Nuclear Energy Concepts

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Nuclear energy is energy from the nuclei of atoms. It is not an invention of the devil. It is quite natural - it occurs and has occurred in nature since the beginning of the universe. It is not a human invention. How to take advantage of this source of energy is a human discovery and application, akin to the discovery by man that he could use and control fire, i.e. chemical energy.

To understand nuclear energy, let us start with the

Law of Conservation of Energy

The total amount of energy in the universe is constant. You cannot create or destroy energy. You can only change it from one form to another, for instance

- potential energy (e.g., of an apple in a tree) to kinetic energy (of the apple when it falls),
- kinetic energy to heat (when the apple hits the ground, its temperature increases slightly).

But wait a minute! This runs counter to our experience! If you burn something, you get energy (heat) without appearing to lose anything!?

Equivalence of Mass and Energy

One of Einstein's greatest discoveries is that the law of conservation of energy holds in fact only when you include mass as a form of energy!

$$\mathbf{E = mc^2} \tag{1}$$

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

Energy from Mass: Chemical Energy and Nuclear Energy

The energy you get from burning something, for example coal,

$$\mathbf{C + O_2 \rightarrow CO_2} \tag{2}$$

comes from a change in mass: the mass of the carbon dioxide molecule is smaller than the sum of the masses of the carbon and oxygen molecules. But the difference is so small as to be unmeasurable.

Chemical energy comes from changes in **atoms** and **molecules** (e.g. Eq. 2) - actually their electron clouds. Chemical energy is the <u>true</u> atomic energy!

Nuclear energy comes from changes in the **nuclei** of atoms. Nuclei are made up of nucleons (protons and neutrons), and they are tiny: their radii are about 100,000 times smaller than those of atoms. The amount of energy needed to keep nucleons bound together in such a small space is much larger than the amount needed to keep electrons within atoms. Consequently, the energies involved in nuclear reactions (changes in nuclei) are much larger than those in chemical reactions - typically **hundreds of thousands** or **millions**, of times greater.

Nuclear Reactions

Nuclear reactions abound in nature:

- Some nuclei transform (decay) by emission of α, β, or γ radiation - these are examples of transmutations of elements (the alchemists' dream!), e.g.
  - α-decay of ^{238}U, the most abundant isotope of uranium (with 92 protons and 146 neutrons in its nucleus) to thorium:
    $^{238}U \rightarrow {}^{234}Th + \alpha$
  - β-decay of molybdenum, produced in a nuclear reactor, to (isomeric) technetium, a radioisotope of great use in diagnostic medicine:
    $^{99}Mo \rightarrow {}^{99m}Tc + \beta$
- Nuclei interact in various ways with particles (α, β, γ, or neutrons) which collide with them, e.g.
  - the break-up of deuterium D (i.e., heavy hydrogen ^{2}H) by energetic gamma rays, producing a proton (H) and a **photoneutron:**
    $D + \gamma \rightarrow H + n$
  - the absorption of a neutron by deuterium to yield an even heavier isotope of hydrogen, tritium, T (or ^{3}H)
    $D + n \rightarrow T$
- Nuclei can under some circumstances interact with one another, e.g.
  - the **fusion** reaction between deuterium and tritium, the one of greatest interest at the present time for application in a fusion reactor (but note that the temperature must be millions of degrees!):
    $D + T \rightarrow {}^{4}He + n$

Application of Nuclear Energy

To <u>apply</u> nuclear energy, we need to have a nuclear reaction which produces energy (by mass conversion), and which can be <u>continuous</u> and <u>controllable</u>.

One such reaction is nuclear fission, the splitting of a (large) nucleus. Let us look at the neutron-induced fission of the uranium-235 nucleus (an isotope of uranium, with 92 protons and 143 neutrons):

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

Note that fission does occur spontaneously in nature. Fission is indeed a decay mode of some nuclides, e.g. of the much more abundant isotope of uranium, ^{238}U (which has 92 protons but 146 neutrons). The main decay mode of ^{238}U, however, is α-decay, and the ^{238}U half-life is $4.47*10^9$ years; its half-life for spontaneous fission alone would be $0.8*10^{16}$ years.

The fission reaction (3) satisfies our criteria for an energy source, since:

- energy is "produced" (liberated), and
- process (3) has the potential of being self-perpetuating, since the fission neutrons which emerge can induce more fissions: we then have a chain reaction, open to control by what we allow these neutrons to do.

The reaction (3) is the operating principle of fission reactors. The energy produced per fission is ~ 200 MeV [~ $3.2*10^{-11}$ J], and while this is several orders of magnitude greater than the energy produced by combustion, it still represents approximately only **0.09%** of the mass energy of the uranium nucleus! The energy appears mostly (85%) as kinetic energy of the fission fragments, and in small part (15%) as kinetic energy of the other particles emerging from the fission reaction. The energy is quickly reduced to heat, which can be used to make steam from water, and generate electricity.

The fission products which arise from the reaction (3) are nuclides of roughly half the mass of uranium. However, note that they are not always the same in every fission. There are a great number of different fission products, each produced in a certain percentage of the fissions. Most fission-product nuclides are "neutron rich"; they decay typically by β- or γ-disintegration, and are therefore radioactive, with various half-lives. To prevent the release of radioactivity, therefore, the used fuel is safely stored **and contained.**

Some examples of long-lived fission products are:

- ^{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

We must also consider the actinides, or transuranics, which are nuclides produced from the absorption of neutrons by ^{238}U. These are isotopes of plutonium, americium, curium, etc. For example, the following chain of reactions produces ^{239}Pu:

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

Actually, ^{239}Pu itself is fissile, and will be subject to subsequent fissions in the fuel. In a CANDU reactor, half the energy produced is from the plutonium created "in situ"!

The actinides also tend to have long half-lives, e.g. the half-life of ^{239}Pu is 24,000 years.

Thermal Reactors

The fission reaction in ^{235}U occurs much more readily when the inducing neutron travels "slowly". But the neutrons created in fission are very energetic: they have energies of the order of 1 MeV, i.e. speeds of 10,000 km/s! To increase the probability of fission, the neutrons are slowed to "thermal" energies (i.e. to **thermal equilibrium** with the ambient environment) by a **moderator**. Note that thermal neutrons may be relatively "slow", but they still travel at typically 2 km/s!

Thermal-neutron-induced fission is possible with only a few nuclides, which are called **fissile:** for example ^{235}U and two isotopes of plutonium, ^{239}Pu and ^{241}Pu. Only ^{235}U is present in nature. ^{238}U is **fissionable**, but not by thermal neutrons, and so is not fissile. But the abundance of ^{235}U is only a small fraction (0.7%) in natural uranium. So, in order to have a self-sustaining chain reaction, we must ensure that too many neutrons are not unproductively "lost" in other events. Ways to do that are to

- artificially <u>enrich</u> the uranium (i.e., increase the percentage of ^{235}U), as in the U.S. PWR (Pressurized Water Reactor), or
- ensure "economy" of neutrons by choosing heavy water (D_2O), a very poor neutron absorber, for the moderator, as in the CANDU (Canada Deuterium Uranium) reactor.

The uranium fuel in most reactors is in the form of UO_2, a very strong ceramic. In CANDU, the fuel takes the shape of fuel bundles about 50 cm long. A bundle may contain 28 or 37 fuel "elements", each consisting of about 20-25 UO_2 pellets encased in a zirconium sheath. Each fuel bundle contains about 20 kg of uranium.

Fuel Requirements in Perspective

The energy generated in fission per unit of fuel is immense compared to the energy generated in combustion. One kilogram of uranium in a CANDU reactor produces about 180 MW.h of fission energy, or about 60 MW.h of electricity. If my 4-person household's average electricity use is typical, about 1,000 kW.h per month [12,000 kW.h = 12 MW.h per year], then a single kg of uranium is sufficient for 5 households for one year. That is, a mere **200 g** (< 0.5 lb) of uranium will serve the electricity needs of a household for an entire year. If the electricity were obtained from coal, then the mass of fuel would need to be about 30,000 times as large, i.e. about **6,000 kg** of coal. Consequently, the cost of nuclear electricity is insensitive to fluctuations in price of uranium.

A CANDU-6 reactor producing about 680 MW of electricity uses approximately 120 tonnes of uranium per year. This corresponds to a volume of uranium of only **12 m^3!** **This is to be compared to the ~ 4,000,000 tonnes of coal which would be required in a fossil plant.**

The same ratio applies to the amounts of used uranium fuel and ash from the generating stations. The very small mass of used nuclear fuel is safely stored and isolated from the environment. This is not true of the products of combustion (CO_2, SO_2, NO_x, …), which end up in the atmosphere. **Since most coal also contains uranium, a fossil plant may actually release more radioactivity into the environment than a nuclear generating station!**

Control of the Chain Reaction

Several processes compete for neutrons in a nuclear reactor:

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

The self-sustainability of the chain reaction depends on the relative rates of production and elimination (or loss) of neutrons. It is measured by a quantity called the effective reactor multiplication constant, k_{eff}. When

$k_{eff} < 1$, the reactor is subcritical: the chain reaction is not self-sustaining, and the reactor shuts down;
$k_{eff} = 1$, the reactor is critical: the chain reaction is exactly self-sustaining, and the reactor power is steady;
$k_{eff} > 1$, the reactor is supercritical: the chain reaction is more than self-sustaining, and the reactor power increases.

Because leakage of neutrons out of the reactor increases as the size of the reactor decreases, a reactor must have a minimum size to work. Below this minimum size or **critical mass,** the leakage is too high and k_{eff} cannot possibly be equal to 1. The critical mass depends on the **shape** of the mass (reactor), the **composition** of the fuel, and the **other materials** in the reactor.

To operate a nuclear reactor, we want most of the time to keep $k_{eff} = 1$ so that everything is nice and steady. We need ways to make $k_{eff} < 1$ when we want to reduce power or shut the reactor down; this is done by inserting rods or devices made of strong neutron absorbers, such as boron, cadmium, or gadolinium. And we need to make k_{eff}

slightly greater than 1, for a short time, when we want to increase power; this is usually done by removing a bit of absorption. In a reactor, we don't want to make k_{eff} much greater than 1, or greater than 1 for a long time, or the power could increase to high values, potentially with undesirable consequences, e.g. melting of the fuel. **Every nuclear reactor contains regulating and shutdown systems to do all the above jobs.**

[A nuclear bomb, in contrast to a 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.**]

The fission reactor, a child of nature at Oklo

Hundreds of millions of years before the 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. The reactor was the result of rich uranium deposits in the presence of water, and the fact that the concentration of ^{235}U in uranium was then about 3.5% (5 times higher than it is presently), which made possible a chain reaction moderated by light water. The reactor seems to have operated for a very long time and to have generated in total about 15,000 MW.years of fission energy! Another interesting finding in Oklo is that there was very little migration of the plutonium and fission products created; this is of great interest with regard to waste storage and the leaching rate of the products of fission in an underground repository.

Brief review of historical milestones in nuclear science and technology

In the late 19th century, the mechanical universe was well understood thanks to Newton's laws, and electromagnetic theory thanks to Maxwell's equations, and physicists thought there would be nothing new to learn, all that would remain would be to perform calculations to more and more significant figures. And then the floodgates of modern physics opened, and new discoveries came fast and furious at an unprecedented pace over the last century. The following are some of the milestones of importance in nuclear physics and technology.

- 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 the atomic nucleus (at center of atom, much smaller, greatest part of atomic mass, positive charge)

- 1913, Bohr publishes model of atom (electrons orbiting the nucleus)
- 1913, discovery of isotopes
- 1932, Chadwick discovers the 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
- 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; 1955 Jan., goes to sea
- 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
- 1966 Oct., Douglas Point nuclear power plant starts up; 1968 Sep, in-service
- 1971 Feb., Pickering Nuclear Generation Station, Unit 1 starts up
- 1977-78, Bruce A NGS
- 1983-84, CANDU-6 reactors 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+, MMIR, 2 new medical-isotope reactors at CRL
- 2000s, 2 CANDU-6 units at Qinshan (China)