Fuel for the Next Millennia

Dan Meneley
University of Victoria
2001 March 08

AECL EACL
Atomic Energy of Canada Limited
Énergie atomique du Canada limitée

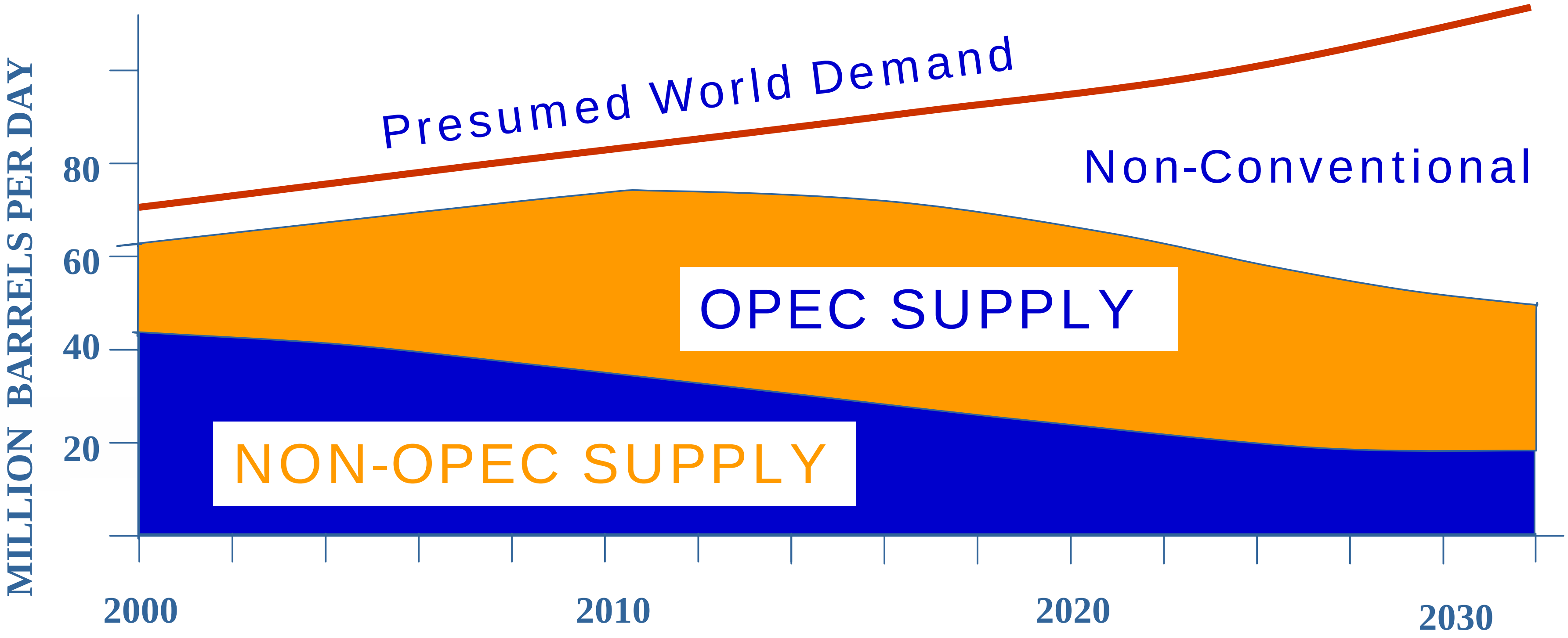
Canada

Energy Sources

- Nuclear energy
  - Natural fusion in the sun
    - Direct
    - Stored
      - Wind
      - Hydro
      - Wood, Coal, Oil,Gas
  - Man made sources
    - Fission of heavy elements
    - Fusion of light elements
  - Radioactive materials in the earth
- Kinetic energy of the solar system
  - tides

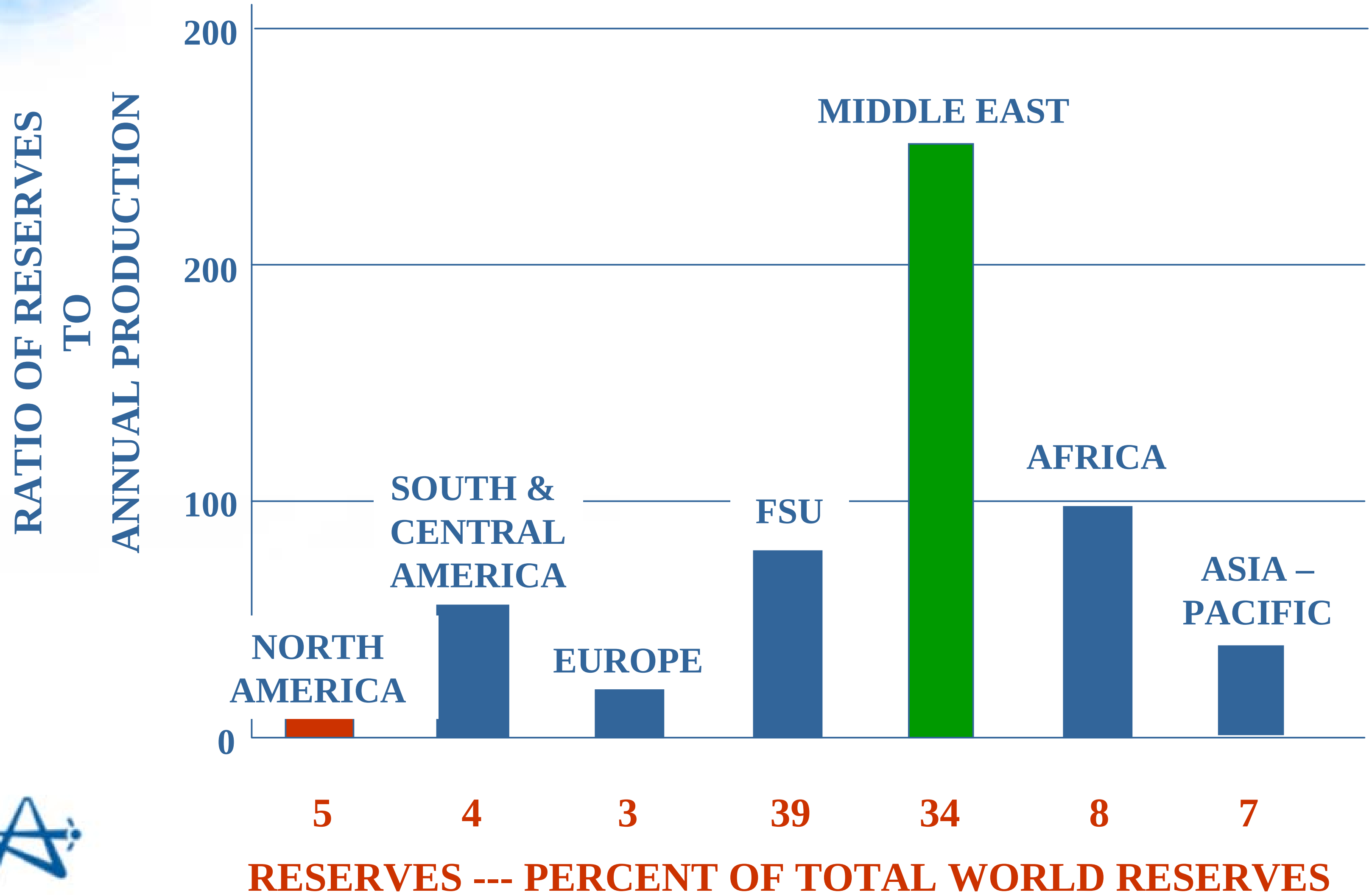
World Oil Supply Profiles

Source: International Energy Agency



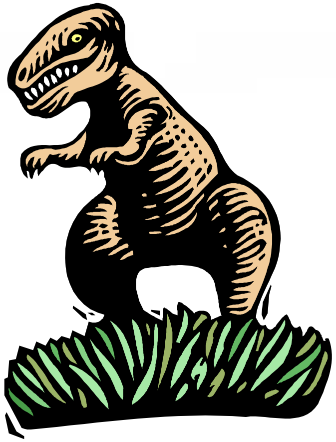
Natural Gas – An Uneven Resource

Source: BP Amoco, June 2000

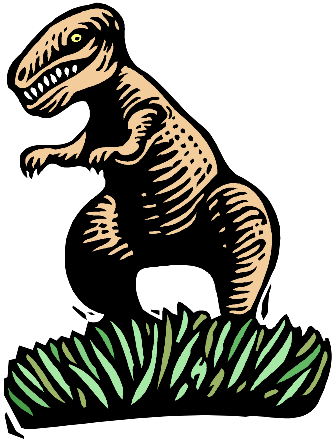


Adaptation Time Constants

- Changes from one primary energy source to the next are inevitably slow
- Planning must consider at least a 50-year period after decisions are made
- Delayed decisions usually lead to severe price dislocation and shortages



ADAPTOR AUT PAREO



Mechanisms for Adaptation

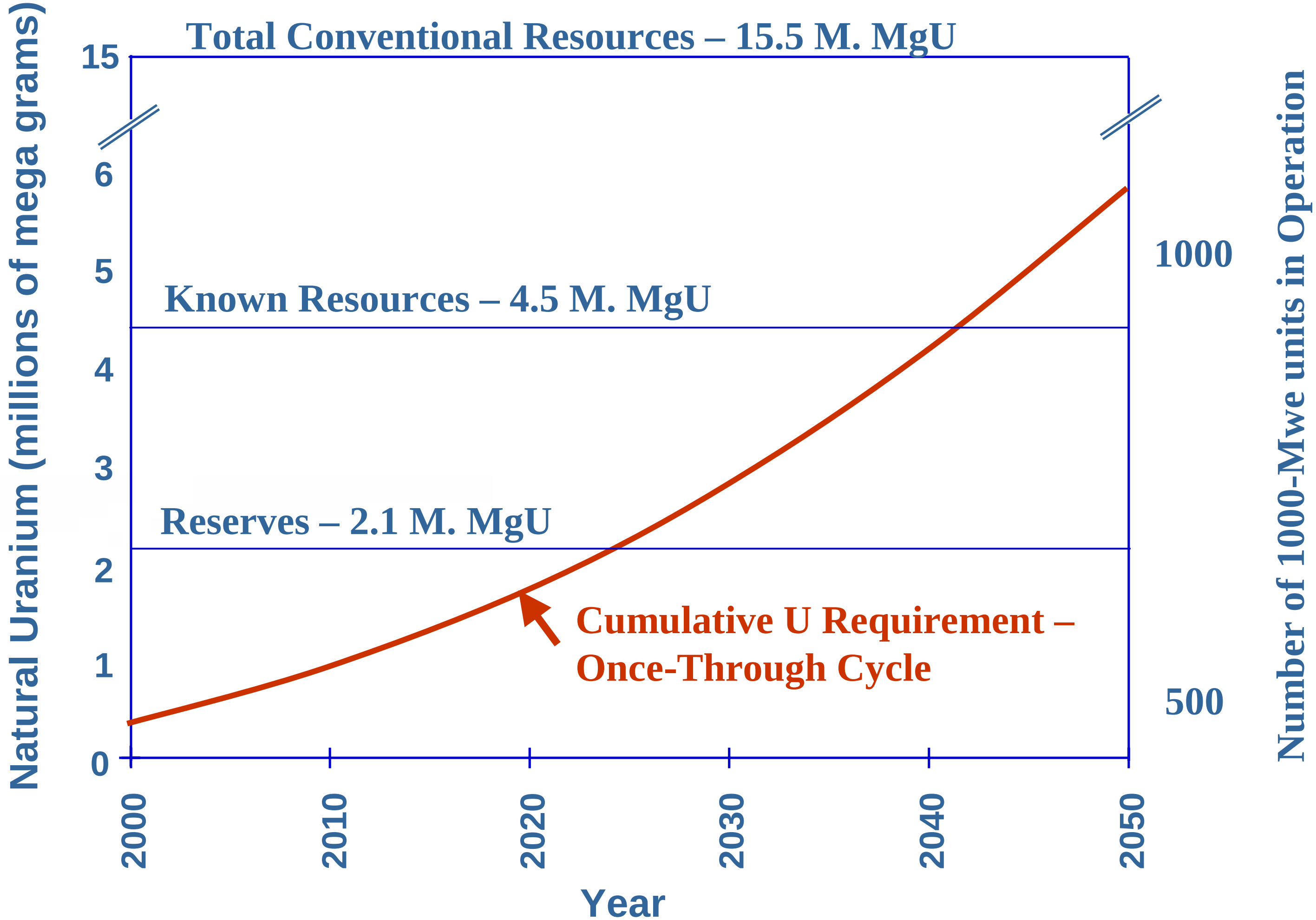
- **Reduce our expectations**
  - Lower the standard of living of rich countries, increase that of poor countries
  - Change lifestyles toward less energy-intensive social structures

- **Do more with less – do not waste**
  - Introduce energy-efficient technologies
  - Make use of all available, abundant, sources of primary energy
  - Minimize the damage to global environment
  - Adopt a strategy to address the mal-distribution of resources in the world

- **Sustain the population**
  - Understand and agree on a set of ethics for sustainable human procreation

Uranium Fuel Demand and Supply Today

OECD-NEA Report, Nuclear Power and Climate Change, 1998



Uranium Fuel Supply in the Future

- Known, but low-concentration deposits occur in phosphate ores and in seawater.

- These deposits could be utilized if about ten times more energy could be gained from each gram of uranium extracted, according to Japanese studies. (At least fifty times more potential energy is available than we now gain from each gram.)

- The seawater concentration probably is in equilibrium with the sea bottom rock, so that uranium extracted would be replaced through leaching.

- Conclusion: Seawater contains an effectively infinite amount of uranium, if we can learn to recycle our fuel and to take more energy from it.

Thorium

- Resources
  - Thorium is not used for energy production today
  - Assured plus estimated reserves total 4.1 million mega grams
- Pure "potential energy"
  - Thorium contains no fissile isotope.
- A fissile isotope is required in nuclear fuel
  - When a neutron is captured in Th232 the result is U233, which is fissile.
  - U233 is an excellent fuel for thermal reactors
- Some Characteristics
  - Thorium dioxide is stable, even in the high radiation environment inside a reactor
  - Thorium dioxide is less soluble than uranium dioxide → difficult to reprocess

Today's technology – LWR, HWR

Continue using natural uranium in existing CANDU reactors

- Use slightly-enriched fuels in some units to improve mined uranium utilization, and operating economics.

Produce electricity using fissile materials released from nuclear weapon programs.

- Mix HEU with depleted U for use in LWR
- Mix Pu with depleted U for use in LWR and HWR

Increase the amount of mixed-oxide fuel recycle in LWR plants, using reprocessed fuel from LWR.

Hold a large fraction of used nuclear fuel in storage without any reprocessing. Continue holding some separated plutonium extracted from used fuel in storage and available to start breeder reactors when needed.

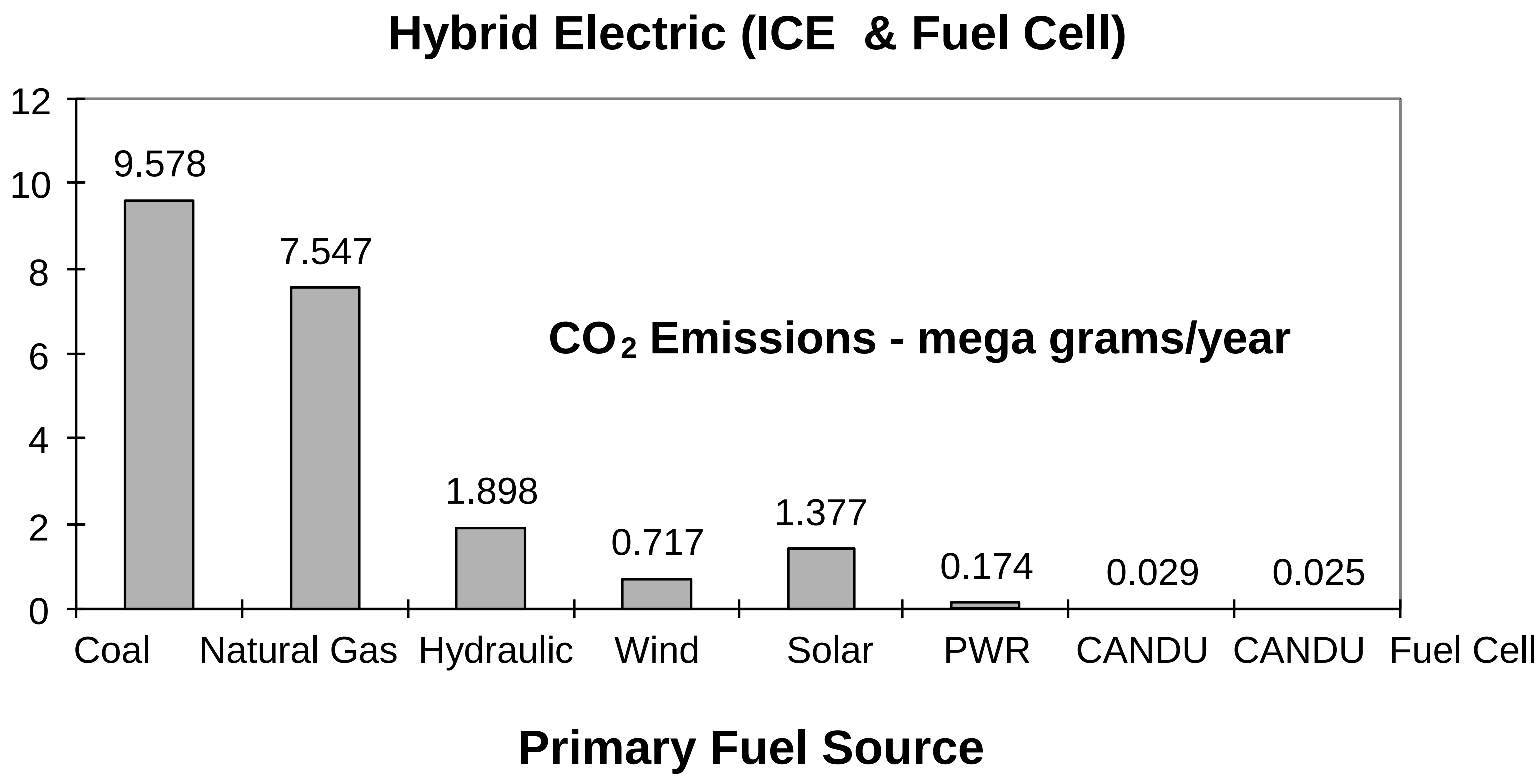
Non-Electric Applications of Nuclear Energy

- Transportation Fuels
- Desalination
- Fuel production from oil sand
- Hydrogen production – electrolysis
- Use of integrated energy systems (from IES?)
- Production of high temperature process gases

Transportation Fuels

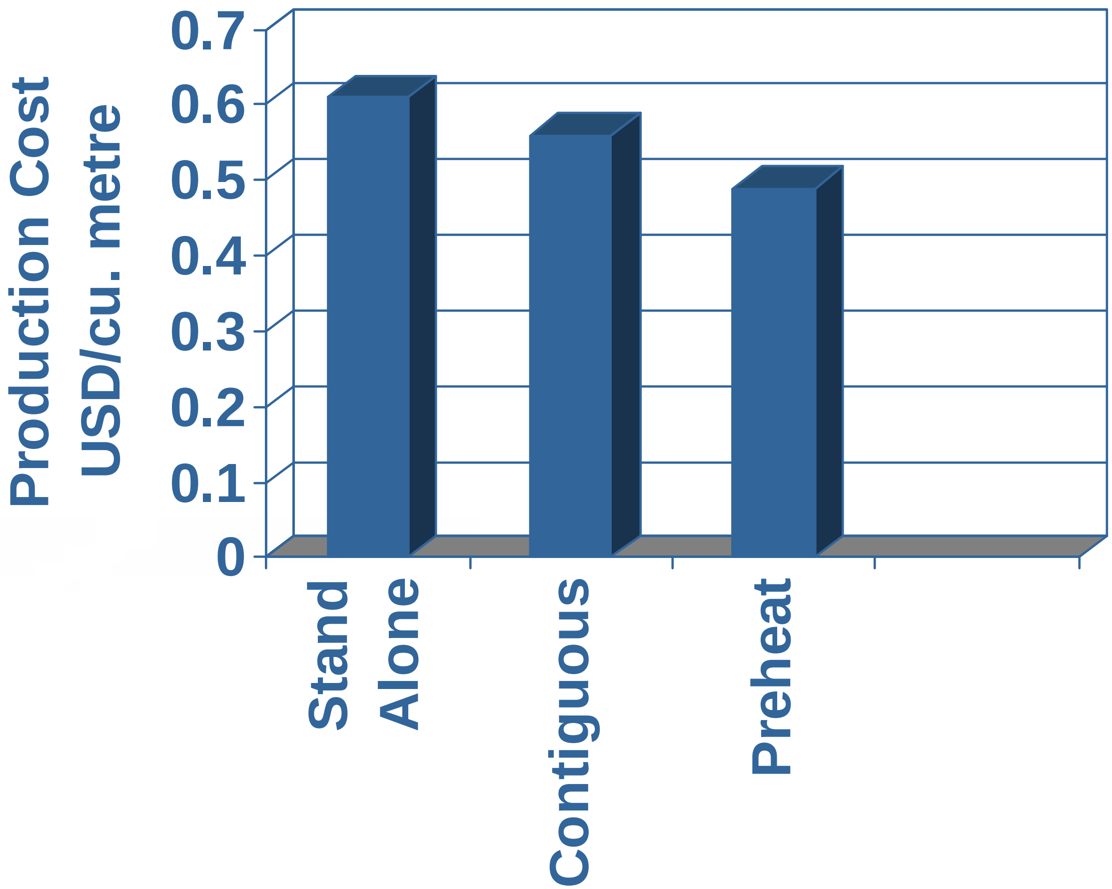
- Nuclear plants to produce hydrogen for fuel cells
- Methanol as energy currency?
- Vehicles operate as hybrids with IC engines?
- Central or distributed water electrolysis

Choice of Primary Energy Source for Transport

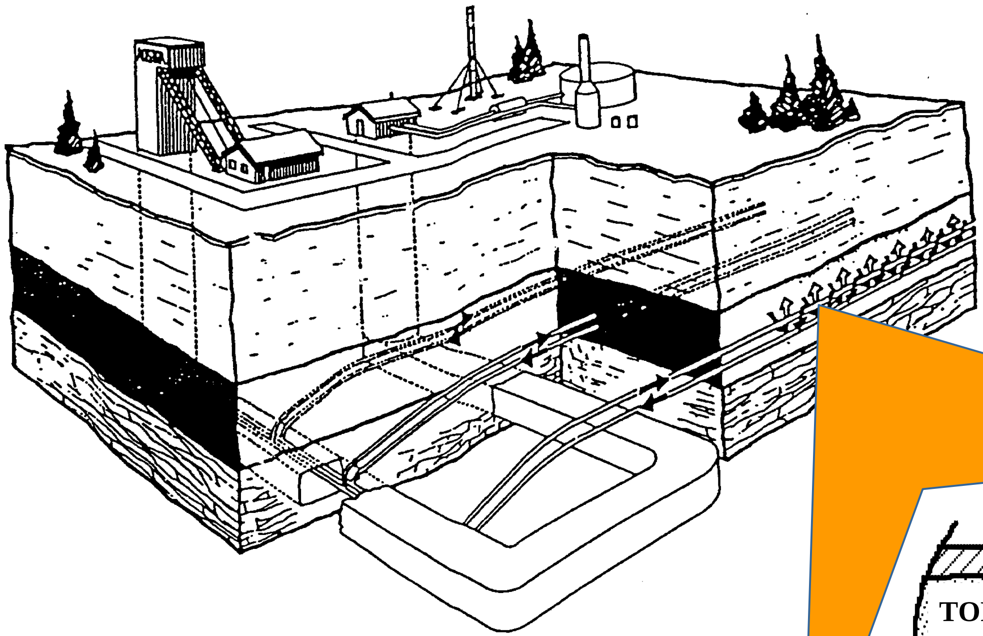


Reduction of Water Desalination Cost

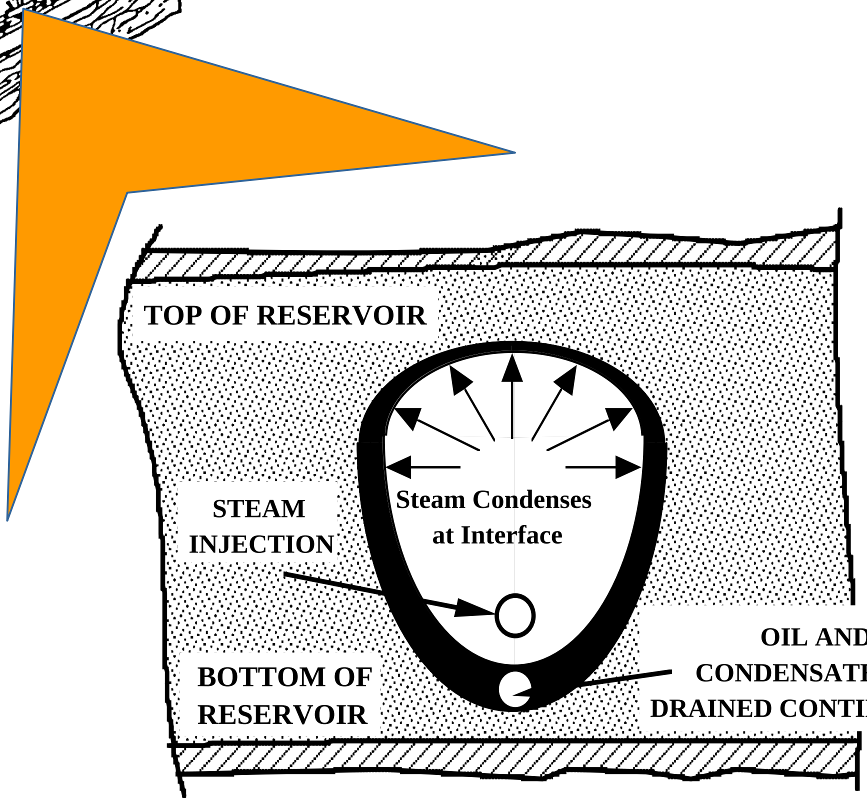
Nuclear preheat, Reverse Osmosis



Production from Canada's Oil Sand



One CANDU unit supplies enough energy to produce ~150,000 bbl/day of synthetic crude oil

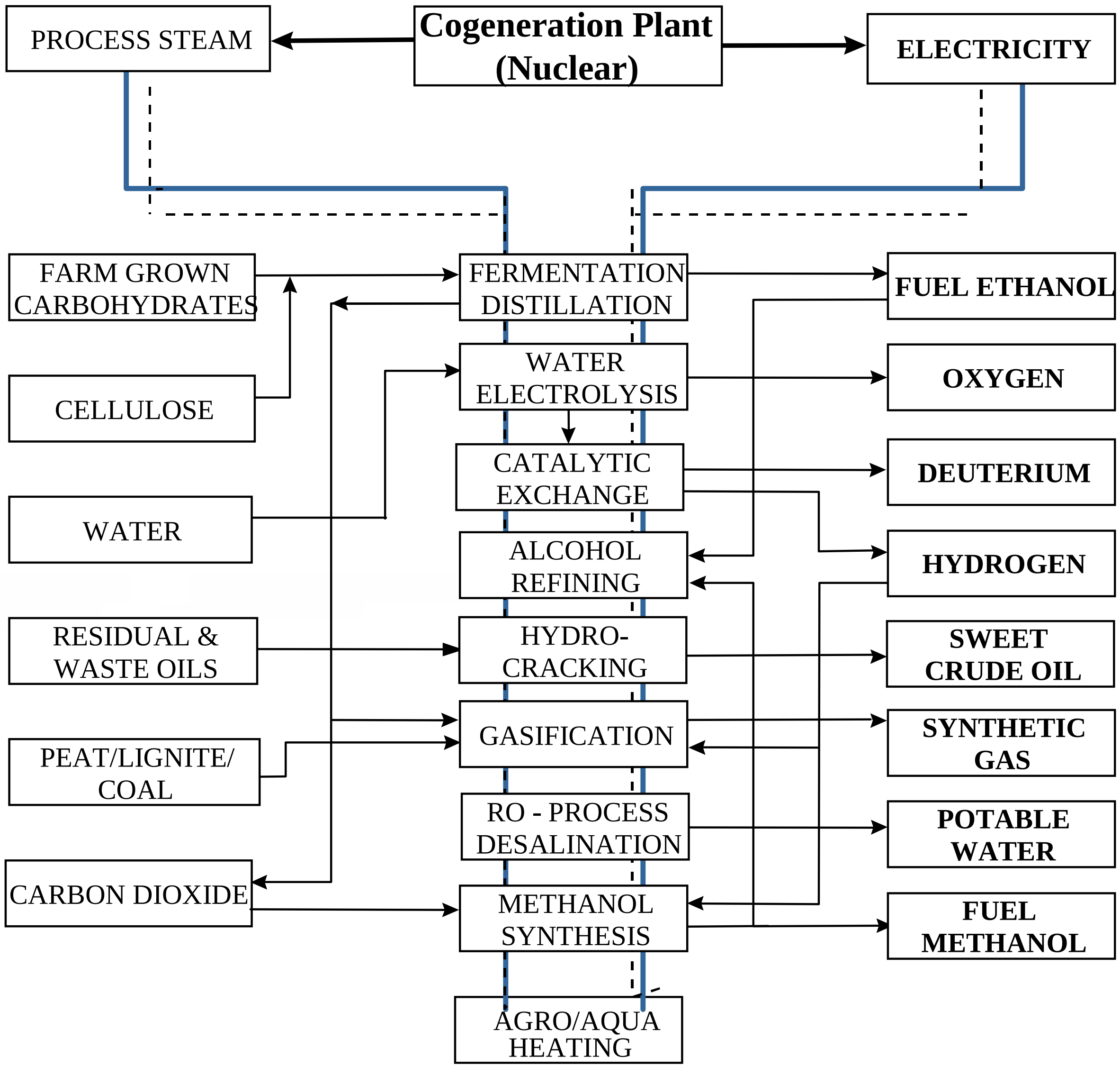


NUCLEAR FISSION SUPPORTS PRODUCTION OF:

- Steam
- Electricity
- Hydrogen

The Bruce Nuclear Power Development

Integrated Processes, Thermal Cascade



Example Electrolysis Plant (Stand-alone)

50 MWe Electrolysis at $.02 per kwh, hydrogen @ $2,000 /Mg
Costs in Canadian Dollars

Capital cost		
	Land, bldg.	1,500,000
	Equipment (256 cells)	28,400,000
Annual revenue		20,100,000
Annual operating cost		
	electricity	13,400,000
	other (interest, amortization, tax)	5,500,000
Annual net revenue		1,200,000

Revenue products

60,000 Mg oxygen at $50 per Mg	3,000,000
7 Mg D2O at 300 k$ per Mg	2,100,000
7,500 Mg hydrogen at $2,000 per Mg	15,000,000

Production of High-Temperature Process Gases

- There is a steady world demand for process gases at a temperature between 1000 C and 1500 C.
- The Pebble Bed Modular Reactor (PBMR) could satisfy this need. This is a reactor type proposed by South Africa, and supported by several other countries.
- CANDU is unable to reach such high temperatures because it uses pressurized-water coolant.
- A plasma torch (electric-arc) or hydrogen torch could be used in combination with a CANDU reactor, to avoid development and installation of yet another reactor type for the purpose.

Manufacturing Nuclear Fuel

- Transmutation (applied alchemy) can be used to increase the amount of fissile nuclear fuel available – necessary for large-scale applications
- Fissile isotopes can be produced in reactors, by capture of one neutron in abundant fertile isotopes.
- Only fast reactors operating on the uranium-plutonium cycle can produce enough excess neutrons to allow rapid fuel "breeding"

  One fast fission → 2.9 fission neutrons → minus one neutron for next fission → minus ~0.5 neutrons lost → leaving ~1.4 neutrons for breeding new fuel

- Fissile isotopes also can be produced from accelerators designed to produce many excess neutrons – eg. via nuclear spallation reactions

Next steps

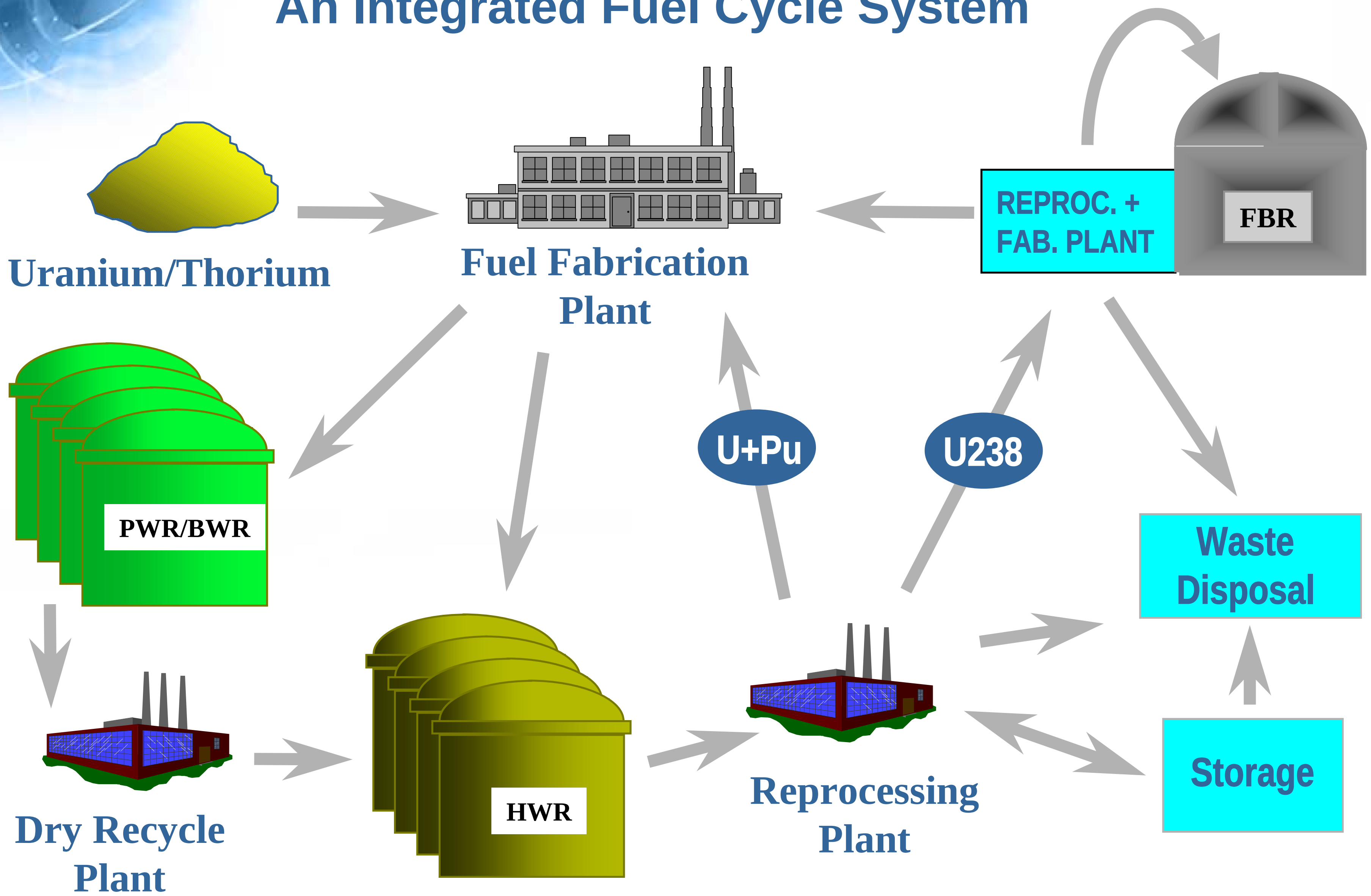
- Apply LWR-HWR "Tandem" cycles
  - e.g. PWR-CANDU DUPIC cycle in Korea
  - Spent fuel from LWR is good fuel for CANDU if some fission products are removed.
- Use reprocessed plutonium in MOX (U-Pu) fuels in LWR
  - Or save reprocessed plutonium for later use in fast reactors
- Increase fuel burnup in HWR, decrease recycle costs
- Introduce ex-weapon fissile materials into all reactors.
- Introduce the thorium-MOX once-through fuel cycle in HWR
- Develop pebble-bed modular reactor (PBMR) to produce process gas and liquid fuels

The international nuclear weapons control regime puts a very strong emphasis on the protection of nuclear fuel from unauthorized use. This initiative will continue to shape the development of peaceful nuclear energy applications.

Reactor Developments

- Gen-4 program – led by US and IAEA
  - Inherently safe, proliferation resistant, economically competitive
- Next-generation CANDU
  - Emphasis on economics – compete with today's international natural gas combined cycle plants
  - CANDU has already achieved a very high level of safety
  - Proliferation resistant design is "built in" to all CANDU power stations
- Fast breeder reactor
  - Led by Russia and India –emphasis on increasing mined uranium energy yield
- Reprocessing
  - Led by UK and France – lower cost, less waste ('dry' processes)

An Integrated Fuel Cycle System



AECL
Atomic Energy
of Canada Limited

EACL
Énergie atomique
du Canada limitée