The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

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

19 - 30 May 2008

Heavy Water Reactors
2. R&D Activities for Design and Safety Analysis

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2. R&D Activities for Design and Safety Analysis

Blair P. Bromley

Reactor and Radiation Physics Branch

AECL – Chalk River Laboratories

Joint ICTP-IAEA Workshop on

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Advanced Reactor Technologies

Tuesday, May 27, 2008

AECL EACL

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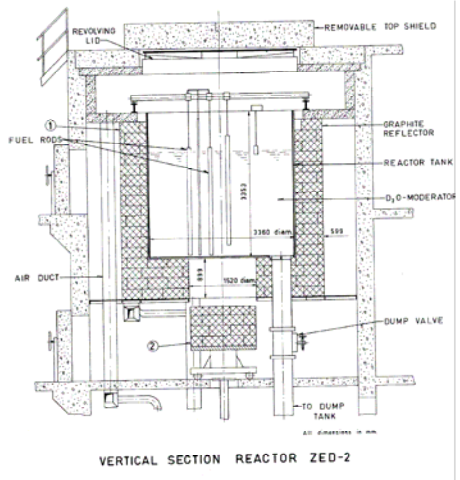
Outline

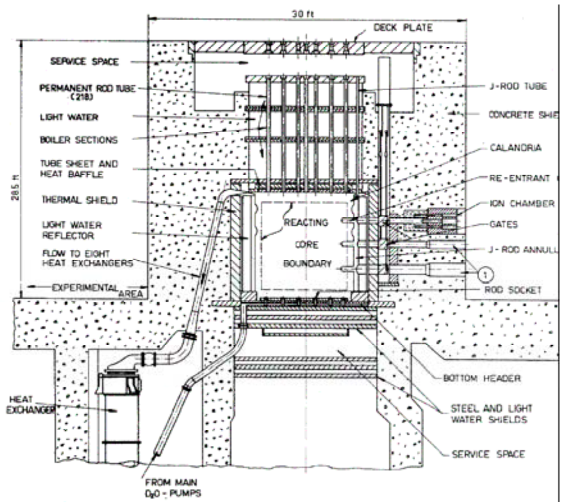
- Types of Measurements/Testing
- Heavy Water Research Reactors
  - Critical Facilities (< 1 kW)
  - High-power Facilities
- International Participation
  - Historical
  - Present Day
- Present R&D Efforts and Needs for HWR's
  - Canada (CANDU, ACR)
  - International (Gen-IV, GNEP)

Types of Measurements/Testing

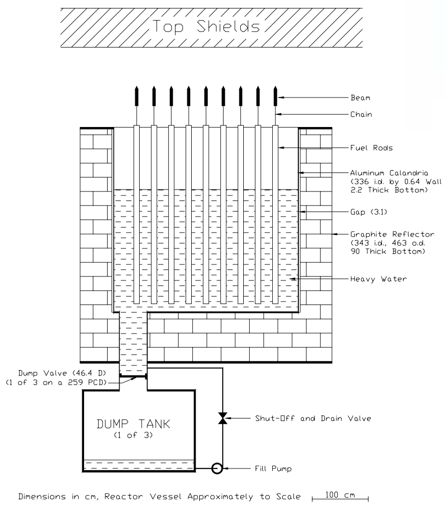
- Low-power (Critical Facility)
  - – Critical height measurements
  - – Activation foil measurements
  - – Fine structure
  - – Transient / period measurements



- 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



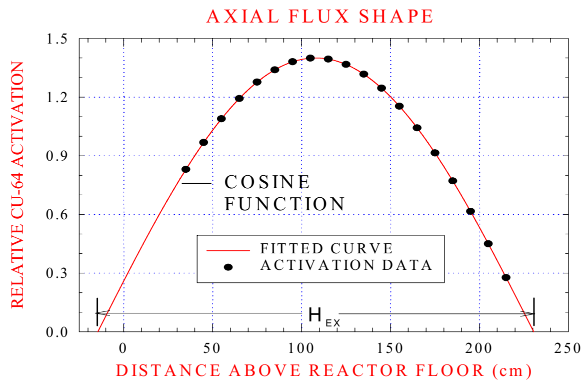
Types of Measurements/Testing



- **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 $H_{crit\text{-}calc} = H_{crit\text{-}exp}$**
    - **For substitution experiments, infer bucklings from ΔH_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



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

Types of Measurements/Testing

- **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, D**
    - **Aluminum usually used for wrapping.**

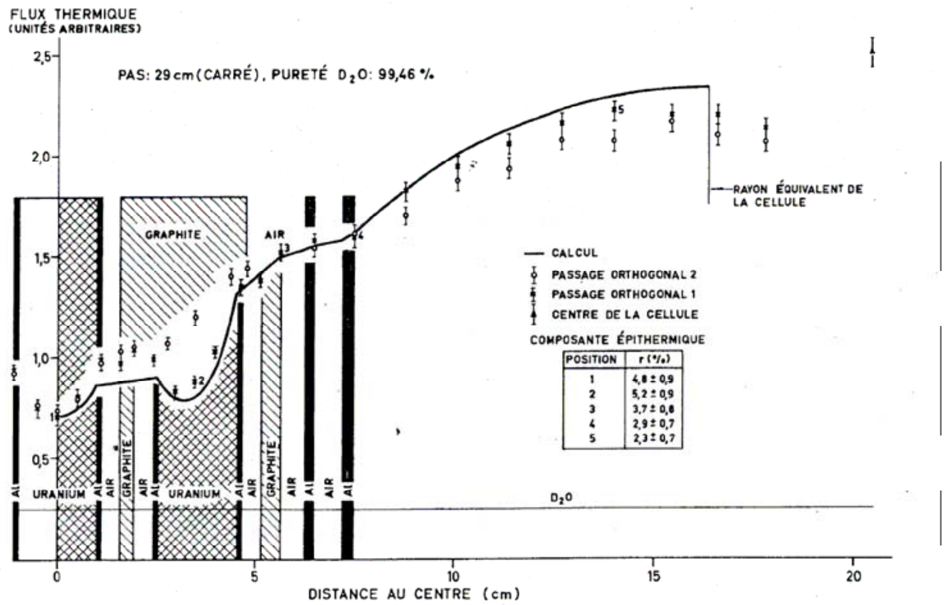


Figure 10

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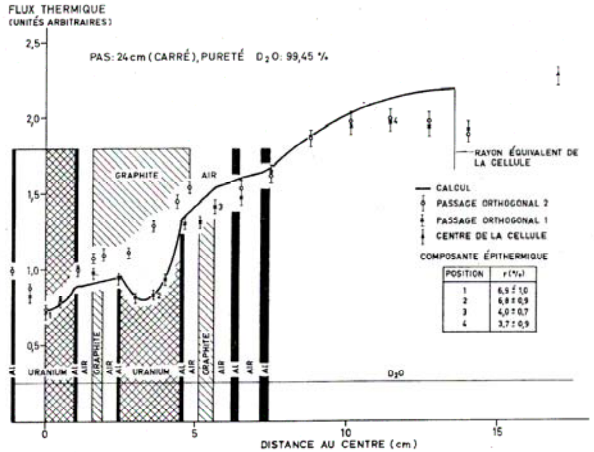
Types of Measurements/Testing

- **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
      - Determine also effective neutron temperature, Tn



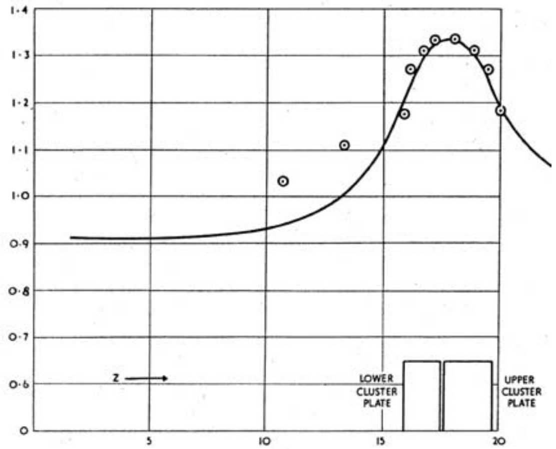


Fig. 14

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
      - Reactor stable period measurements
      - $\phi(t) = A_0 \times e^{t/T}$
      - Infer the dynamic reactivity or control rod worth
      - 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

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)**
- **Norway:**
  - **NORA (1961)**
- **Sweden:**
  - **R-O (1959)**

HW Critical Facilities

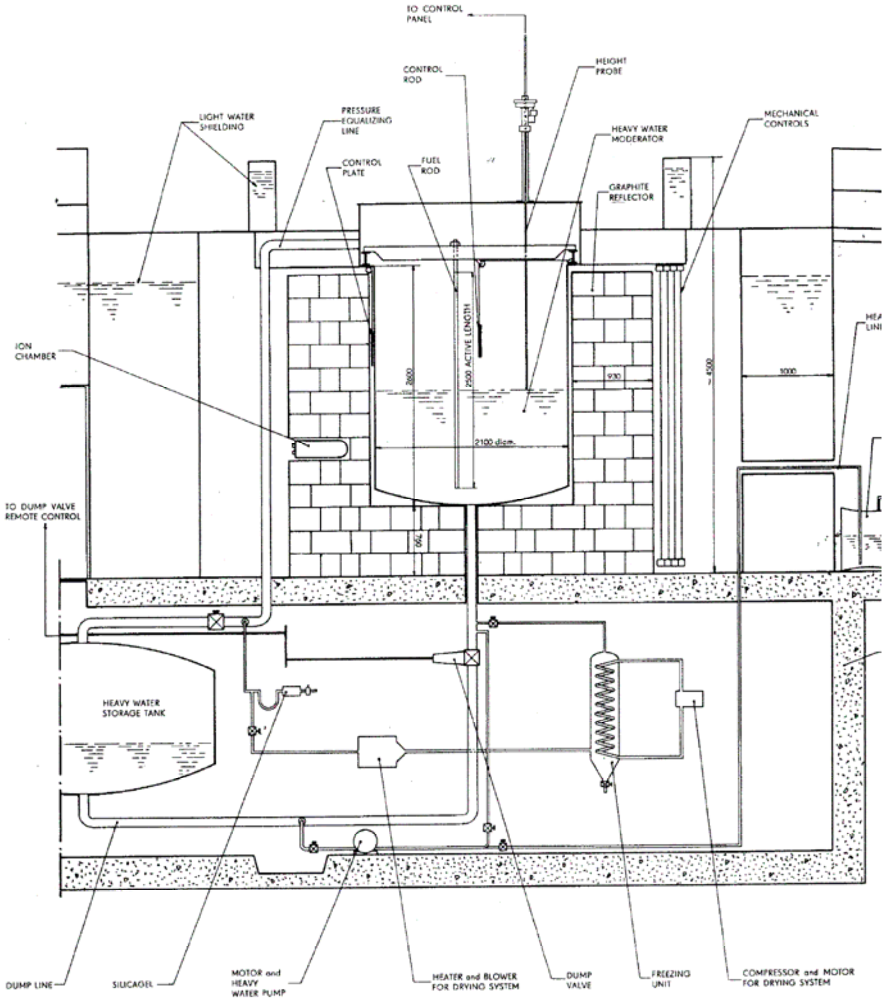
- **Italy:**
  - ECO (1965), RB-3 (1971) – support for HWOCR
- **Czech Republic:**
  - TR-0 (1972)
- **Yugoslavia:**
  - RB (1958) – Operating today
- **Japan:**
  - DCA (1969) – support for FUGEN design

HW Critical Facilities

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

ZEEP (Canada, 1945)

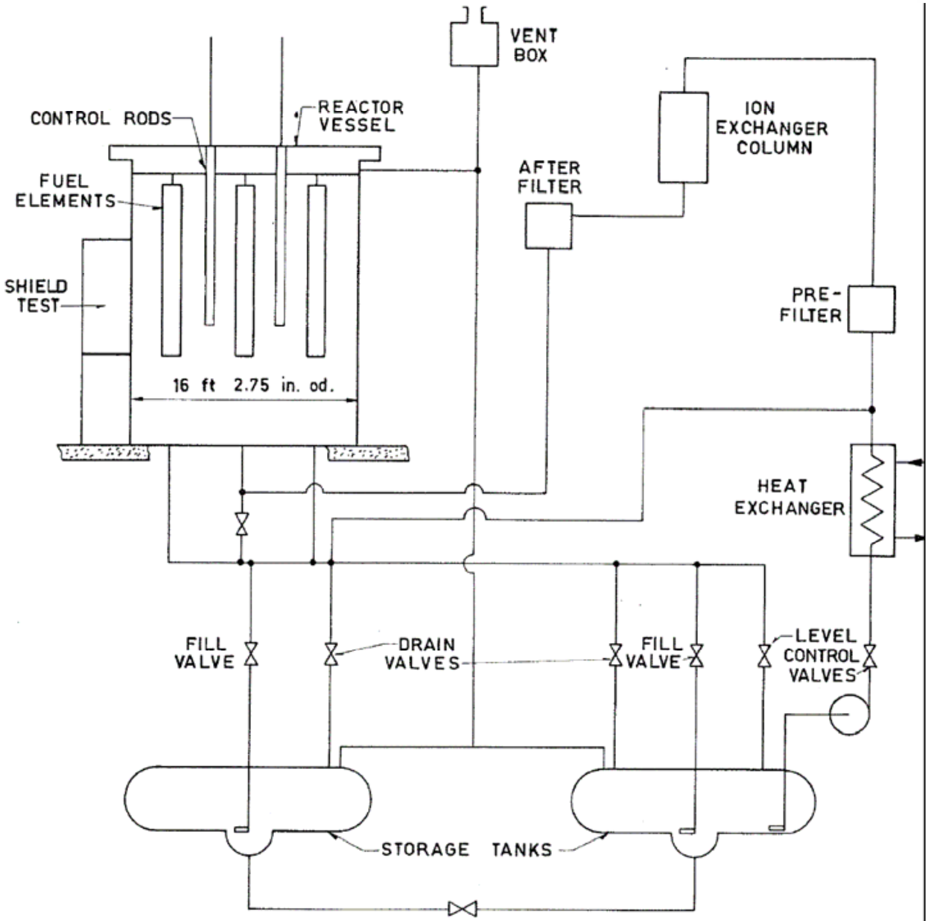
- **Canada 2nd country to build critical facility**
  - **Lattice Physics tests to support NRX, NRU, NPD-2, CANDU**



VERTICAL SECTION ZEEP

PDP (U.S.A, 1953)

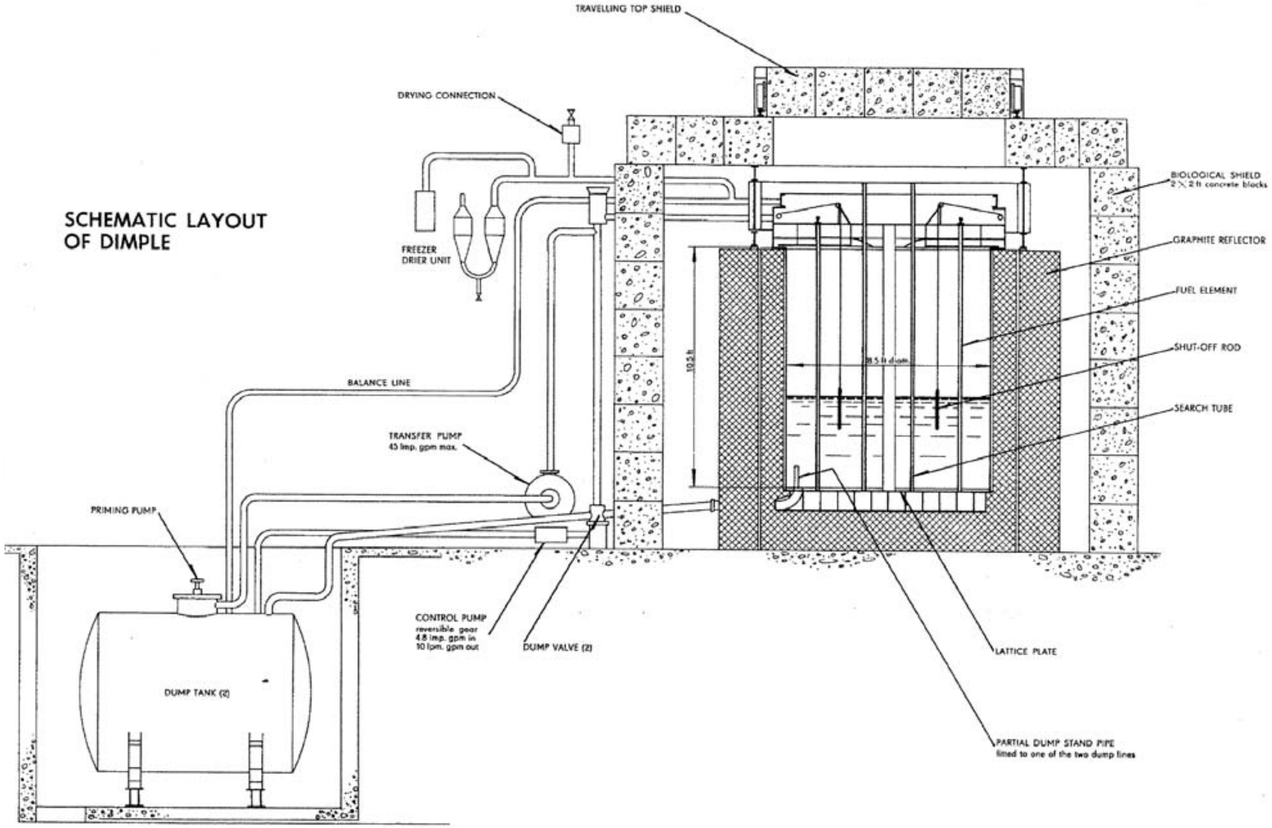
- Process Development Pile
  - Lattice physics studies for heavy water reactors



FLOW DIAGRAM REACTOR PDP

DIMPLE (U.K., 1954)

- Critical experiments supported SGHWR program, and others.



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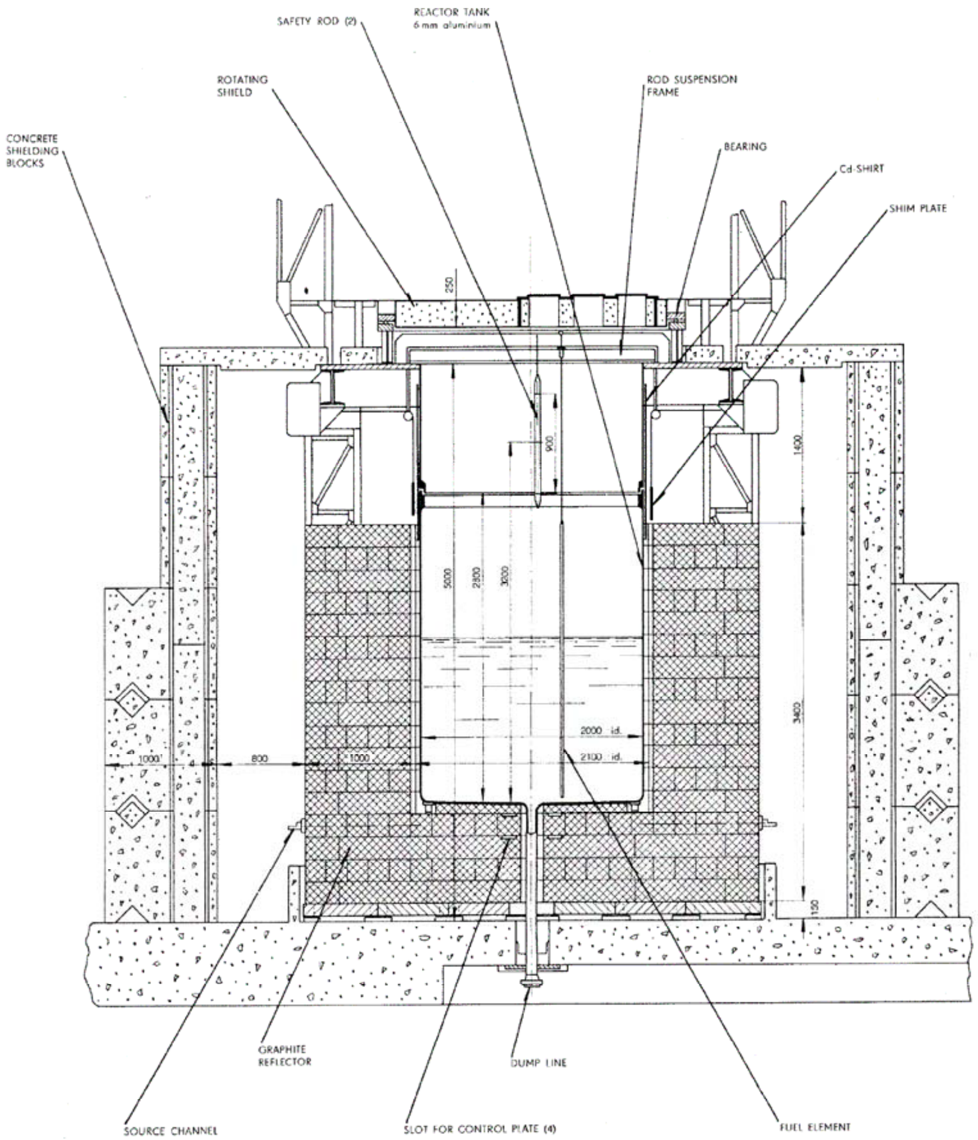
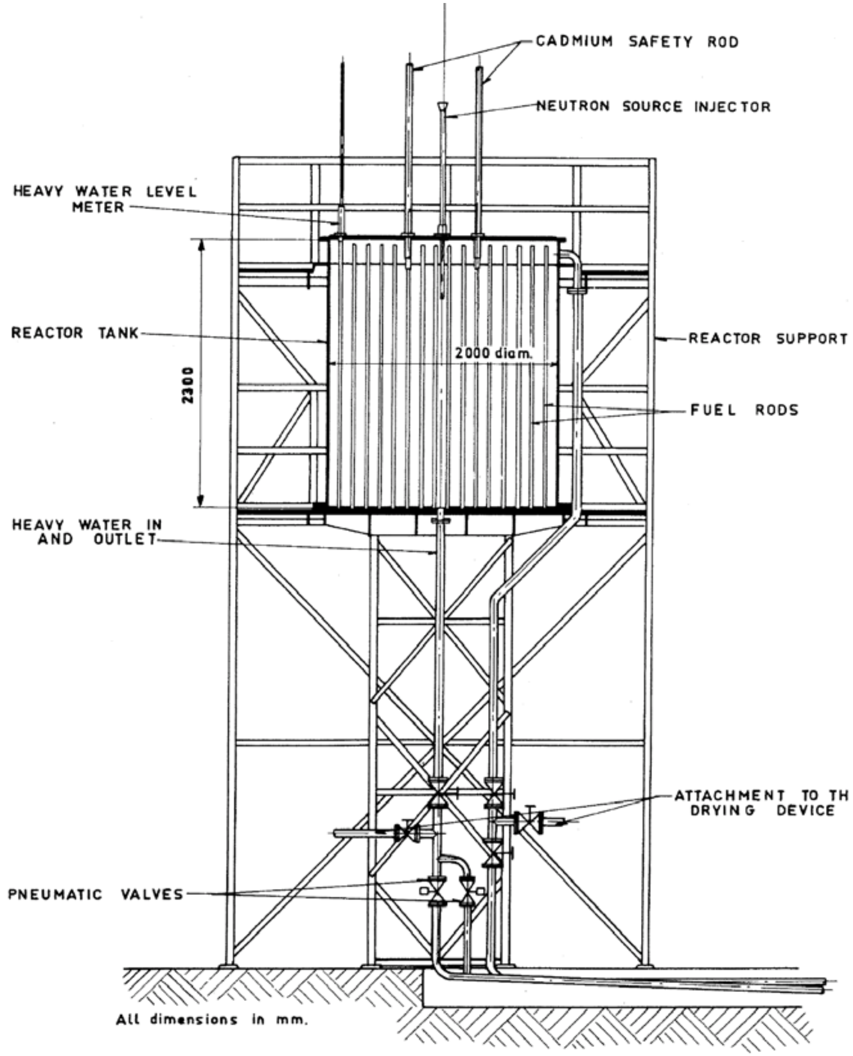
Aquilon (France, 1956)

- **Supported work on EL-1, EL-2, EL-3 and EL-4**



RB (Yugoslavia, 1958)

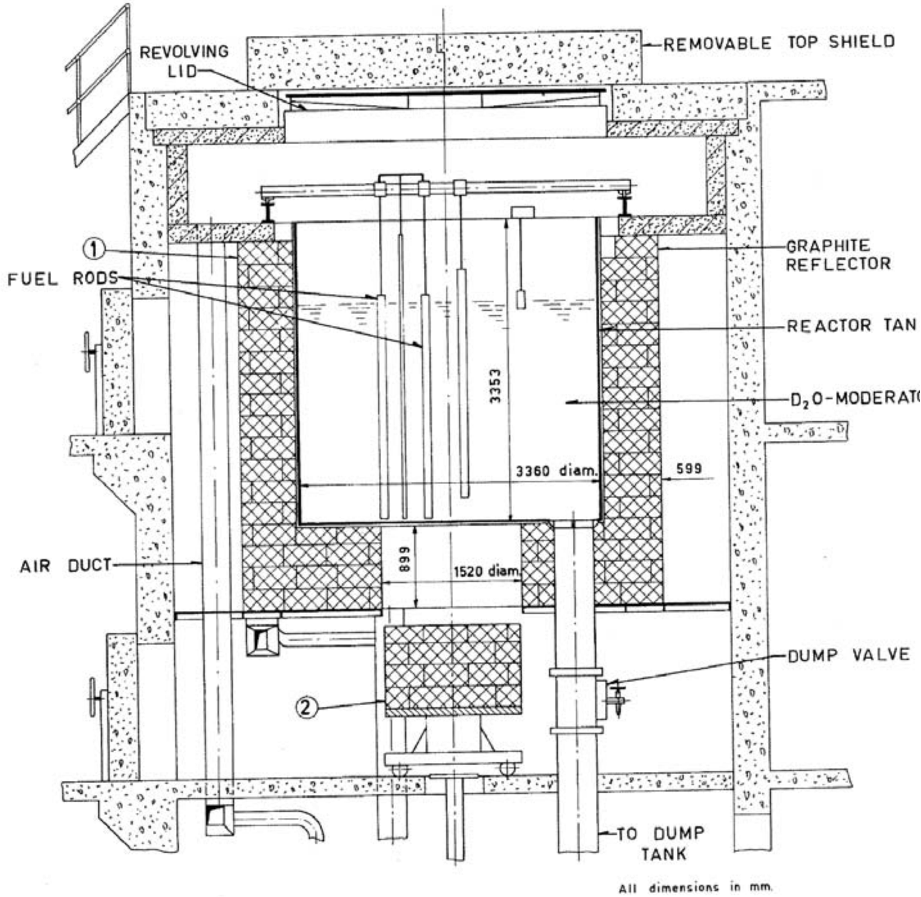
- **Bare critical lattices**
  - **Teaching, training and basic research**
  - **In operation today.**



VERTICAL SECTION BARE CRITICAL ASSEMBLY RB

ZED-2 (Canada, 1960)

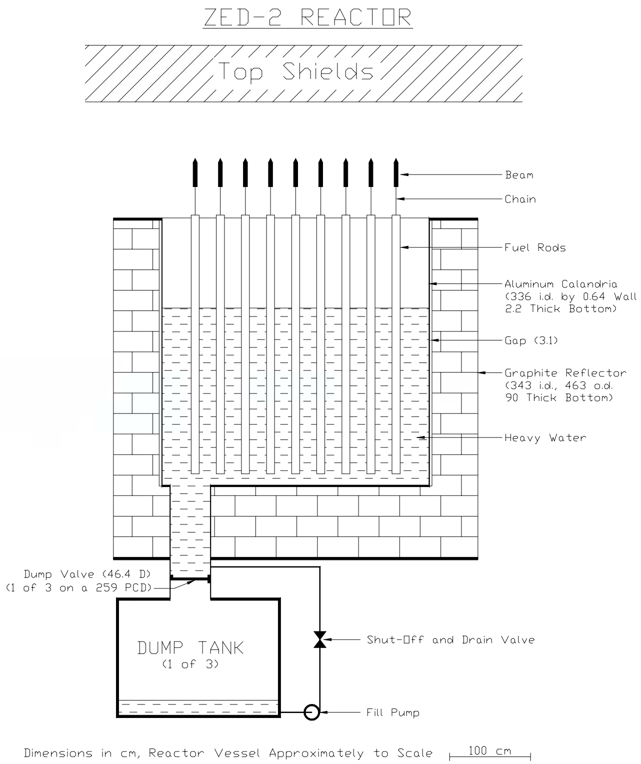
- Critical Facility, operating today.
  - Lattice experiments support CANDU and ACR
  - Heated channel experiments operate up to 300°C

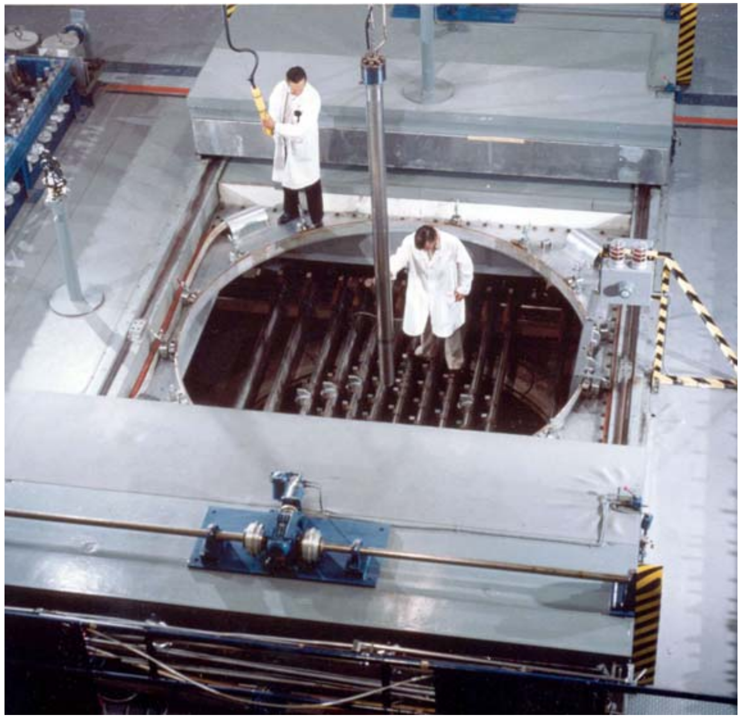


VERTICAL SECTION REACTOR ZED-2

ZED-2 Critical Facility

- Tank-type critical facility, 3.3 m diameter & depth
  - Moderator height adjusted to control criticality and power
  - Power level ~ 100 Watts





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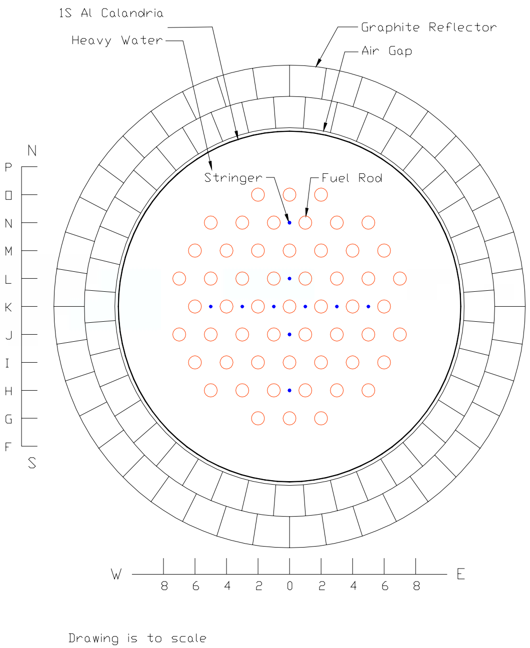
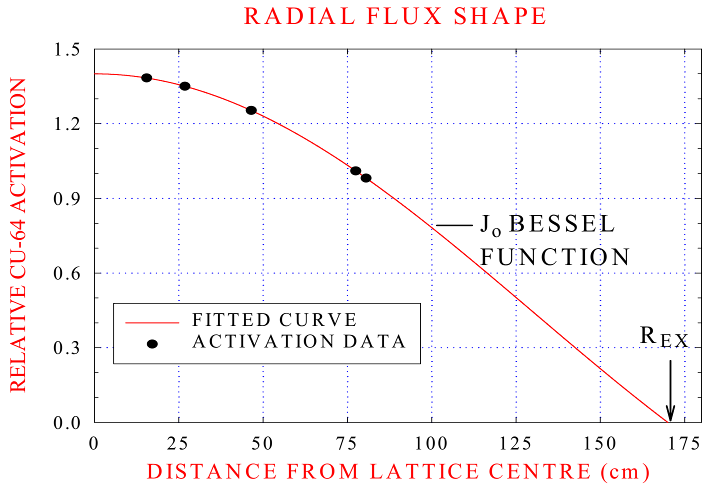
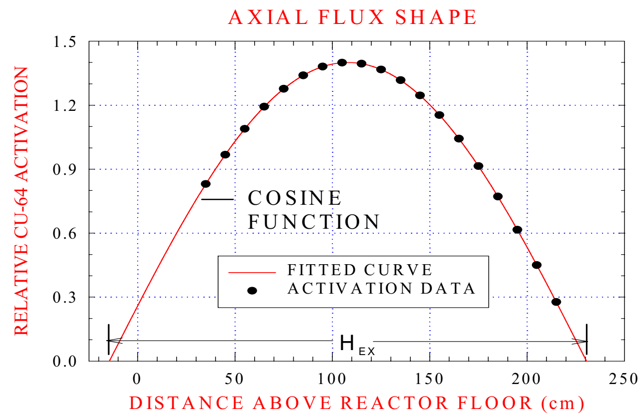
Example: Full-Core Flux Map

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



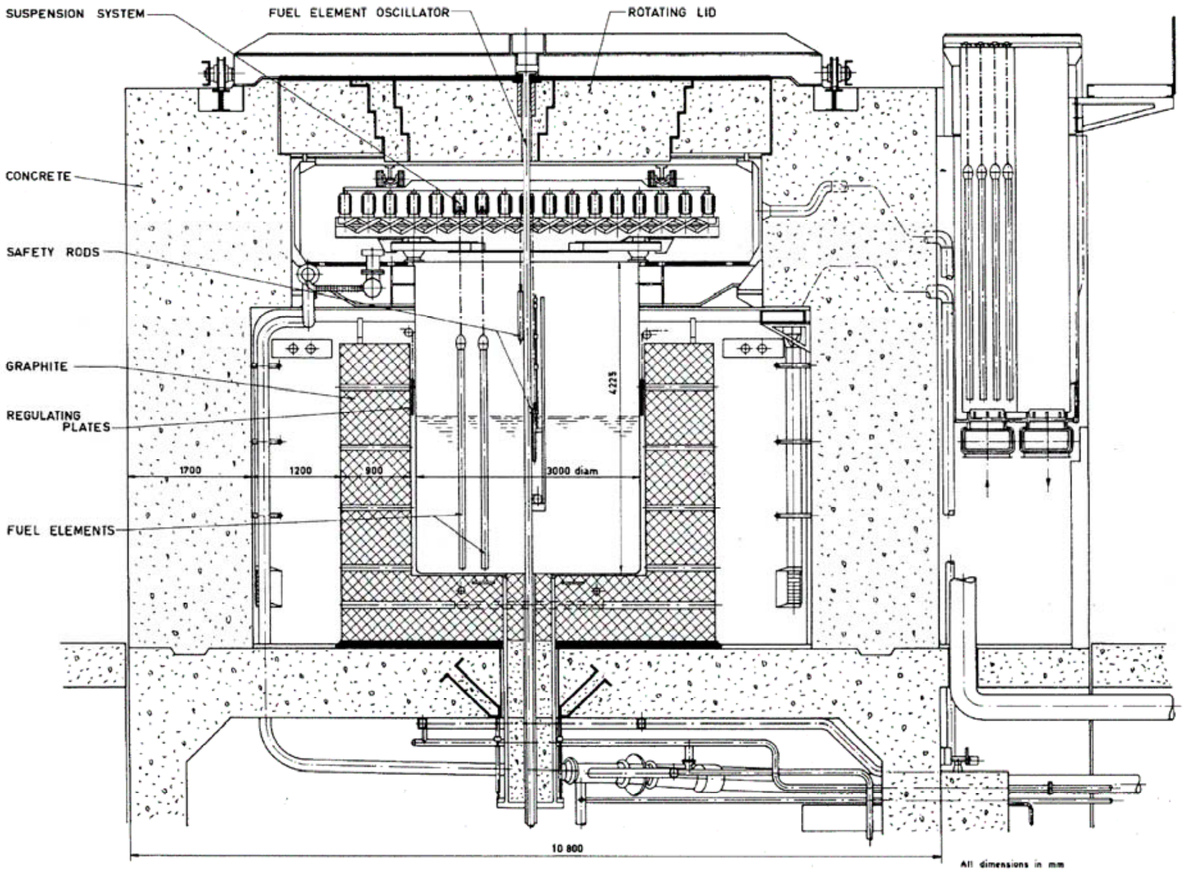




$$\text{Buckling} = (2.405/R_{EX})^2 + (\pi/H_{EX})^2$$

ORGEL (Italy, 1965)

- **1 kW, lattice studies with organic coolant**



VERTICAL SECTION REACTOR ECO

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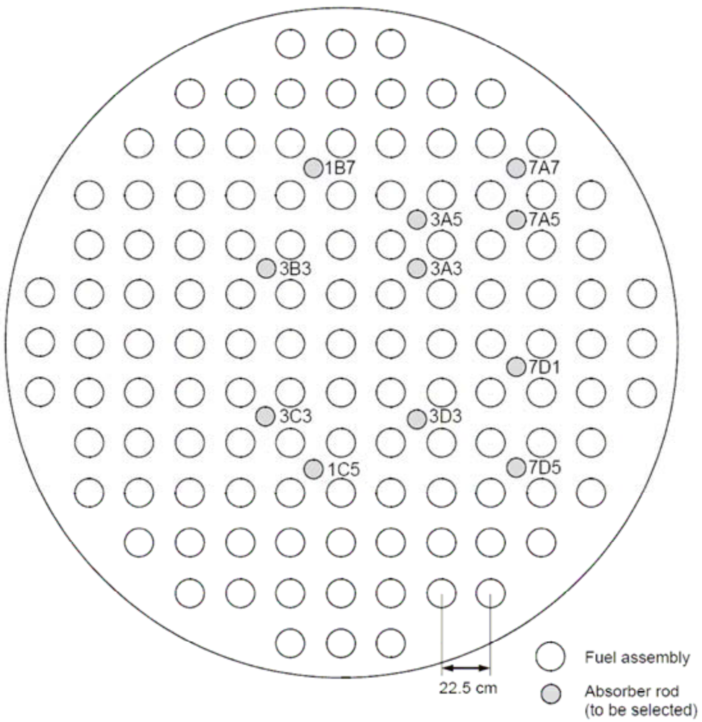
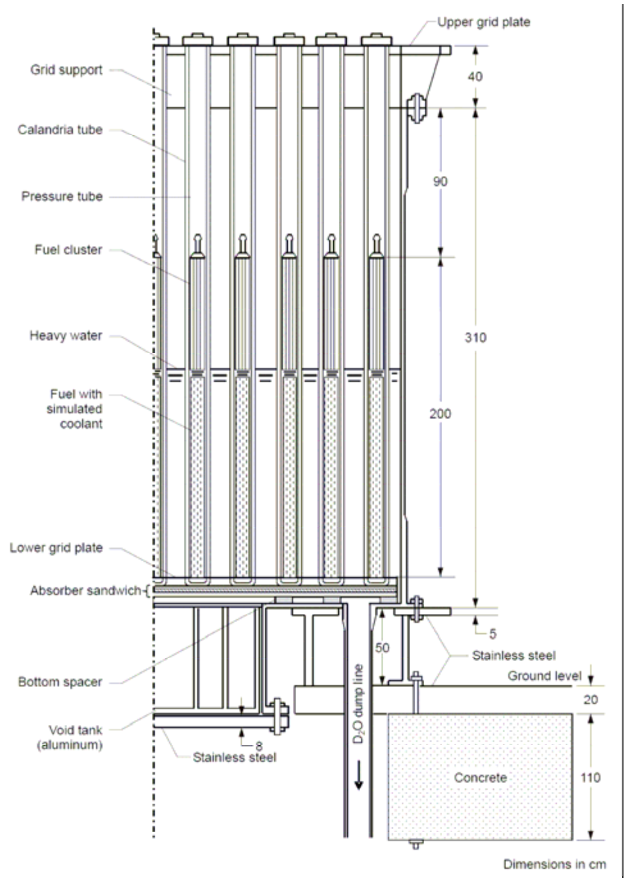
DCA (Japan, 1969)

- **Deuterium Critical Assembly**
  - **Bare lattice experiments to support FUGEN project**





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HW Research Reactors

- **Canada:**
  - NRX (40 MW, 1947)
  - NRU (110 MW,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)

HW Research Reactors

- U.S.A.: Strong interest in HW for research
  - 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

HW 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)

HW Research Reactors

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

HW Research Reactors

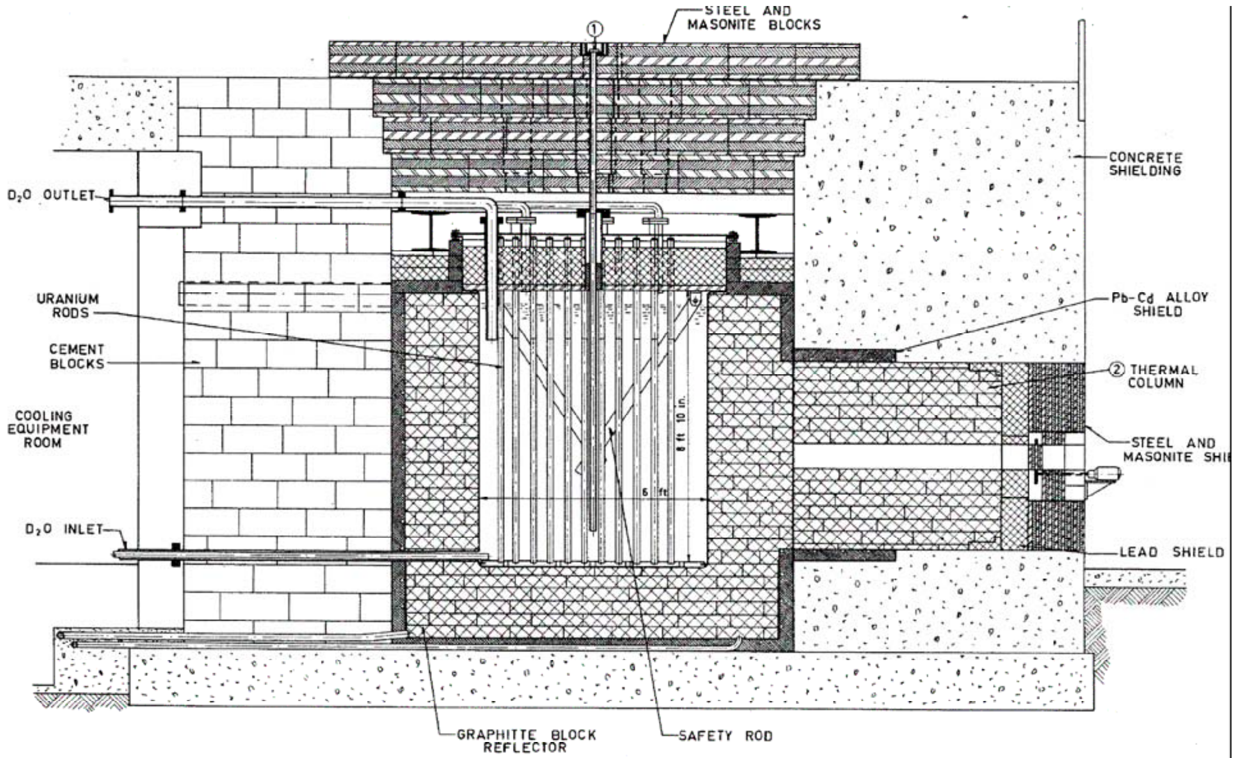
- Algeria:
  - ES-SALAM (15 MW, 1992) – Operating today
- Italy
  - ISPRA-1 (5 MW, 1959), ESSOR (43 MW, 1967)
- Israel:
  - IRR-2 (26 MW, 1963) – Operating today
- Yugoslavia:
  - RA (6.5 MW, 1959)

HW 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)

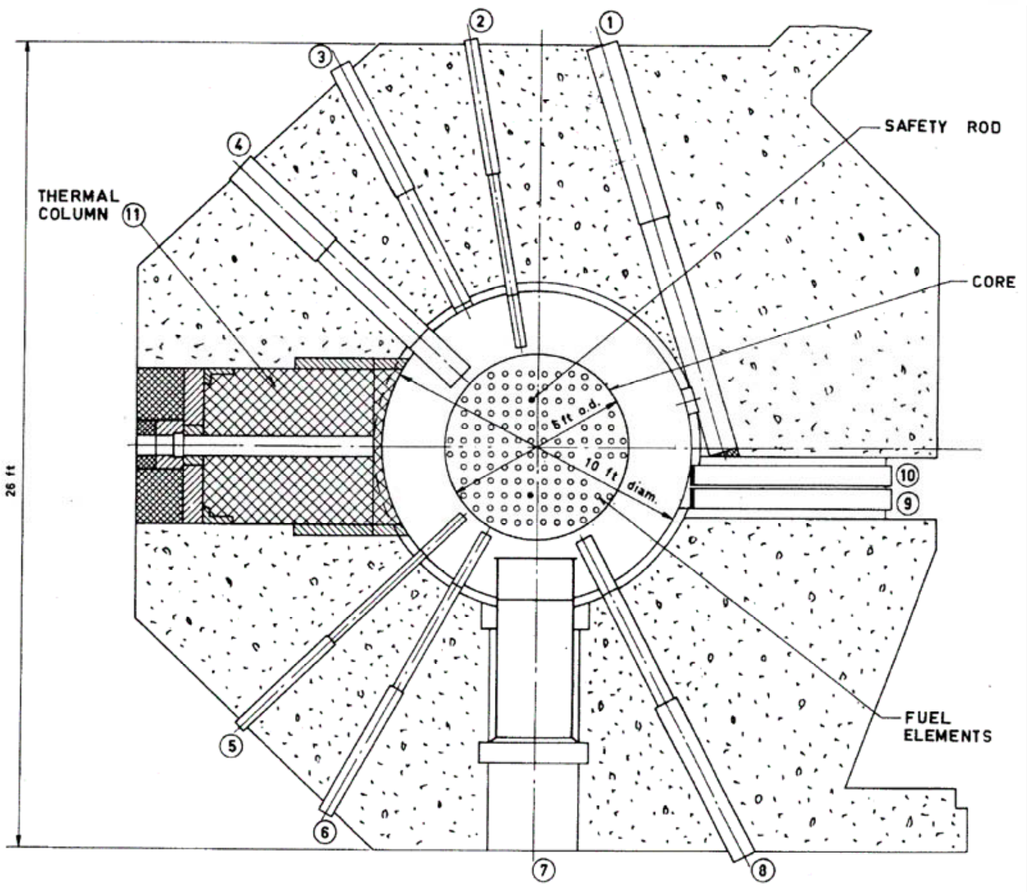
- Chicago Pile 3 (300 kW)
  - World's first critical heavy water reactor
  - Absorption measurements; oscillator techniques



VERTICAL SECTION REACTOR CP-3

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

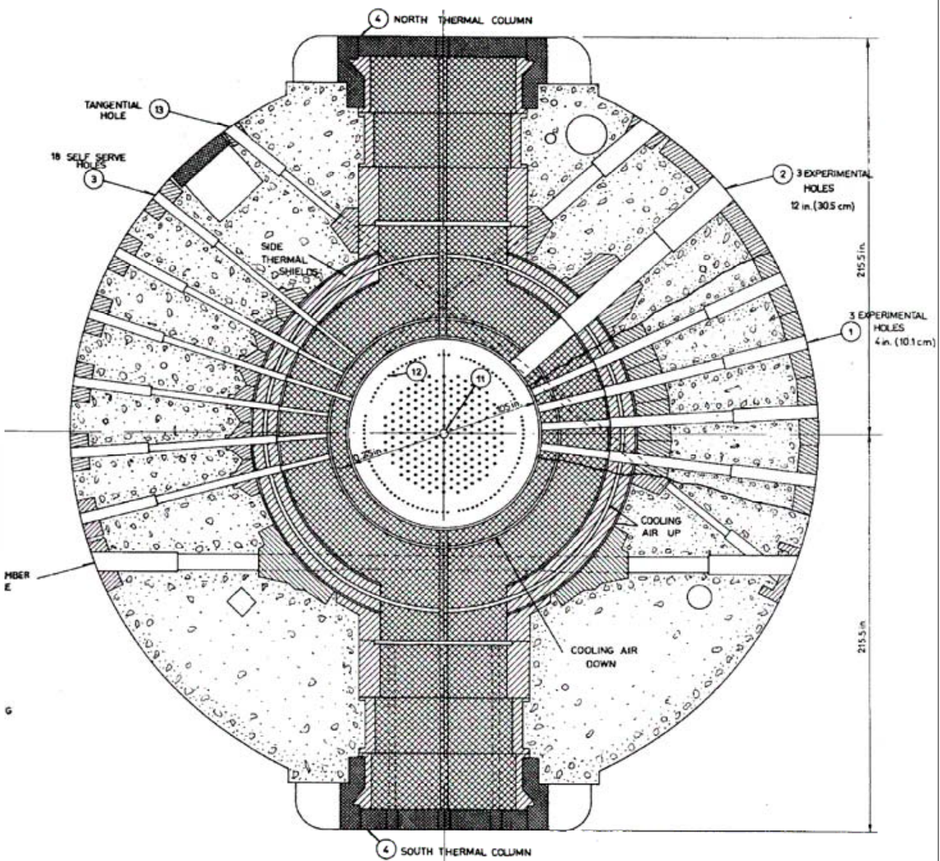
- CP-3 modified to operated with enriched uranium
- 275 kW



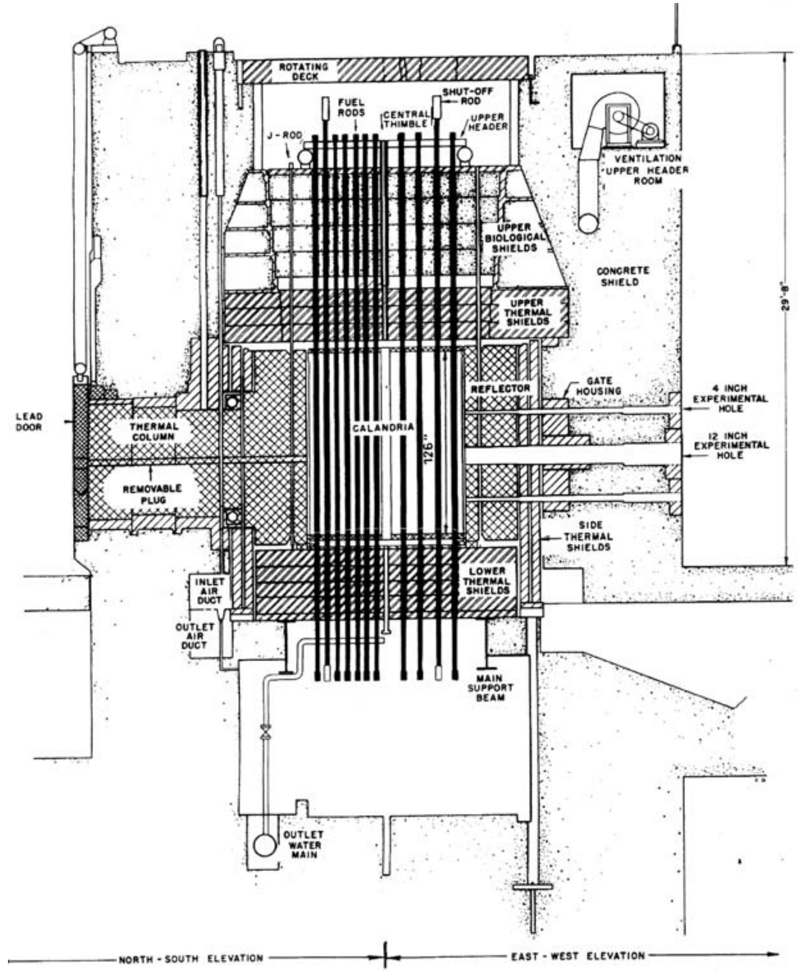
HORIZONTAL SECTION REACTOR CP 3'

NRX (Canada, 1947)

- **40 MW, Operated until early 1990's**



HORIZONTAL SECTION NRX



VERTICAL SECTION REACTOR NRX

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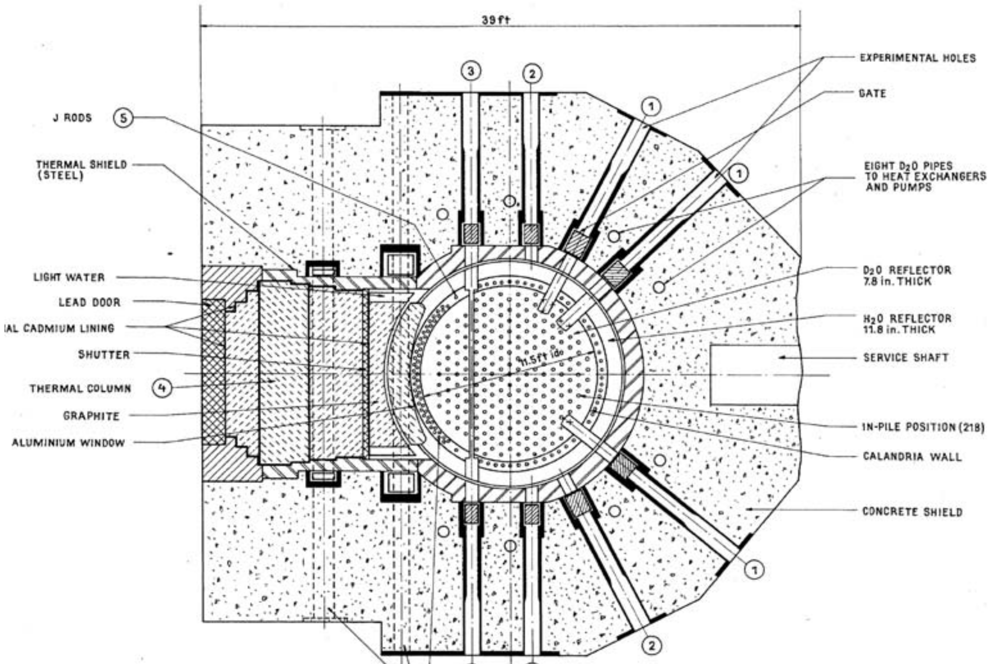
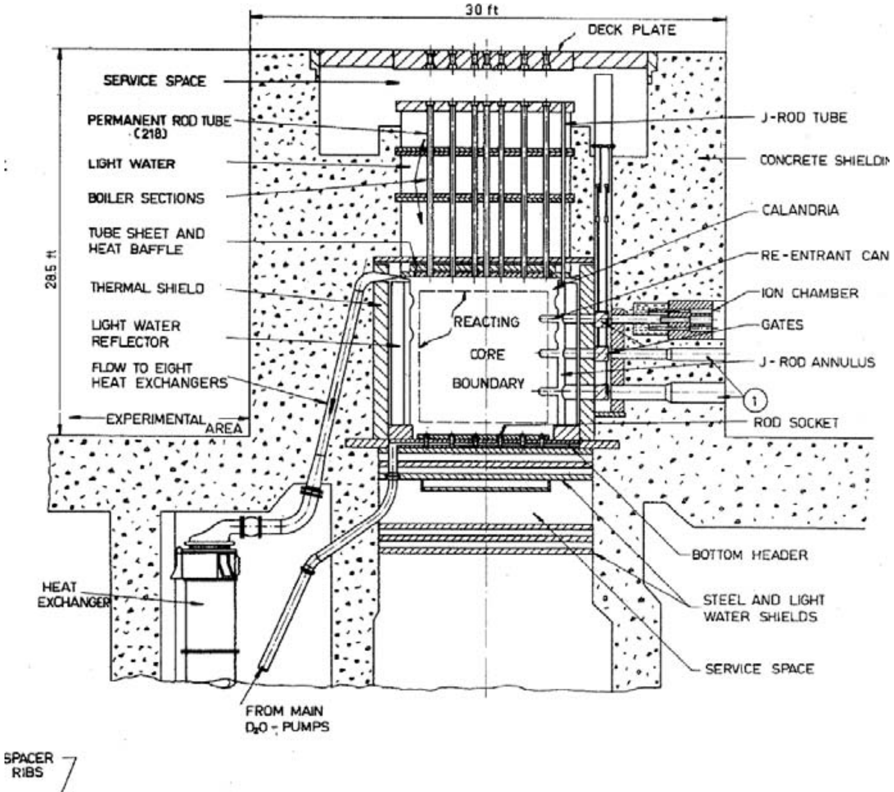
NRU (Canada, 1957)

- **110 MW, operating today**



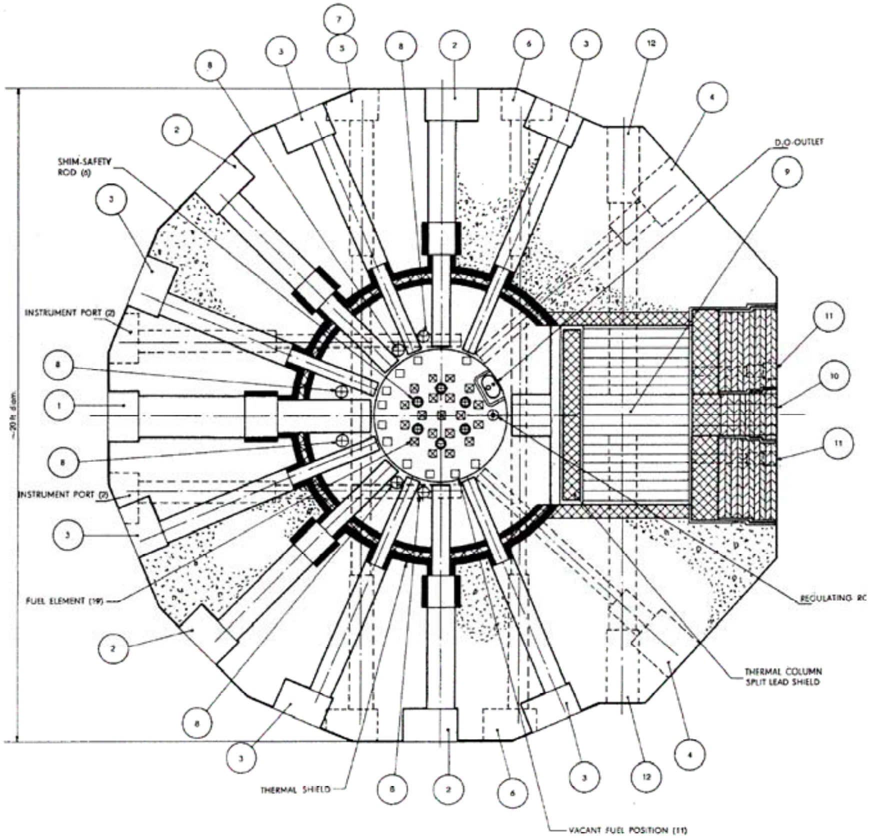
HORIZONTAL SECTION
REACTOR NRU



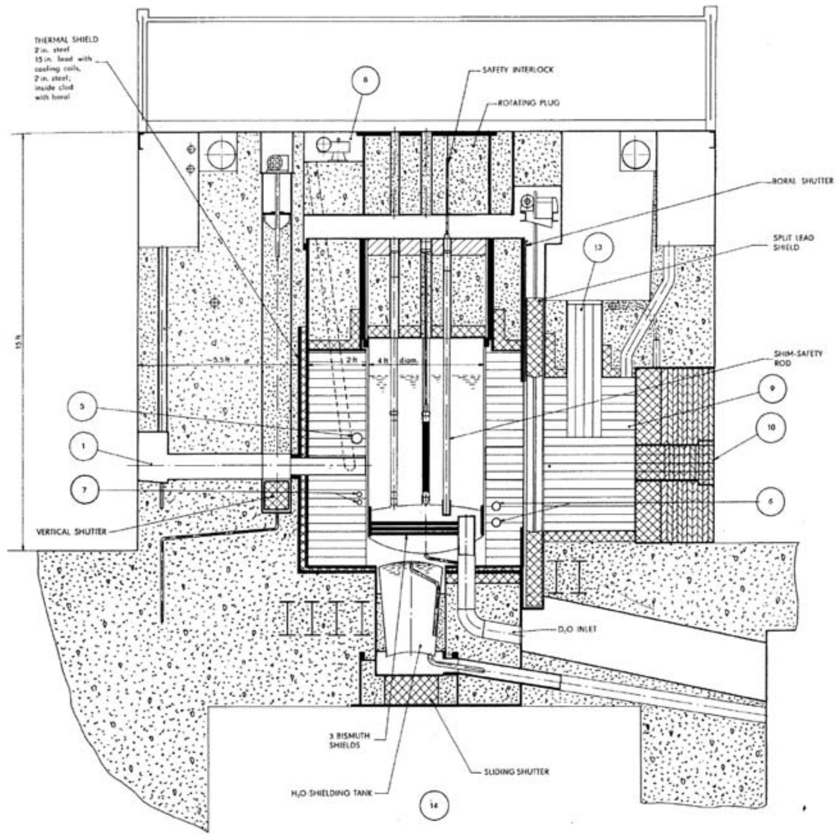
VERTICAL SECTION
REACTOR NRU

MITR (U.S.A, 1958)

- 1 MW, Multiple neutron beam experiments.



MITR HORIZONTAL SECTION



MITR VERTICAL SECTION

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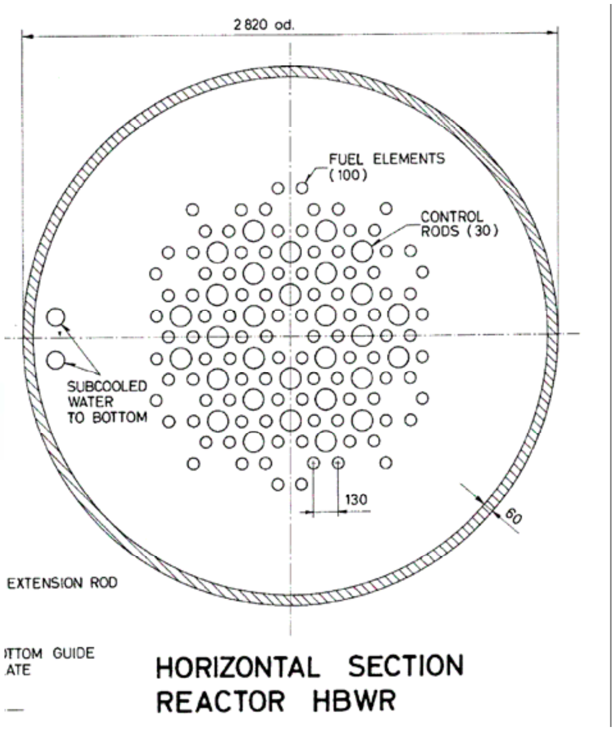
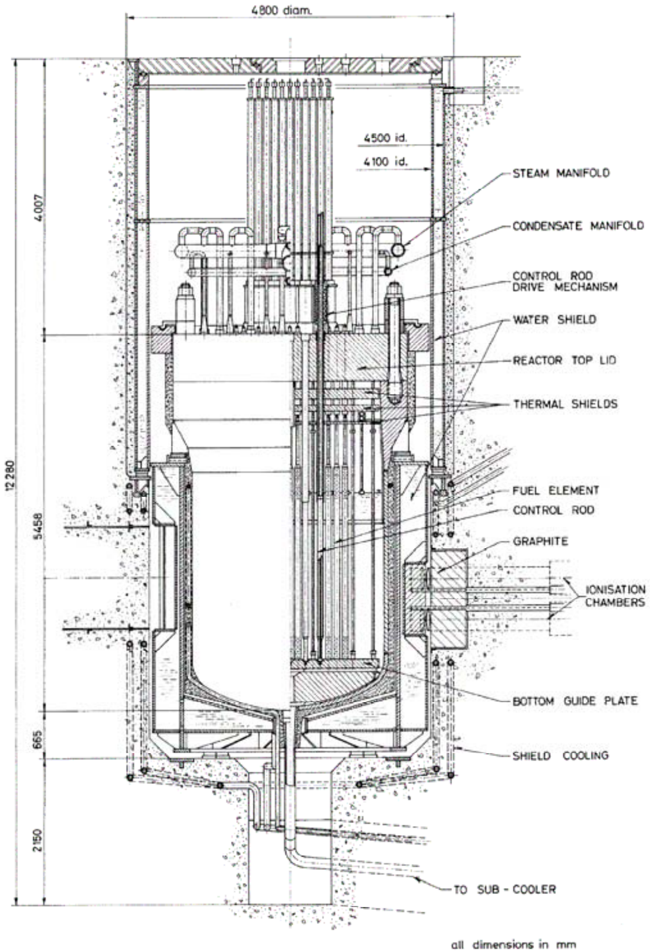
HBWR (Norway, 1959)

- 20 MW, boiling heavy water reactor
  - still operating today



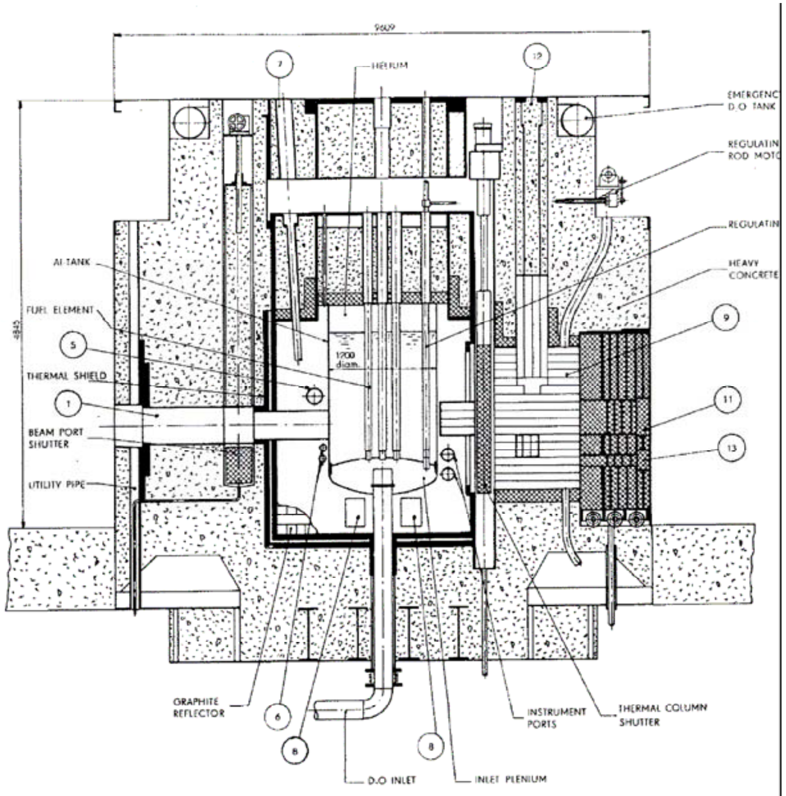
HORIZONTAL SECTION
REACTOR HBWR



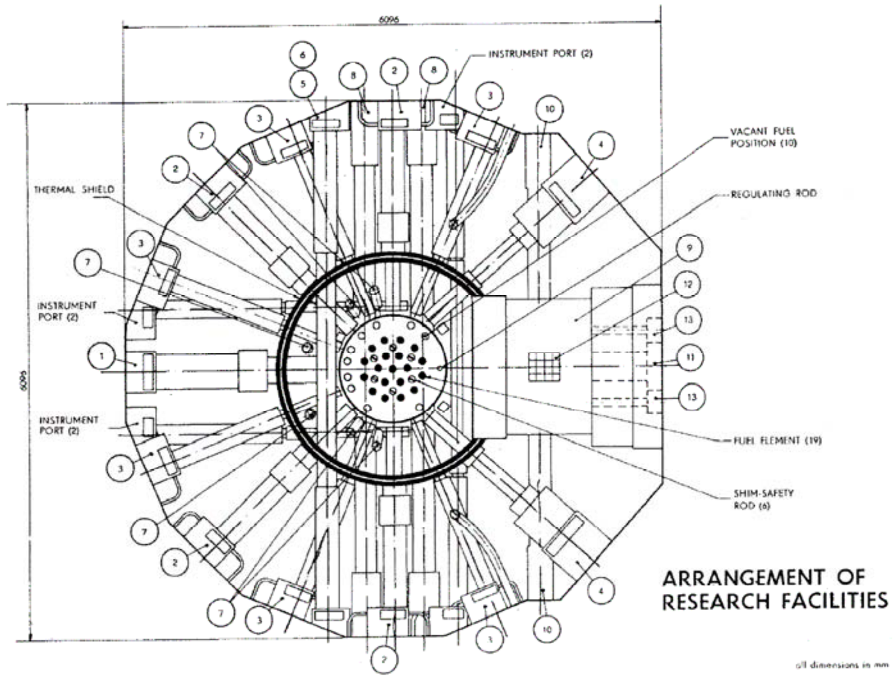
VERTICAL SECTION REACTOR HBWR

ISPRA-1 (Italy, 1959)

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



ISPRA VERTICAL SECTION



ARRANGEMENT OF RESEARCH FACILITIES

all dimensions in mm

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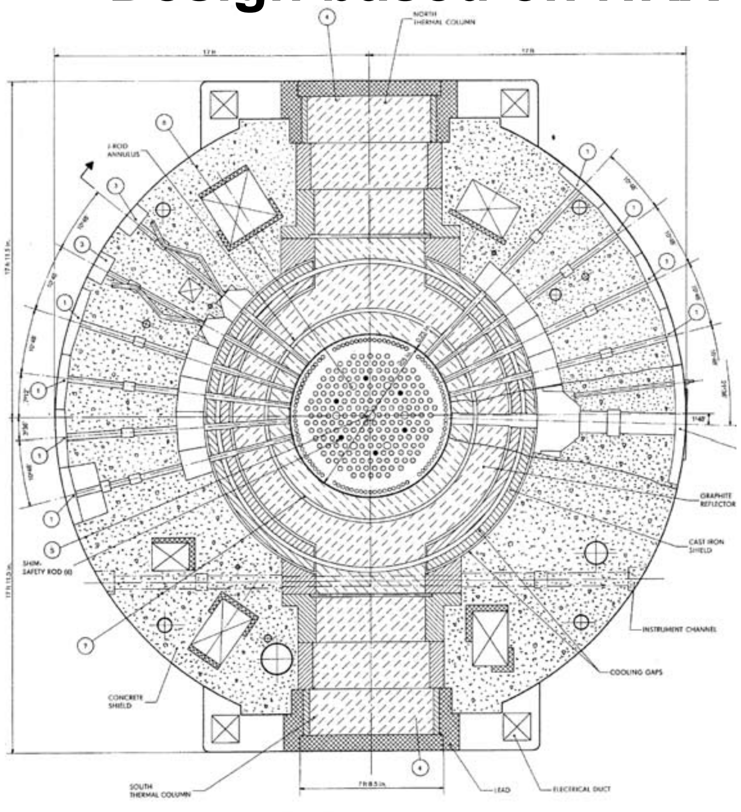
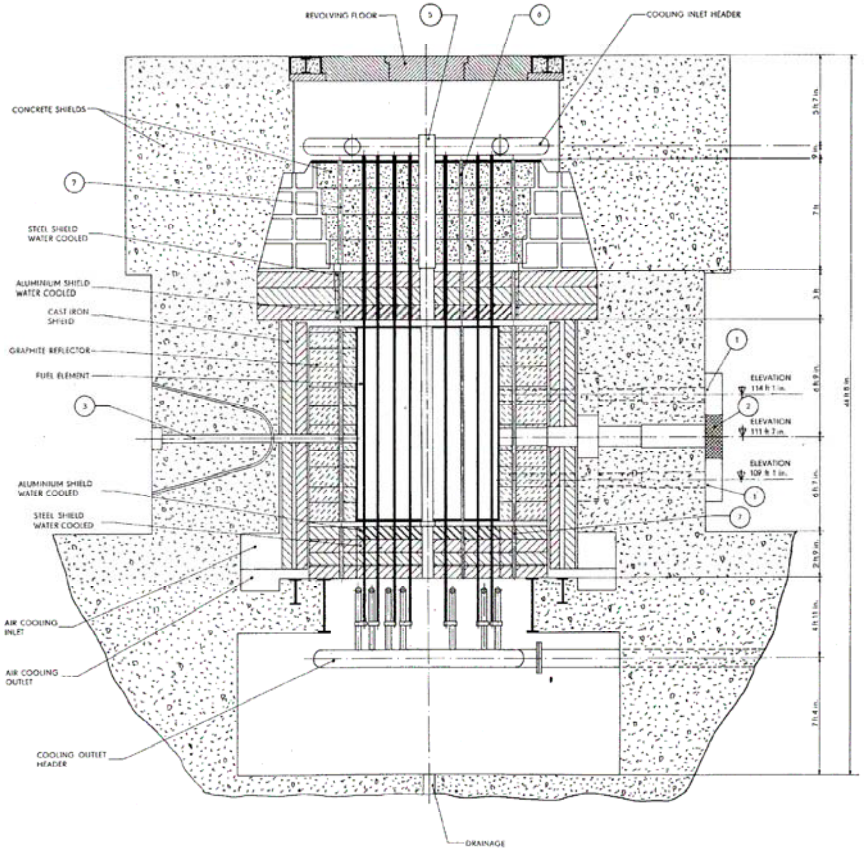
CIRUS (India, 1960)

- **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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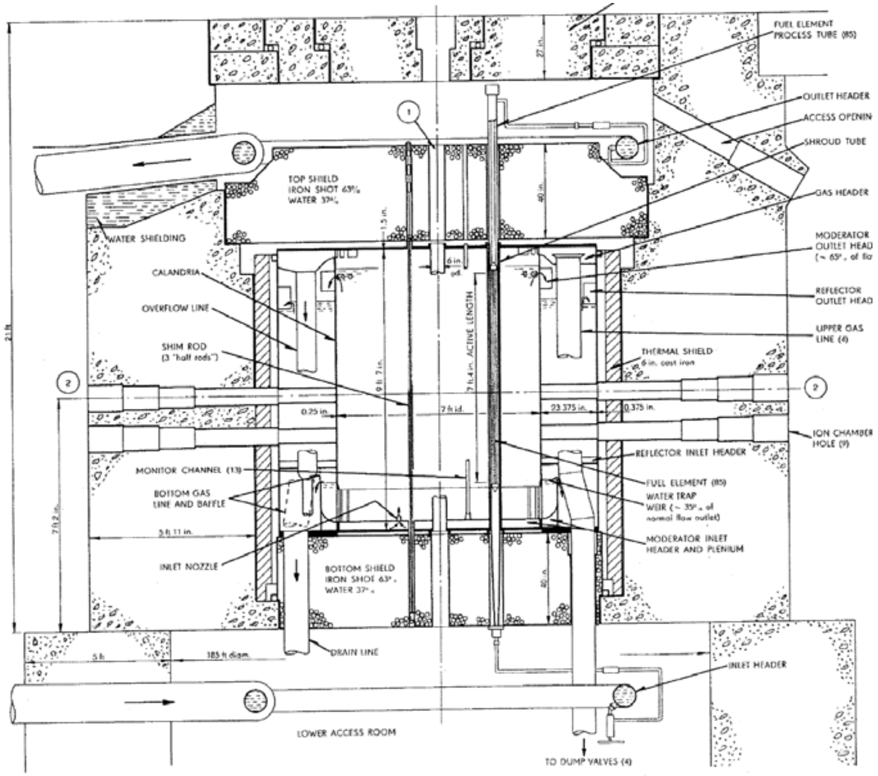
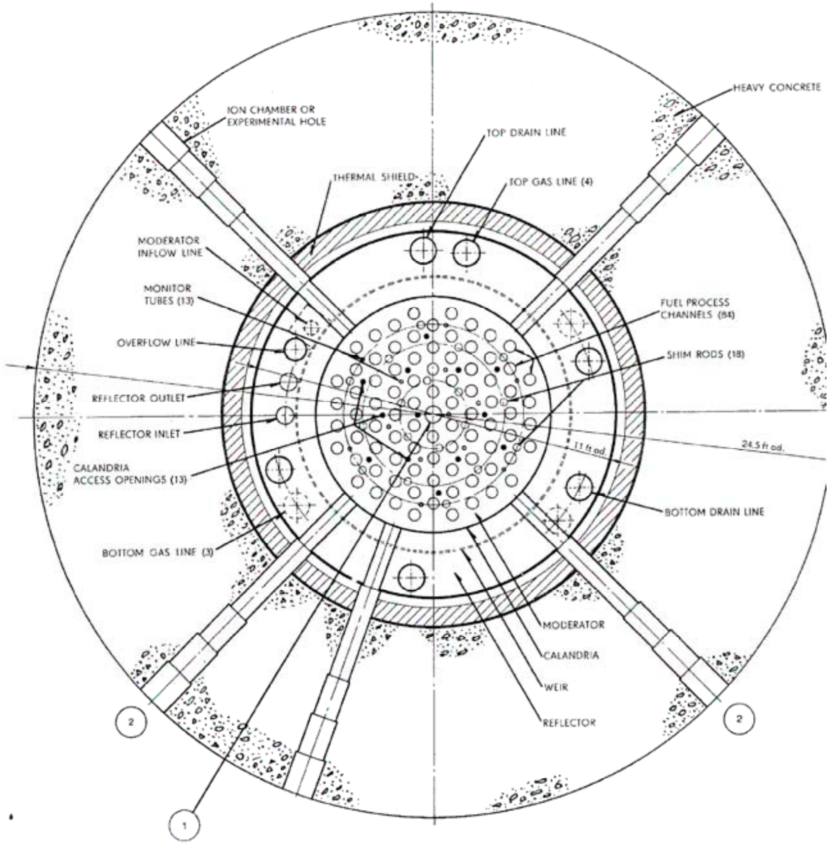
PRTR (U.S.A, 1960)

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



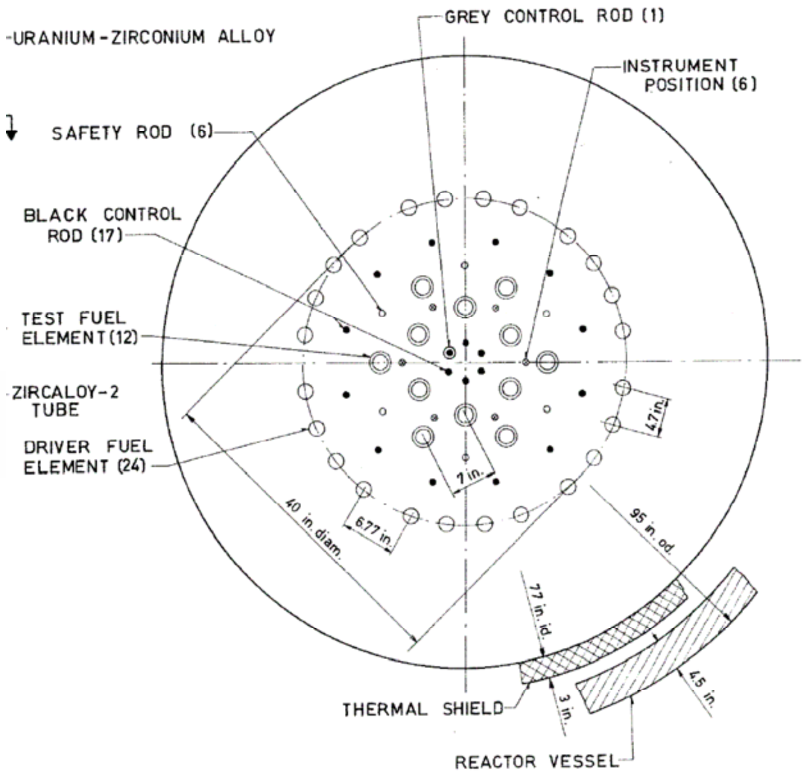
VERTICAL SECTION PRTR



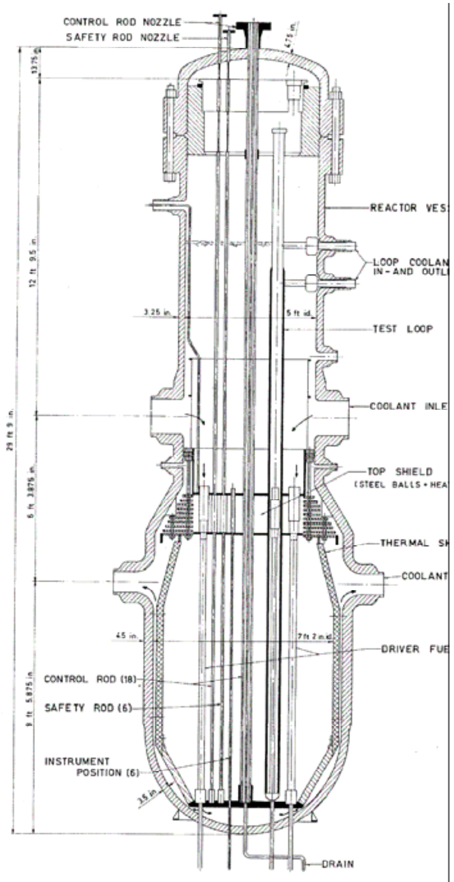
HORIZONTAL SECTION PRTR

HWCTR (U.S.A., 1962)

- **Heavy Water Components Test Reactor**
  - **61 MW, Savannah River**



HORIZONTAL SECTION REACTOR HWCTR



VERTICAL SECTION REACTOR HWCTR

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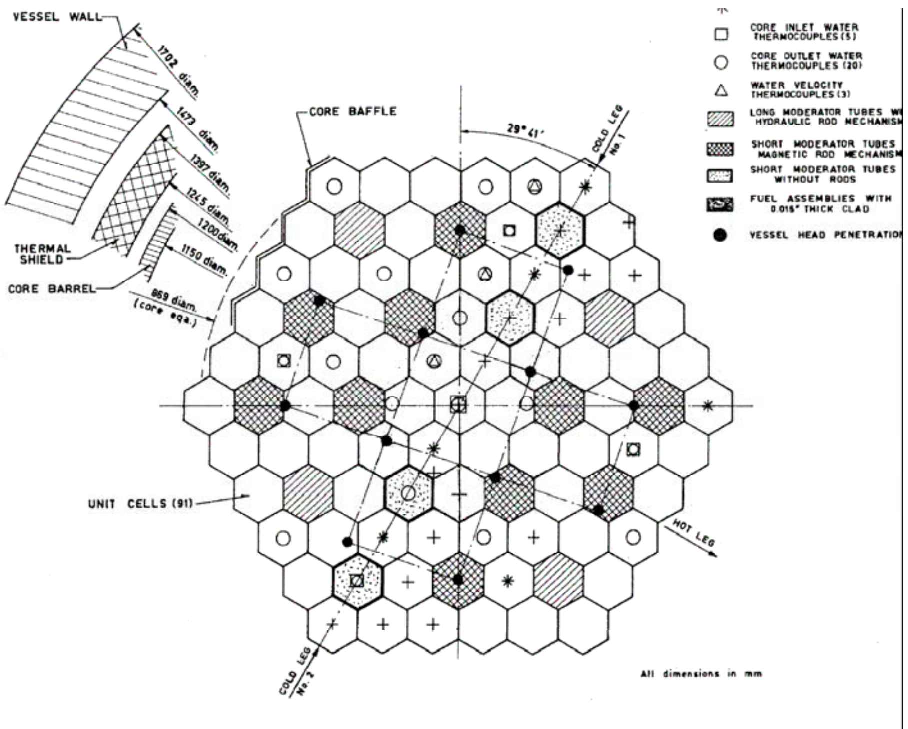
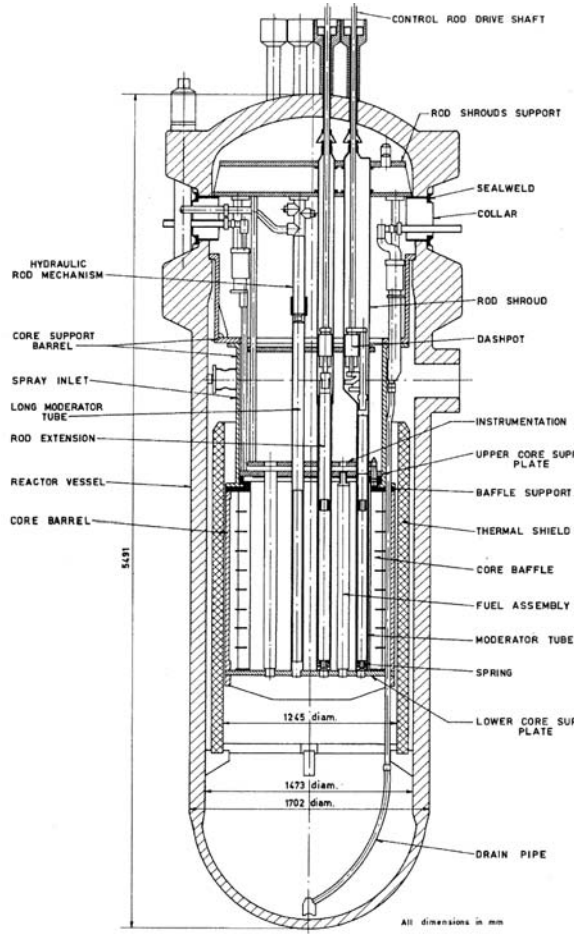
BR-3 Vulcain (Belgium, 1965)

- **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

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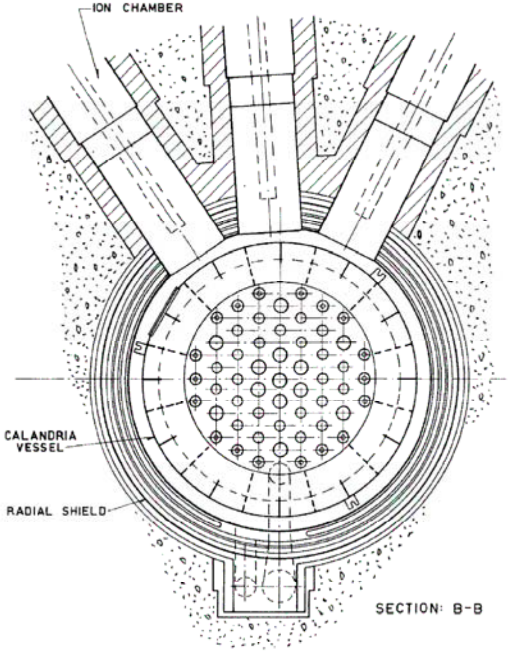
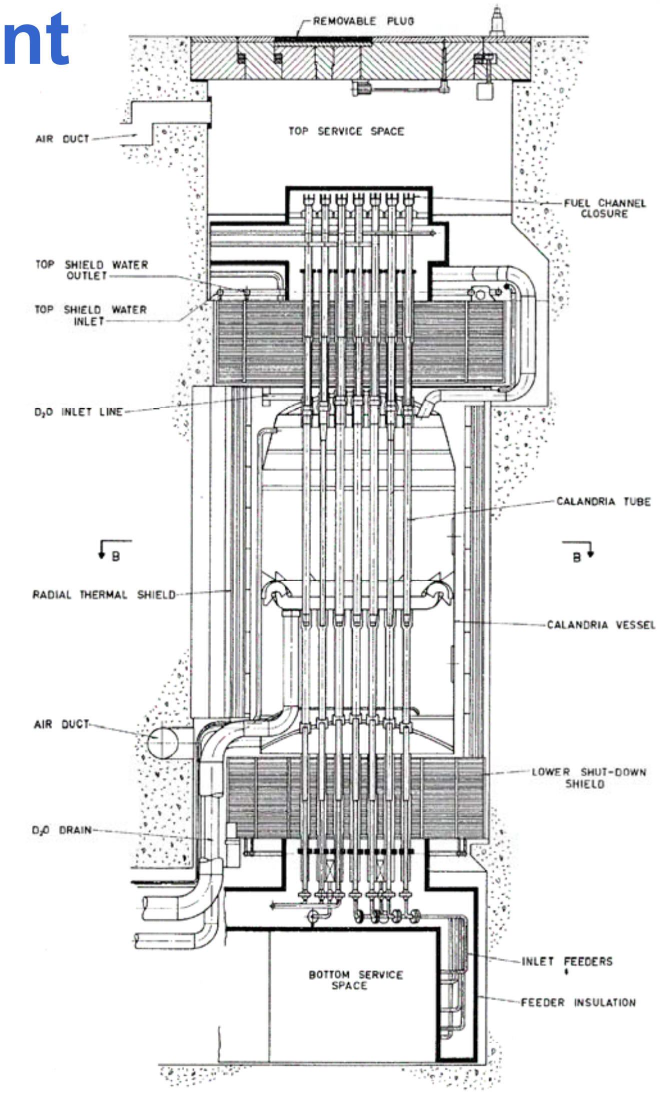
WR-1 (Canada, 1965)

- **40 MW, testing organic coolant**
  - **Operation successful.**



HORIZONTAL SECTION REACTOR WR-1

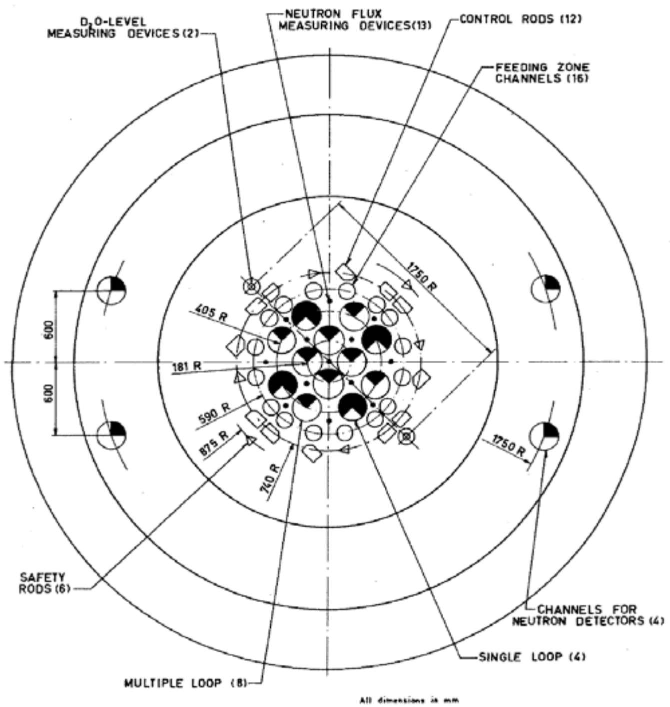


VERTICAL SECTION REACTOR WR-1

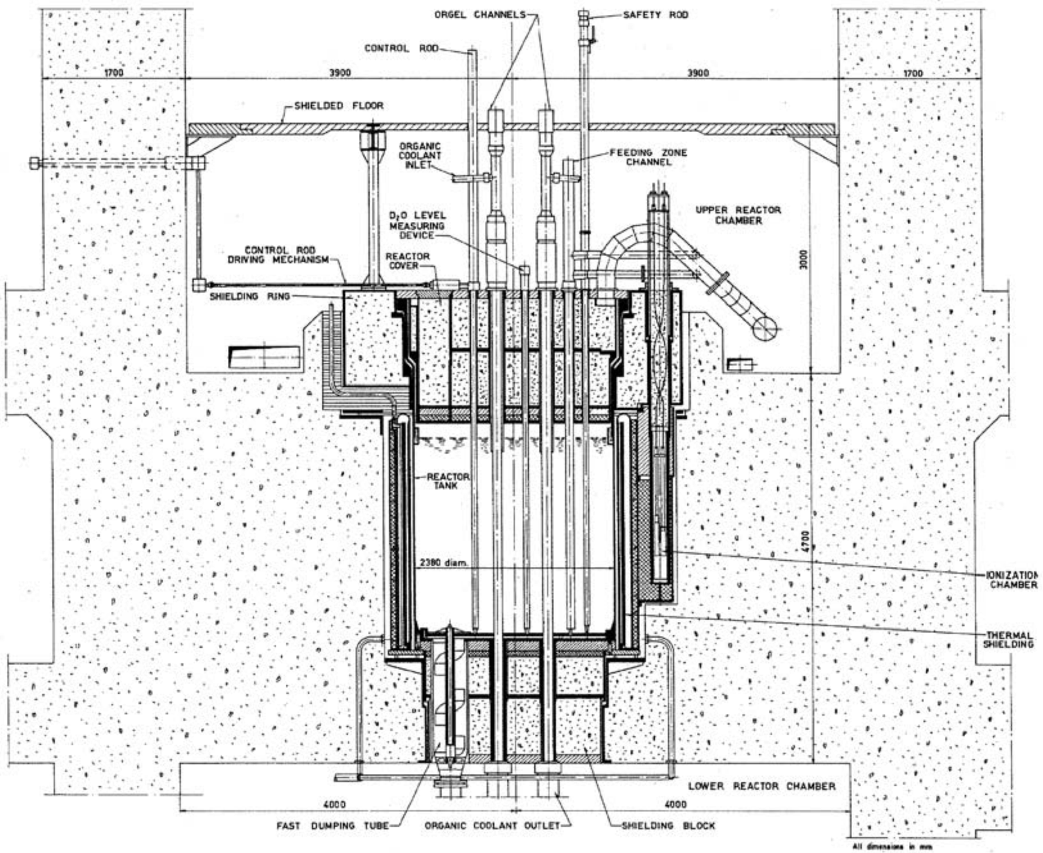
UNRESTRICTED

ESSOR (Italy, 1967)

- **37 MW, tests for organically-cooled HWR’s**



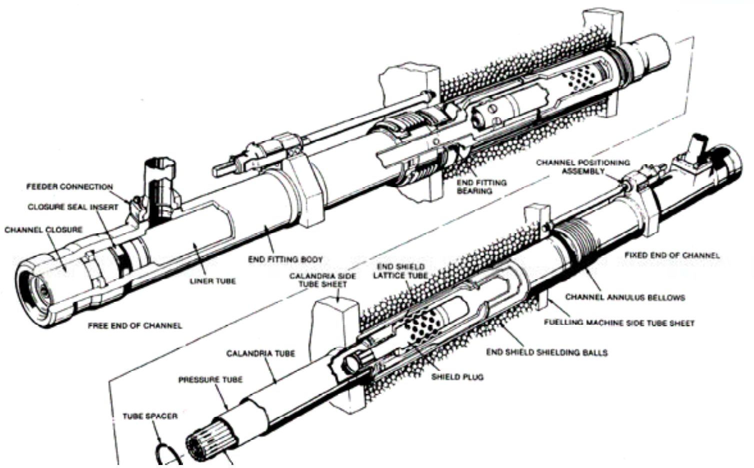
HORIZONTAL SECTION REACTOR ESSOR



VERTICAL SECTION REACTOR ESSOR

Present 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.**



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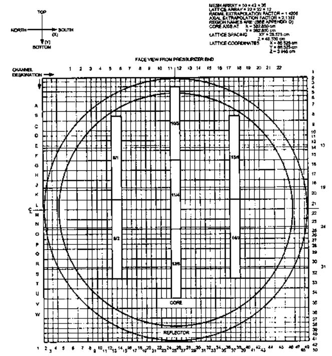
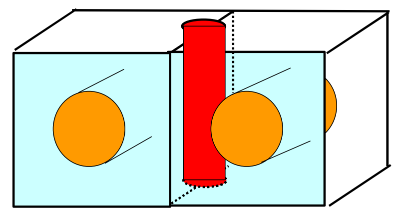
Present R&D Efforts and Needs

- **Physics Issues**
  - Biases and uncertainties in reactivity coefficients
  - Scaling from critical experiments to power reactors
  - Modelling approximations / development
    - Deterministic vs. Stochastic (Monte Carlo)
    - Heterogeneous vs. Homogenous
      - Size of homogenization regions.
      - Multi-cell modeling
      - Discontinuity factors
    - Transport vs. Diffusion
    - 2-group vs. multi-group
    - 2-D lattice cell vs. 3-D lattice cells
    - Reactivity devices (orthogonal to lattice)





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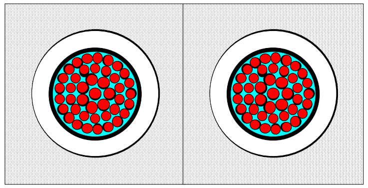
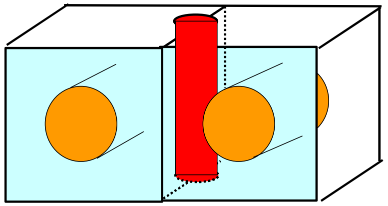
Present R&D Efforts and Needs

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





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Present R&D Efforts and Needs

- **Physics Issues**
  - **Nuclear Data**
    - **Accuracy and uncertainty estimates**
    - **Co-variance data**
    - **Thermal scattering data , S(α,β)**
      - 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 and 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 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, $\pm\delta$ 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)

Gen-IV / GNEP

- Supercritical Water
  - Materials, mechanical design
  - Reactor physics
- Advanced Fuel Cycles
  - Recycling Pu and Actinides 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

Conclusions

- International participation broad based
  - Use of heavy water reactors for research wide-spread.
  - Many countries today maintain at least one heavy water reactor.

- Present day efforts
  - Critical experiments for code validation
  - Nuclear data being re-evaluated for improved agreement.
  - Code development and validation ongoing.
  - Canada, India are leading the way in HW research
    - Support for CANDU, ACR-1000, AHWR, etc.

A Few References

- **More recent:**
  - IAEA, Nuclear Research Reactors in the World, reference data series #3, Sept. (2000).
  - http://www.iaea.org/worldatom/rrdb/
  - NEA/NSC/DOC (2006)1 : International Handbook of Evaluated Reactor Physics Benchmark Experiments, March (2006).

- **Older, but good:**
  - IAEA, Heavy Water Lattices: 1st Panel Report, Vienna, 4 Sept., (1959).
  - IAEA, Heavy Water Lattices: 2nd Panel Report, Technical Series No. 20, Vienna, 18-22 Feb. (1963).
  - IAEA, Exponential and Critical Series, Volume 2, Vienna, (1964).
  - IAEA, Directory of Nuclear Reactors, Vols. 2, 3, 5, 6, 8, Vienna, (1959-1970).
  - United Nations, Proceedings of International Conference on the Peaceful Uses of Atomic Energy, 2nd and 3rd Conferences, Geneva, (1958, 1964).

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November 3, 2007

50th Anniversary of NRU

- 50 years of science and technology.
- Millions of patients treated from medical radioisotopes.
- Test bed for CANDU technology.
- Neutron scattering experiments.
- Materials testing
  - Space Shuttle Challenger SRB casing / welds.
- Thousands of visiting researchers.
- www.aecl.ca/nru50

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