Sustainability of Nuclear Power

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Carleton Sustainable Energy Research Centre
Seminar Series
2011 March 28

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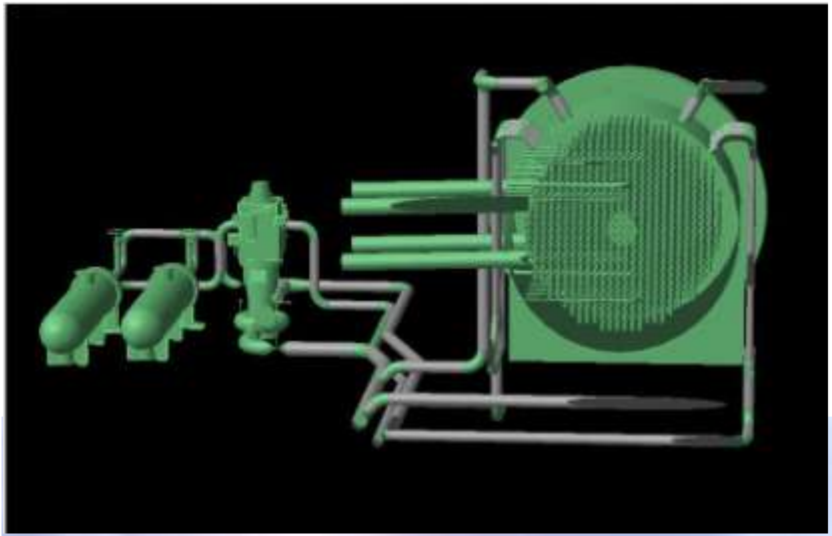
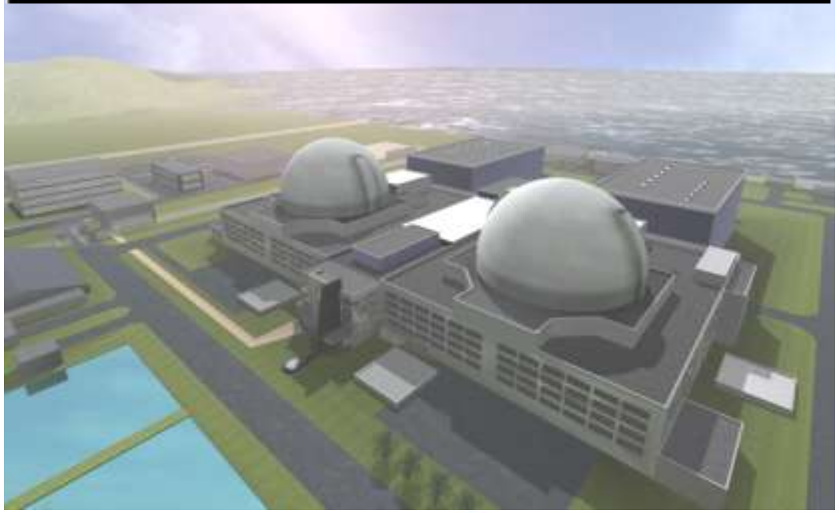
The drivers for nuclear growth

- Population Growth
- Economics
- Environment
- Energy Security





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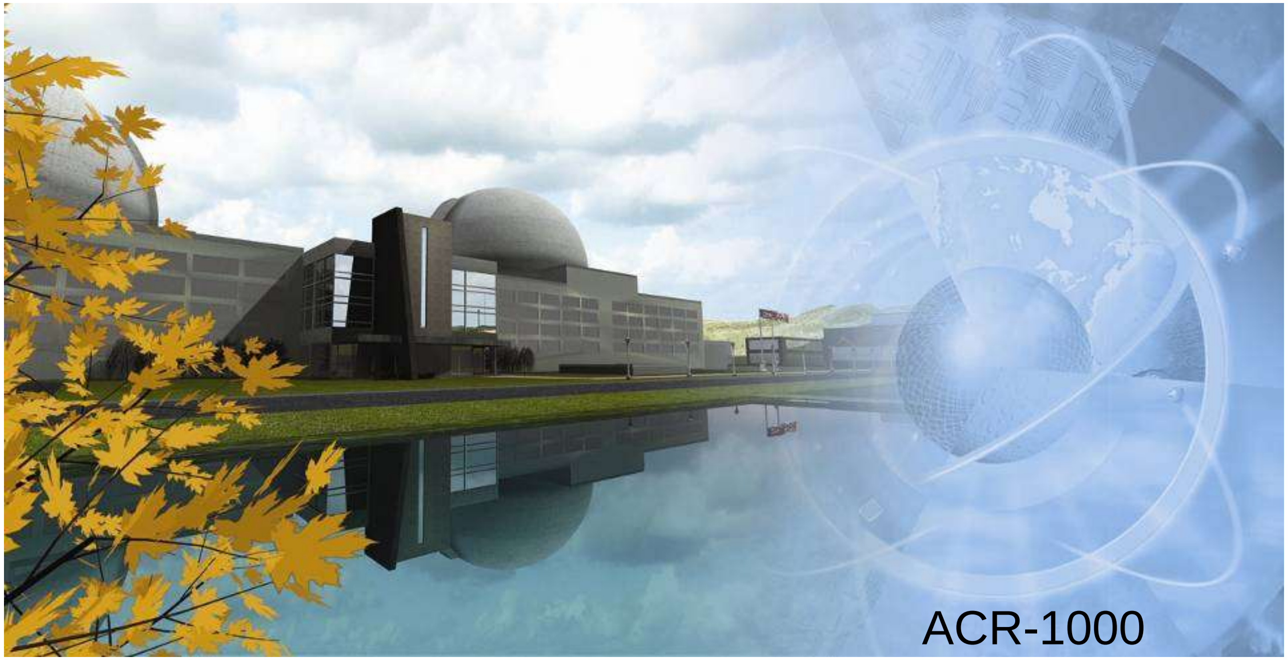
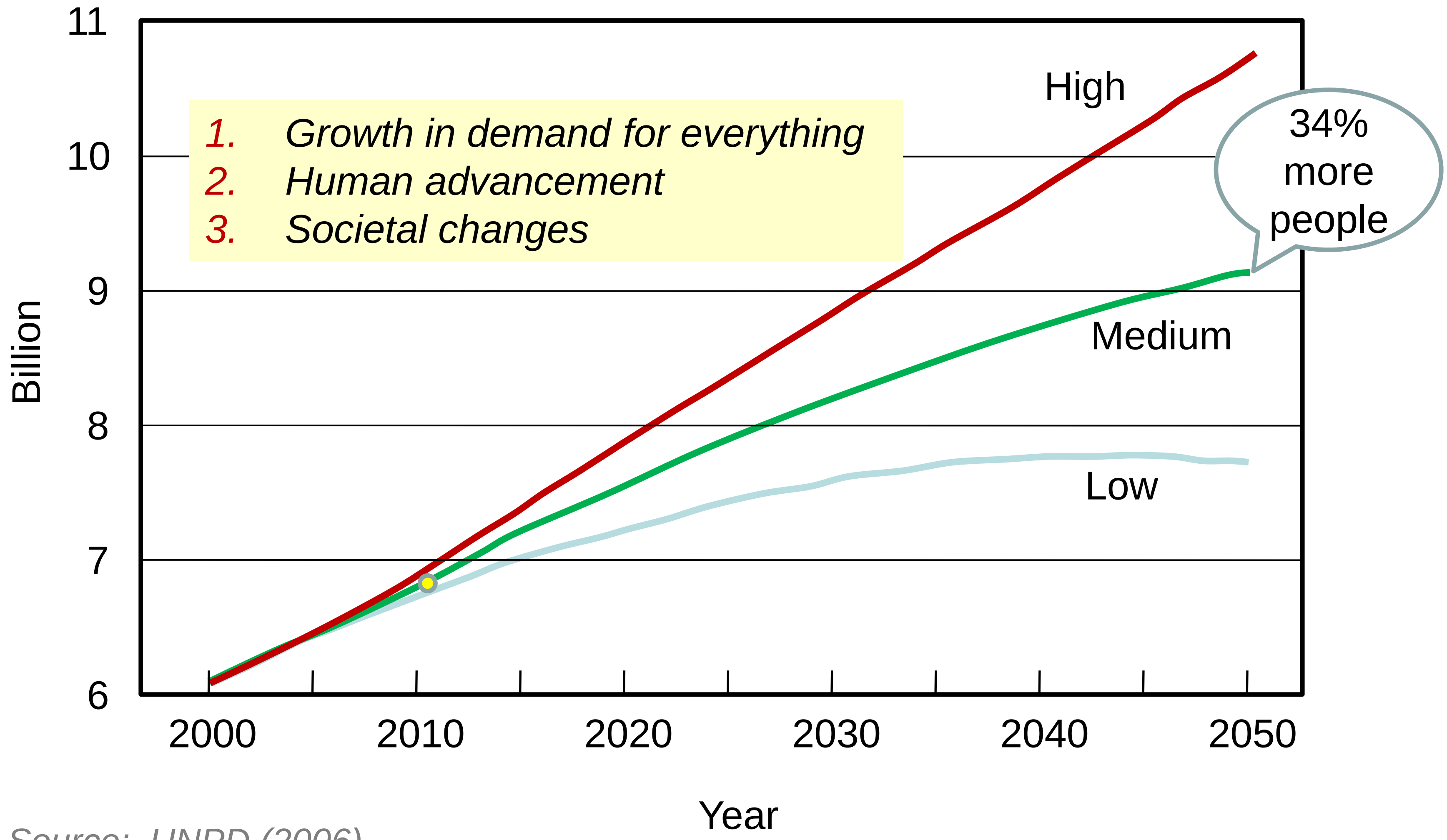


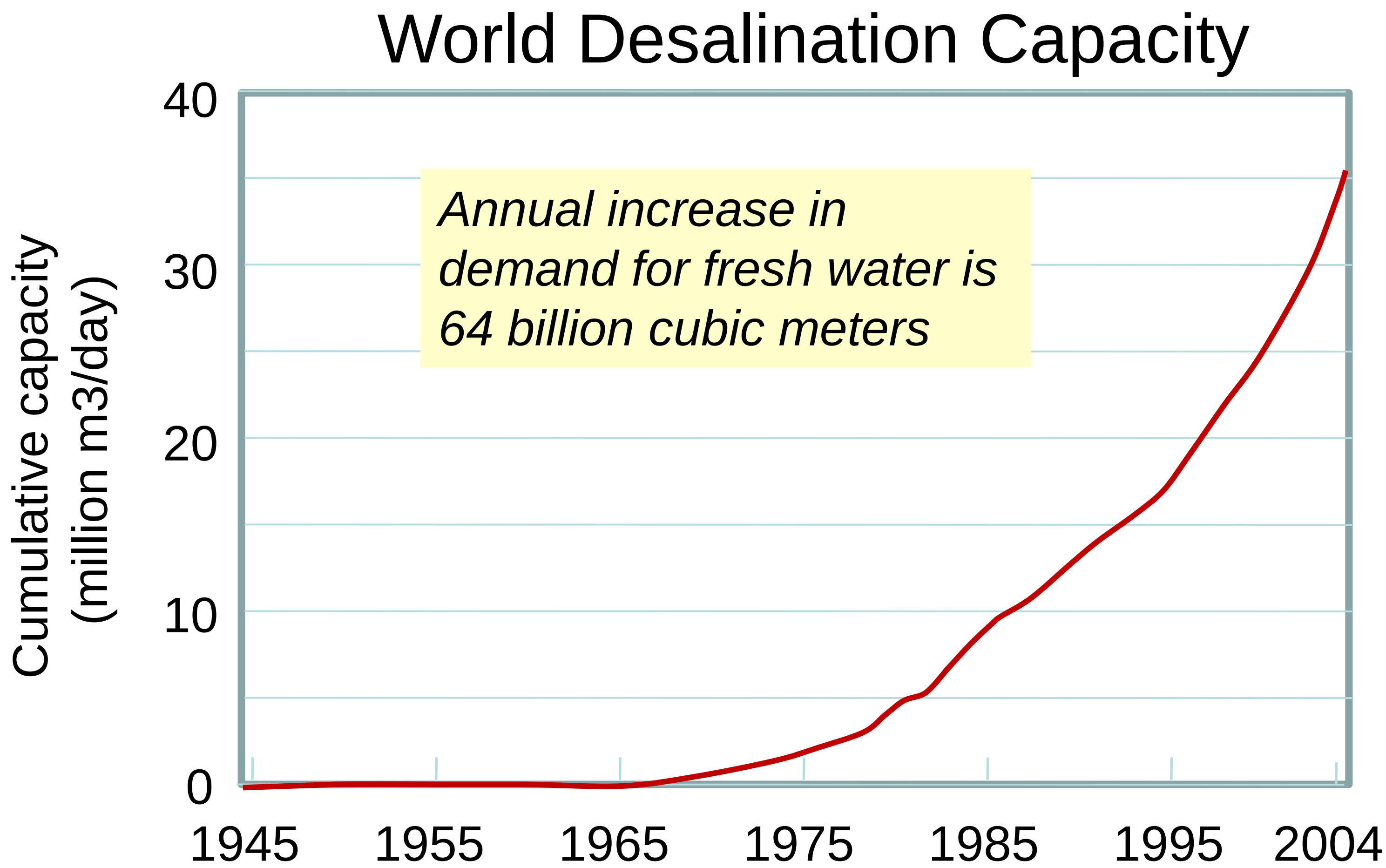
POPULATION & ECONOMICS

UN Projections of world population



Source: UNPD (2006)

Example: Population growth drives need for water



Source: OECD/NEA (2008) from Pacific Institute (2007)

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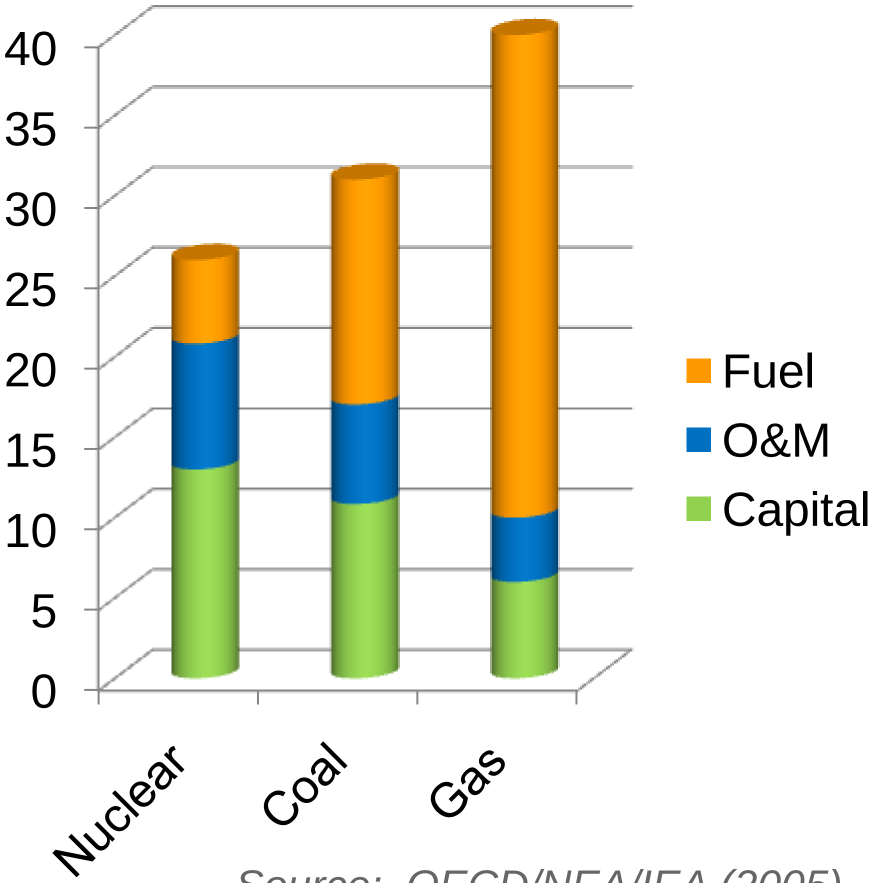
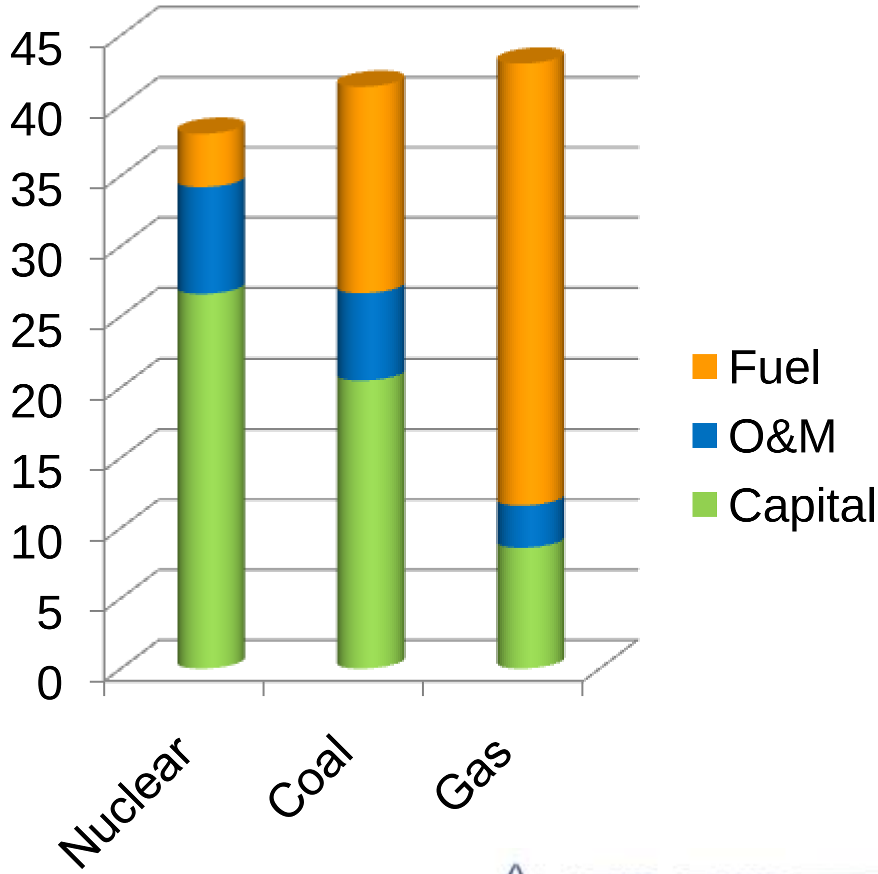
Canadian generation costs (US$/MWh)

5% Discount Rate



10% Discount Rate



Source: OECD/NEA/IEA (2005)

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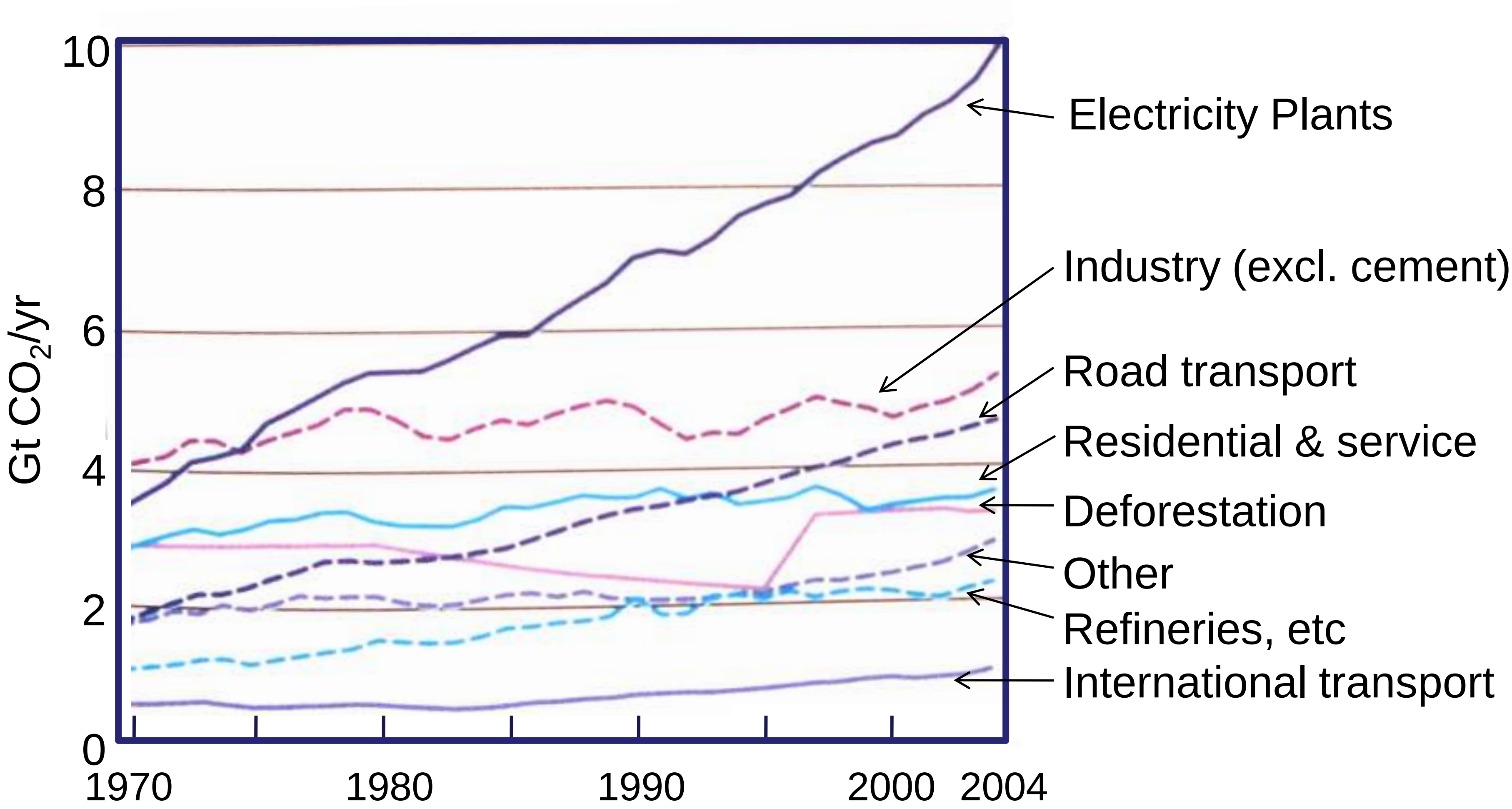
Pt Lepreau

ENVIRONMENT

Sources of global anthropogenic CO_2 emissions



Source: OECD/NEA Outlook (2008). Data from Intergovernmental Panel on Climate Change (2007)

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Emissions produced by 1 kWh of electricity based on life-cycle analysis

Generation Option	Greenhouse gas emissions gram equiv CO_2/kWh	SO_2 emissions milligram/kWh	NO_x emissions milligram/kWh	NMVOC milligram/kWh	Particulate matter milligram/kWh
Hydropower	2-48	5-60	3-42	0	5
Coal - modern plant	790-1182	700-32321	700-5273	18-29	30-663
Nuclear	**2-59**	**3-50**	**2-100**	**0**	**2**
Natural gas (combined cycle)	389-511	4-15000	13+-1500	72-164	1-10
Biomass forestry waste combustion	15-101	12-140	701-1950	0	217-320
Wind	7-124	21-87	14-50	0	5-35
Solar photovoltaic	13-731	24-490	16-340	70	12-190

Source: *Hydropower-Internalized Costs and Externalized Benefits*; Frans H. Koch; International Energy Agency (IEA)-Implementing Agreement for Hydropower Technologies and Programmes; Ottawa, Canada, 2000

Adopted from S Kuran, CNS presentation 2011Feb

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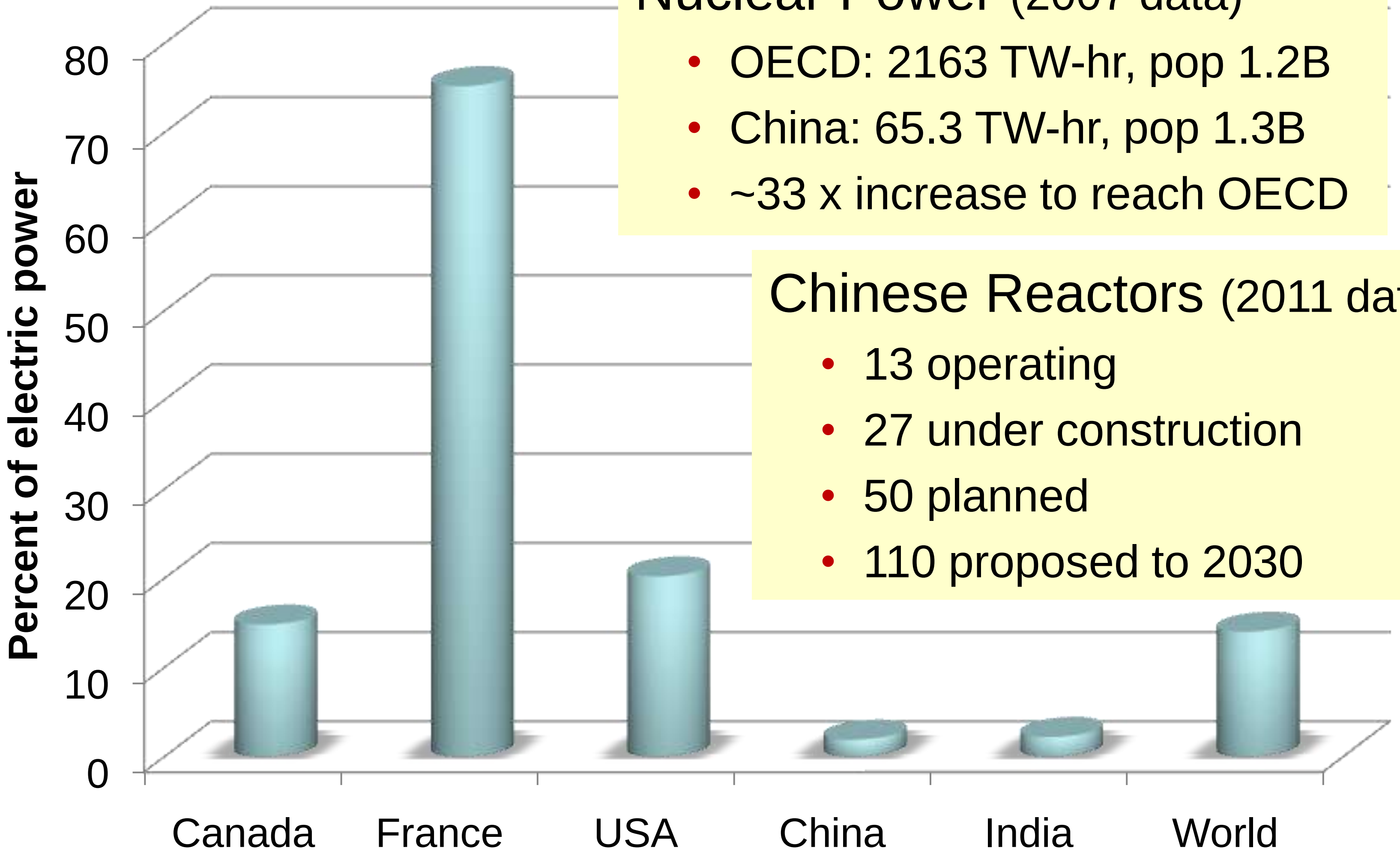
Enhanced CANDU 6

IMPACT ON GROWTH

Nuclear power's share in 2009



Nuclear Power (2007 data)

- OECD: 2163 TW-hr, pop 1.2B
- China: 65.3 TW-hr, pop 1.3B
- ~33 x increase to reach OECD

Chinese Reactors (2011 data)

- 13 operating
- 27 under construction
- 50 planned
- 110 proposed to 2030

Source: World Nuclear Association and OECD/NEA, 2011 Feb

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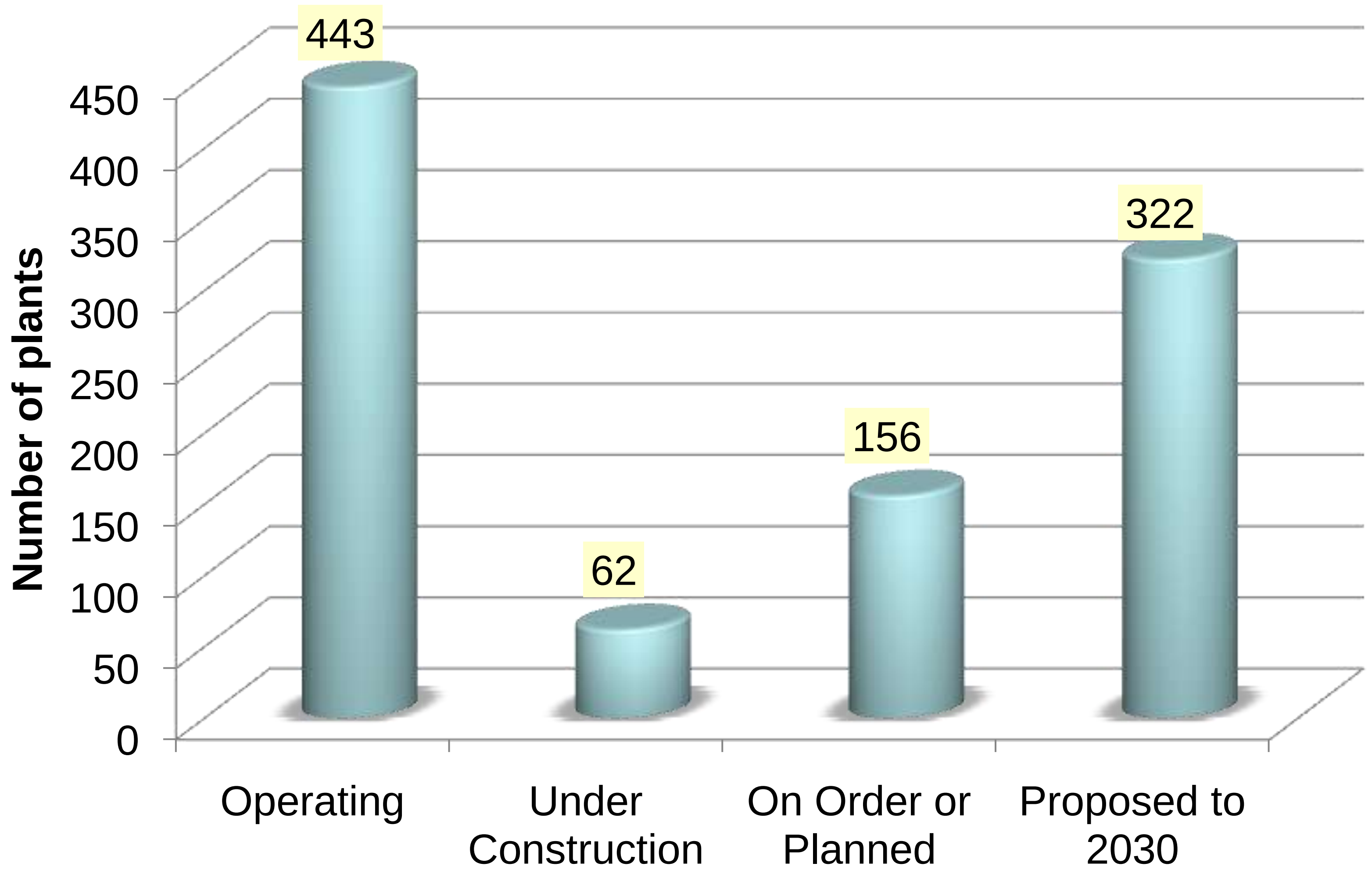
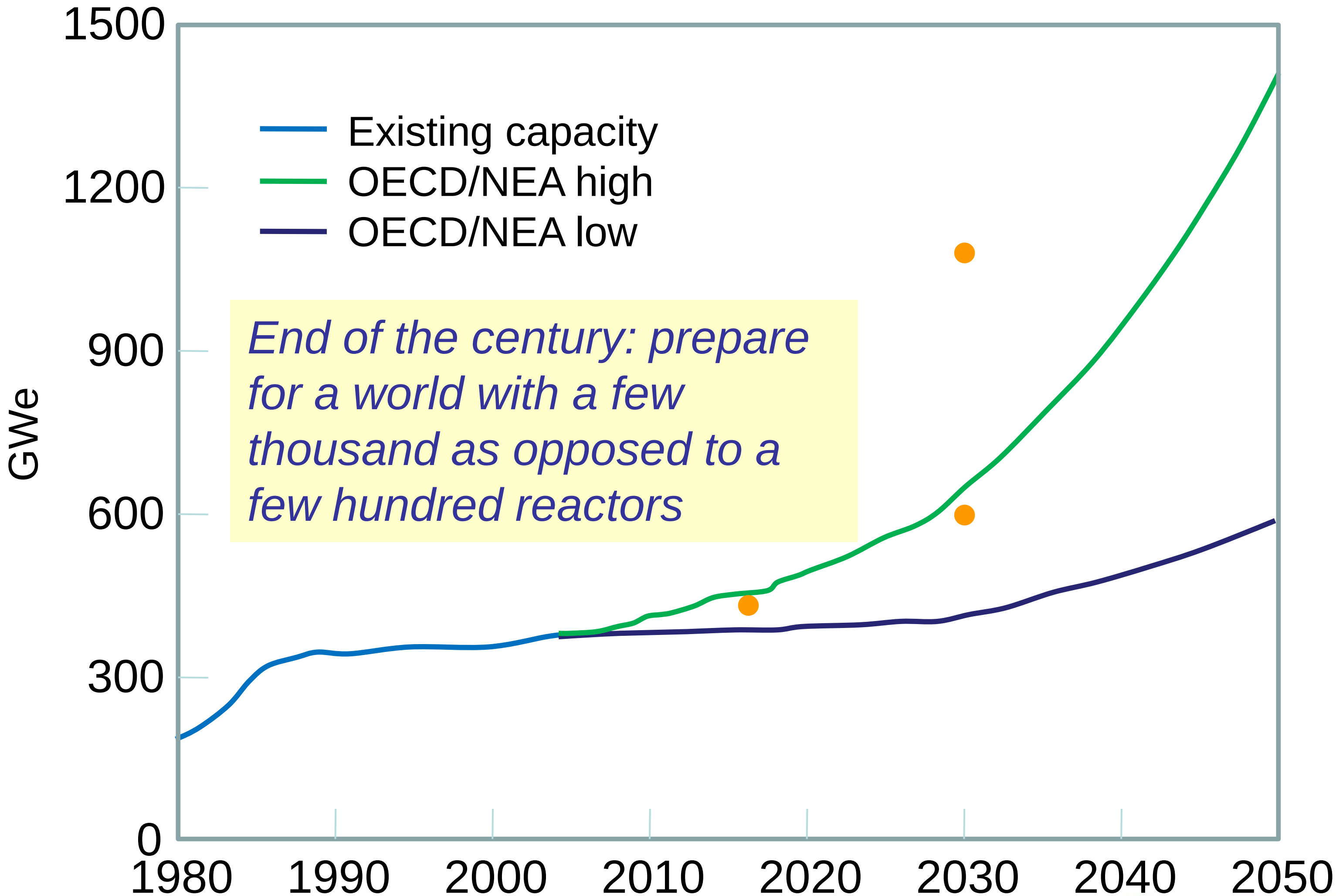
World nuclear power plants



Source: World Nuclear Association, 2011 Feb

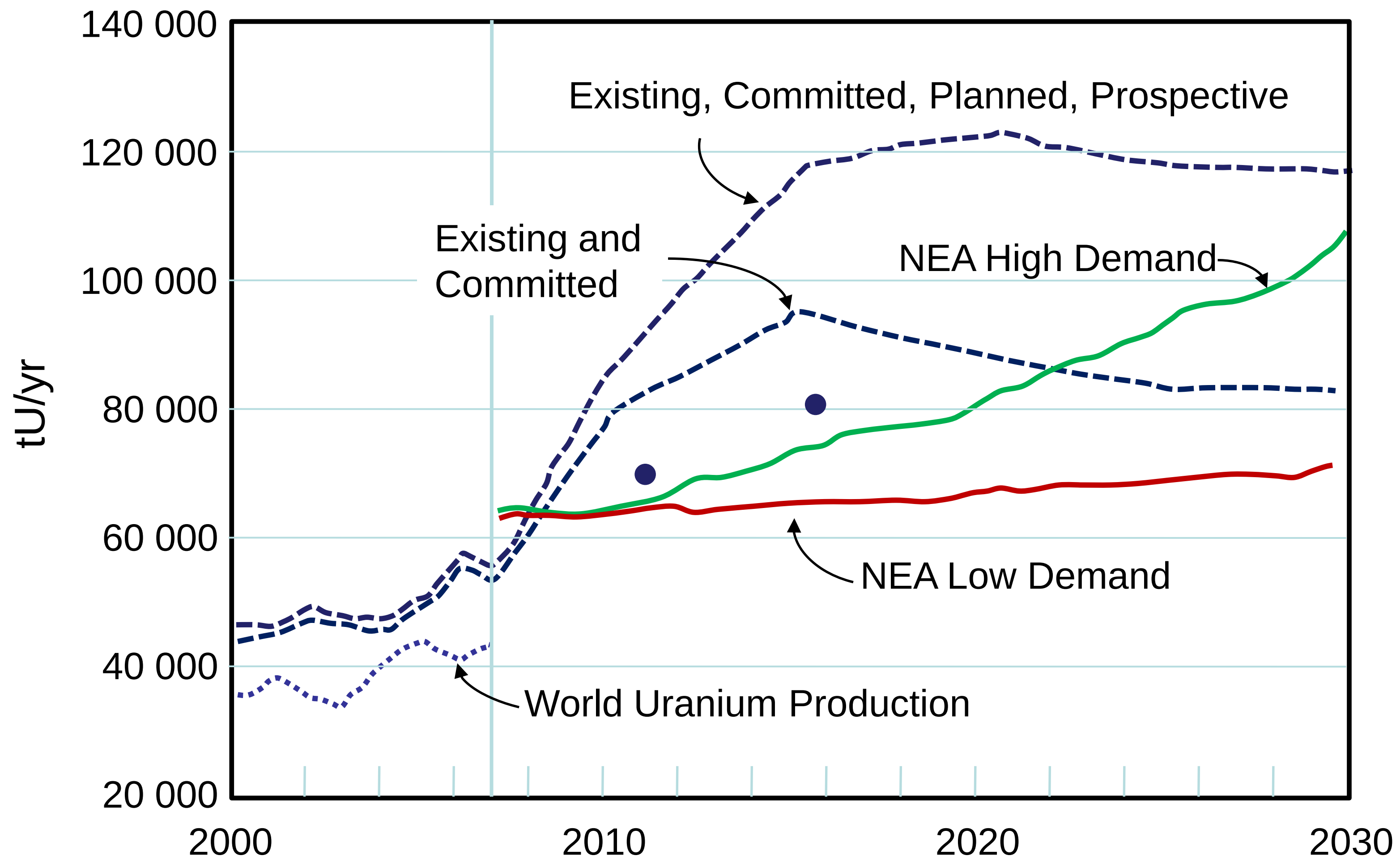
Projected nuclear capacity: OECD/NEA scenarios



FUEL SUPPLY

Bruce

Annual world uranium production capacity



Source: OECD/NEA (2008)

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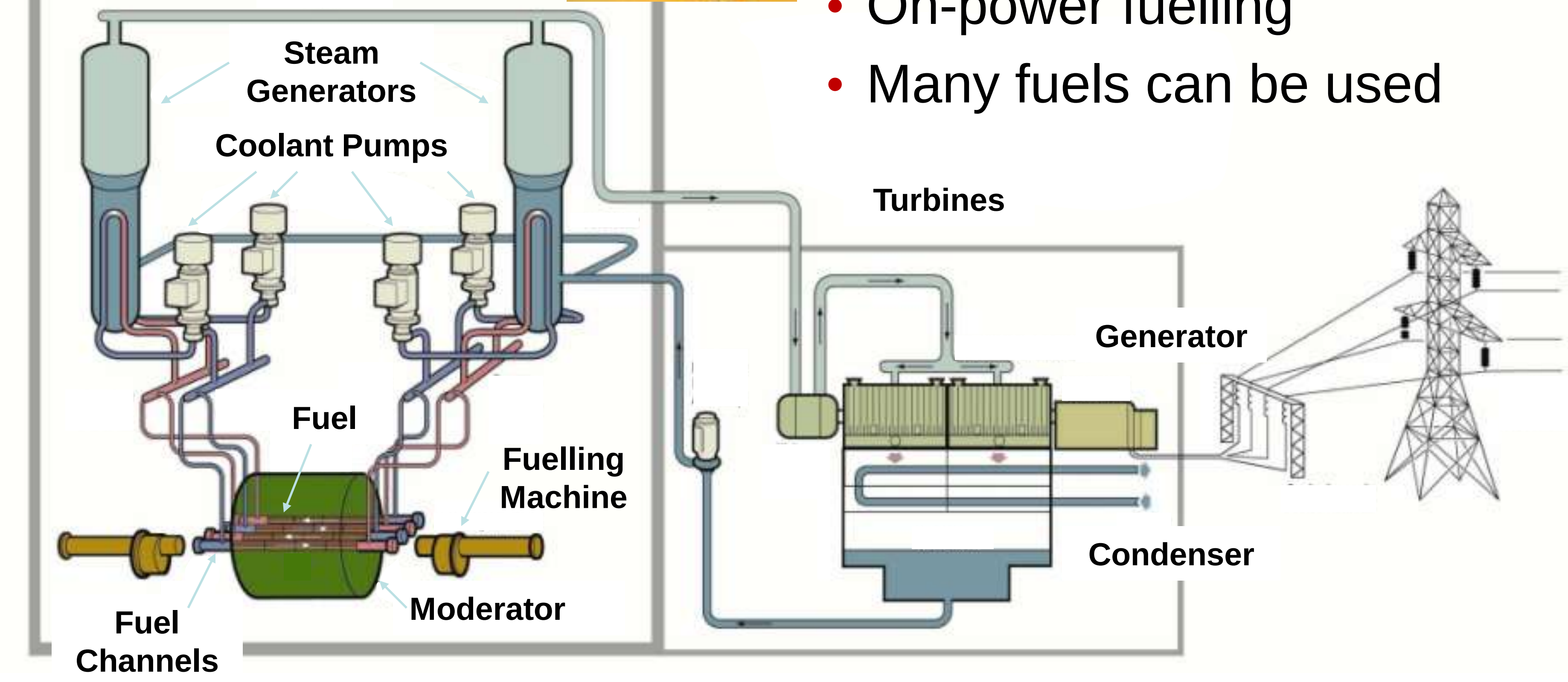
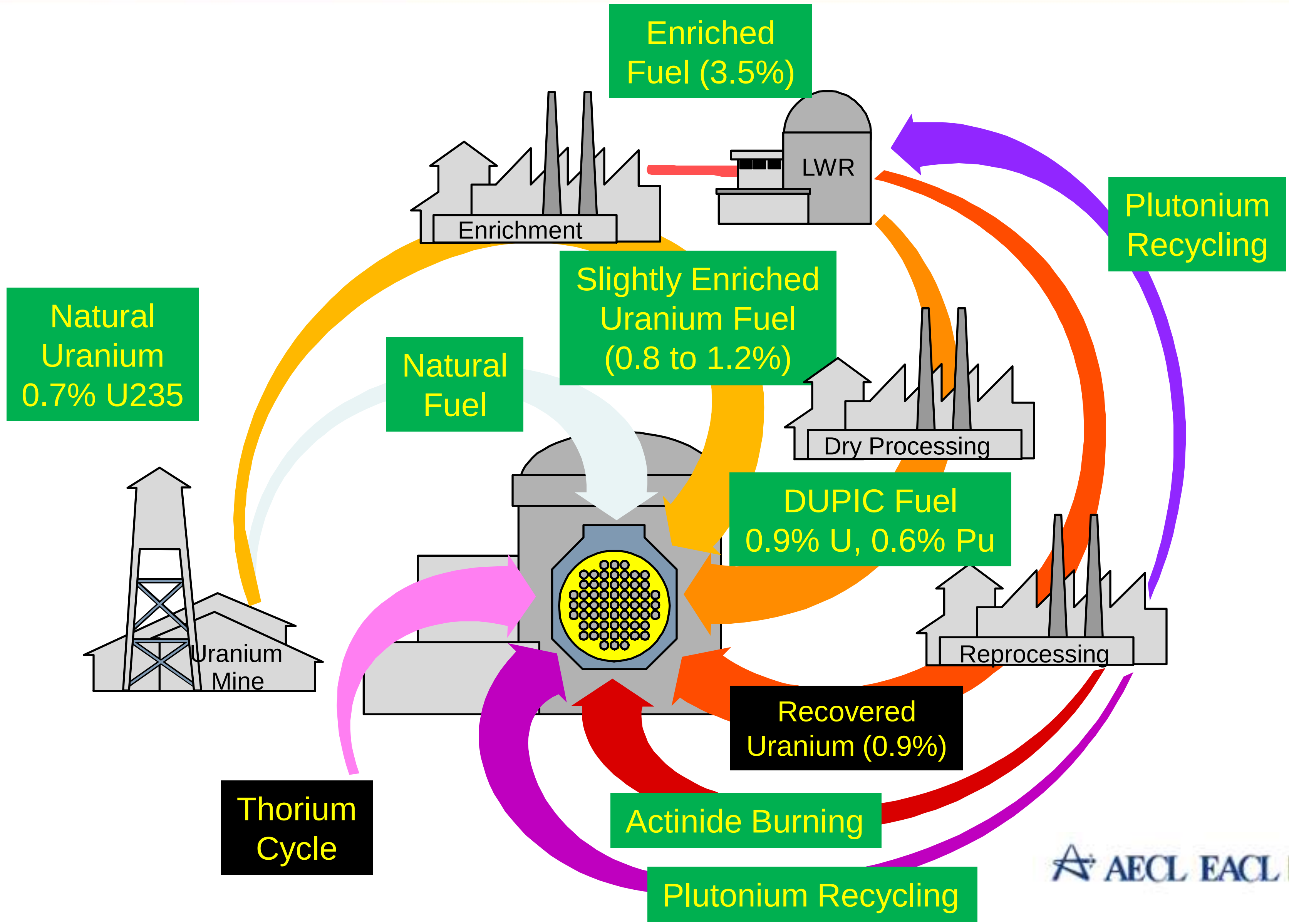
CANDU fuel cycle advantages

- Highest neutron efficiency
- Simple fuel bundle design
  - Adapt to optimize fuel cycle
  - Can test individual bundles
- On-power fuelling
- Many fuels can be used



CANDU fuel cycles



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Flux comparison for 1 GWe Reactors

Actinide Destruction

Reactor Type	Fissile Inventory (tonnes)	Thermal Flux (n/cm^2-sec)	Fast Flux (500 keV, n/cm^2-sec)
CANDU	1	1.4e14	0.7e14
PWR	2-3	8e13	3e14
FBR	3-4	---	0.5e16 – 1e16
CANDU Actinide Fuel in Inert Matrix	0.05	5e15	0.7e14

Source: Dastur & Gagnon 1994

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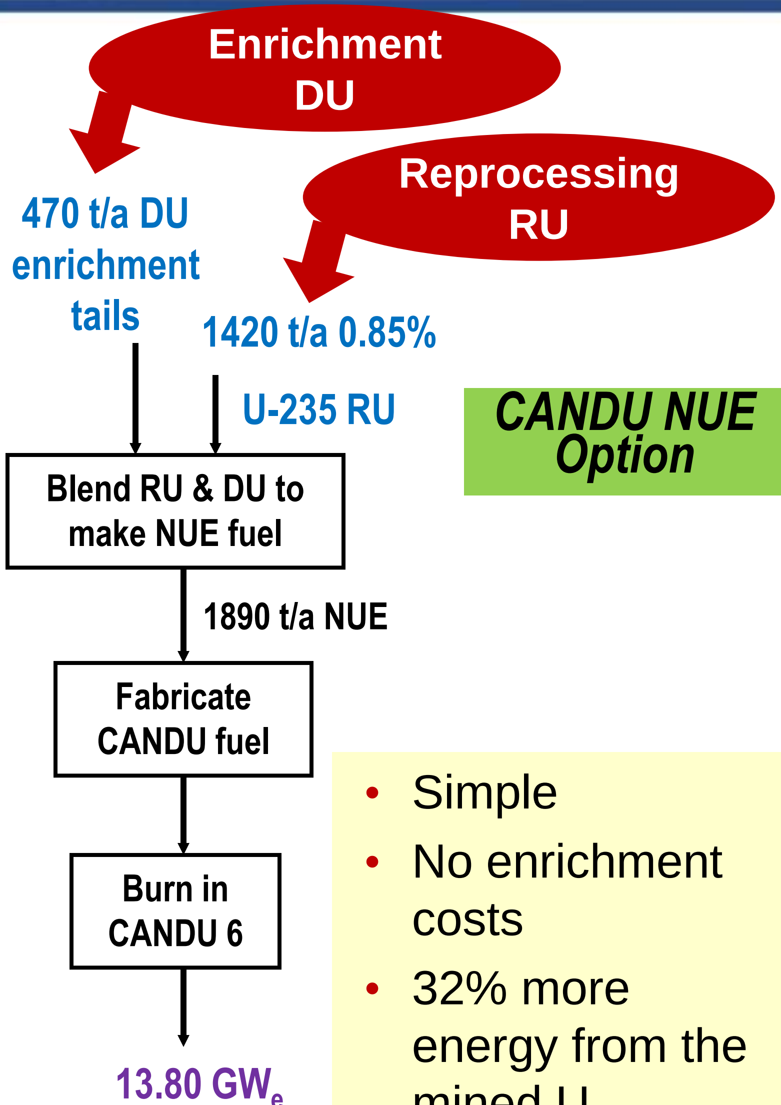
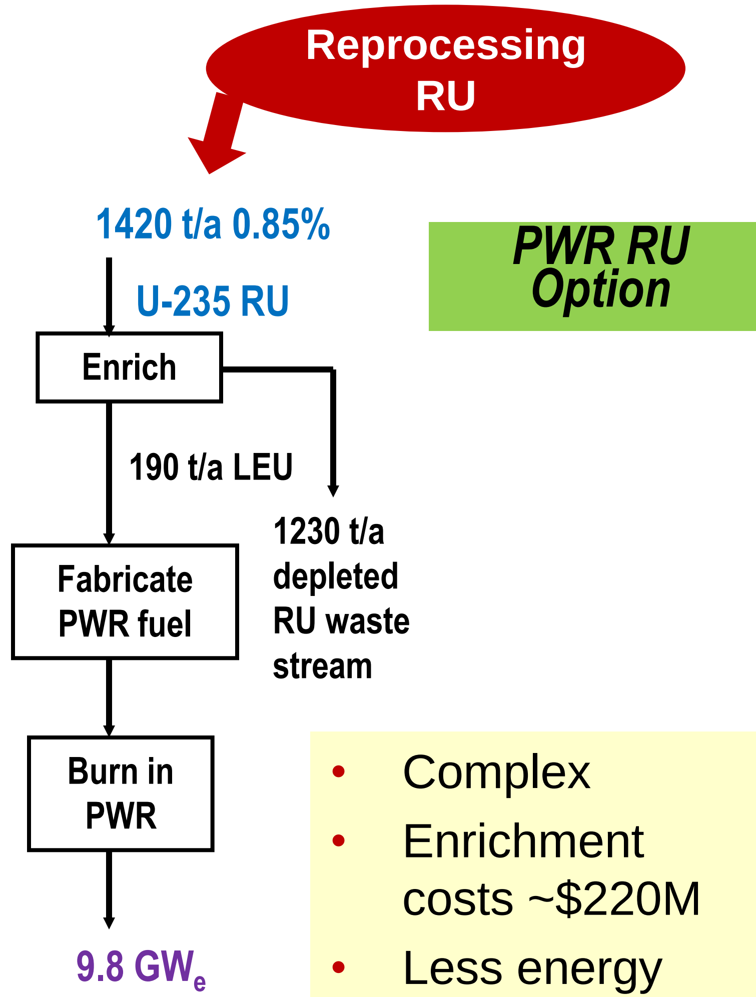
Using LWR waste streams



- Simple
- No enrichment costs
- 32% more energy from the mined U



- Complex
- Enrichment costs ~$220M
- Less energy extracted

Adopted from S Kuran, CNS presentation 2011Feb

Example: RU/DU in Qinshan

- MOU: AECL, TQNPC, CNNFC and 2010 March, 12 bundles into two fuel channels
  - 2010 Oct, 4 bundles removed for PIE
  - 12 more bundles loaded
  - All testing to date is successful
  - 2011 April, finish irradiations
- Discussing full core loading

Adopted from S Kuran, CNS presentation 2011Feb

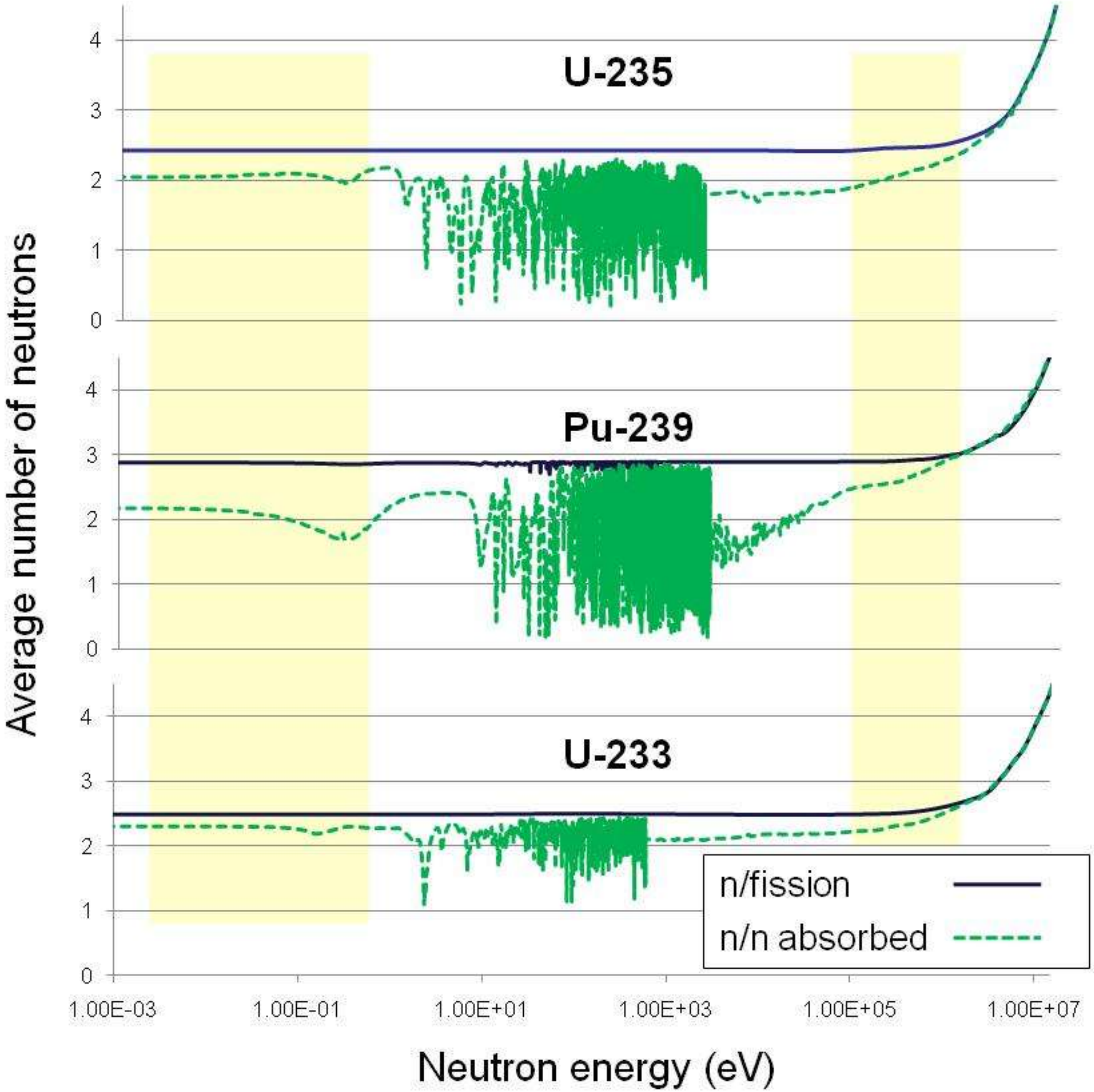
$$^{232}\mathrm{Th} + n \longrightarrow {}^{233}\mathrm{Th}$$

$$^{233}\mathrm{Th} \xrightarrow[t_{1/2}=22m]{\beta} {}^{233}\mathrm{Pa}$$

$$^{233}\mathrm{Pa} \xrightarrow[t_{1/2}=27d]{\beta} {}^{233}\mathrm{U}$$

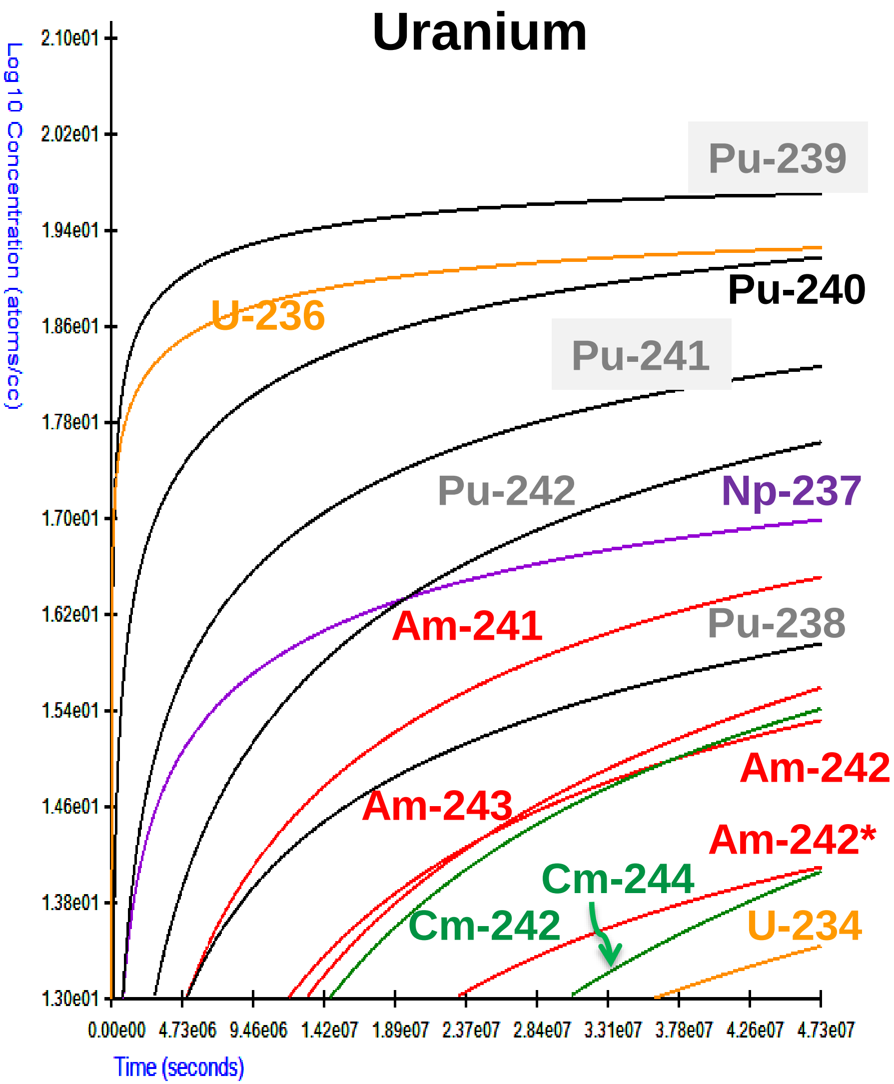
THORIUM

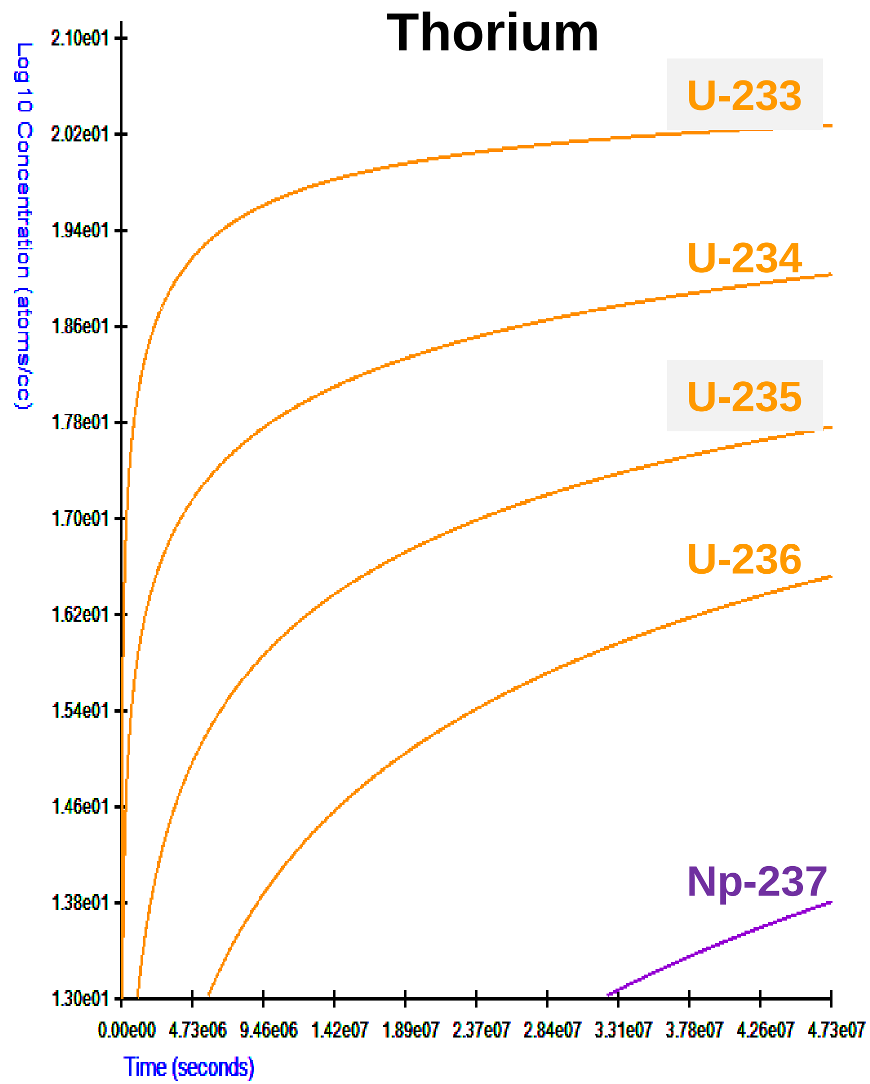
- 3-4x more abundant than U
- Found in China and India
- High thermal conductivity
- Cleaner, much less Minor Actinides



Favourable U-233 neutronics in thermal region

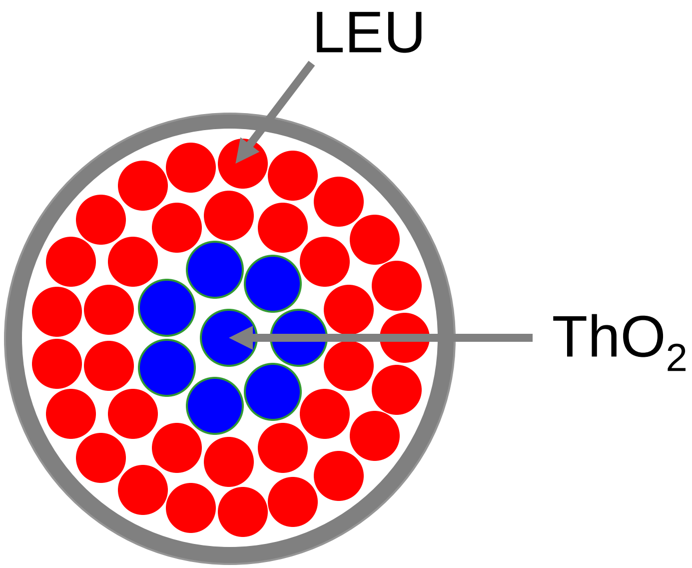
Long-lived actinide production

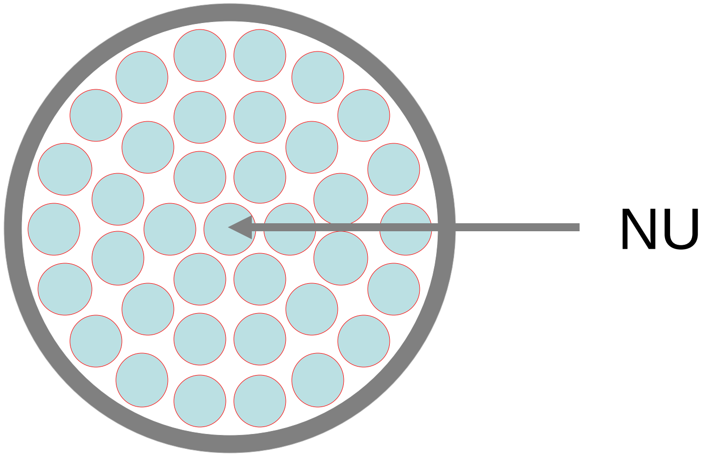




Th/LEU fuel for CANDU

43-element Standard CANFLEX & 37-element Bundle Designs





Standard CANFLEX Bundle

With 8 large Natural Thorium Pins

Standard 37-element Bundle

All NU Fuel Pins

Adopted from S Kuran, CNS presentation 2011Feb

Uranium consumption reductions

Reactor	Fuel/Burnup	NU Consumption [tNU/TWh]	Improvement from PWR reference
PWR PWR Reference	LEU : 4.0 wt% ^{235}U 42 MWd/kgHE	25.3	---
PWR PWR Ref. High Burnup	LEU: 4.5 wt% ^{235}U 50 MWd/kgHE	21.3	16%
CANDU 6 C6 Reference	NU: 0.71 wt% 7.5 MWd/kgHE	18.9	25%
Thorium CANDU TCR Th-LEU	LEU/Th: 1.65 wt% ^{235}U 20 MWd/kgHE	14.3	43%

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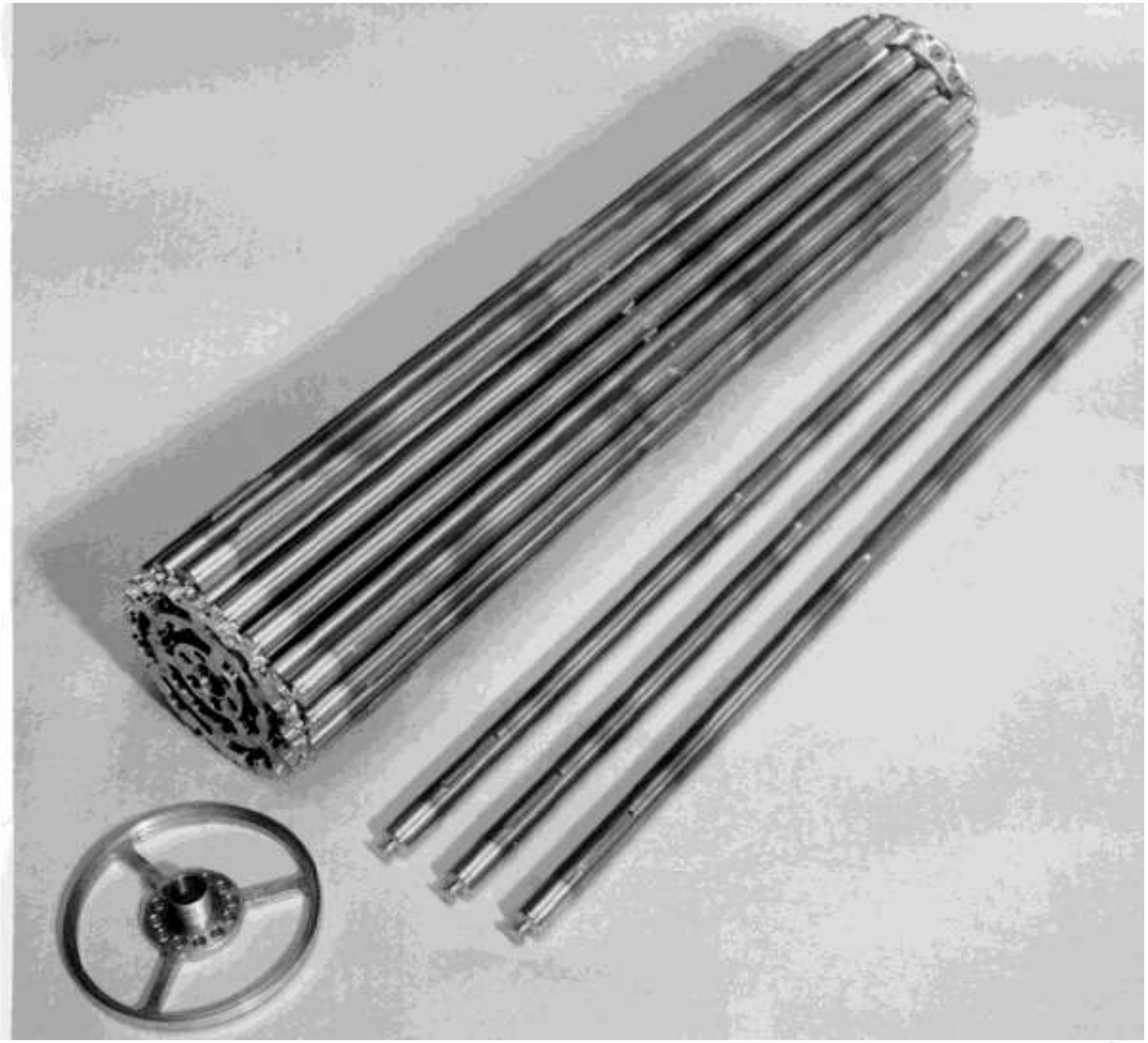
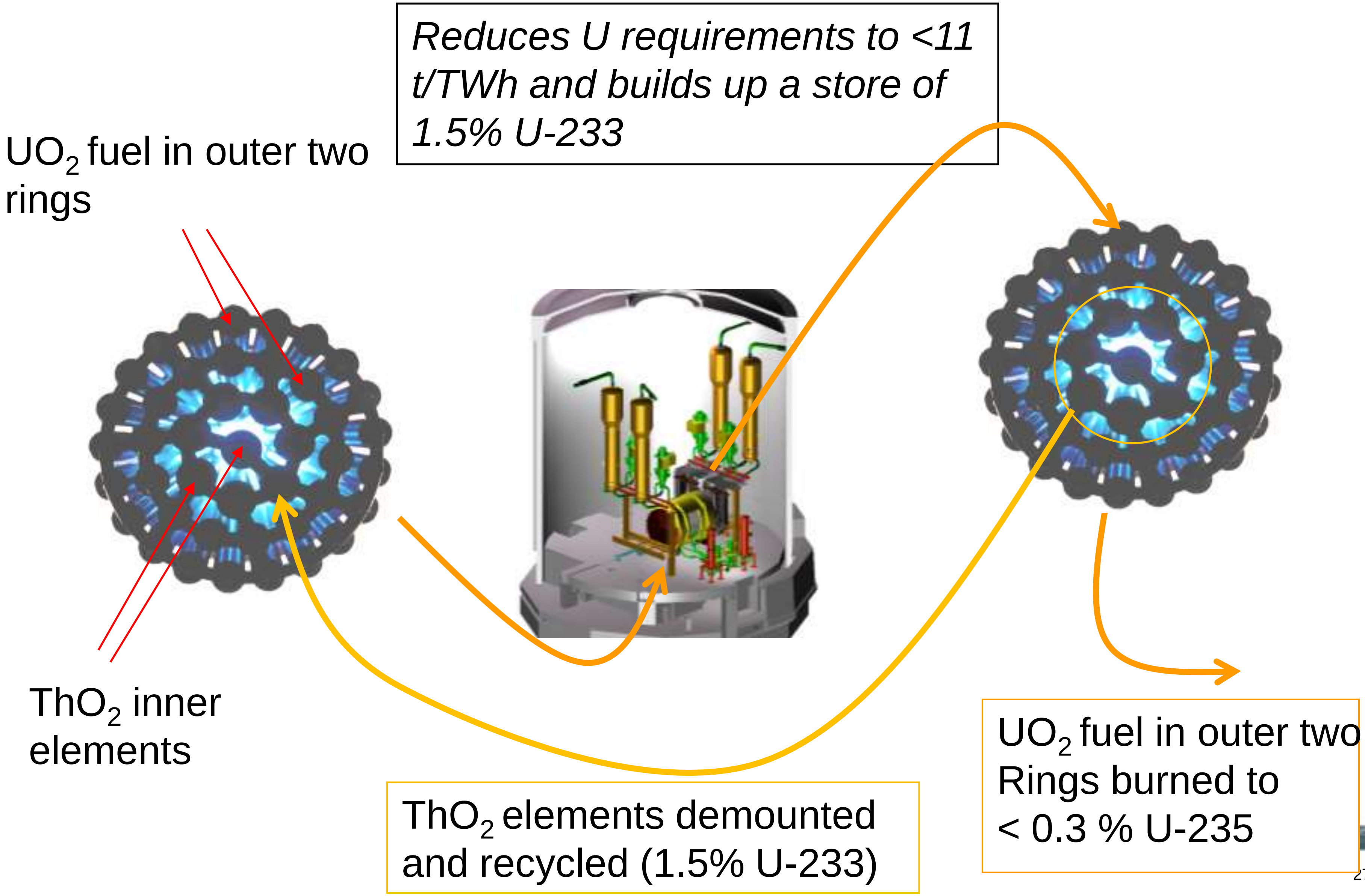
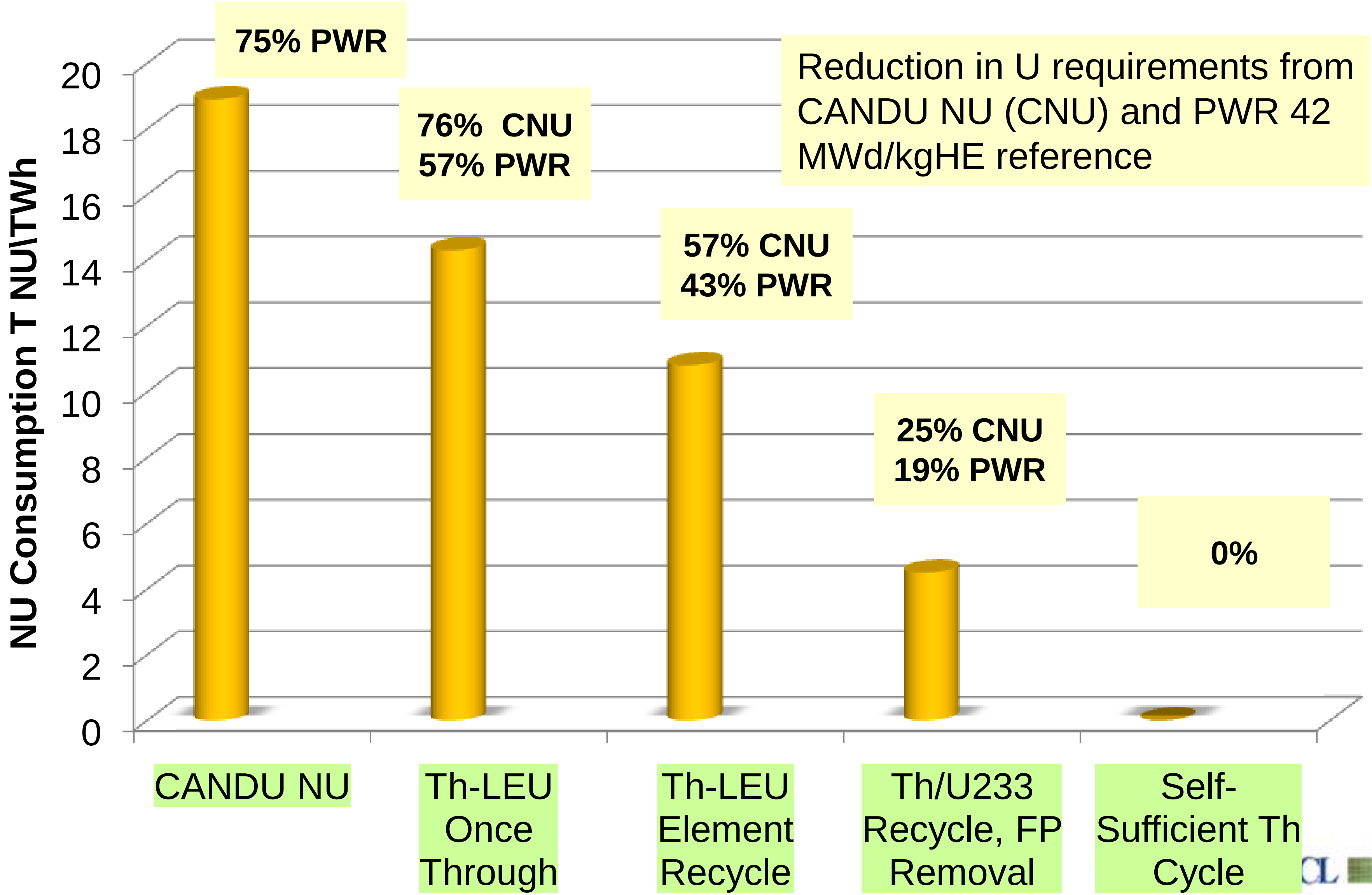
Demountable fuel bundles



Thorium direct recycle (no reprocessing) using demountable elements



CANDU thorium fuel cycles



China/Canada Thorium CANDU Reactor (TCR)

- AECL and Chinese partners (TQNPC, CNNFC and NPIC) have shown that the C6 reactor, with minimal changes, can use Th-LEU fuel with good uranium utilization
- Independent Chinese expert panel reviewed results and have made the following recommendation to government:

> ***"All experts unanimously recommended that China shall build two more CANDU Heavy Water Reactor units to utilize various advantages of this type of fuel."***

- The parties are pursuing preliminary technical and planning work for TCR and Th fuel development

Source: S Kuran, CNS presentation, 2011Feb

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Pickering

CONCLUDING REMARKS

Energy Transfer From a Fission Fragment