Science of Nuclear Energy and Radiation

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Nuclear Energy Concepts

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Nuclear Energy

Nuclear energy is energy from the nuclei of atoms. It is not an invention of the devil.

It occurs and has occurred in nature since the beginning of the universe.

It is <u>not</u> a human <u>invention</u>, but a human <u>discovery</u> and <u>application</u>, akin to that of fire (i.e. chemical energy).

Law of Conservation of Energy

Total amount of energy in universe is constant. Cannot <u>create</u> or <u>destroy</u> energy, can only change it from one form to another, e.g.

- potential energy (e.g., of apple in tree) to kinetic energy (of falling apple),
- kinetic energy to heat (when apple hits ground, temperature increases slightly).

Seems to run counter to experience!

Equivalence of Mass and Energy

Einstein: Law of conservation of energy holds only when you include mass as a form of energy!

$$\mathbf{E = mc^2} \qquad (1)$$

[An equation which has certainly captured the public imagination!]

Energy from Mass: Chemical Energy and Nuclear Energy

Energy from burning, e.g.,

$C + O_2 \longrightarrow CO_2$

comes from change in mass, but so small as to be unmeasurable.

Chemical energy: changes in **atoms** and **molecules** (their electron clouds):

the <u>true</u> atomic energy!

Energy from Mass: Chemical Energy and Nuclear Energy

Nuclear energy comes from changes in **nuclei** of atoms.

Nuclei made up of protons and neutrons, radius ~ 1/100,000 of atomic radius.

Binding energy for a very small space is very great, therefore:

Energies involved in nuclear reactions hundreds of thousands, or millions, of times, greater than those in chemical reactions.

Nuclear Reactions

- Decay by emission of α, β, or γ radiation:

  γ–decay of ^{238}U: $^{238}U \longrightarrow {}^{234}Th + \alpha$

  β–decay of ^{99}Mo: $^{99}Mo \longrightarrow {}^{99m}Tc + \beta$

  (^{99m}Tc important medical radioisotope)
- Interaction of nuclei with colliding particles:

  Deuterium break-up: $D + \gamma \rightarrow H + n$

  (photoneutron production)

  Formation of tritium from deuterium:

  $D + n \longrightarrow T$

^{235}U	^{238}U
92 Protons ●	92 Protons ●
143 Neutrons ●	146 Neutrons ●

Nuclear Reactions

- Interaction of nuclei together:

  Fusion reaction: $D + T \rightarrow {}^4He + \alpha$

  [Note: of interest for application in fusion reactor, but temperature must be millions of degrees!]

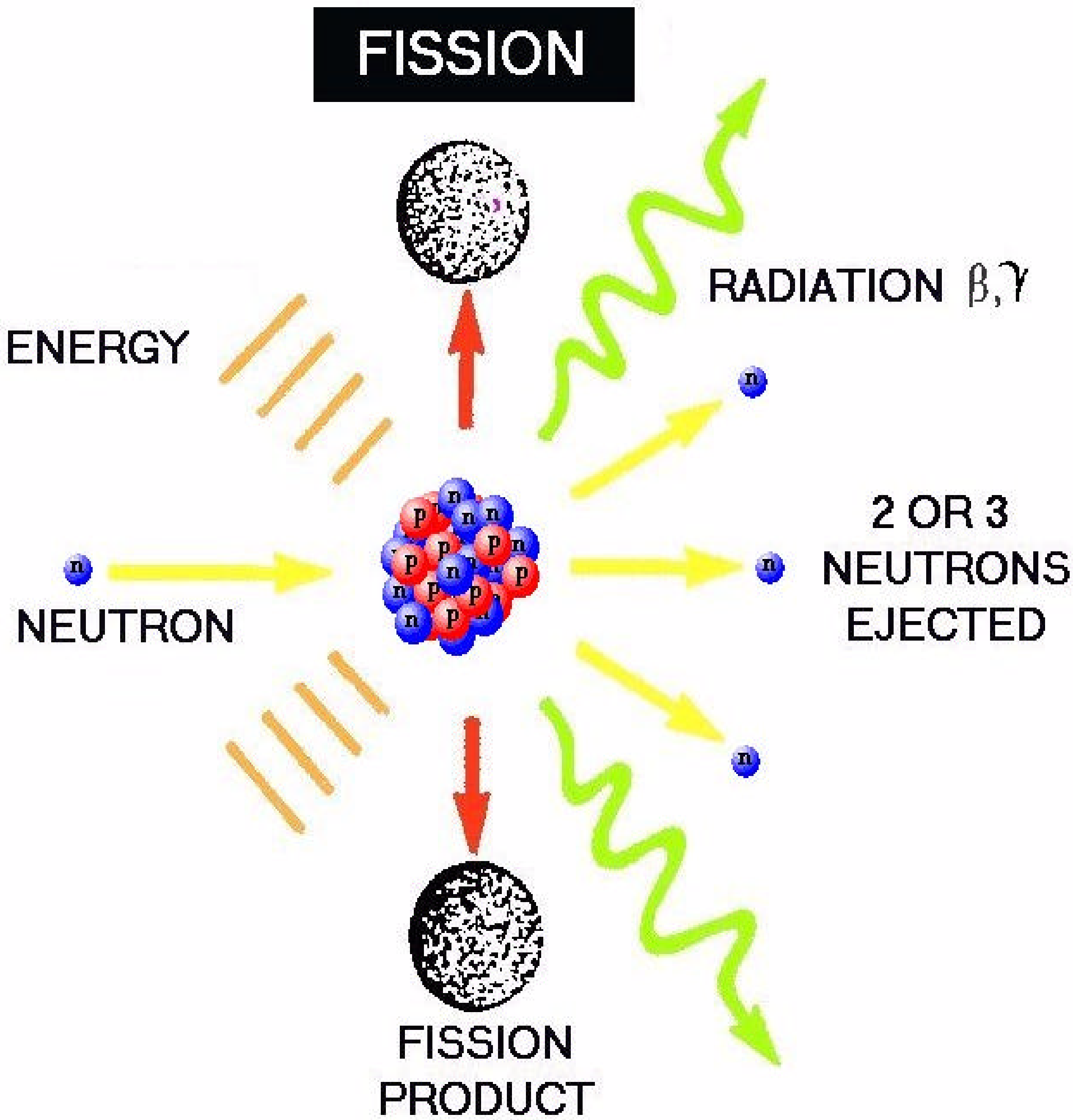
Application of Nuclear Energy

Need a nuclear reaction which produces energy (by mass conversion), and which can be continuous and controllable.

Fission is such a reaction: splitting of a large nucleus, e.g. ^{235}U:

$$^{235}U + n \rightarrow 2 \text{ large pieces (fission products)} + 2\text{-}3 \text{ neutrons} + \beta, \gamma + \text{energy} \qquad (3)$$

Fission occurs spontaneously in nature, but with very long half-lives: e.g., fission decay mode of ^{238}U would have half-life of $0.8*10^6$ years.


FISSION
RADIATION β,γ
ENERGY
2 OR 3
NEUTRONS
EJECTED
NEUTRON
FISSION
PRODUCT

Application of Fission

Fission reaction (3) satisfies criteria for energy source:

- energy is “produced” (liberated), and
- process has potential of being self-perpetuating, since fission neutrons which emerge can induce more fissions: **chain reaction.**

This is the operating principle of fission reactors.

Energy from Fission

Energy produced per fission ~ 200 MeV

[~ $3.2*10^{-11}$ J].

This is several orders of magnitude greater than energy produced by combustion, but approximately only **0.09%** of mass energy of the uranium nucleus!

Energy appears mostly (85%) as kinetic energy of fission fragments, and in small part (15%) as kinetic energy of other particles.

Energy quickly reduced to heat, used to make steam from water, and generate electricity.

Fission Products

The fission products are nuclides of roughly half the mass of uranium.

However, not always same in every fission: great number of different ones, each produced in a certain percentage of the fissions.

Most are “neutron rich”; decay typically by β- or γ-disintegration; are radioactive.

To prevent release of radioactivity, used fuel is safely stored and contained.

Fission Products

Some examples of long-lived fission products:

- **^{85}Kr, half-life 10.4 y**
- **^{90}Sr, half-life 28 y**
- **^{137}Cs, half-life 30 y**
- **^{99}Tc, half-life $2.1*10^{5}$ y**
- **^{129}I, half-life $1.7*10^{7}$ y**

Actinides

(Or transuranics) Produced from absorption of neutrons by ^{238}U: plutonium, americium, curium, etc.

e.g., production of ^{239}Pu:

$^{238}U + n \rightarrow\ ^{239}U \rightarrow\ ^{239}Np + \beta \rightarrow\ ^{239}Pu + 2\ \beta$

^{238}U is said to be fertile: ^{239}Pu is fissile, participates in subsequent fissions. Half the energy produced in CANDU is from plutonium created “in situ”!

Actinides also tend to have long half-lives, e.g. for ^{239}Pu 24,000 y.

Thermal Reactors

Fission in ^{235}U occurs much more readily when inducing neutron travels “slowly”.

But neutrons created in fission have energies of order of 1 MeV, speeds of 10,000 km/s!

To increase probability of fission, neutrons are slowed to “thermal” energies (**thermal equilibrium** with ambient environment) by a **moderator**.

Thermal neutrons may be relatively “slow”, but still travel at typically 2 km/s!

Thermal Reactors

Thermal fission possible with only few nuclides, called **fissile:** e.g. ^{235}U, ^{239}Pu, ^{241}Pu; only ^{235}U present in nature. [^{238}U **fissionable**, but not by thermal neutrons - not fissile.]

Abundance of ^{235}U is only 0.7% in natural U: for self-sustaining chain reaction, must ensure too many neutrons are not "lost":

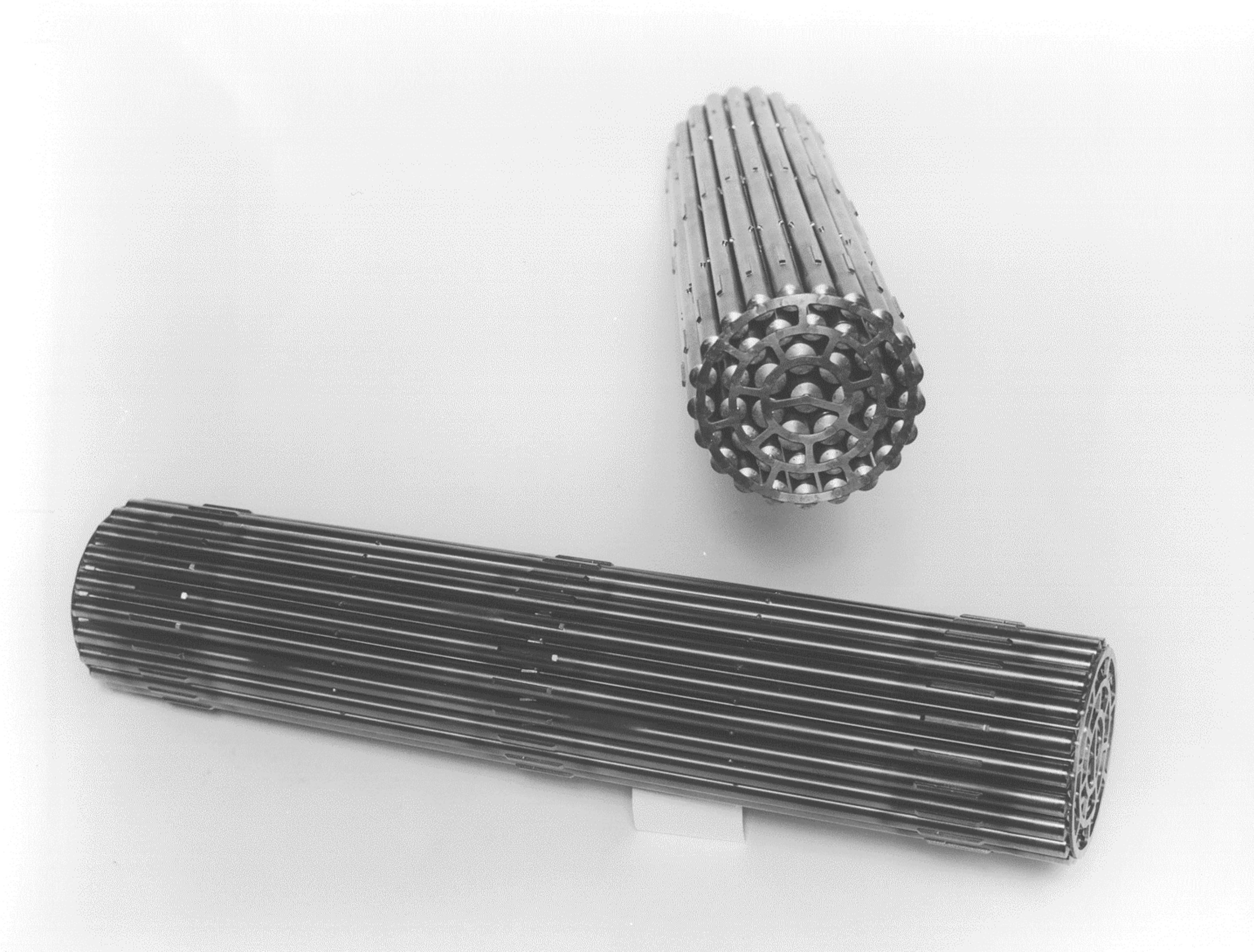
- artificially enrich uranium (increase % of ^{235}U): U.S. PWR (Pressurized Water Reactor), or
- ensure neutron "economy" - use heavy water (D_2O), very poor n absorber, for moderator: CANDU (Canada Deuterium Uranium) reactor.

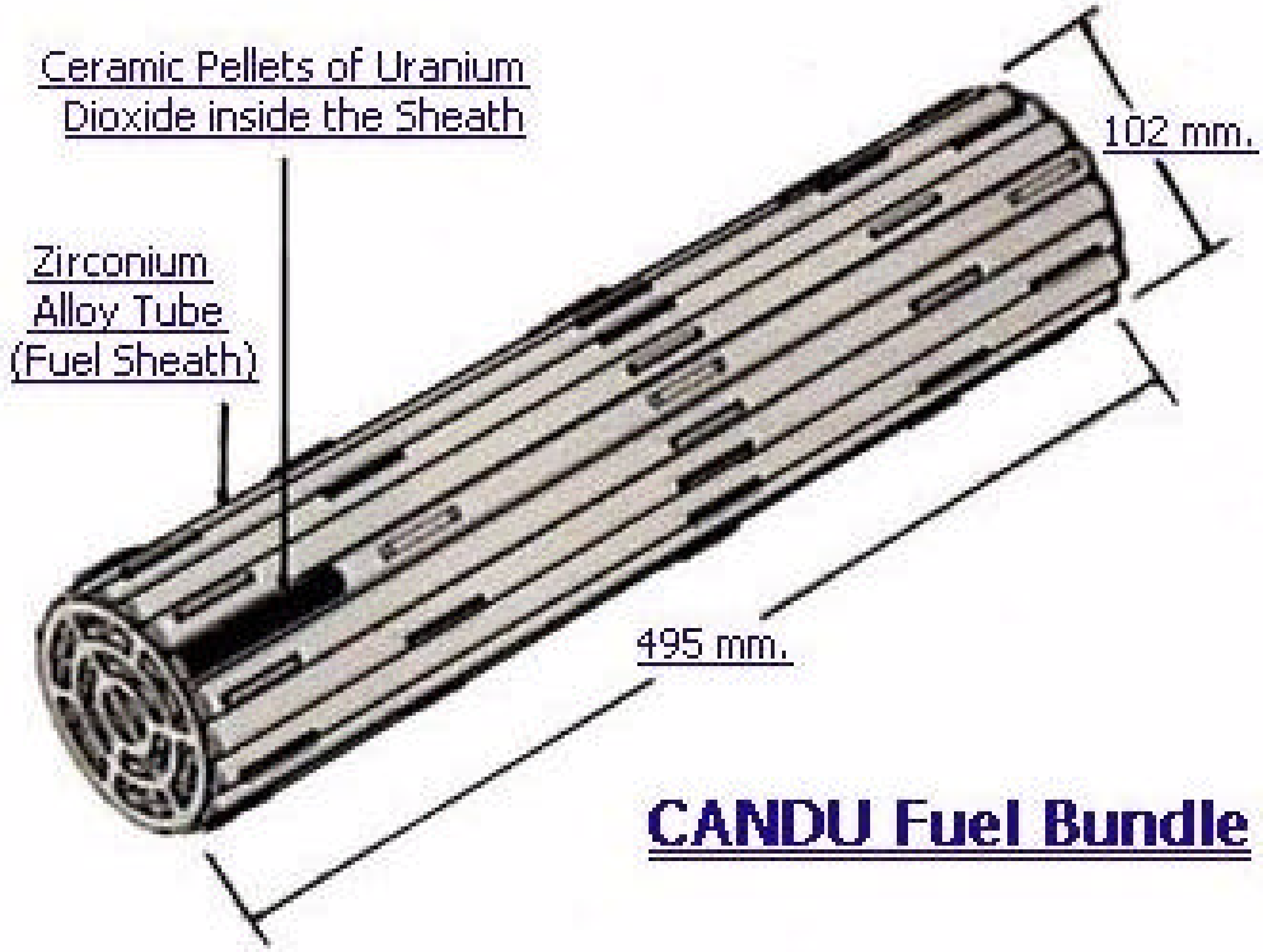
Reactor Fuel

Fuel in most reactors is in form of UO_2, a very strong ceramic.

In CANDU, fuel bundles about 50 cm long.

Bundle contains 28 or 37 fuel “elements”, each with ~ 20-25 UO_2 pellets encased in zirconium sheath. Fuel bundle contains about 20 kg of uranium.





CANDU Fuel Bundle

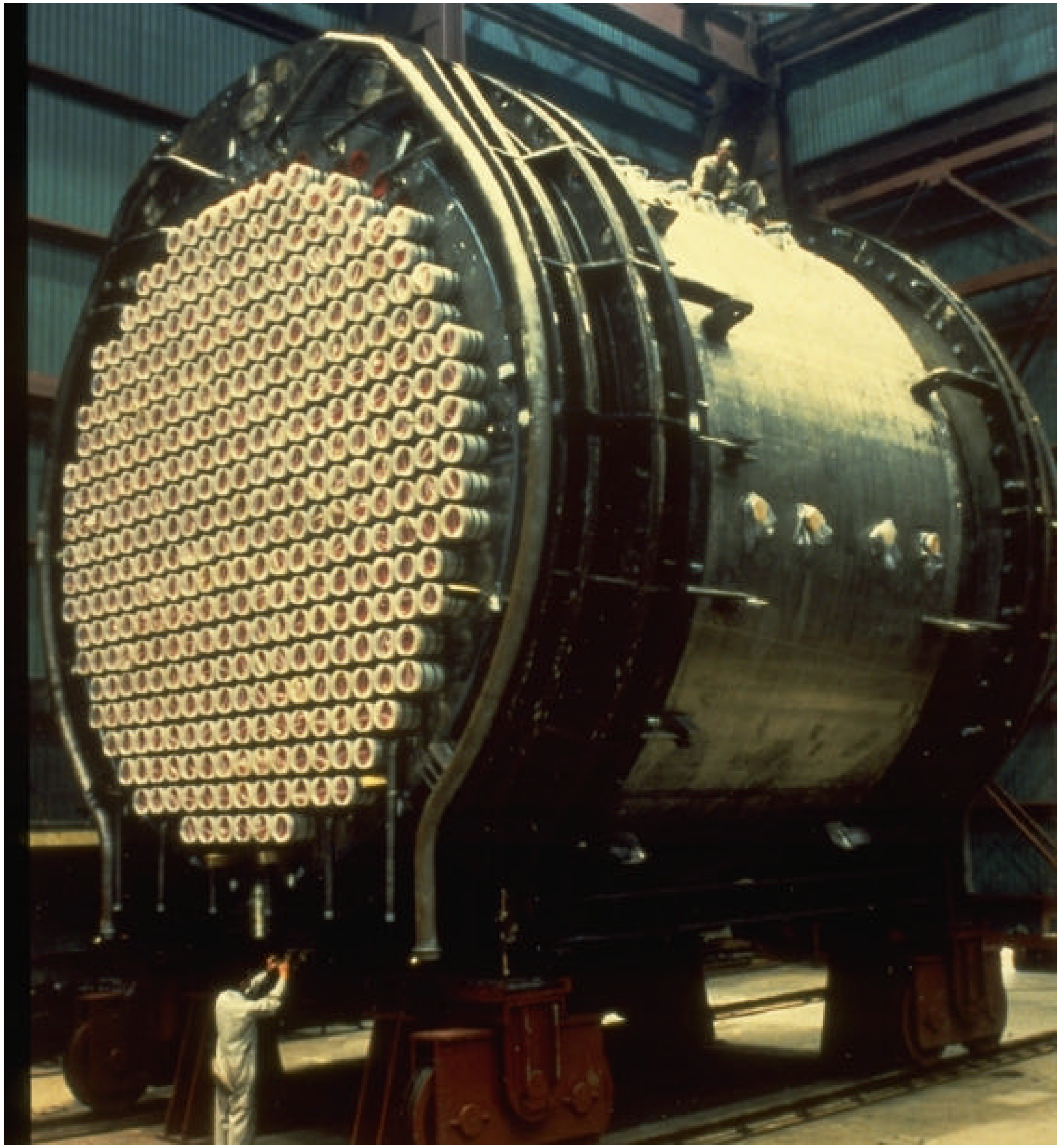
CANDU Reactor

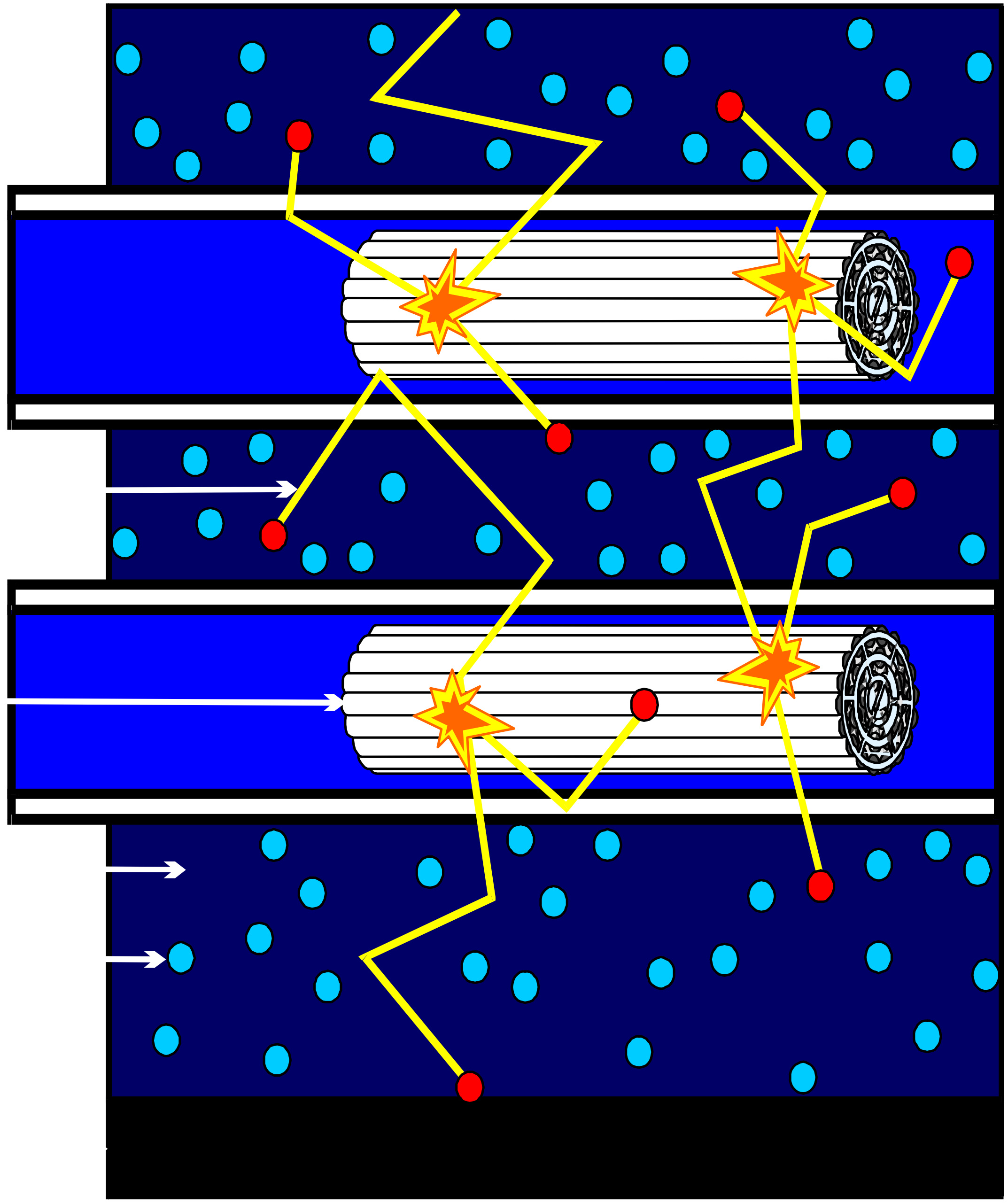
CANDU is a **pressure-tube** reactor:

The fuel is placed in fuel channels (12 bundles each), which contain the circulating coolant (D_2O) under pressure.

The moderator surrounds the fuel channels; most fission neutrons are slowed down in the moderator before re-entering the fuel and inducing more fissions.

The pressure-tube concept allows on-power refuelling and has other advantages.





Fuel Requirements

Energy in fission immense:

1 kg (U) in CANDU = ~ 180 MW.h(th)

= 60 MW.h(e).

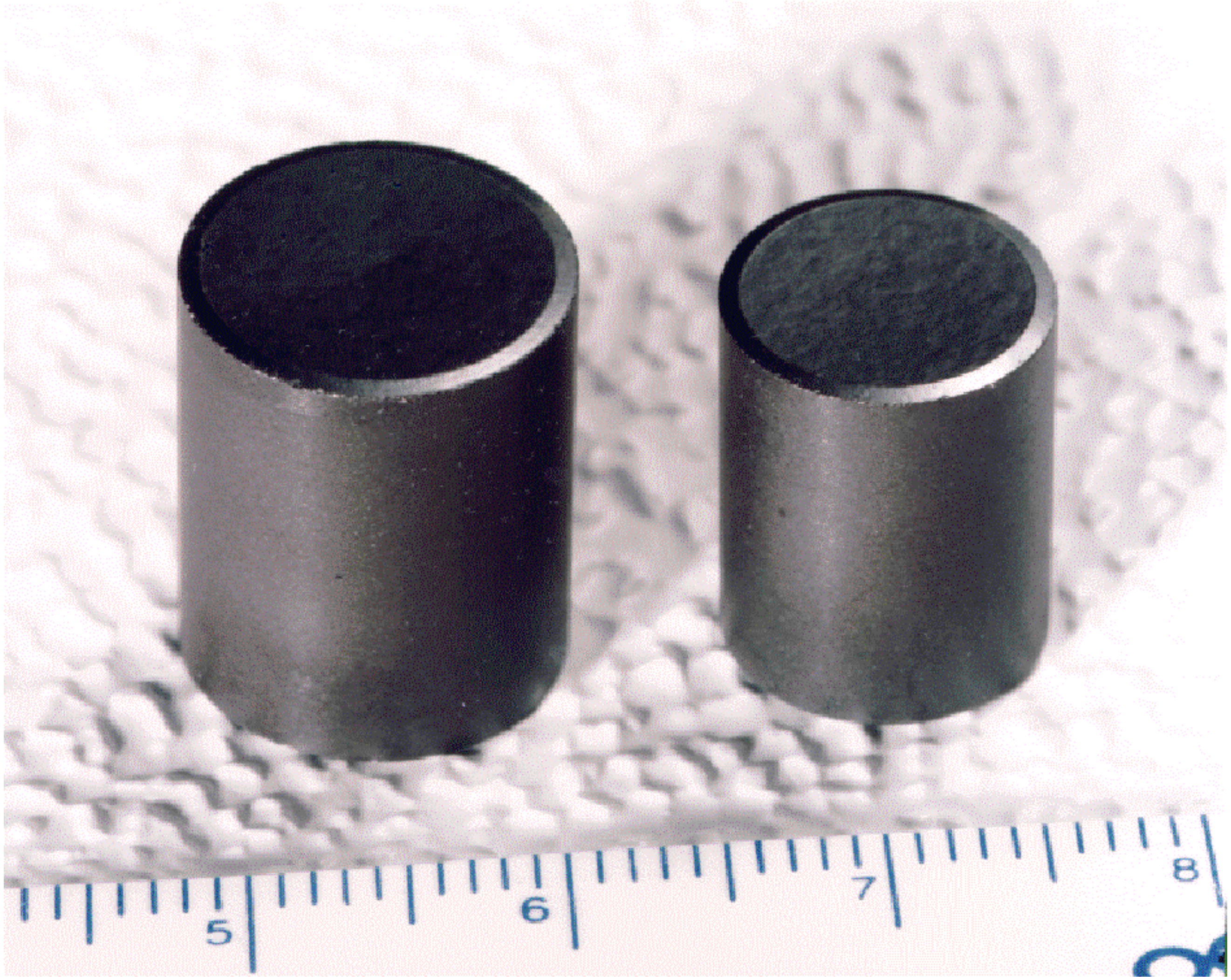
Typical 4-person household's electricity use

= 1,000 kW.h/mo = 12 MW.h/year, then

a mere **200 g** (< 0.5 lb) (U) - 6 to 8 pellets - serves 1 household for an entire year. [Cf: If from fossil, ~ 30,000 times as large, ~ **6,000 kg** coal.]

Cost of nuclear electricity insensitive to fluctuations in price of U.

Pellets



Fuel Requirements

1 CANDU-6 = 680 MW(e) uses ~ 120 tonnes of uranium per year. This corresponds to a volume of U of only **12 m^3**! This is to be compared to the ~ 4,000,000 tonnes of coal in a fossil plant.

Same ratio applies to used uranium fuel and ash. Used nuclear fuel safely stored, isolated from environment. Whereas products of combustion (CO_2, SO_2, NO_x, …) end up in atmosphere.

Since most coal also contains U, fossil plant may actually release more radioactivity than a nuclear generating station!

Control of Chain Reaction

Several processes compete for neutrons:

- “productive” absorptions, which end in fission
- “non-productive” absorptions (in fuel or structural material)
- leakage out of reactor

Control of Chain Reaction

Self-sustainability of chain reaction depends on relative rates of production and elimination of neutrons.

Measured by the effective reactor multiplication constant, k_{eff} = Neutron production/Neutron loss

k_{eff} < 1: reactor subcritical; chain reaction not self-sustaining, reactor shuts down;

k_{eff} = 1: reactor critical; chain reaction exactly self-sustaining, reactor power is steady;

k_{eff} > 1: reactor supercritical; chain reaction more than self-sustaining, power increases.

Control of Chain Reaction

Leakage of neutrons out of reactor increases as size of reactor decreases

Therefore a reactor must have a minimum size to work.

Below this minimum size or **critical mass,** leakage is too high and k_{eff} cannot = 1.

Critical mass depends on **shape** of the mass (reactor), **composition** of fuel, and **other materials** in reactor.

Control of Chain Reaction

To operate reactor, we want most of the time k_{eff}= 1 so everything nice and steady.

Need ways to make $k_{eff} < 1$ to reduce power or shut the reactor down; done by inserting rods or devices made of strong neutron absorbers, such as boron, cadmium, or gadolinium.

And need to make k_{eff} slightly > 1, for a short time, to increase power; usually done by removing a bit of absorption.

Control of Chain Reaction

Don't want to make k_{eff} much > 1, or

> 1 for long time: power could increase to high values, with undesirable consequences, e.g. melting of fuel.

Every nuclear reactor contains regulating and shutdown systems to do all above jobs.

[Nuclear bomb, in contrast to reactor, is designed to be **very** supercritical on **fast** neutrons, to generate a huge amount of **uncontrolled** energy in a very short time. **No reactor can explode like a nuclear bomb.**]

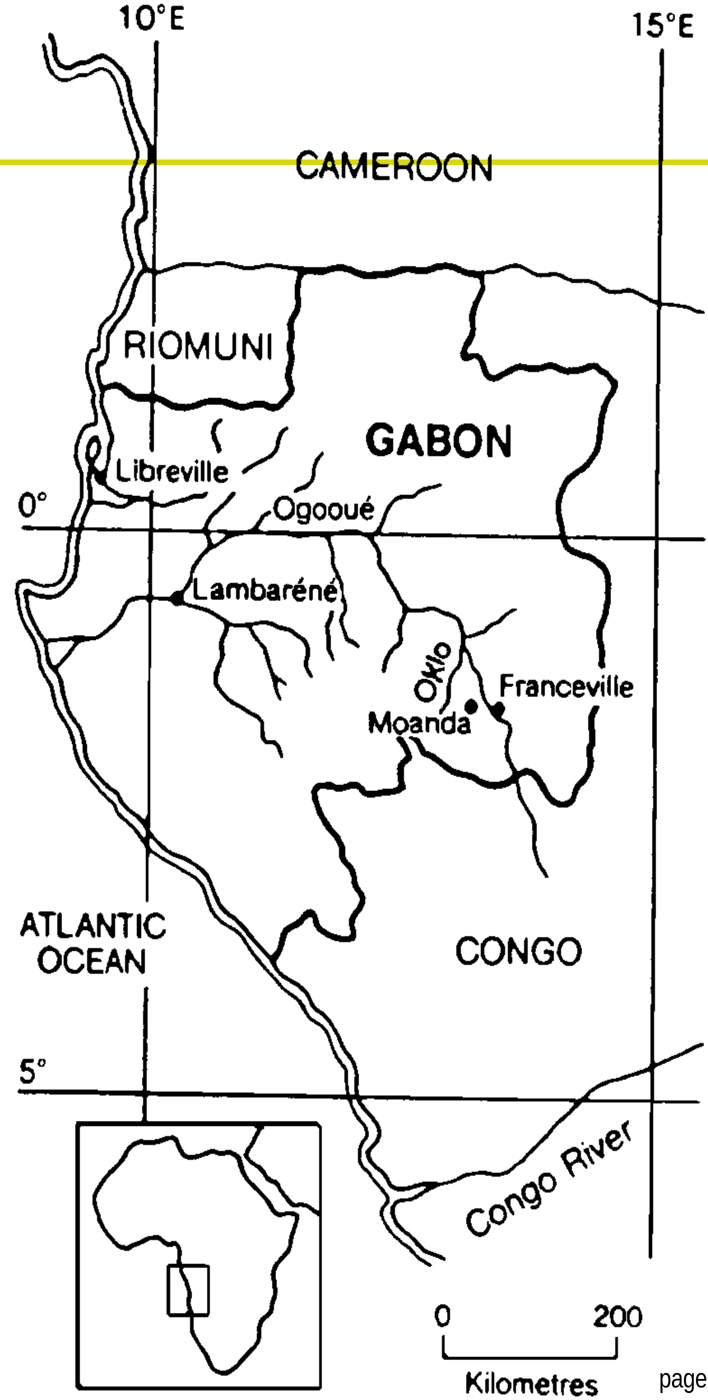
Oklo Reactor, Child of Nature

Hundreds of millions of years before first fission reactor built by humans, nature had built its own at Oklo, in Gabon, West Africa.

Indeed, such a reactor was discovered to have spontaneously started in Oklo some 1,800 million years ago.

Reactor was result of rich uranium deposits in presence of water. Concentration of ^{235}U in U was then ~ 3.5% , made possible chain reaction moderated by light water.

Map of Gabon showing position of Oklo River



Oklo Reactor, Child of Nature

Oklo reactor seems to have operated for very long time and to have generated ~ 15,000 MW.years of fission energy!

Another interesting finding: there was very little migration of plutonium and fission products; of great interest for waste storage and leaching rate of the products of fission in an underground repository.

Review of Historical Milestones

In late 19th century, mechanical universe well understood (Newton's laws), and electromagnetic theory (Maxwell's equations).

Physicists thought nothing new to learn, only perform calculations to more and more significant figures.

Then floodgates of modern physics opened: new discoveries came at unprecedented pace over last century.

Following are some of the milestones of importance in nuclear physics and technology.

Historical Milestones

- 1895, Roentgen discovers X-rays (ionizing radiation): nuclear medicine
- 1896, Becquerel discovers radioactivity
- 1898, Marie and Pierre Curie discover new elements radium and polonium
- 1905, Einstein's special theory of relativity, equivalence of mass and energy
- 1911, Rutherford discovers atomic nucleus (at center of atom, much smaller, greatest part of atomic mass, positive charge)
- 1913, Bohr publishes model of atom (electrons orbiting nucleus)

Historical Milestones

- 1913, discovery of isotopes
- 1932, Chadwick discovers neutron (suggested by Rutherford in 1920)
- 1939, Hahn/Strassmann/Meitner/Frisch discover fission of uranium
- 1942, Fermi produces fission chain reaction in uranium/graphite “pile”
- 1945 Jul. 16, U.S. tests fission bomb in New Mexico
- 1945 Aug 6/9, U.S. A-bombs over Hiroshima/Nagasaki, ends war in Japan

Historical Milestones

- 1945 Sep. 5, ZEEP reactor starts operation at Chalk River Laboratories (CRL) - **2nd operating nuclear reactor in the world!**
- 1947 Jul., NRX reactor starts operation at CRL
- **1951, cobalt therapy demonstration (Canada)**
- 1954 Jan., USS Nautilus submarine launched
- 1957 Nov., NRU reactor starts operation at CRL [current source of many radioisotopes]
- 1957 Dec., Shippingport Atomic Power Station starts up near Pittsburgh
- 1962 Apr., Nuclear Power Demonstration (NPD) plant starts up near CRL

Historical Milestones

- 1966 Oct., Douglas Point nuclear power plant starts up; 1968 Sept., in-service
- 1971 Feb., Pickering NGS, Unit 1 starts up
- 1977-78, Bruce A NGS
- 1983-84, CANDU-6 at Pt. Lepreau (NB) and Gentilly-2 (Qué.), Embalse (Argentina), Wolsong-1 (South Korea)
- 1980s, 1990s, Pickering B, Bruce B, Darlington, Wolsong 2-4, Cernavoda-1
- 1999+, 2 MMIR medical-isotope reactors (CRL)
- 2000s, 2 CANDU-6 at Qinshan (China)