# The CANDU Program and AECL

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## CANDU:

CAN=Canada, D=Deuterium, U=Uranium

A distinctive, world-class nuclear-reactor system successfully developed in-house by a country with a relatively small population. A great success story.

In 1987, CANDU was voted one of Canada's top 10 engineering achievements!

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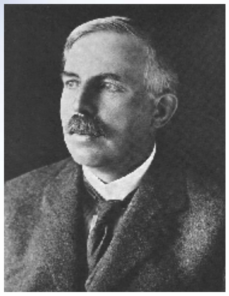
## Atomic and Nuclear Physics: Canada Contributes Early



Ernest Rutherford (1871-1937) Nobel Prize in Chemistry, 1908

- Significant work done in Canada very early in the history of atomic physics – most importantly in research on radioactivity by Lord Ernest Rutherford (discoverer of the atomic nucleus) at McGill University in Montreal, 1898 –1907:
  - the law of exponential decay; the term “half life” enters the language!
  - Radioactive emissions categorized into 3 types: $\alpha$, $\beta$, $\gamma$.



## At McGill University, 1905

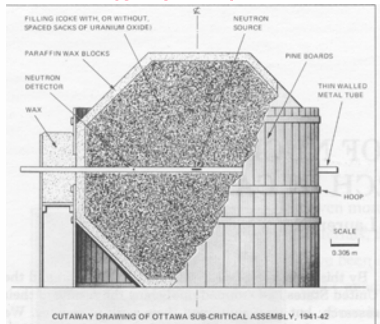
**Otto Hahn, 26 yrs. old (1944 Nobel Prize, Chemistry)**

**Ernest Rutherford**

## Early Canadian Work on Fission

George Laurence & subcritical assembly.

As soon as fission is discovered, research work goes on in Canada. George Laurence (later first President of the Atomic Energy Control Board) works on neutron multiplication in uranium, using carbon (graphite) as a moderator.

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## World War II

- Canada gets involved with the allies in the war effort on fission.
- Canada's mandate for the war effort: build a heavy-water plutonium-production reactor (to be called NRX).
- To work in a safer location, British physicists, and French physicists who had escaped to Britain, are moved to Canada.
- The French (Lew Kowarski) bring their heavy water!
- The "Montreal Laboratory" is established – a British-French Canadian team at the University of Montreal.
- The team is moved to new labs at Chalk River in 1944.
- Decision to build a prototype zero-power heavy-water reactor, ZEEP, for research.

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## 1944: Chalk-River then…

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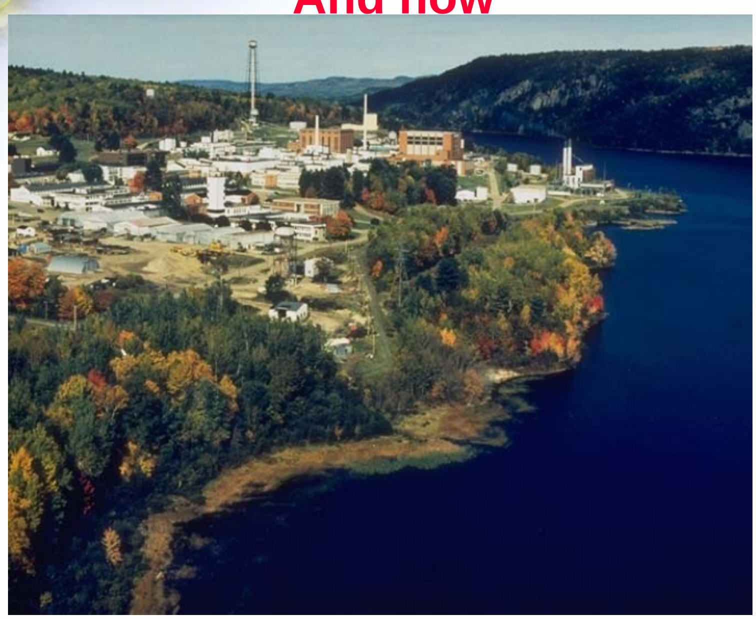
## And now



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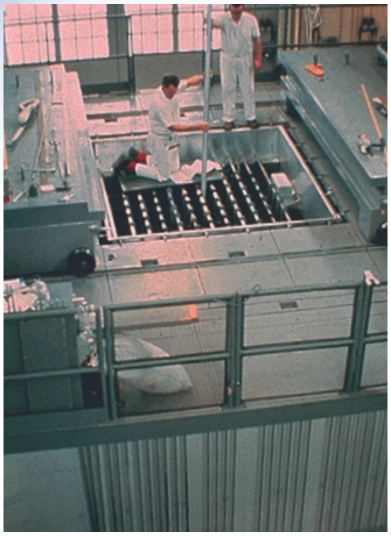
## ZEEP



Lew Kowarski's Baby

Achieves criticality 1945 Sept. 5: days after end of WWII, and first sustained man-made nuclear chain reaction outside USA!

Provides excellent research data for heavy-water reactors over the years.

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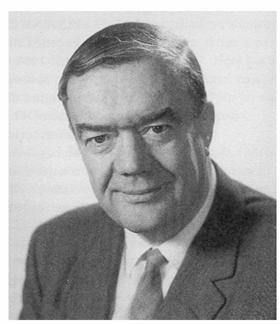
## The Origins of CANDU

- 1946: Wilfrid Bennett Lewis takes over as Head of Chalk River. He is recognized as "Father" of CANDU.
- Lewis is the driving force in Canada behind the application of nuclear science to electricity production.
- Canada decides to build its program on its attained expertise: natural-uranium fuel and heavy-water moderator.

See excellent book on
early history of Chalk River
"Canada Enters the Nuclear Age"
McGill-Queen's University Press, 1997
Available from AECL & CNS



W.B. Lewis
[Past ANS
President]

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## More Canadian Nuclear Milestones

- 1947: NRX (20 MW) achieves criticality. Never produced Pu for war effort, but highest neutron flux in world in its day.
- Research in Chalk River on fuels and zirconium contributes to the US nuclear submarine program.
- 1950: Approval for building NRU (200 MW).
- 1951: Dr. Harold Johns develops Cobalt Therapy Machine – continues to save thousands and thousands of lives annually to this day.
- 1952: AECL is established as a Crown Corporation.
- 1954: AECL's Power Division established in Toronto (design authority for CANDU)

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## Chalk River Early Research Reactors



***NRU: Provider of radionuclides to the world – then and now.***

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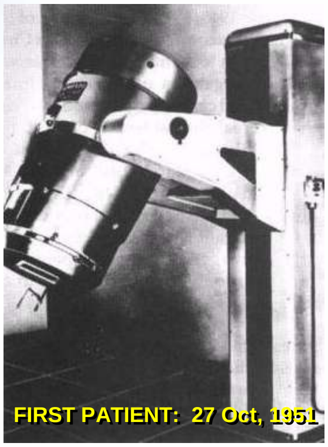
# 1951 COBALT CANCER THERAPY

## "The Atom Bomb That Saves Lives"

MacLean's Magazine

University of Western Ontario, London




University of Saskatchewan, Saskatoon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# Atomic Energy of Canada Limited

- Became a Commercial Crown Corporation in 1952, with mandate to lead Canadian nuclear industry in developing peaceful benefits of nuclear energy
- Current staff: 3,500
- AECL activities: reactor vendor, R&D, reactor services, refurbishment, waste management
- AECL designs, builds and services reactors around the world

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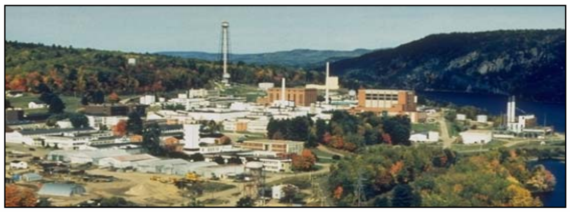
## AECL: Major Sites

Head Office, Sheridan Park, Mississauga: Executive offices; product design & development; nuclear services; business development. 1,500 staff.



Chalk River Laboratories: Nuclear safety, health & environment R&D; nuclear platform infrastructure; legacy management. 1,800 staff.

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## First CANDU Prototype: NPD

- First Canadian nuclear electric power: Nuclear Power Demonstration reactor (NPD), 20 MWe
- Achieves criticality in 1962
- Demonstrates soundness of the CANDU design concept:
  - heavy-water moderator: superior neutron economy & uranium utilization, allows use of natural U (without excluding other fuels)
  - Horizontal pressure-tube design: no large pressure-vessel needed, allows calandria with benign environment (low temperature, pressure)
  - on-power refuelling

  [This has remained the CANDU concept all along.]
- Operates for 25 years and meets all objectives in operations, research, and training.
- Opens the way for large CANDUs
- Is closed down in 1987.
- Wins ANS Historic Landmark Award in 2002!

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# ANS Historical Landmark Awarded to NPD


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# CANDUs in Canada & Worldwide

| | |
|---|---|
| • 4 at Pickering 'A' - 4 x 514 MWe | 1971 - 73 |
| • 4 at Bruce 'A' - 4 x 750 MWe | 1977 - 78 |
| • 4 at Pickering 'B' - 4 x 514 MWe | 1982 - 86 |
| • 4 at Bruce 'B' - 4 x 750 MWe | 1984 - 87 |
| • 4 at Darlington - 4 x 880 MWe | 1992 - 95 |
| • Gentilly 2 | 1983 |
| • Point Lepreau | 1983 |
| • Wolsong 1 (Korea) | 1983 |
| • Embalse (Argentina) | 1984 |
| • Wolsong 2 | 1997 |
| • Wolsong 3, 4 | 1997 - 99 |
| • Cernavoda 1 (Romania) | 1996 |
| • Qinshan 1, 2 | 2002-2003 |
| • Cernavoda 2 | 2007 |

- 2006: More reactors proposed for Ontario
- Cernavoda 3, 4 being considered (financing) in Romania

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## 4-Unit Stations – e.g., PICKERING

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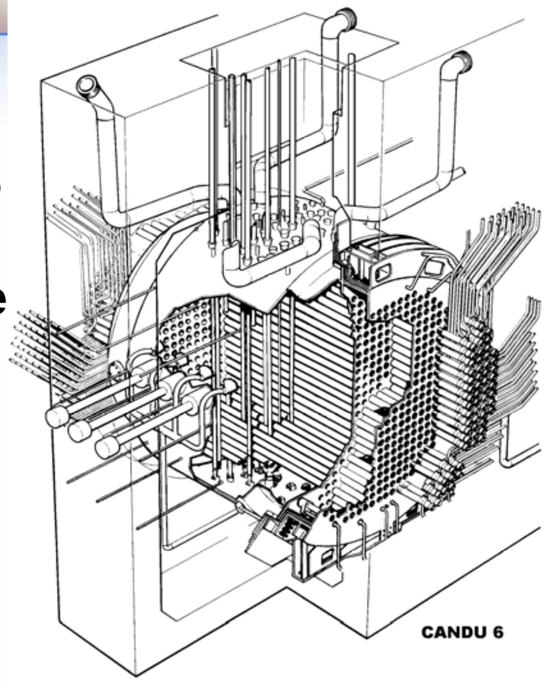
## Record-Breaking Twin CANDUs at Qinshan, China, 2003

**CANDU 6 Reactor (700-MWe Class)**






## Reactor Physics at AECL

- Reactor Physics Branches:
  - In AECL Design Office in Sheridan Park (in Mississauga, suburb of Toronto), and
  - at Chalk River Laboratories (200 km NW of Ottawa)
- Exciting, challenging work on-going on a multitude of projects and tasks
- Dedicated “satellite” physics groups seconded to specific Project Branches (e.g., ACR-1000)
- “Nuclear renaissance” is taking off in Canada, just as it is in the US and other countries

## Reactor Physics Work at AECL

- Types of work (some more detailed discussion later):
  - New Reactor Design (Enhanced CANDU 6, Advanced CANDU Reactor)
  - Reactor Analysis
  - Operating-Station Support
  - Work in Support of Station Refurbishment
  - Work on Advanced Fuels and Fuel Cycles
  - Development and Application of Computer Codes and Methods: Lattice Physics (WIMS-AECL), Full-Core Codes (RFSP, MCNP)
  - Computer-code validation, documentation, QA
  - Experimental reactor physics in research reactors (ZED-2, NRU) at Chalk River
  - Analysis of experiments

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## Reactor Physics Work at AECL

- Other types of work:
  - Radiation Transport, Shielding, Dispersion Analysis, Environmental Analysis, Heat Balance
  - Support to Licensing
  - Communications with Regulator (Canadian Nuclear Safety Commission)
  - Support to various Projects within AECL: work on safety analysis, fuel design and performance, research-reactor design (MMIR Project)
  - R&D Support Work for CANDU Owners' Group (international association of utilities operating CANDUs)
  - Work on Gen IV

## Plant Refurbishment

- Scheduled for refurbishment in next several years:
  - Pt. Lepreau in New Brunswick (Canada)
  - Wolsong 1 (Korea)
  - Embalse (Argentina)
  - Under consideration: Gentilly-2 (Canada)
  - Bruce A, Units 1 and 2 (Canada)
- Physics work:
  - Design new “initial core”
  - Revisit safety analysis
  - Work in shielding and dose assessment in support of on-site refurbishment teams.



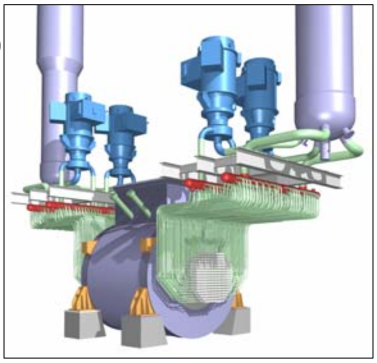
## Design: Enhanced CANDU 6

- Evolution of CANDU-6 design
- Slightly increased power level (740 MW)
- Simplification of systems
- Physics work:
  - Design of initial core
  - Review of layout of reactivity devices
  - Safety Analysis

## New Reactor Design - ACR

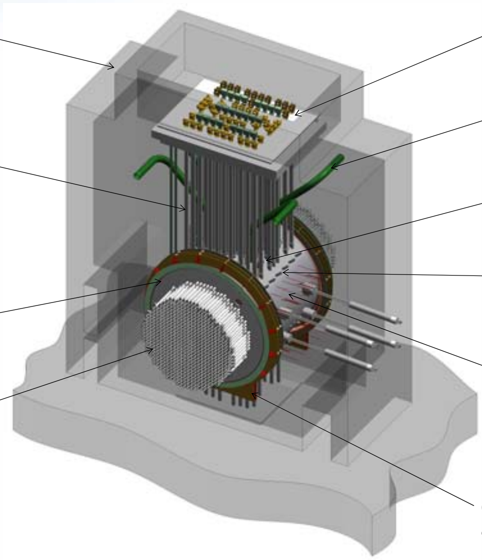
- Design Work on Advanced CANDU Reactor, ACR-1000 (~1,150 MWe)
- Generation 3+, builds on successful CANDU features
- Major incentive: large reduction in capital cost
- Use of light water as coolant, instead of heavy water (moderator remains heavy water)
- Reduced heavy-water inventory by reduction in lattice pitch
- Further reduction in heavy water by increase in insulating gap between pressure tube and calandria tube
- Use of low-enriched uranium (~1.8-2% enrichment)
- Simplification of many reactor systems
- Higher steam pressure for improved thermal efficiency
- Core Design Progressing

- ACR has
  - $H_2O$ coolant
  - tighter lattice pitch

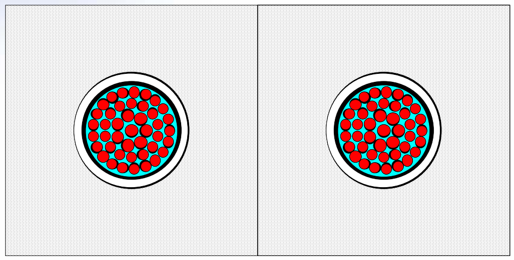




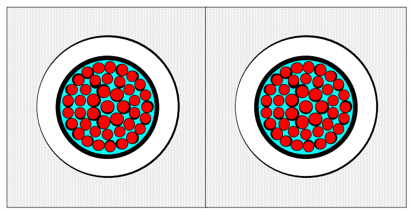
## ACR –1000 Reactor Assembly



## Lattice-Cell Comparison



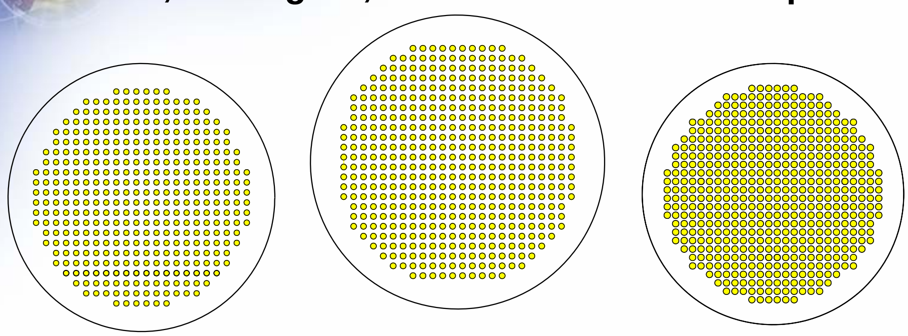
CANDU-6 Cells



ACR Cells



## CANDU 6, Darlington, ACR Reactor Core Comparison

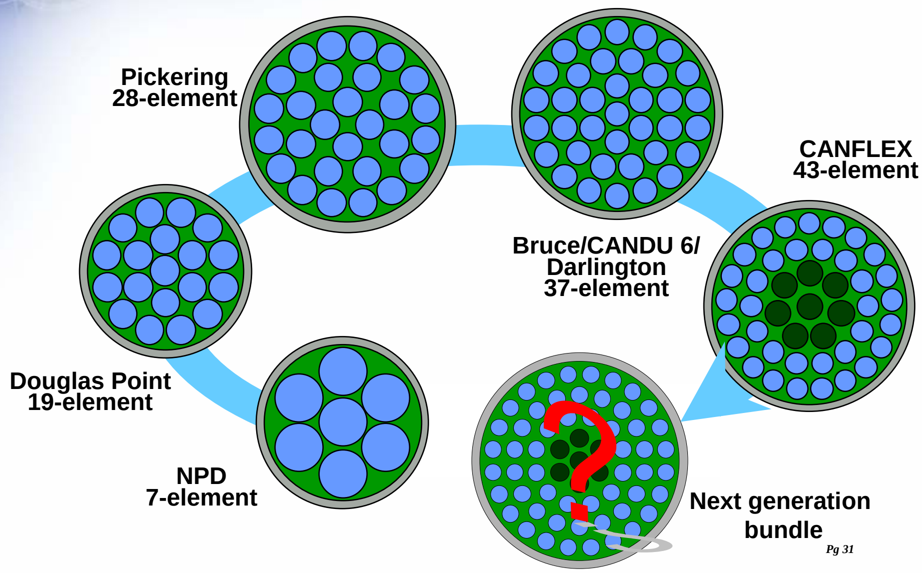


CANDU 6 | Darlington | ACR - 1000

| | CANDU 6 | Darlington | ACR-1000 |
|---|---|---|---|
| Number of channels | 380 | 480 | 520 |
| Reactor Core Diameter (m) | 7.6 | 8.5 | 7.6 |
| Lattice Pitch (cm) | 28.6 | 28.6 | 24 |
| Total D2O Volume Relative to CANDU 6 | 1 | 1.3 | 0.52 |

- **Calandria 7.6m (similar to CANDU 6)**
- **But 50% more power in ACR-1000 compared to CANDU**

## Work on Evolution of CANDU Fuel

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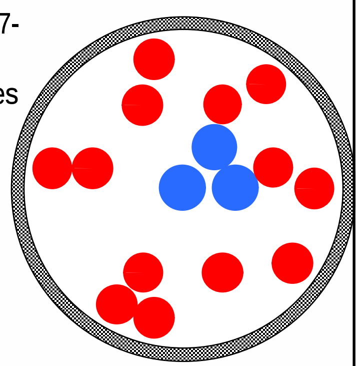
## CANFLEX Bundle

- 2 element sizes, 43 elements
  - reduces peak element ratings compared to 37-element bundle
- CHF (critical heat flux) -enhancement appendages
  - improves thermalhydraulic performance by promoting turbulence of coolant
  - restores lost margins due to plant ageing
- Qualified for commercial implementation



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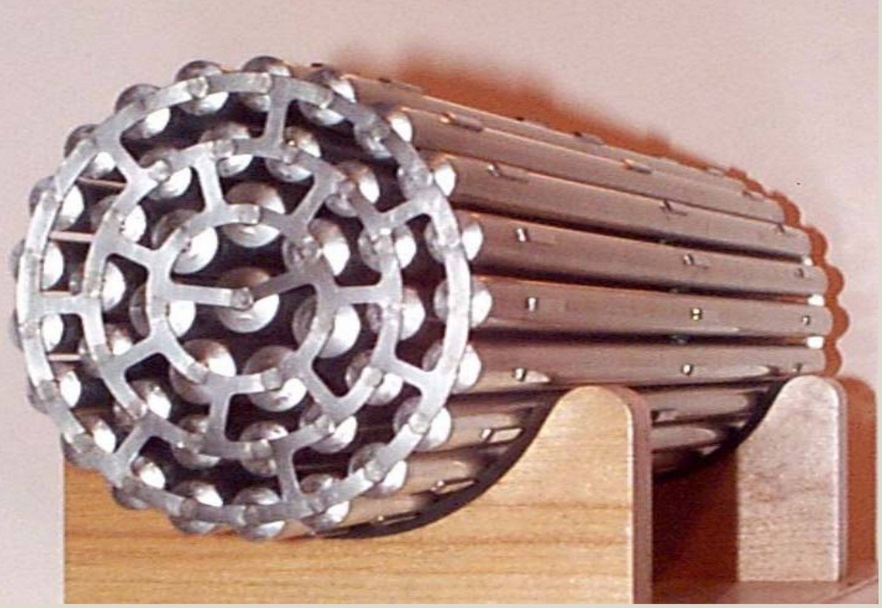
## CANFLEX Fuel Bundle



## Work on Advanced Fuel and Fuel Cycles

Incentives:

- Reduce fuel-cycle costs
- Increase bundle power, reactor power
- Reduce capital cost of new reactors (by optimizing power shape)
- Provide higher operating margins, higher safety margins
  - restore lost margins (due to plant ageing, or to licensing restrictions)
- Provide greater operational flexibility, such as power maneuvering
- Allow adjustment of reactivity coefficients
- Reduce volume of used fuel
- Further improve uranium utilization
- Make use of different fuel materials
  - plutonium from nuclear weapons
  - reprocessed LWR fuel
  - thorium

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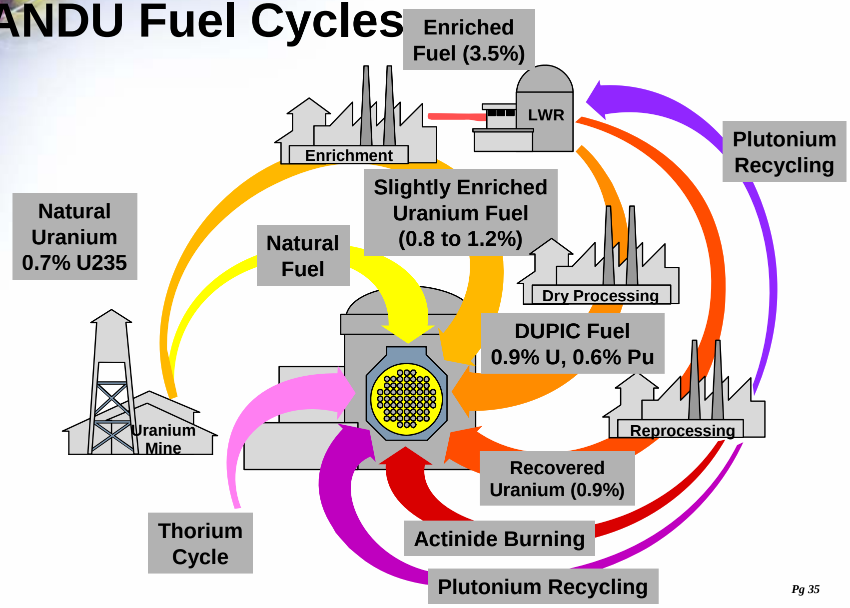
## CANDU Fuel Cycles

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## Slightly Enriched Uranium (SEU)

- CANDU has high flexibility in fuel use:
- Has high neutron economy and is very efficient in burning natural uranium, but can also use other fuels, e.g., Slightly-Enriched Uranium
- SEU:
  - ~0.9% U-235 to ~1.2% U-235
  - Discharge burnup ~14 MWd/kg(U) to ~ 21 MWd/kg(U), 2-3 times greater than that of natural uranium
  - Lower fuel-cycle cost, reduced volume of spent fuel
  - Lower disposal costs

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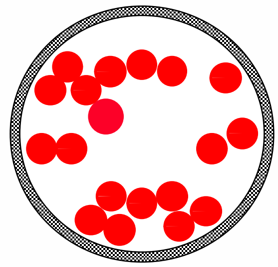
## Low-Void-Reactivity Fuel (LVRF)

- SEU in outer elements
- Neutron absorber in central element
  - Burnable poison mixed with natural uranium (NU)
- Can tailor the "coolant void reactivity"
  - by varying the poison content

  and burnup
  - by varying the enrichment
- Currently being qualified for implementation in Bruce reactors, with demonstration irradiation in core
- Research work also proceeding on higher-burnup LVRF



Poison in NU

SEU

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## Computer Codes and Methods

- For application to new reactor designs, and to new fuels and fuel cycles
- Work on Lattice-Physics Code WIMS-AECL, mostly performed at Chalk River:
  - New geometrical capabilities (e.g., improved treatment of corners in square cell with cylindrical channel)
  - Distributed resonance treatment
  - Multicell capability, to model several lattice cells simultaneously
  - Nuclear-data-library generation (for new data sets, added nuclides)
  - Coding verification
  - Documentation of new functionalities (Theory Manual, User's Manual, etc.)

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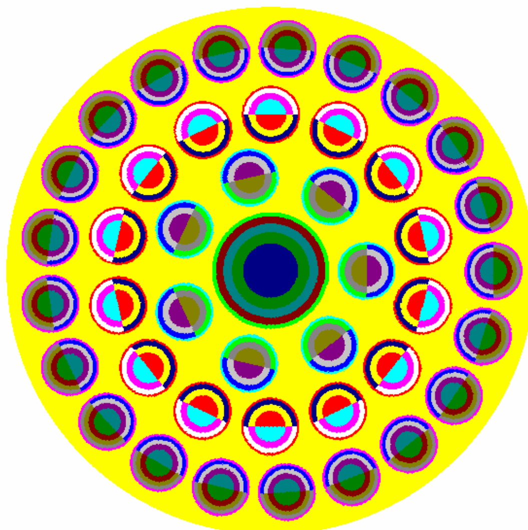
## Distributed Resonance Self-Shielding



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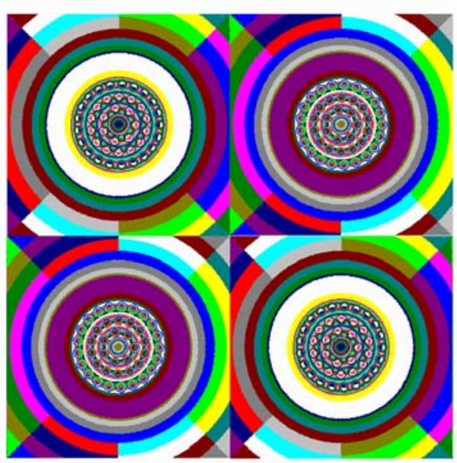
## Multicell Capabilities

### Checkerboard Lattice



Periodic Boundary Conditions

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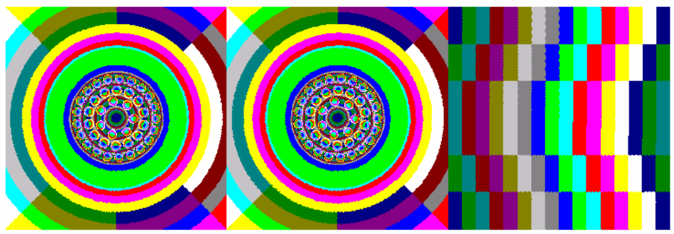
## Multicell Capabilities

### Core-Reflector Interface (e.g, 3-Cell Model)

Periodic or Reflecting Boundary

Reflecting Boundary



Vacuum

Periodic or Reflecting Boundary

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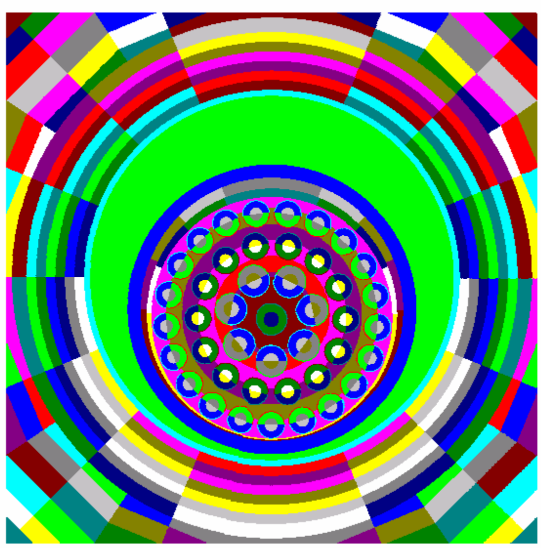
## Geometry Enhancements

### Modelling of Pressure-Tube Creep and Sag



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## Computer Codes and Methods

- Work on Full-Core Code RFSP, mostly performed at Sheridan Park:
  - New capabilities to cater to greater core heterogeneity and increased neighbour-coupling effects, e.g., checkerboard coolant voiding and core-reflector interface, by taking advantage of multicell capability in WIMS-AECL
  - Benchmarking against MCNP and other codes
  - Coding Verification
  - Documentation of new functionalities (Theory Manual, User's Manual,…)

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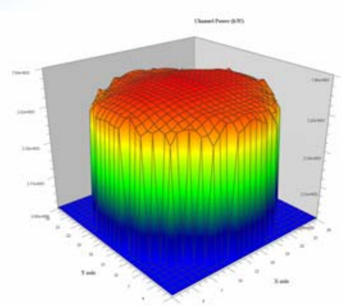
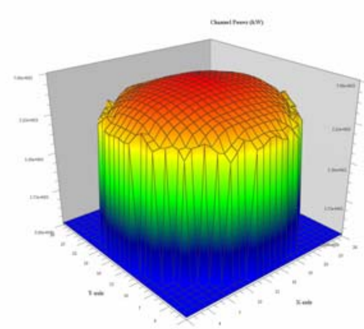
## RFSP-IST-Calculated Channel-Power Distributions for an ACR-1000 Core with and without the Multicell Correction Method

Without: With:

Multicell Correction at Fuel-Reflector Interface





## Computer Codes and Methods

- Highly increased use of MCNP in benchmarking and in design support:
  - Calculation of lattice properties
  - Possible use in calculating reactivity-device properties
  - Full-core simulations (e.g., benchmarking RFSP vs. MCNP)
  - Calculation of heat deposited
- Applications will surely increase
- One small example of a recent “different” application: core calculation with bundles in different locations rotated relative to one another.

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## Computer Codes and Methods

- Code validation on-going against measurements made in ZED-2 reactor at Chalk River and in external facilities:
  - DCA (deuterium critical assembly) [Japan]
  - DIMPLE [UK]
  - FUGEN Reactor [Japan]
- Validation will cover the WIMS/DRAGON/RFSP design code suite, as well as MCNP

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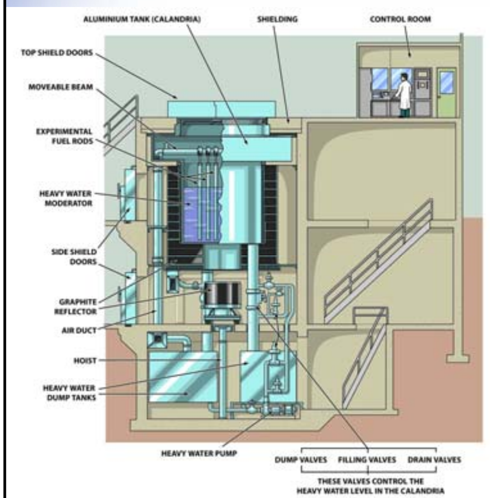
## Experimental Work:
## ZED-2 (Zero Energy Deuterium) Reactor at CRL

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## Measurements in ZED-2

- Material buckling (reactivity)
  - Full-core flux maps
  - Substitution experiments (test fuel substituted in part of reference lattice)
  - reactivity coefficients
    - void reactivity; fuel temperature; fuel/coolant temperature; moderator temperature, moderator purity, and moderator poison
- Reaction rates in foils
  - U-235, Pu-239, Dy-164, Cu-63, Mn-55, Au-197, In-115, Lu-176
  - reaction-rate ratios are sensitive indicators of the energy spectrum
  - for example In-115 has a large epithermal resonance at 1.457 eV and Cu-63 is ~ one-upon-v, In-115/Cu-63 capture is used to establish positions of asymptotic spectrum in a lattice
- Worth of reactivity devices (e.g., shutoff rod, zone controllers)

## Measurements in NRU: Fuel Irradiations for Fuel-Performance Analysis

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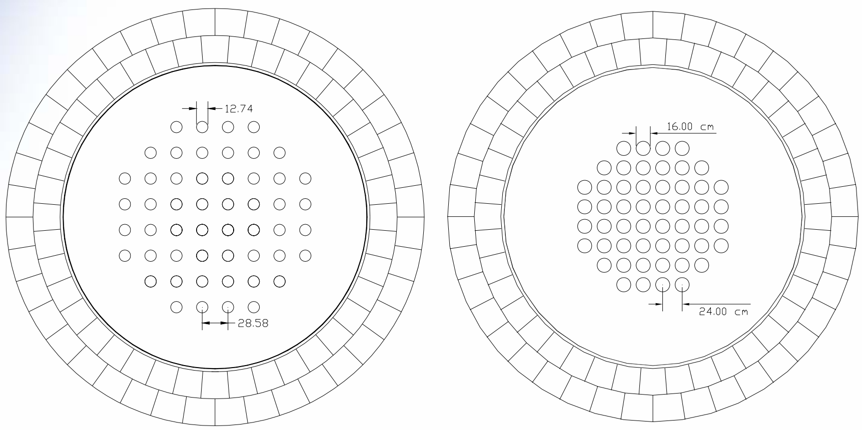
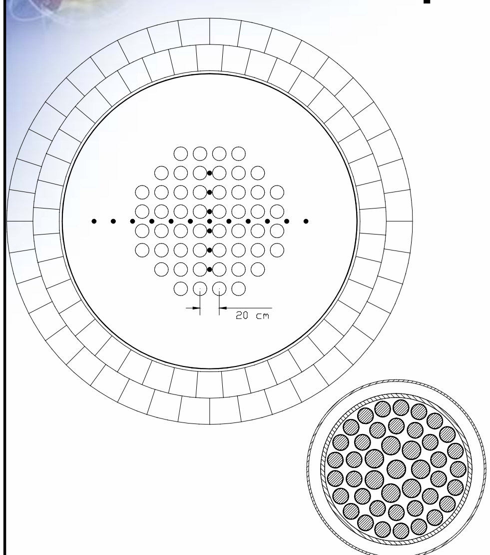
## ACR Lattice in ZED-2

CANDU 6-Type Lattice | ACR-Type Lattice




• ZED-2 ACR lattice captures the important physics in an ACR reactor *Pg 49*

## Flux-Map Measurements




- **Two axial measurements using stringers with Cu and In foils located one pitch from the lattice center in the East-West direction**
- **Radial measurements at 12 locations in the East-West direction and six locations in the North-South direction**

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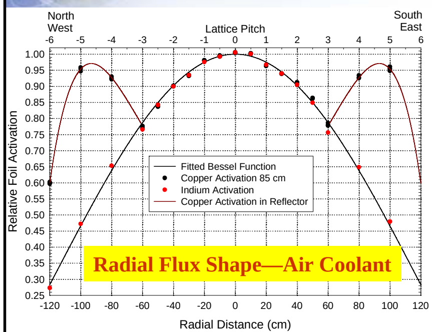
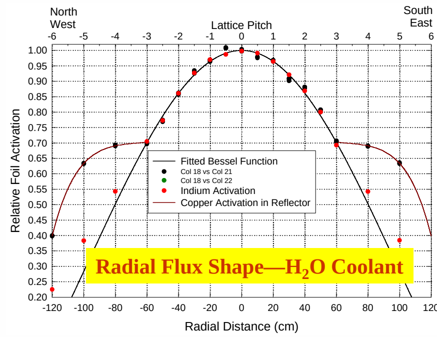
# MEASUREMENTS AT TIGHT PITCH




- **Flux maps show activation data in Cu and In foils clearly differentiates between regions in lattice and in reflector in terms of spectrum**
- **Data confirms thermal-flux peaking in reflector on voiding the channels**
- **Data will be used for validation of RFSP/WIMS and MCNP**
- **Developing method based on MCNP analysis for extension of results of substitution experiments to determine buckling of infinite lattice.**

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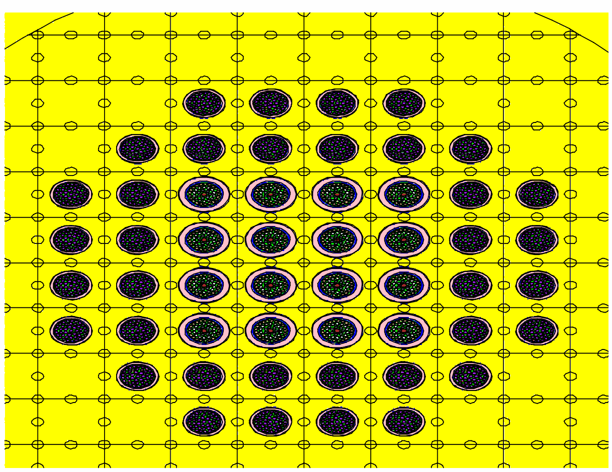
# Substitution Experiments- Example

**Test Fuel in 4 x 4 Substitution Region in Reference-Fuel Lattice**



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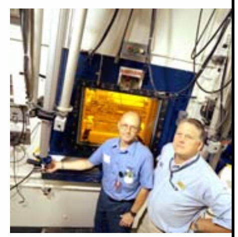
## CRL Experimental Facilities Supporting R&D in Physics and Fuel

**Fuel Fab Lab**

**Thermalhydraulics Lab**

**Surface Science Lab**

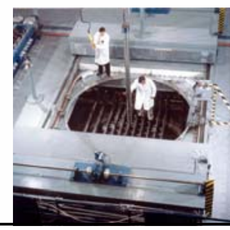
**Hot-cells**



**NRU**

**RFFL**

**ZED-2**



## Summary: Opportunities

- Range of opportunities for exciting and challenging work at both Sheridan Park and Chalk River in:
  - Design and analysis in physics, shielding, and radiation transport
  - Code development and validation
  - Experimental work on research reactors
- Opportunities for foreign assignments at CANDU projects and operating plants
- Opportunities for work in related areas, such as fuel design and analysis, thermalhydraulics, Licensing and Project work

Let the nuclear renaissance bloom!

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AECL
EACL

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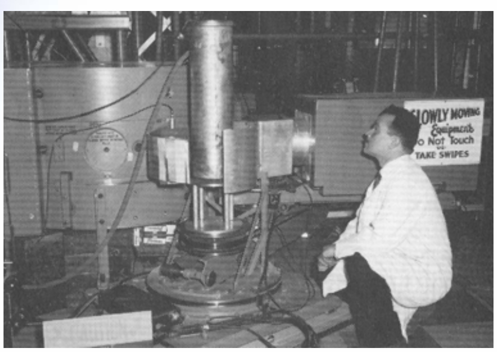
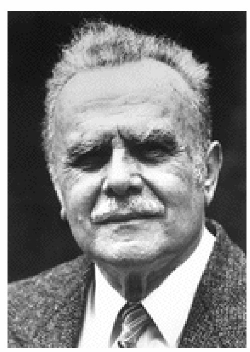
# 1950s: Neutron-Scattering Research




Brockhouse and His
Triple Axis Spectrometer, 1958



Bertram Brockhouse
(Nobel Prize in Physics, 1994)

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## NPD

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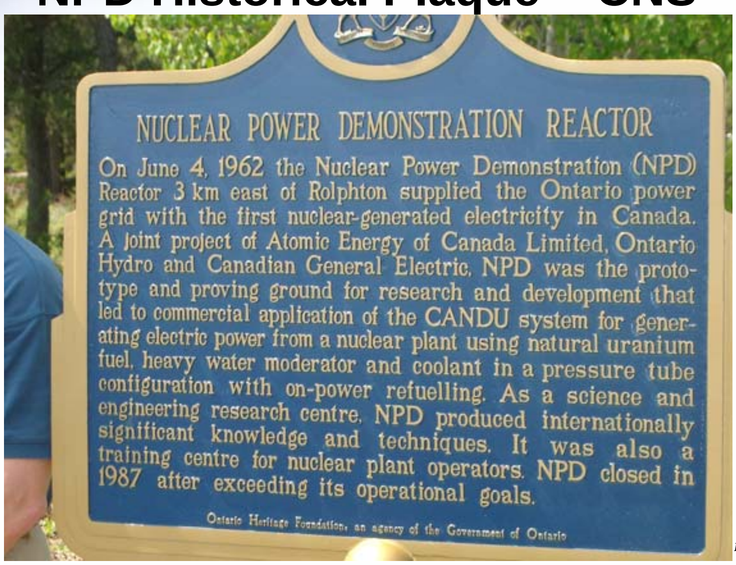
## NPD Historical Plaque - CNS

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## BRUCE

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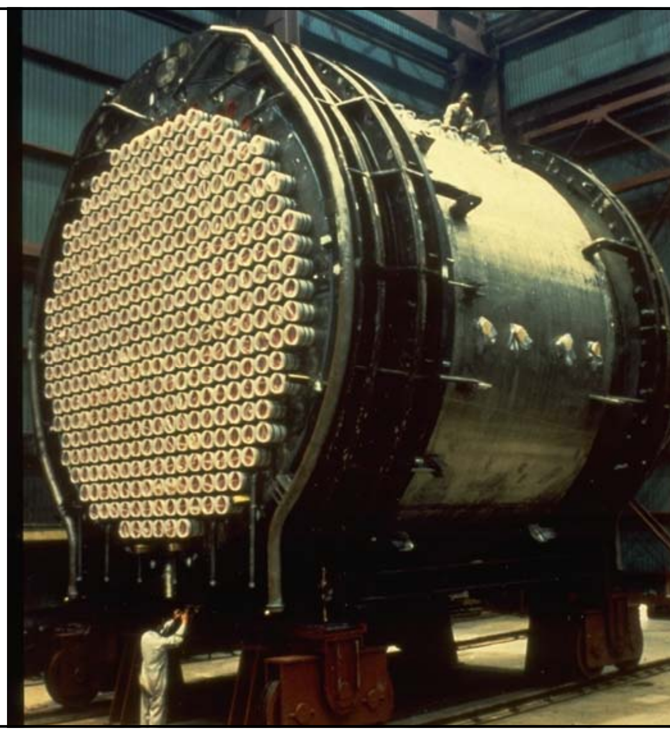
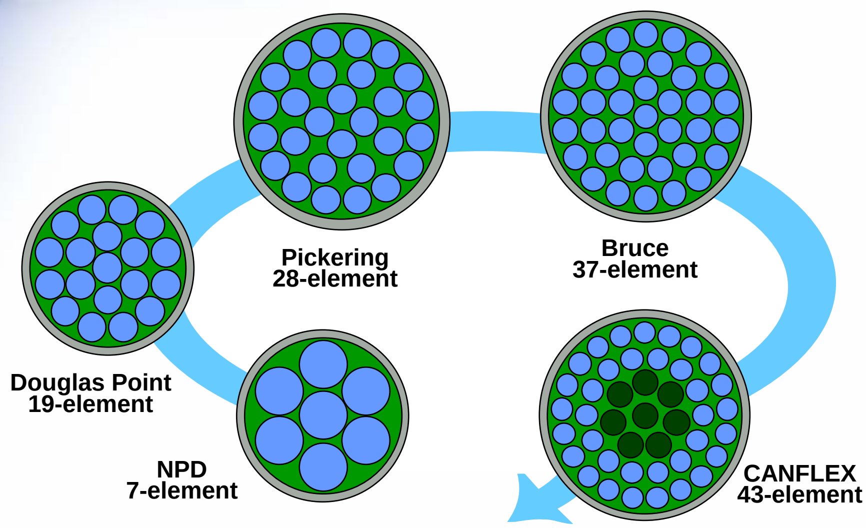


## Evolution of CANDU Fuel

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## Exports: CANDU 6 Worldwide

The Pickering design was adapted into a single-unit station, the CANDU 6, which has enjoyed great success:

| | |
|---|---|
| • Gentilly 2 | 1983 |
| • Point Lepreau | 1983 |
| • Wolsong 1 | 1983 |
| • Embalse | 1984 |
| • Wolsong 2 | 1997 |
| • Wolsong 3, 4 | 1997 - 99 |
| • Cernavoda 1 | 1996 |
| • Qinshan 1, 2 | 2002-2003 |
| • Cernavoda 2 | 2006 |

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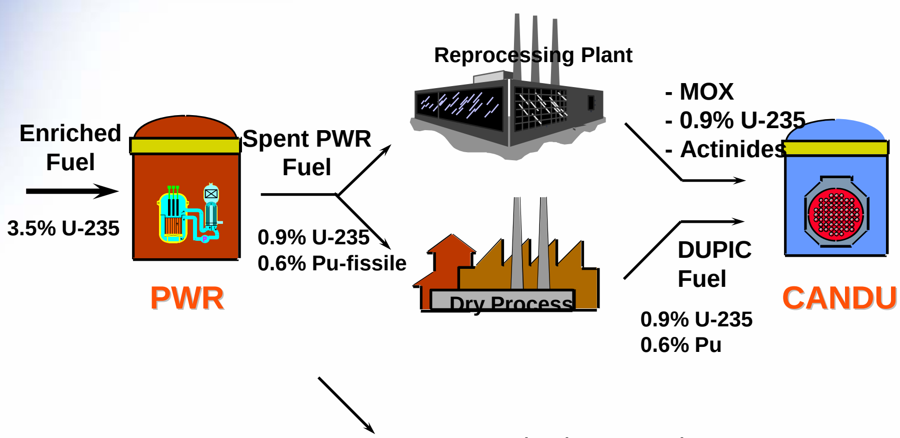
## Wolsong 3



## CANDU / PWR Synergism




“Unconventional” reprocessing . . .
“Advanced” recycling . . .

## Thorium Fuel Cycles in CANDU

- Ensure long-term fuel supply, using single reactor technology
  - no need for fast breeder reactors (FBR); but can complement FBRs
- Thorium has no fissile component
  - neutrons must be added to start the cycle
  - valuable U-233 builds up in the fuel (analogous to Pu-239 in uranium fuel)
  - recycling of U-233 in spent fuel can reduce uranium requirements by 90%
  - range of CANDU thorium fuel cycles possible
- Pu/Th is an effective option for w-Pu annihilation in existing CANDU reactors (94% of $Pu_f$ is destroyed)

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## Once-Through Thorium (OTT) Cycles

- U-233 is produced & burned in-situ; no reprocessing necessary
  - future mine of valuable U-233 produced in spent fuel at no additional cost
  - U-233 can be later recovered using proliferation-resistant technology, possibly cheaper and simpler than conventional reprocessing
- In optimal cycle, U-utilization & fuel cycle costs comparable to SEU
- Option 1: thorium and “driver” fuel irradiated in separate channels
  - can vary the relative fuelling rates; thorium remaining in longer
  - SEU most likely “driver” fuel; DUPIC, MOX, natural uranium also possible
- Option 2: thorium and “driver” fuel in same bundle

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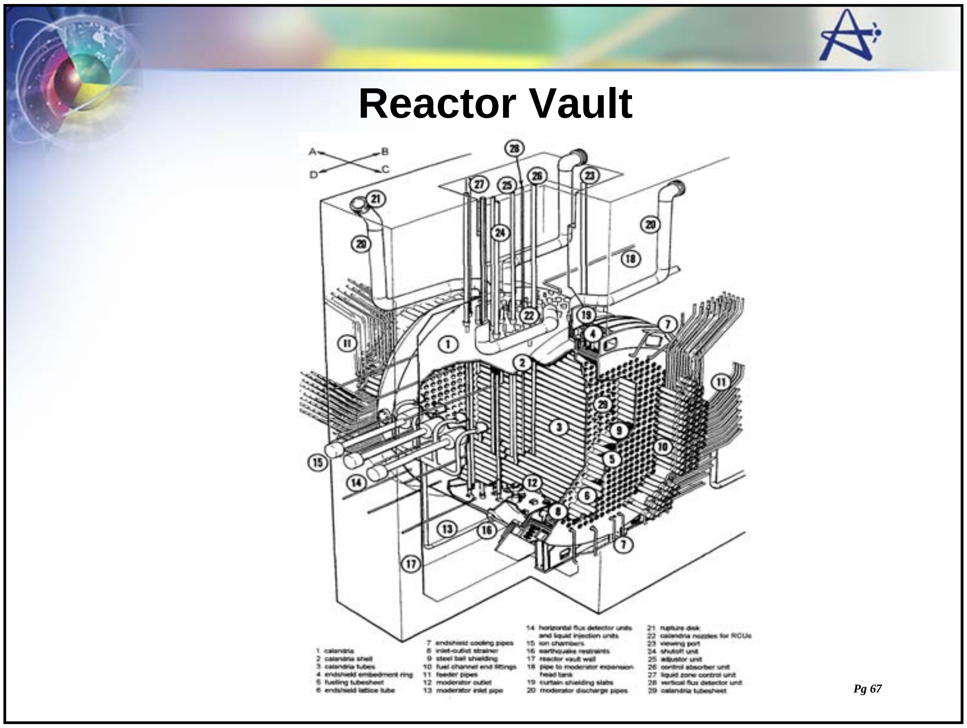
Reactor Vault
A
B
C
D
1 calandria
2 calandria shell
3 calandria tubes
4 endshield embedment ring
5 fuelling tubesheet
6 endshield lattice tube
7 endshield cooling pipes
8 inlet-outlet strainer
9 steel ball shielding
10 fuel channel end fittings
11 feeder pipes
12 moderator outlet
13 moderator inlet pipe
14 horizontal flux detector units and liquid injection units
15 ion chambers
16 earthquake restraints
17 reactor vault wall
18 pipe to moderator expansion head tank
19 curtain shielding slabs
20 moderator discharge pipes
21 rupture disk
22 calandria nozzles for RCUs
23 viewing port
24 shutoff unit
25 adjustor unit
26 control absorber unit
27 liquid zone control unit
28 vertical flux detector unit
29 calandria tubesheet
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