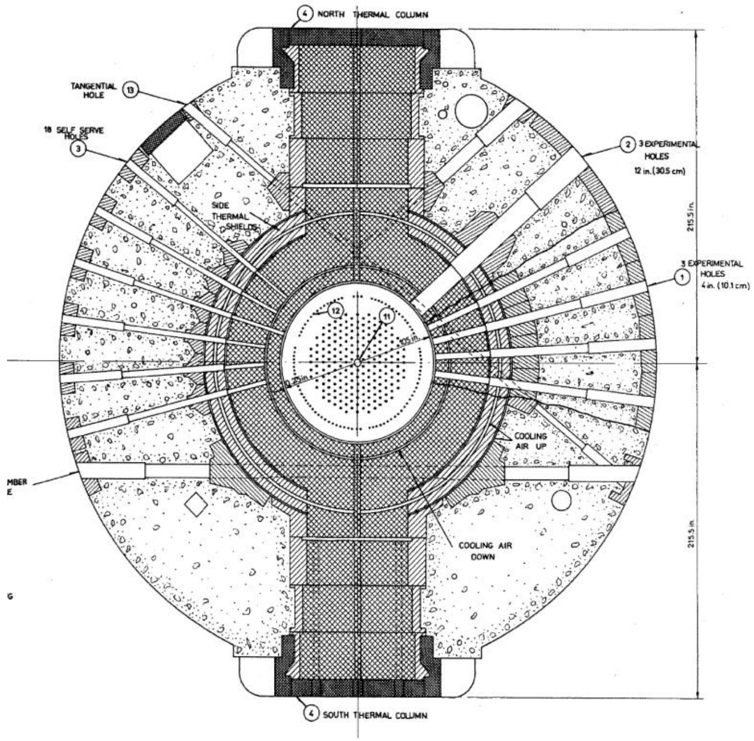
- CP-3 modified to operated with enriched uranium
- 275 kW



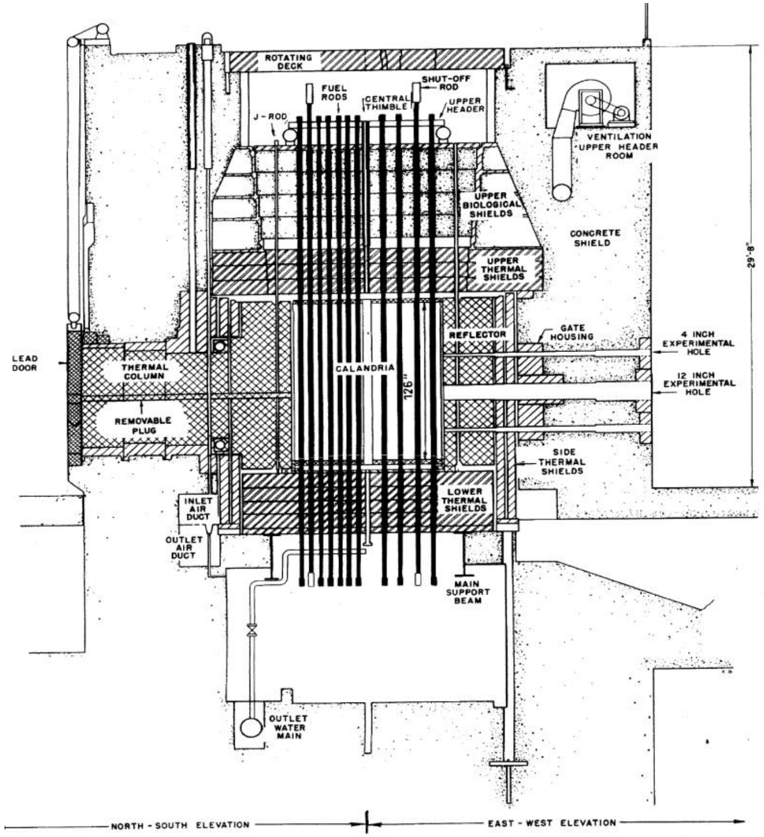
HORIZONTAL SECTION REACTOR CP 3'

NRX (Canada, 1947)

- 40 MW, Operated until early 1990's
  - Materials, components testing; isotope production.
  - Neutron beam experiments.



HORIZONTAL SECTION NRX



VERTICAL SECTION REACTOR NRX

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NRX (Canada, 1947)

- 40 MW, Operated until early 1990's
  - Materials, components testing; isotope production.
  - Neutron beam experiments.

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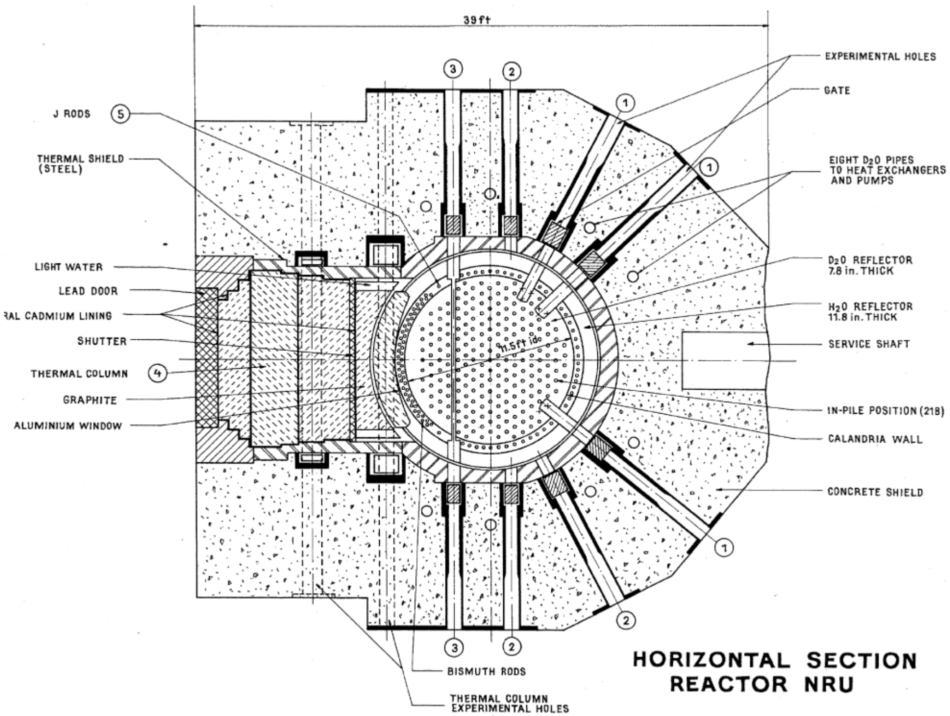
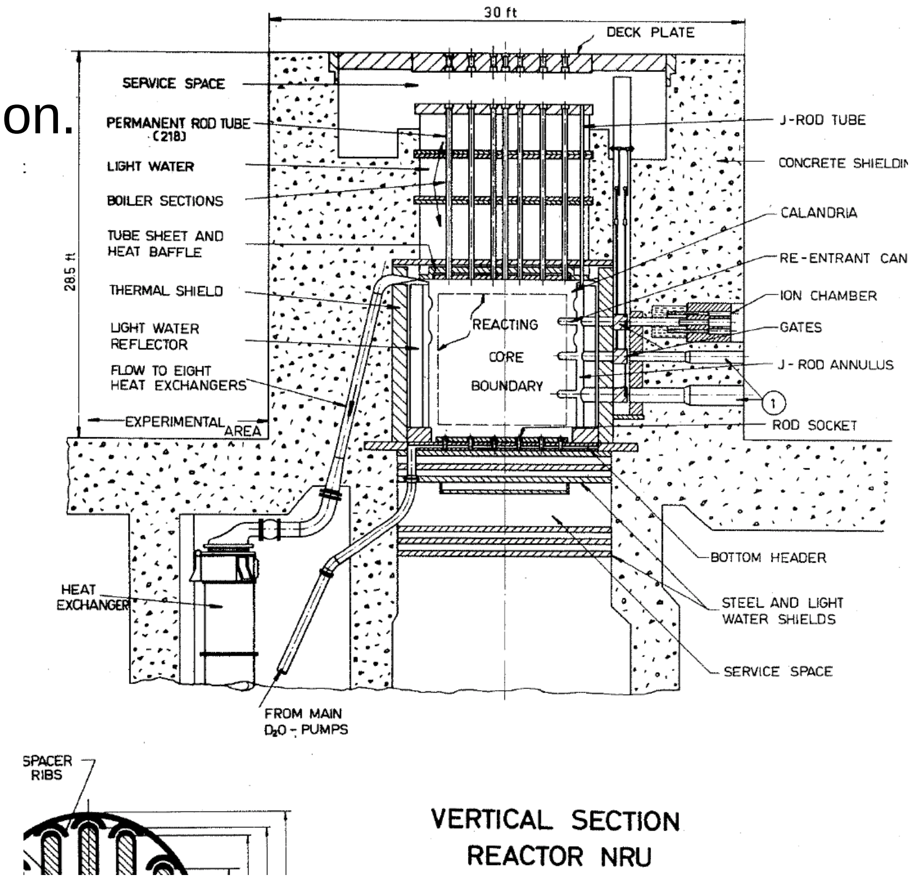
NRU (Canada, 1957)

❑ National Research Universal

- 135 MW (LEU), operating today.
- Testing materials, components.
- Neutron beams, isotope production.





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NRU (Canada, 1957)

- National Research Universal
  - ~200 MW (NU)
  - ~ 65 MW (HEU)
  - ~135 MW (LEU),
    - Runs on LEU fuel today.
    - Operating today.
  - Testing materials, components.
  - Neutron beams, isotope production.

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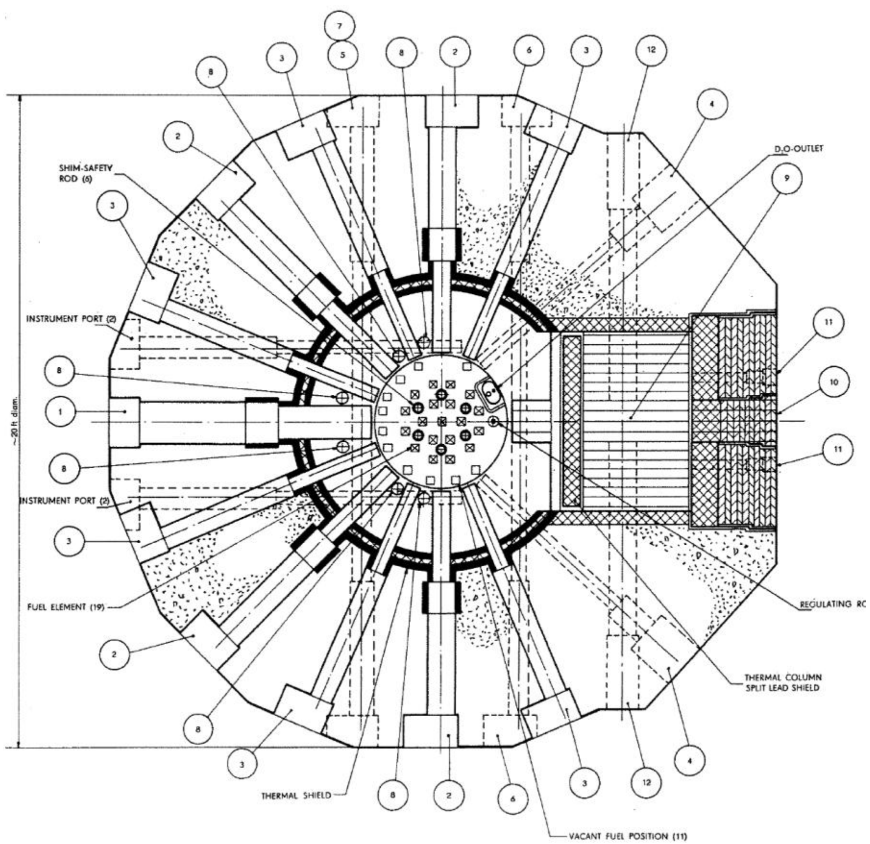
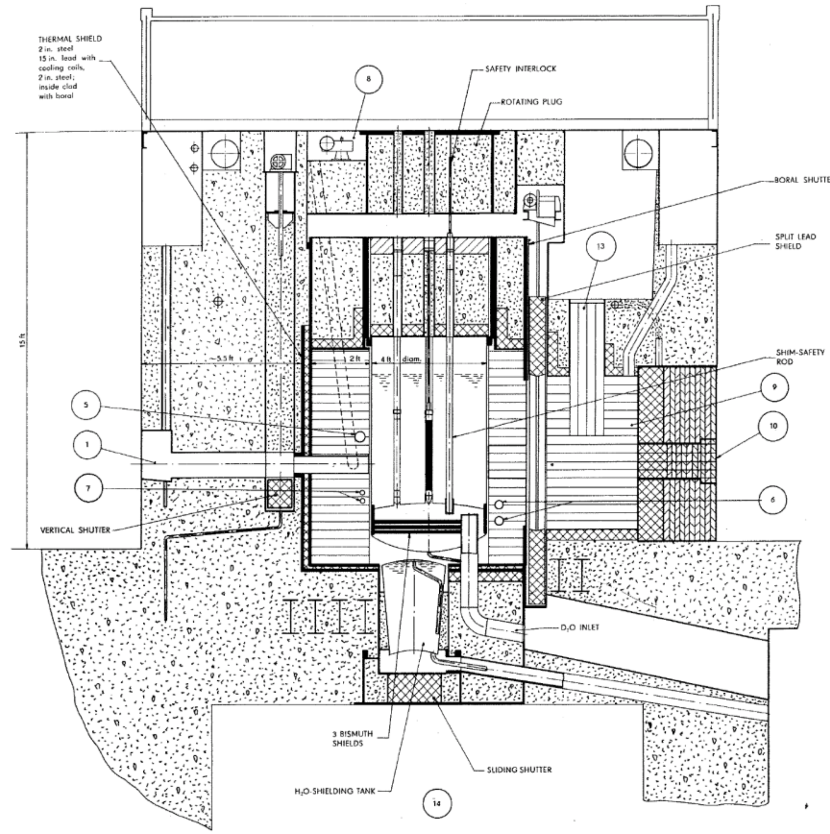
MITR (U.S.A, 1958)

- 1 MW, Multiple neutron beam experiments.



MITR HORIZONTAL SECTION



MITR VERTICAL SECTION

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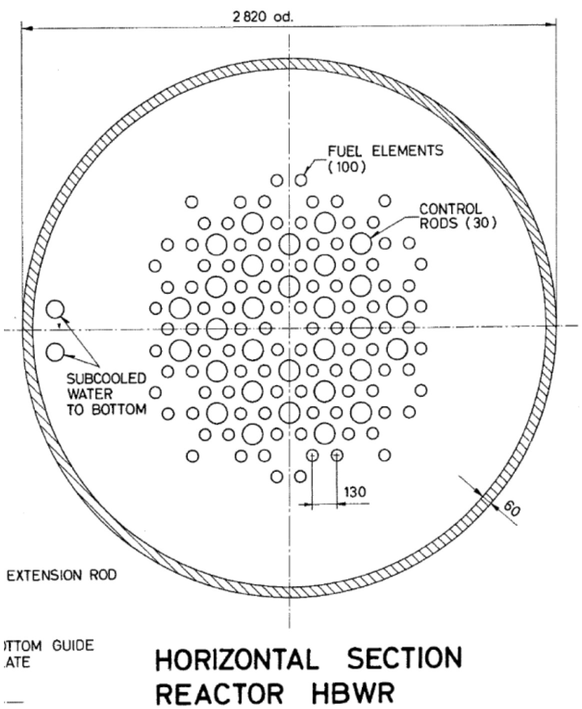
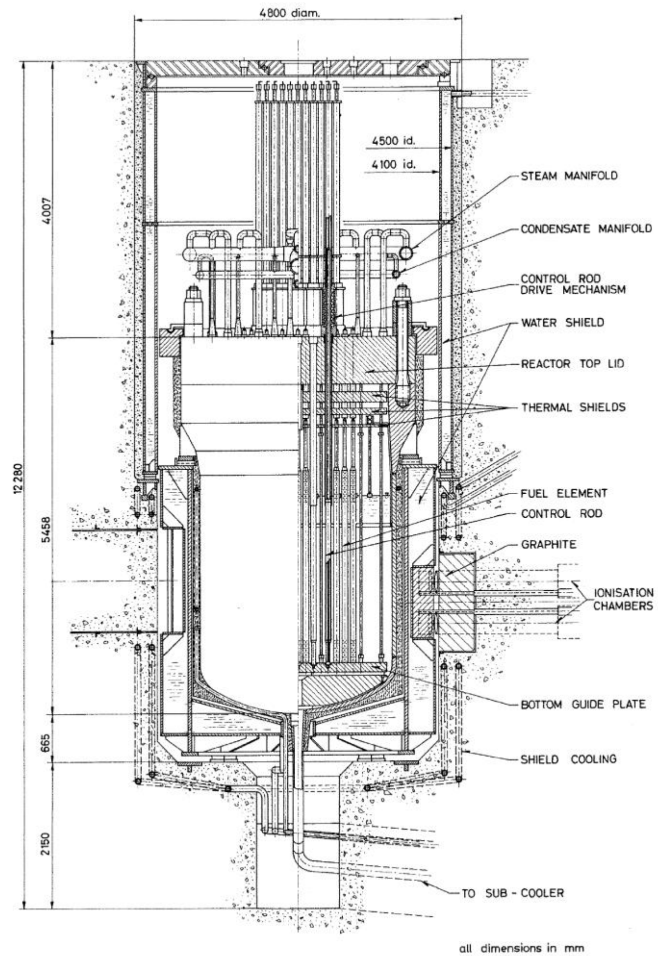
HBWR (Norway, 1959)

- 20 MW, boiling heavy water reactor
  - Still operating today.
  - Neutron source, components testing.





VERTICAL SECTION REACTOR HBWR

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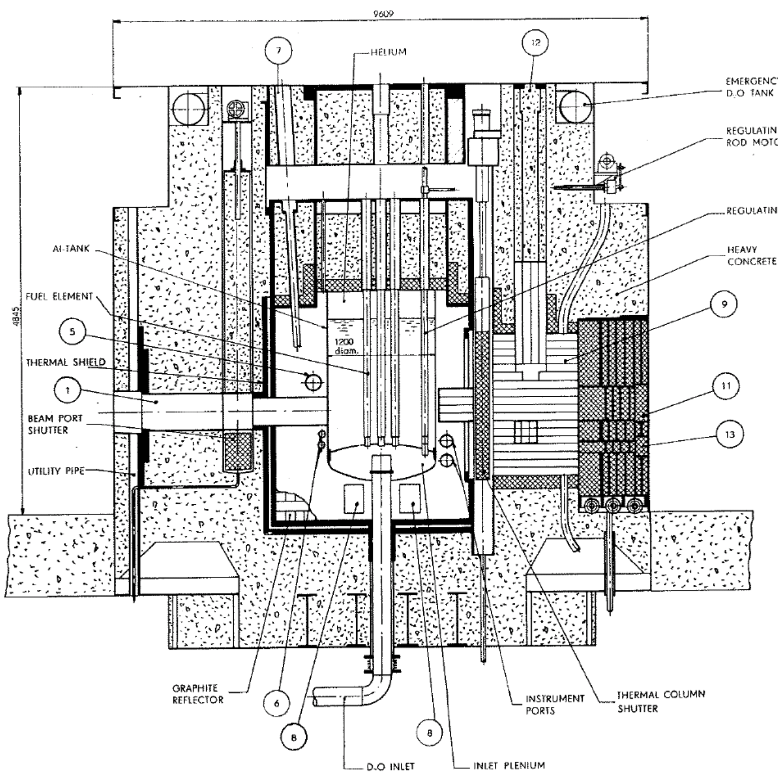
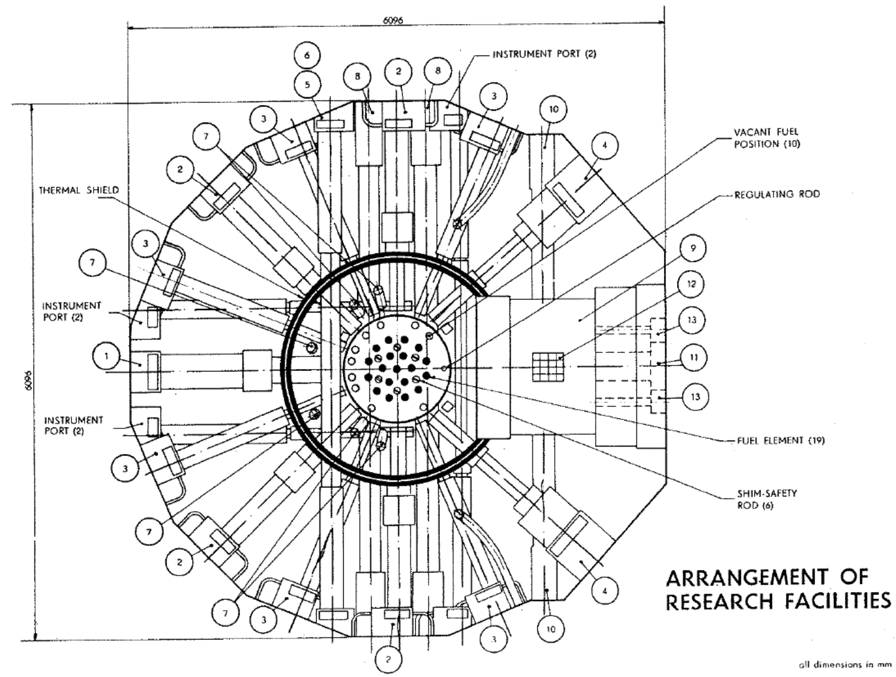
ISPRA-1 (Italy, 1959)

- 5 MW, Research in neutron physics, isotope production, reactor engineering.



ISPRA VERTICAL SECTION



ARRANGEMENT OF RESEARCH FACILITIES

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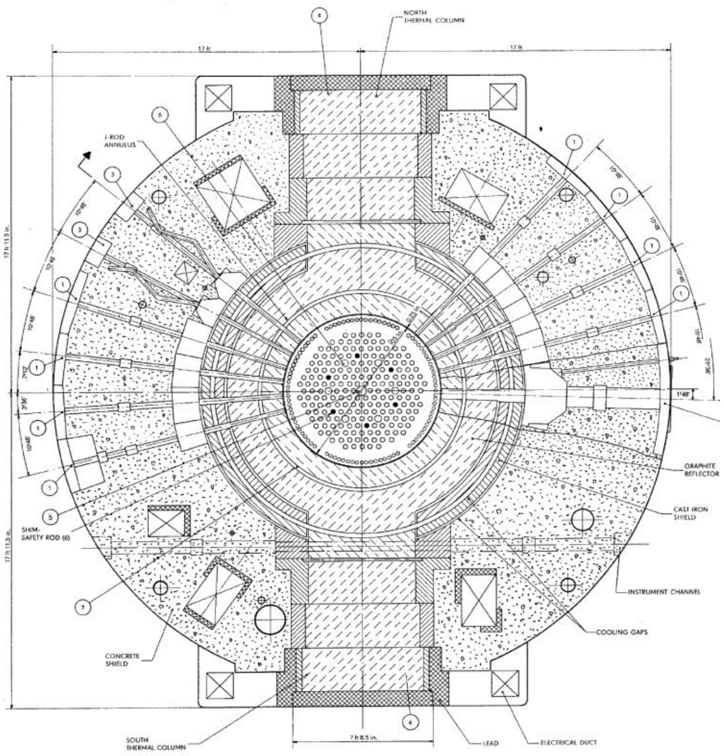
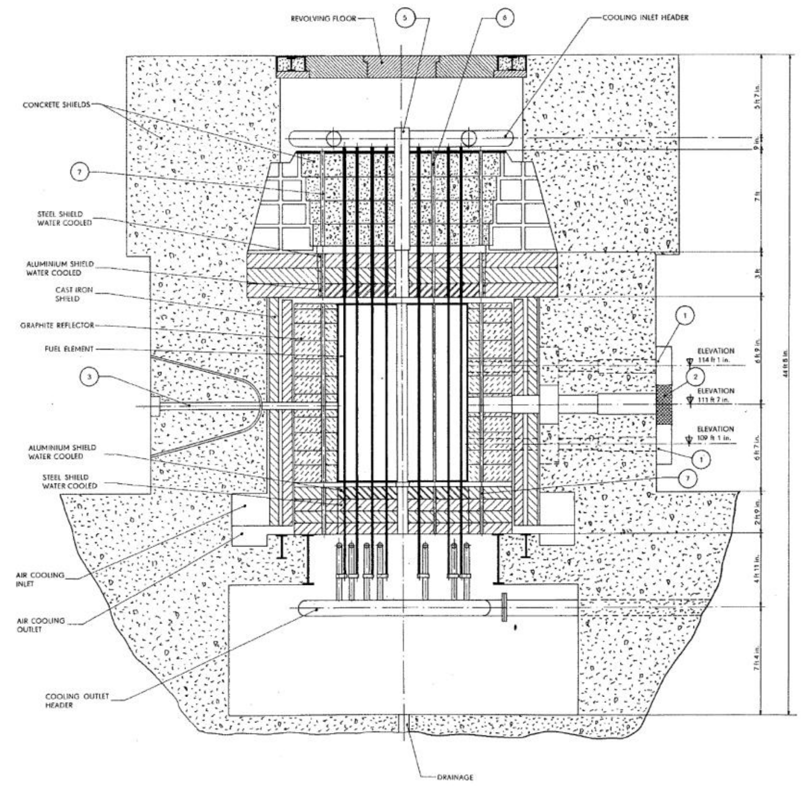
CIRUS (India, 1960)

- 40 MW, Multi-purpose research facility
  - Support for India's heavy water reactor program
  - Design based on NRX



CIR HORIZONTAL SECTION



CIR VERTICAL SECTION

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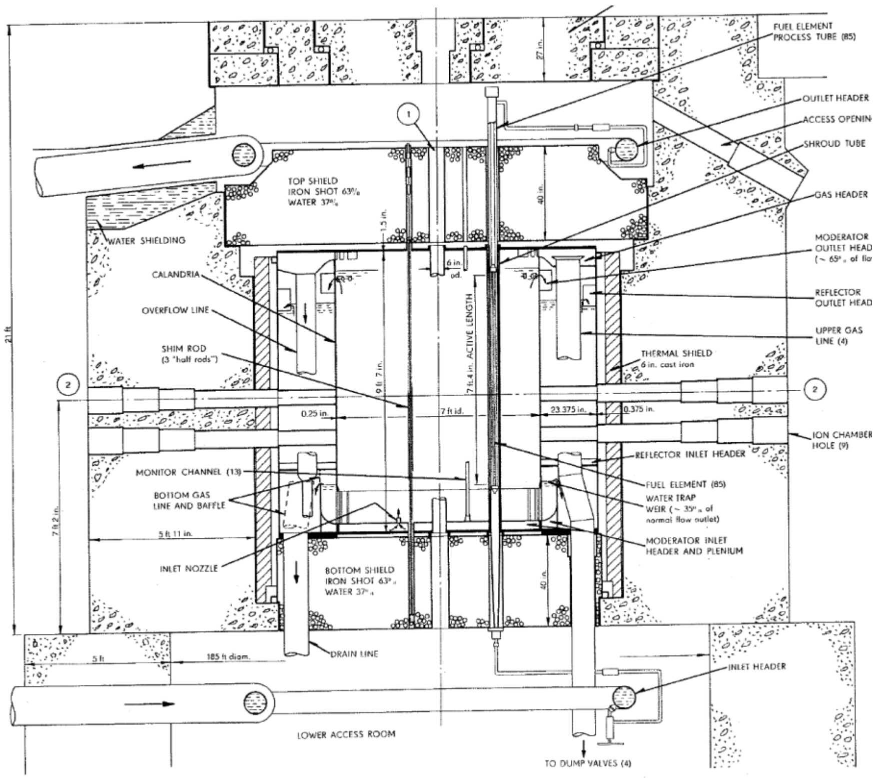
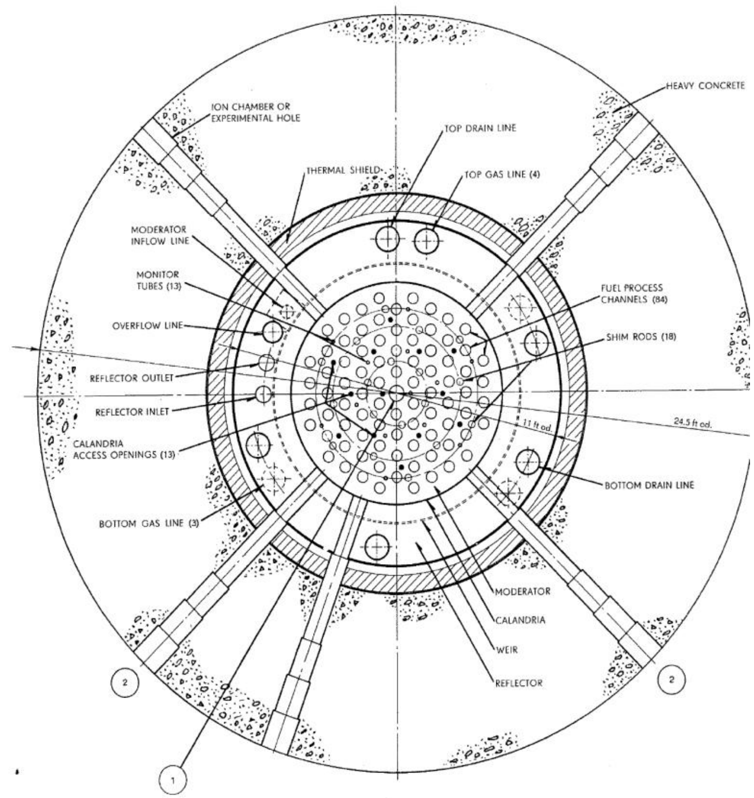
PRTR (U.S.A, 1960)

- Plutonium Recycle Test Reactor, 70 MW
  - Irradiation testing of Pu-fuels, Pu-recycling.



VERTICAL SECTION PRTR



HORIZONTAL SECTION PRTR

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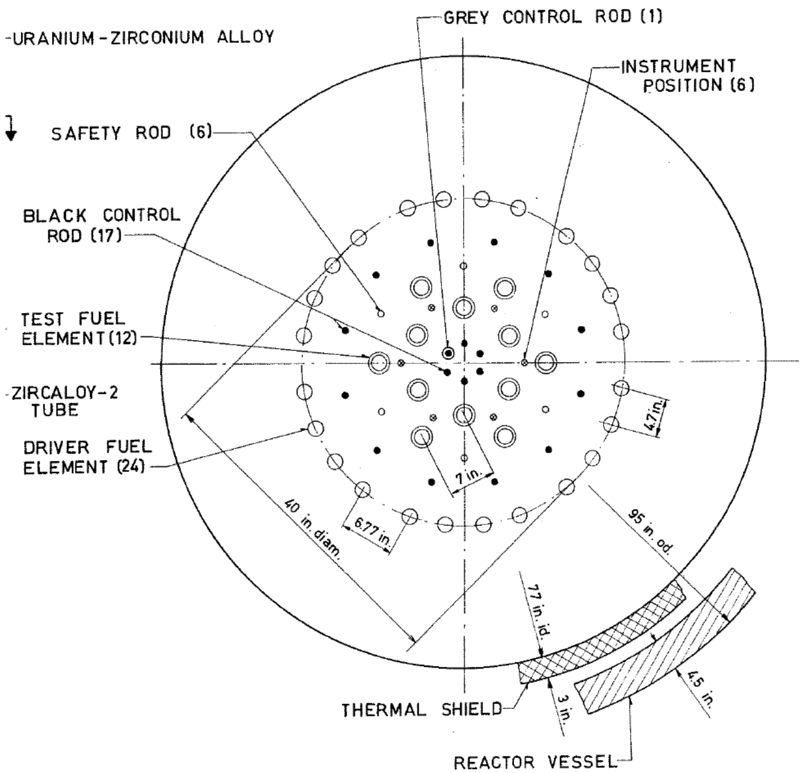
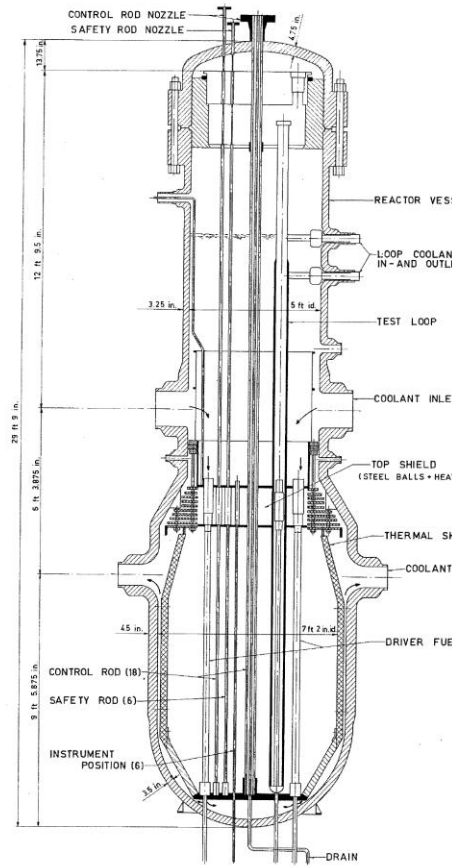
HWCTR (U.S.A., 1962)

- Heavy Water Components Test Reactor (HWCTR)
  - 61 MW, Savannah River



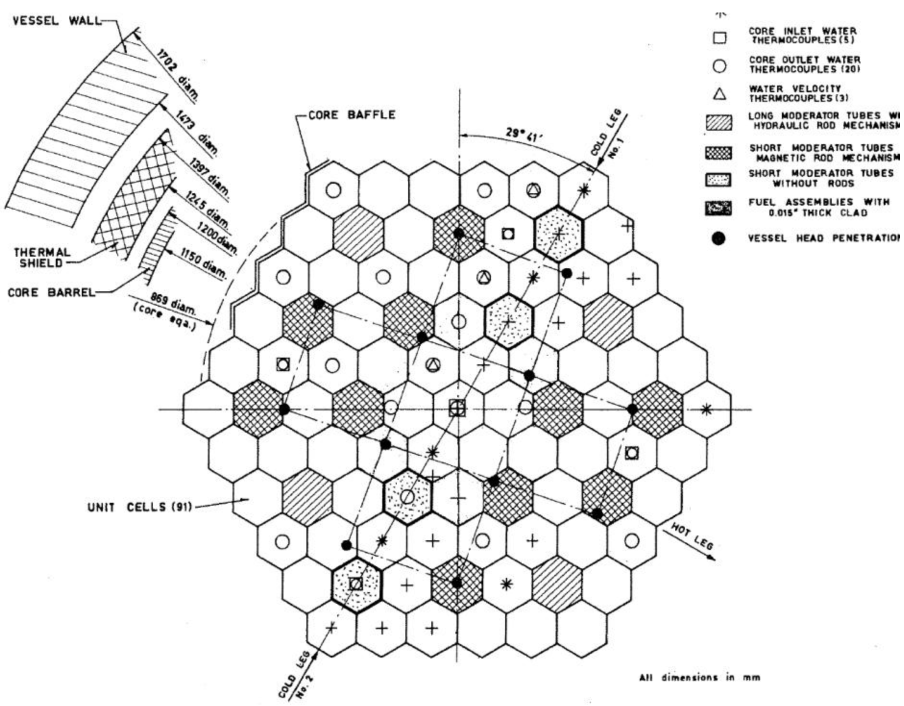
HORIZONTAL SECTION REACTOR HWCTR



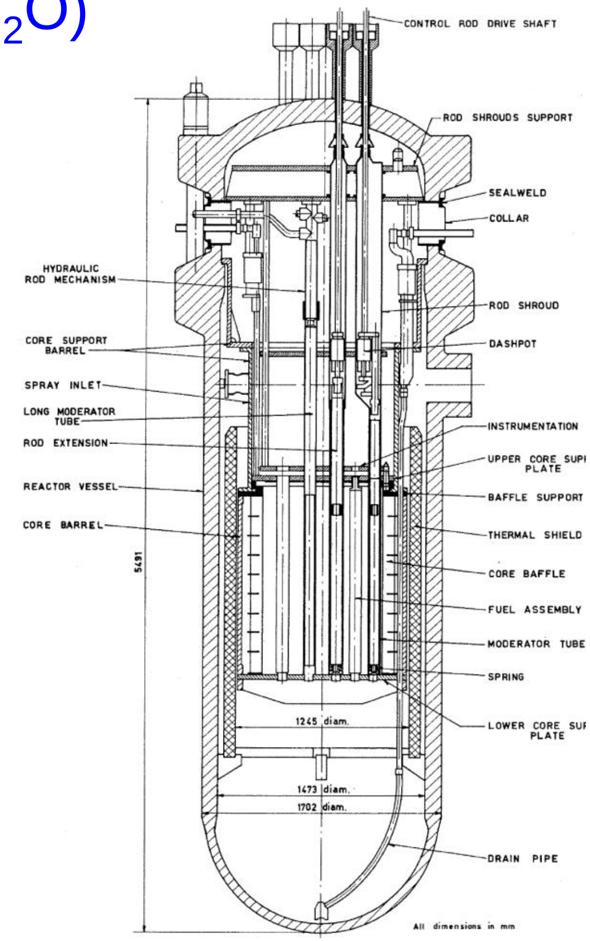
VERTICAL SECTION REACTOR HWCTR

BR-3 Vulcain (Belgium, 1965)

- 41 MW, PWR, Spectral Shift (D_2O/H_2O)
  - Physics and engineering tests



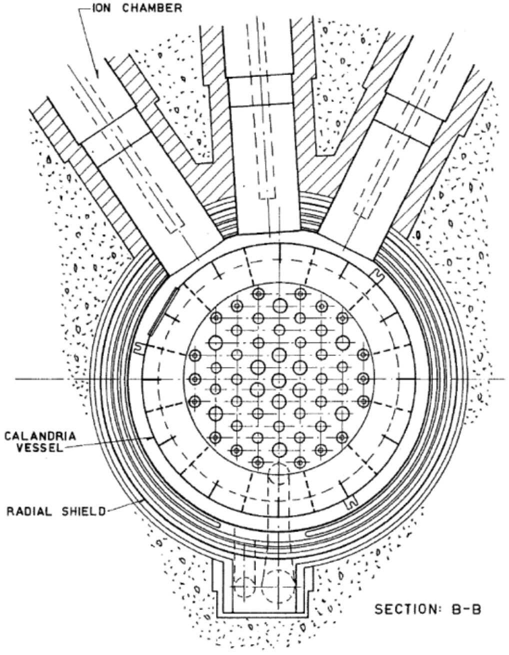
CORE CROSS SECTION REACTOR BR-3 VULCAIN



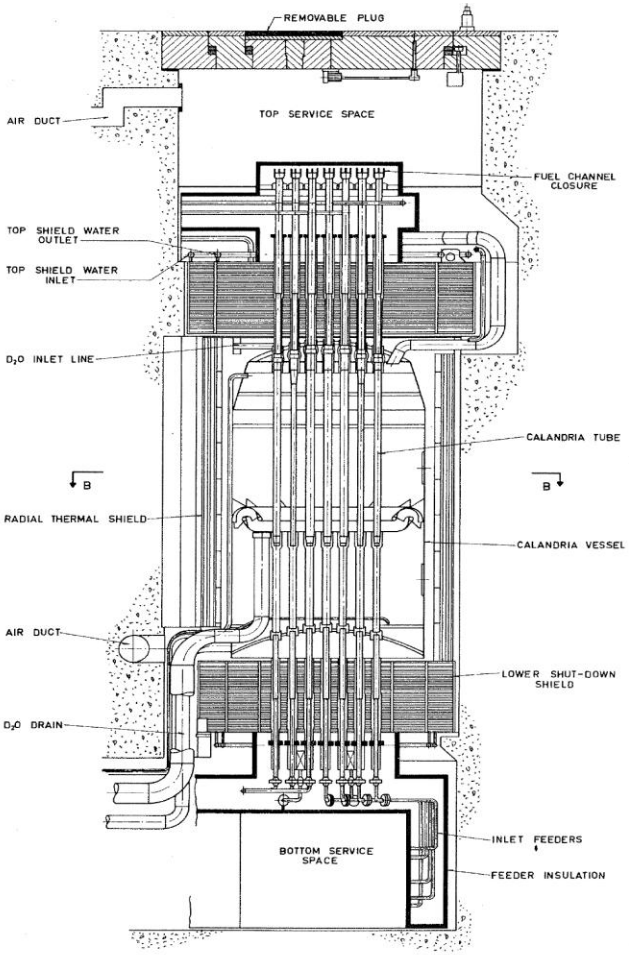
VERTICAL SECTION REACTOR BR-3 VULCAIN

WR-1 (Canada, 1965)

- 40 MW, testing organic coolant
  - Operation successful.



HORIZONTAL SECTION REACTOR WR-1



VERTICAL SECTION REACTOR WR-1

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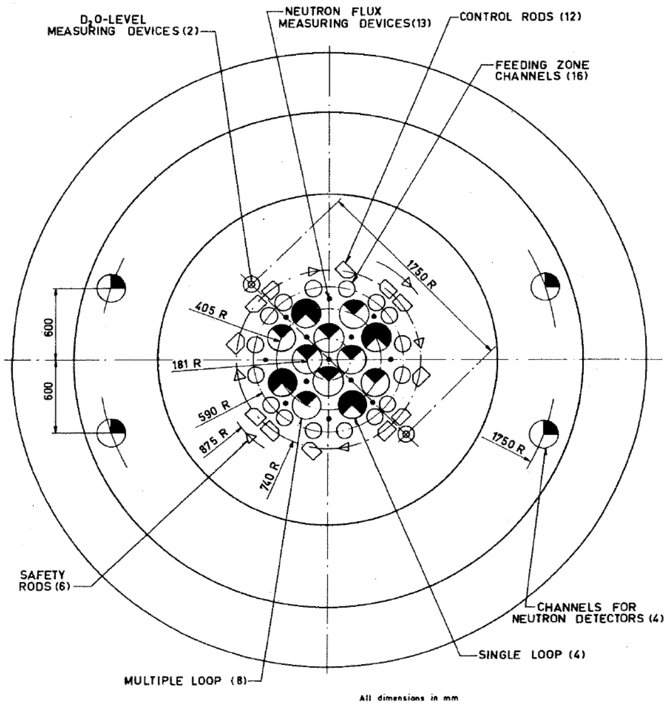
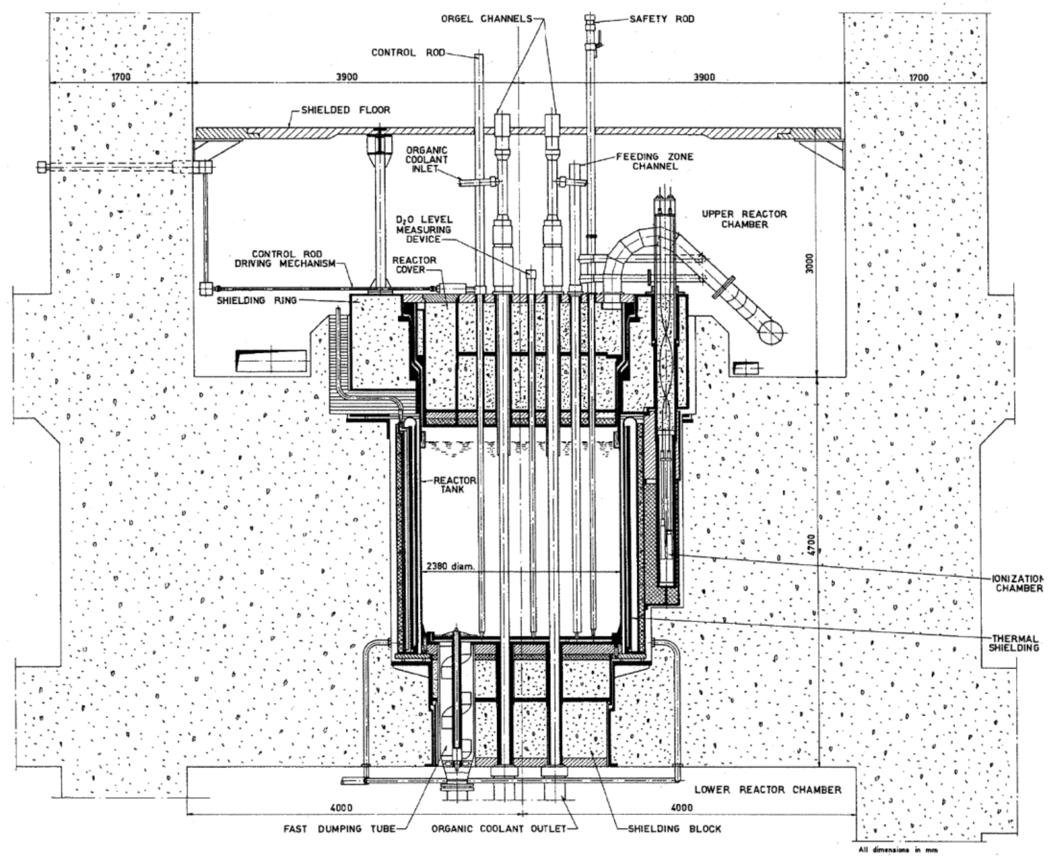
ESSOR (Italy, 1967)

- 37 MW, tests for organically-cooled HWR's



HORIZONTAL SECTION REACTOR ESSOR



VERTICAL SECTION REACTOR ESSOR

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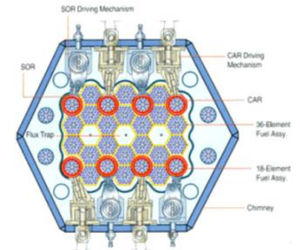
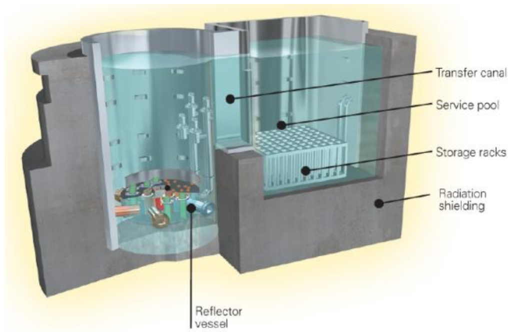
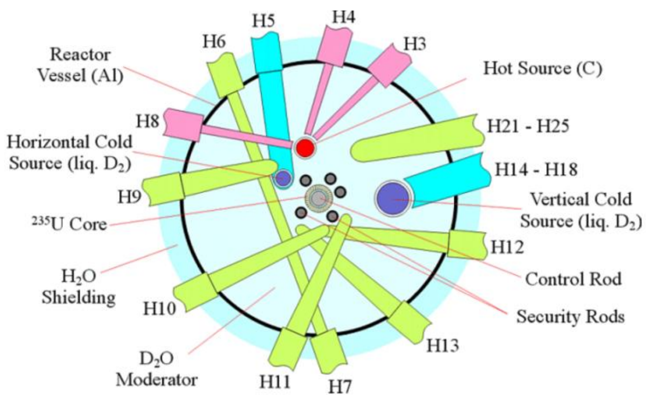
Heavy Water Usage in Other Research Reactors

- Not the primary moderator, but:
- Main usage as a reflector:
  - Conserve neutrons.
  - Create high thermal neutron flux region in reflector for beam sources, and irradiation sites for target materials.
- Examples of use of heavy water reflector:
  - HANARO (South Korea)
    - http://hanaro.kaeri.re.kr/english/rd.htm
  - OPAL (Australia)
    - http://www.ansto.gov.au/discovering_ansto/anstos_research_reactor/
  - ILL - HFR Grenoble (France)
    - http://pd.chem.ucl.ac.uk/pdnn/inst3/reactors.htm

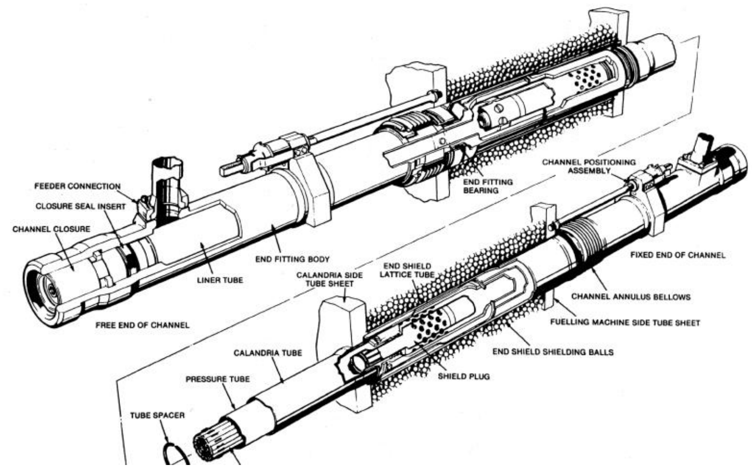






HWR R&D Efforts and Needs

❑ Engineering Issues

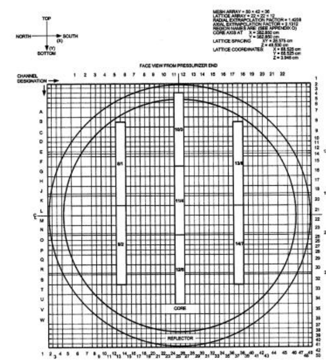


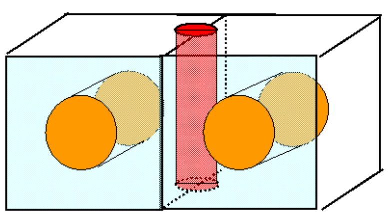
- Mechanical components
  - Wear and erosion.
  - Creep and sag.
  - Pumps and fluid seals.
  - Lifetime in radiation environment.
- Material degradation
  - eg. Hydrogen embrittlement of Zircaloy.
  - Exposure to high temperature, high pressure environments.
- Chemistry / Materials Science
  - Corrosion .
  - Compatibility of materials.
  - Insulators / liners for PT's.
  - Feeders / Header connections to PT's.

HWR R&D Efforts and Needs

❑ Physics Issues

- Biases and uncertainties in reactivity coefficients.
  - Due to approximations in governing equations, solution methods, model approximations, nuclear data, etc..
- Scaling from critical experiments to power reactors.
  - Do biases/uncertainties change?
- Modelling approximations / development.
  - Deterministic vs. Stochastic (Monte Carlo).
  - Heterogeneous vs. Homogenous.
    - o Size of homogenization regions.
    - o Multi-cell modeling.
    - o Discontinuity factors.
  - Transport vs. Diffusion.
  - 2-group vs. multi-group.
  - 2-D lattice cell vs. 3-D lattice cells.
  - Reactivity devices (orthogonal to lattice).



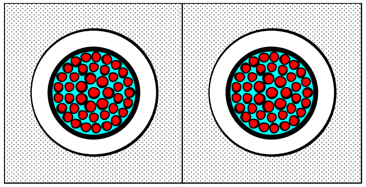


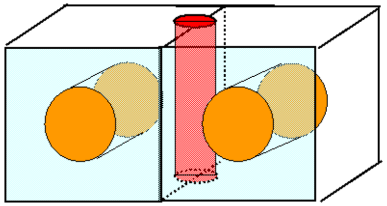
HWR R&D Efforts and Needs

❑ Physics Issues

➢ Lattice Physics Calculations.

- Critical spectrum / leakage models.
- Resonance self-shielding for key isotopes / elements.
  - o Actinides.
  - o Zirconium.
  - o Absorbers / burnable poisons (Gd, Dy, etc.).
- Single cell vs. multi-cell.
- Consistency with core calculations..
- Burnup with representative environment.
  - o Tmod, Tcool, Tfuel, flux spectrum, power density
- 3-D effects.
  - o Axial variation of fuel / coolant.
  - o Endplates / structural materials.
  - o Reactivity devices.





HWR R&D Efforts and Needs

Physics Issues

- Nuclear Data
  - Accuracy and uncertainty estimates
  - Co-variance data
  - Thermal scattering data , $S(\alpha,\beta)$
    - D_2O, H_2O, O in UO_2, C (graphite), Be, ^7Li.
    - Temperature corrections.
  - Absorption / Resonance data
    - U-238, U-235, Pu-239, higher actinides.
    - Th-232, U-233 (for thorium cycle).
    - Zr, Hf (impurity).
    - Gd, Dy, other neutron absorbers.
    - Structural materials.
  - Fission product yields
    - Delayed neutron precursors.

CANDU/EC-6 and ACR-1000

- CANDU, CANDU-6 / EC6, ACR-1000
- 17 Reactor Physics Phenomena of interest

Identification	Reactor Physics Phenomenon
***PH01**	**Coolant-Density-Change Induced Reactivity**
PH02	Coolant-Temperature-Change Induced Reactivity
PH03	Moderator-Density-Change Induced Reactivity
PH04	Moderator-Temperature-Change Induced Reactivity
PH05	Moderator-Poison-Concentration-Change Induced Reactivity
PH06	Moderator-Purity-Change Induced Reactivity
PH07	Fuel-Temperature-Change Induced Reactivity
PH08	Fuel-Isotopic-Composition-Change Induced Reactivity
PH09	Refuelling-Induced Reactivity
****PH10**	**Fuel-String-Relocation Induced Reactivity (CANDU only)**
PH11	Device-Movement Induced Reactivity
PH12	Prompt/Delayed Neutron Kinetics
PH13	Flux-Detector Response
PH14	Flux Distribution in Space and Time
PH15	Lattice-Geometry-Distortion Reactivity Effects
****PH16**	**Coolant-Purity-Change Induced Reactivity (CANDU only)**
PH17	Core Physics Response to Moderator Level Change

CANDU/EC-6 and ACR-1000

- Codes used to predict physics behavior
  - WIMS-AECL (lattice physics – multi-group transport)
  - DRAGON (incremental xsec's for reactivity devices)
  - RFSP (core physics, refuelling, transients)
  - MCNP (stochastic / benchmark comparisons)
- Biases, Δ, and uncertainties, ±δ are quantified.
  - Prediction of k_{eff}, dk_{eff}/dx ($x=\rho_{cool}$, T_{fuel}, T_{mod}, etc.)
  - Prediction of flux / power distributions $\phi(x,y,z)$
- Scaling issues
  - Extending results from critical experiments, research reactors to larger power reactors (S/U analyses)
  - TSUNAMI (SCALE 6) used for S/U analysis for cross section data and extension.

India's AHWR / PHWR's

- R&D needs parallel/similar to Canada
- Extra emphasis on:
  - Physics for mixed-fuel bundles (U, Pu, Th).
  - Thorium fuel lattice physics.
  - Nuclear data libraries.

Gen-IV / Advanced Fuel Cycles

- Supercritical Water
  - Materials, mechanical design.
  - Reactor physics.
- Advanced Fuel Cycles
  - Recycling Pu and Actinides in HWR's.
  - Recycling spent fuel, recovered uranium (RU) in HWR's.
  - Thorium-based fuel cycles.
  - Alternative fuel matrices.
    - UC, cermets, Si-based matrices
  - Reactivity and burnup calculations.
  - Reactivity coefficients.
  - Fuel management.

Conclusions

- Critical facilities provide key information for lattice physics.
  - Critical height, activation foils, period measurements.
- Research reactors provide engineering and fuel burnup data.
  - Test bed for technologies..
- Heavy water research reactors in use today.
  - Engineering, fuel testing, neutron beams, isotope production .

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Conclusions

- International participation broad-based.
  - Use of heavy water reactors for research wide-spread.
  - Many countries today maintain at least one heavy water reactor.
  - Excellent neutron economy with heavy water is advantageous for research reactors.
- Present day efforts.
  - Critical and transient experiments for code validation.
  - Nuclear data being re-evaluated for improved agreement.
  - Code development and validation ongoing.
  - Fuel and component irradiation and testing.
  - Canada, India are leading the way in HWR research.
    - Support for CANDU/EC-6, ACR-1000, AHWR, etc.
    - Support for Advanced Fuel Cycles (MOX, MA, Thorium, etc.).
      - Testing new fuel materials, bundles.

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Useful Websites

- http://www.iaea.org/worldatom/rrdb/
- http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1
- http://nucleus.iaea.org/CIR/Browse.aspx
- http://www-nds.iaea.org/wimsd/

Acknowledgements

- *Gary Dyck, Bronwyn Hyland, Jeremy Pencer, Geoff Edwards*
- *Fred Adams, Erik Hagberg, David Irish, Bruce Wilkin*
- *Michael Zeller, Gerald McPhee, Alex Rauket*
- *Darren Radford, Bhaskar Sur, Richard Didsbury*
- *Jeremy Whitlock, Peter Boczar*
- *Michele Kubota*
- *Ken Kozier*
- *Dan Meneley (UOIT)*

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).

- Visit www.fjohss.eu