CH0204 Organic Chemical Technology

Lecture 15

Chapter 5 Nuclear Industries

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Overview of topics

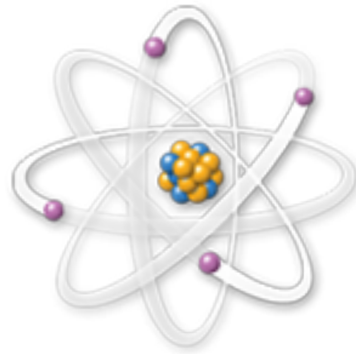
Chapter 5 Nuclear Industries

1. Nuclear fuels
2. Nuclear fuel cycle
3. Nuclear reactions
4. Nuclear reactors

Nuclear Reactions - *Fission Reaction*

Atom – Element – Isotopes

An atom resembles a miniature solar system. In the center of the atom is the nucleus around which electrons orbit, like planets moving around the sun.



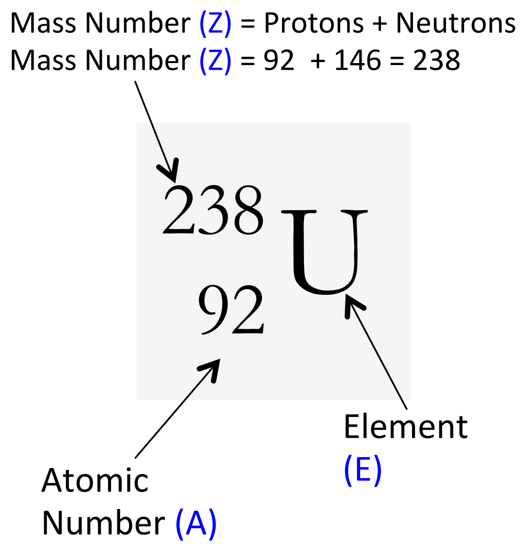
The nucleus, composed of protons and neutrons, contains most of the mass of the atom. Electrons move around the nucleus in relatively large orbits with nothing in between.

Atoms that contain an equal number of protons and electrons are referred to as elements.

There are 90 kinds of naturally occurring elements. An atom of uranium is the heaviest found in nature, with 92 protons in its nucleus. It's even heavier than lead.

Isotopes are variants of a particular chemical element. Elements with same number of protons but differing numbers of neutrons

The sum of the protons and neutrons in the nucleus of an isotope is defined as the mass, therefore each isotope of a given element has a different mass number (ie: ^{238}U, ^{235}U, etc.)



Source: http://www.cameco.com/uranium_101/uranium-overview/properties-and-uses/

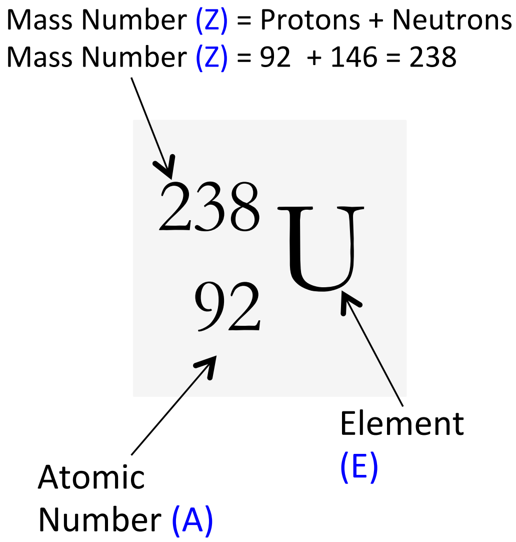
Nuclear Reactions - *Fission Reaction*

^{238}U is the most abundant (99.270%), has 146 neutrons and is the most stable natural uranium isotope with a half-life of approximately 4.468 billion years.

However, it is the isotope ^{235}U (0.725%) with 143 neutrons and a half-life of about 703.8 million years, that has changed life on earth.

It is fissile, which means if its nucleus is struck by another neutron, it can release energy by splitting into smaller fragments.

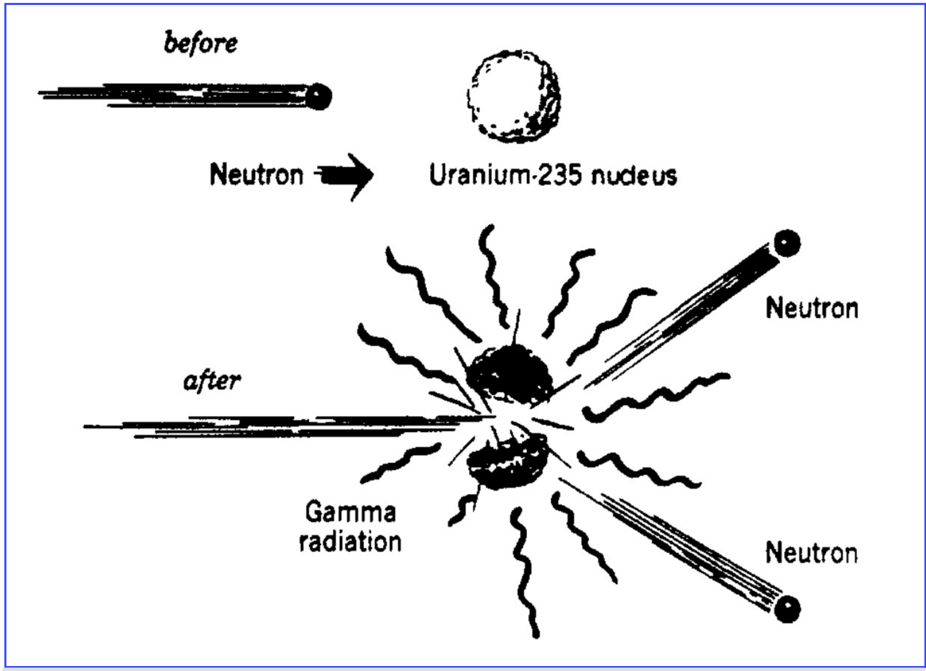
If some of the fragments are the other neutrons, in turn they can strike other ^{235}U atoms and cause them to split too, creating a nuclear chain reaction.



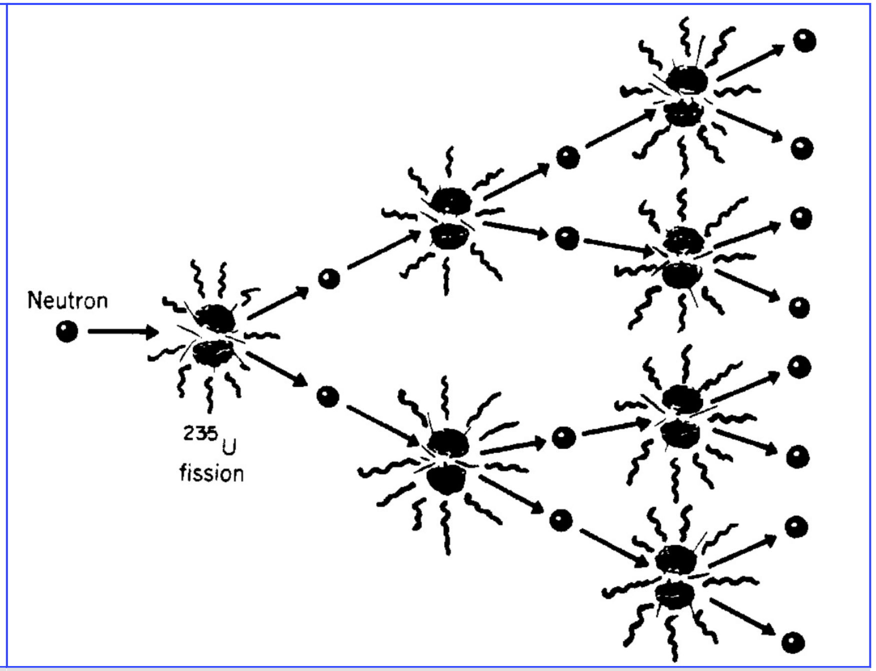
Source: http://www.cameco.com/uranium_101/uranium-overview/properties-and-uses/

Nuclear Reactions - *Fission Reaction*

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{144}_{56}\mathrm{Ba} + ^{89}_{36}\mathrm{Kr} \xrightarrow{\beta\ \gamma} ^{144}_{60}\mathrm{Nd} \xrightarrow{\beta\ \gamma} ^{89}_{39}\mathrm{Y}$$



Fission of single nucleus ^{235}U by neutron



Fission chain reaction

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{239}_{92}\mathrm{U} \xrightarrow[23\ \mathrm{min}]{\beta\ \gamma} ^{239}_{93}\mathrm{Np} \xrightarrow[2.3\ \mathrm{days}]{\beta\ \gamma} ^{239}_{94}\mathrm{P}$$

Nuclear Reactions-*Fission Reaction*

Matter can be transformed by a chain reaction into energy

$E = mc^2$ (Einstein's Law)

Where E is the energy that from the mass m that disappears, multiplied by the square of the velocity of light c^2.

Nuclear Reactions-*Fission Reaction*

Uranium-235 + neutron → fission products + energy + 3.025995 neutrons

Fission Products = Neodymium – 144 and Yttrium - 89

Reactants		Products		Difference
^{235}U	235.043915	^{144}Nd	143.910039	
Neutrons	1.008665	^{89}Y	88.905871	
		3 neutrons	3.025995	
Total	**236.05258**		**235.841905**	**0.210675**

A fraction 0.210675/235.043915 of the mass of the ^{235}U atom disappears in this fission reaction. This reduction in mass is the measure of amount of energy released in this fission reaction.

Nuclear Reactions-*Fission Reaction*

Einstein equation expressing the equivalence of energy and mass

$$\Delta E = \Delta m\, c^2 \quad \text{(Einstein's Law)}$$

predicts when Δm kilograms of mass disappears, ΔE joules of energy appears in its place.

In this relation, c is the velocity of light, $(2.997925 \times 10^8)^2$.

Thus, the energy released in this fission reaction is

$(0.0008963)\ (2.997925 \times 10^8)^2 = 8.06 \times 10^{13}$ J/kg ^{235}U

Nuclear Reactions-*Fission Reaction*

Through fission, one atom of ^{235}U is capable of releasing 50 million times more energy - about 200 Million electron Volts (MeV) – compared to the combustion of a single carbon atom – about 4 electron Volts (eV).

This means that one tiny pellet of uranium that weighs about 0.24 ounces (6.083 g) can generate as much energy as 3 barrels of oil (1 barrel = 119.24 liters i.e. 3 barrel = 357.72 liters), 17,000 cubic feet of natural gas (1 cubic feet = 481.4 liters i.e. 17,000 cubic feet = 18.6 x 10^6 liters), or 2,000 pounds of coal (1 pound = 0.4536 kg i.e 2000 pounds = 907 kg).


Uranium Pellet

Oil


Coal


Natural gas

Nuclear Reactions

Fission Reaction - Uranium and thorium reactions in power production

Uranium-235 + neutron $\longrightarrow$ fission products + energy + 2.43 neutrons

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} \xrightarrow{\beta\ \gamma} {}^{144}_{60}\mathrm{Nd} \xrightarrow{\beta\ \gamma} {}^{89}_{39}\mathrm{Y} $$

$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[\text{23 min}]{\beta\ \gamma} {}^{239}_{93}\mathrm{Np} \xrightarrow[\text{2.3 days}]{\beta\ \gamma} {}^{239}_{94}\mathrm{P} $$

$$ {}^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow[\text{23 min}]{\beta\ \gamma} {}^{233}_{91}\mathrm{Pa} \xrightarrow[\text{27 days}]{\beta} {}^{233}_{92}\mathrm{Th} $$

Fusion Reaction - Fusion reactions leads to the production energy by conversion of hydrogen to helium.

$$ 4\,{}^{1}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + 26.7\ \mathrm{meV}\ \text{or}\ 4.3 \times 10^{-5}\ \mathrm{erg} $$

Nuclear Reactors

Nuclear reactors have been defined as devices "containing fissionable material in sufficient quantity and so as arranged to be capable of maintaining a controlled, self-sustaining nuclear fission chain reactions"

These reactors are classified based on isotopes employed as fuels

1. Burners – Uses uranium 235 as enriched fuel
2. Convertors – Uses 238 uranium
3. Breeders – the original fuel may consist of isotope of 239 plutonium and 238 uranium

Nuclear Reactors

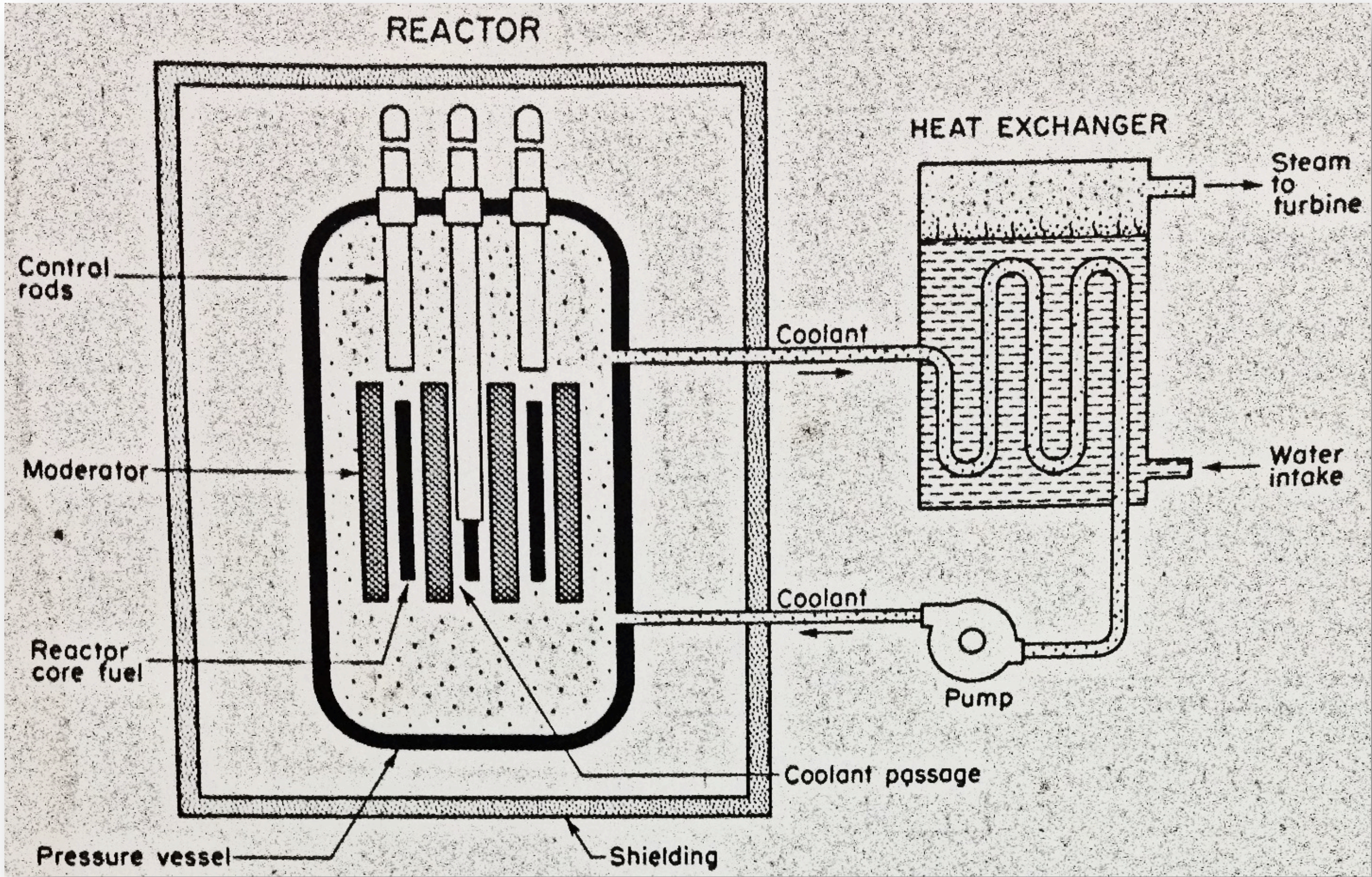
Breeders

The original fuel may consist of isotope of 239 plutonium and 238 uranium.

When fed with combination of fissionable and fertile fuel actually produces more fissionable fuel than they consume

In the reaction the fertile isotope is converted into plutonium to produce more fuel than they consume

Nuclear Reactors



Nuclear Reactors – *Major Components & Func.*

1. Fuels

a) Fission Fuels - contains compounds such as oxides, carbides, nitrides, sulfates and chlorides of

Uranium – ^{233}U, ^{235}U

Plutonium - ^{239}Pu, ^{241}Pu

b) Fertile Fuels - contains atomic elements which by nuclear reactions give fission fuels

Uranium - ^{238}U

Thorium - ^{232}Th

Limitations on the use of thorium as the fuel in nuclear reactors

- Thermal breeding advantages for thorium could not be achieved in aqueous solution because of extreme corrosion problem
- The complicated decay scheme arises fabrication costs
- Lack of technical feasibility

Nuclear Reactors

2. Moderators

   Materials such as graphite or D_2O (heavy water), which slowdown the emitted fast neutrons so that they can react with the fuel .

   (or)

   During the nuclear reaction the rapid multiplication of neutrons are slow down by moderators which results in sustained production of heat.

   Typical moderators are : Pure graphite, D_2O, H_20.

3. Control Rods

   Absorbs neutrons and stops the reactor

   Typical control rods are made up of silver, indium and cadmium

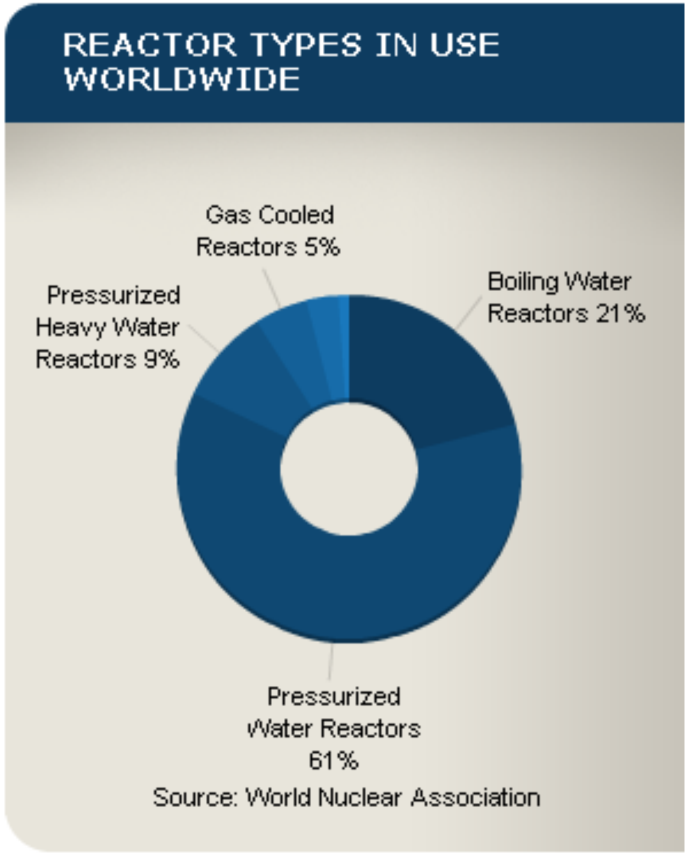
Nuclear Reactors

4. Coolants

Transfer the heat produced in the nuclear fuel to a steam generator to make steam.

Typical coolants used are water, molten metal (Na), Sodium Potassium (NaK)

Nuclear Reactors



Nuclear Reactors

Nuclear Power Reactors: Typical Characteristics

Type of Reactor	Fuel Form	Coolant	Moderator
BWR	Enriched Uranium Dioxide	Water	Water
PWR	Enriched Uranium Dioxide	Water	Water
PHWR (Candu)	Natural Uranium Dioxide	Heavy Water	Heavy Water
GCR	Natural Uranium	Carbon Dioxide	Graphite
AGR	Enriched Uranium Dioxide	Carbon Dioxide	Graphite
LWGR	Enriched Uranium Dioxide	Water	Graphite
FBR	Plutonium Oxide and Uranium Dioxide	Liquid Sodium	None

BWR - Boiling Water Reactor
PWR – Pressurized Water Reactor
PHWR – Pressurized Heavy Water Reactor
GCR – Gas Cooled Reactor

AGR – Advanced Gas Cooled Reactor
LWGR – Light Water Graphite Reactor
FBR – Fast Breeder Reactor

Production of D_2O

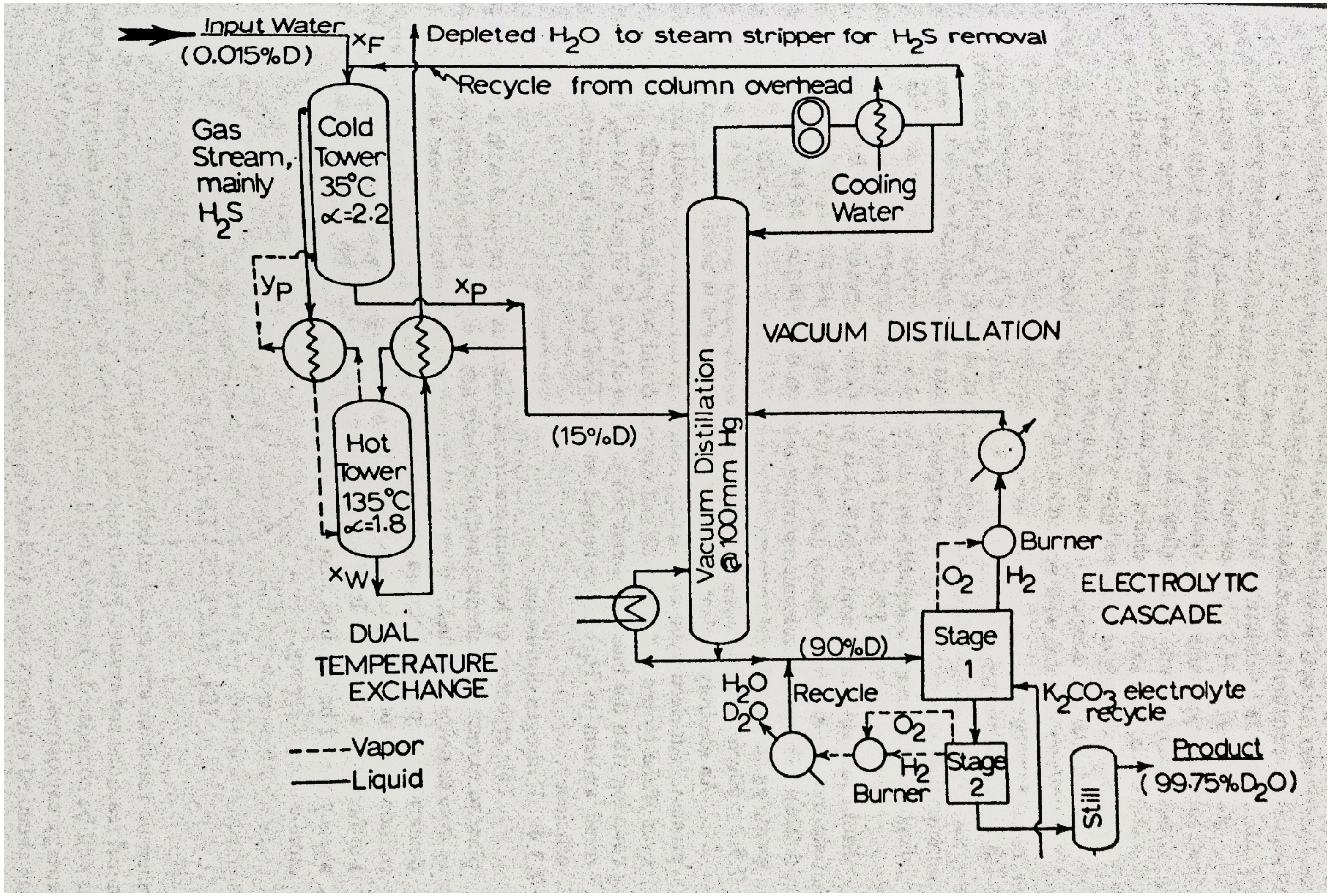
Heavy water exists in natural water as H_2O and in Petroleum sources as HD.

The isotopic atom percentage in both the source is about 0.013%

Methods for separating deuterium

S. No	Method	Material Used	Separation Factor
1	Dual temperature exchange	$H_2S - H_2O$	2.2 at 35°C
2	Distillation	H_2O	1.8 at 135°C
3	Electrolysis	H_2O	-

Production of D_2O



Spent Nuclear Processing

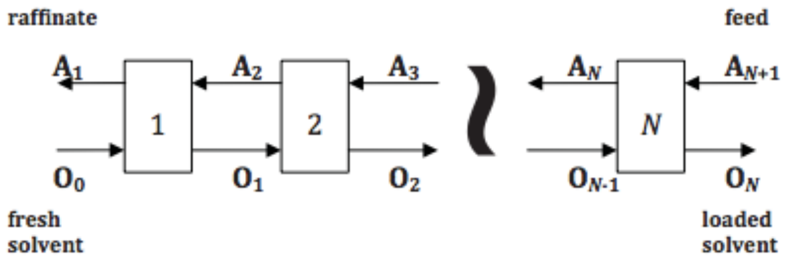
Major Steps involved in the spent (or used) nuclear fuels are as follows

1. Dissolve the spent nuclear with nitric acid
2. Separate the radioactive waste product from plutonium and uranium
3. Purify the product and concentrate them to reuse

One of the method used to separate the radioactive waste product from plutonium and uranium is continuous multistage solvent extraction extraction or also called as PUREX (**P**lutonium and **Ur**anium **Ex**traction Process)

Spent Nuclear Processing

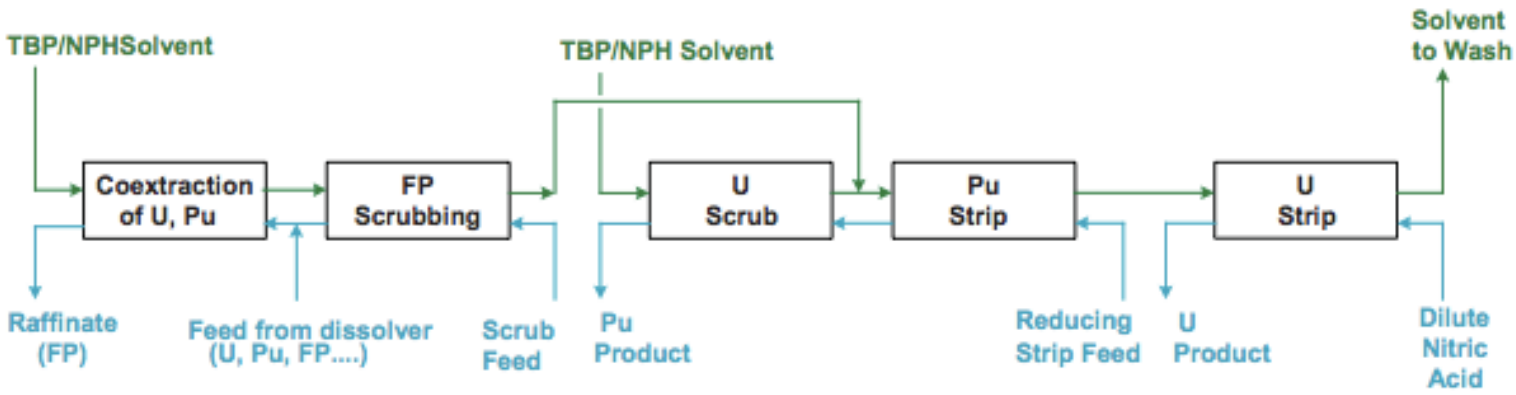
Continuous counter current extraction



In this flow diagram, the aqueous feed stream containing the solute(s) to be extracted enters at one end of the process (A_{N+1}), and the fresh solvent (organic) stream enters at the other end (O_0). The aqueous and organic steams flow countercurrently from stage to stage, and the final products are the solvent loaded with the solute(s), O_N, leaving stage N and the aqueous raffinate, A1, depleted in solute(s) and leaving stage 1. In this manner, the concentration gradient in the process remains relatively constant. The organic at stage O_0 contains no solute(s), while the raffinate stream is depleted of solute(s). Streams A_{N+1} and O_N contain the highest concentration of the solute(s).

Spent Nuclear Processing

Continuous counter current extraction



Spent Nuclear Processing

solution resulting from the dissolution of the used nuclear fuel is the feed to the co-extraction section of the flowsheet. The aqueous feed flows countercurrent to the PUREX solvent, and the U and Pu are extracted by the TBP into the normal paraffin hydrocarbon (NPH) organic phase. The loaded organic phase enters the fission product (FP) scrub section in which a nitric acid scrub solution (approx. 2 M HNO_3) is used to remove co-extracted fission products, such as Zr and Ru, from the solvent. The scrub solution containing the Zr and Ru combines with the feed solution entering the extraction section. The solvent then enters a Pu strip section in which the Pu is back-extracted from the organic phase. This is accomplished by reducing the Pu from the extractable +4 oxidation state to the inextractable +3 state. A

Spent Nuclear Processing

strip solution containing a reductant, such as hydroxylamine nitrate, U (IV), or ferrous sulfamate, is typically used. [7]

Reduction and back extraction of the Pu also results in back extraction of a portion of the uranium. The strip product from the Pu strip section therefore enters a uranium scrub section in which the Pu strip solution is contacted with a fresh solvent feed to re-extract this uranium into the organic phase. The organic phase containing the re-extracted U combines with the loaded solvent from the extraction section which enters the Pu strip section. Once the Pu has been back extracted from the PUREX solvent, the solvent enters the uranium strip section, which utilizes dilute nitric acid (typically 0.01 M HNO_3) at elevated temperature to back extract the U into the aqueous phase.

Spent Nuclear Processing

The resulting solutions from the first cycle PUREX extraction process include a solvent solution that is washed with a carbonate or hydroxide solution to remove degradation products and recycled back to the extraction section, a raffinate stream which is depleted of the U and Pu and disposed of as waste, and the Pu and U product streams. The U and Pu product streams are typically further processed with additional PUREX cycles to purify these streams.

Nuclear waste disposal

The volume of waste to be disposed is surprisingly small.

Temporary storage in tanks permits short half-life materials to decay

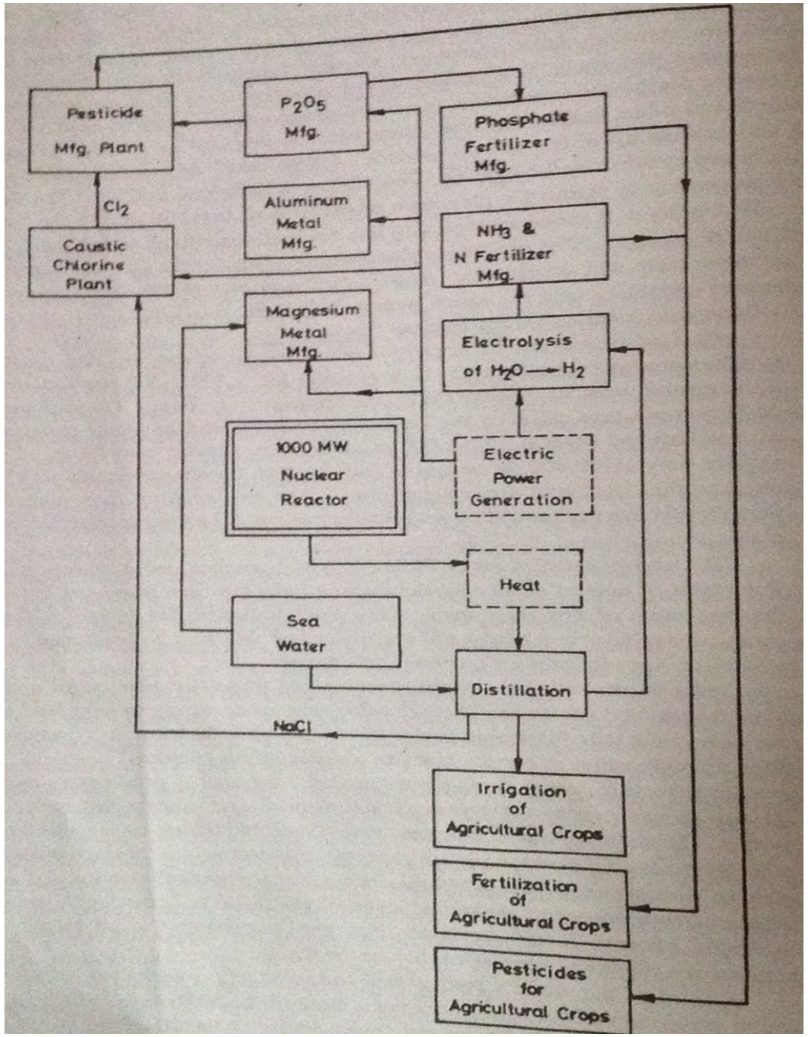
Liquids can be concentrated or their dissolved solids absorbed in ion exchange resins, converted into concrete or glassified, permitting storage in caves, salt mines, deep wells, or the ocean.

By removing long-lived isotopes for separate handling, contactors can greatly reduce the storage time for reactors.

The united States does not favor burial at sea because of possibility of damage to ecosystem and the expense of deep sea recovery. Other countries, however continue this practice.

Nuclear establishments in India

Nuplex (Nuclear Complex)



Thank you