Types of Nuclear Fuel Cycle

- PREFACE

- In today’s world, nuclear energy plays an important role in the production of energy and development of science and technology. In the beginning of 2014, the nuclear industry output in the world was more than 370 gigawatt electric energy resulting from the operation of more than 430 reactors in 33 countries.

This share, according to the predictions performed until the year 2030, will even reach up to around 660 gigawatts.

Iran, is no exception in this trend, and its nuclear development strategy aims at production of 20000 megawatt electricity obtained from nuclear power plants. Further expansion of nuclear plants is absolutely dependent on the deployment of fissionable fuels as the source of energy for providing the needs of such units. In this respect is it a must to have access to the technology of nuclear fuel cycle operation.

- The most important criteria for designing the strategy plan for nuclear fuel cycle is to understand the scientific basis and performance of the most efficient nuclear fuel cycle systems in the world, which can be categorized and differentiated in the following two groups:

First group: uranium fuel cycle

Second group: thorium fuel cycle

2) Uranium fuel cycle

- Uranium upon exploration and processing with the chemical formula (U_3O_8), known as yellow cake (YC), is transferred to the conversion facility and the yellow cake in this facility is changed to natural uranium hexafluoride. In such enrichment facilities, natural uranium hexafluoride is converted to enriched uranium hexafluoride, and in the closed production facilities and fuel complexes, uranium hexafluoride is converted to uranium dioxide powder (pellet) and finally the built (pellets) are placed in special rods and fuel complexes to be used in light water thermal reactors. The mentioned fuels are used in the nuclear power plants for the provision of needed energy. Upon spending of the used fuels, such material are removed from the reactor and temporarily stored to reduce radiation and go through the cooling process. The spent fuels upon cooling and radiation reduction are transferred to permanent storage sites and are maintained in special places in two forms of either permanent or long term storage.
- The entire process which begins from the uranium mining exploration and continues up to the permanent storage or, maintenance of spent fuels, is termed as the “open nuclear fuel cycle”. Each of these installations either alone or collectively can partly or completely affect the open nuclear fuel cycle.
- The below sections offer the description of each of the stages of open nuclear fuel cycle along with comprehensive study of the global conditions of such installations in order to get acquainted with their performance.

2-1) the process of uranium excavation from the mine ores and production of yellow cake

- The first phase of the fuel cycle is the uranium exploration, which requires to be excavated through mining and mineralization operations of the element’s mine ores. At present time, more than 80 countries in the world are active in the field of excavation and 20 in the area of uranium production. Iran through the production of uranium oxide in Bandar Abbas is the last of the 20 nations mentioned above.

Uranium excavation in the world first began in the early years of 1940s. The purpose of excavation first followed military objectives but since the 1950 decade, upon the building of nuclear power plants, the importance of the elements other applications became more evident.

The first atomic reactor was built in 1957 in England with 50 megawatt power and until 2014 the number of reactors had reached 430 in the world.

The figure below indicates the importance of uranium excavation and its consequent production in the world.

- Uranium mine ores are categorized and sorted according to the degree of assay rocks.

Usually the assay of uranium mineral ores are measured with the index (PPM) and one (PPM) is defined as one gram of uranium in one ton of mine ore. The average uranium assay is 2-4 PPM which varies in different sources. Table one (1) below depicts the average level of uranium in different sources of around 200 types of uranium minerals. The ones that have commercial applications in the process of excavation and mineralization are shown in table (2)

Tab (1) concentration of uranium
In various natural resources

MINERAL TYPE	COMPONENTS
URANIUM OXIDE	Uraninit – neshbland, gawit, bekerlit
URANIUM OXIDE	Branerit, davidit, pyroch lor
URANIUM SILICATE	Cafenit, uranofan, uranotorit
URANIUM PHOSPHATES	Atonit, turbernit
URANIUM VANADATES	Carnotit, tyoamit
URANIUM CARBON COLIT MATERIAL	Kamix araninit with carbon material

Tab (2) uranium commercial
minerals

SOURCE	CONCENTRATION (PPM)
CARBONATE	2/2
SAND STONE	0/5
SHILL	3/7
GRANITE	3
BASALT	1
SEA WATER	0/01

- Uranium is an element found extensively in the earth’s crust and is usually used as the main feed for the production of nuclear fuel in the nuclear power plants. The most important isotopes of this element in natural form are uranium 238 (9913 level) and uranium 235 with a content level of only 0/7.

Uranium isotope 235 can be fission by slow (thermal) neutrons with the consequent release of large amount of energy and is therefore used in the nuclear fuel production industry.

- The procedure for processing the yellow cake concentrate in the world usually depends and varies on the type of mineral assays. In practice, the above process is divided into two main parts.

- Uranium extraction from different mine ores.

- Uranium extraction from phosphate mine ores.

- In each of the above processes, depending on the type of mineral ores deployed, different extraction and excavation methods can be deployed.

_ Uranium Exploration and Excavation from Mineral Ores

- Uranium commercial and industrial excavation process from the mineral ores with almost appropriate assay content is categorized in the following three groups:

First group: underground mines.

Second group: surface mines

Third group: open pit mining.

- Uranium excavation process from underground mines is usually performed through traditional way by digging cylindrical and horizontal shafts in the ground and transferring mine ores to the ground surface. Uranium excavation from surface (surficial) mines is done the same way with much less cost, and the extracted uranium mine ore is moved to the ground surface.

In both processes the mine ores are sent to the uranium separation facility. On the other side, in the open pit mining there is no need to move the ores to another location, but the separation process is done through adding solvents to the mine ores.

- In general, in order to extract and process the uranium from the mine ores it is necessary to carry out the following steps.

A) Breaking and grinding of mine ores

B) Washing phase in acid or alkaline

C) Chemical dissolving and sedimentation

D) Production of yellow cake (U308)

- Uranium excavation from phosphate compounds

- Another method for the provision of uranium needed for nuclear power plants is by excavation and extraction of uranium from phosphate and acid phosphoric compounds which is extensively used in chemical fertilizers.

In this way through extraction of uranium from such compounds, in addition of preventing the entry of uranium into the ecology of nature, about 10% of the global demand for uranium can be provided. With respect to the extraction and excavation of uranium from phosphate compounds, different procedures have seen innovated and some are used in commercial and industrial ways as follows:

- Extraction process from phosphoric acid.
- Extraction process from octilpyrophosphoric acid.
- Extraction process from octilphenil phosphoric acid.
- The uranium extraction process from moist phosphoric acid is the most common procedure in an industrial manner in which uranium separation is done in two cycles.

Uranium extraction process from phosphate compounds due to its rather high cost, as compared to the extraction from mine ores, is presently almost abandoned.

2-2) General explanation for uranium processing and conversion

- One of the most important installations in the nuclear fuel cycle is the conversion of yellow cake or (U_30_8) to different uranium compounds such as UF_6, UF_4, UO_2, uranium metal and UO_3. Such compounds exist either as enriched from uranium 235 isotope or natural uranium and are respectively applied in the nuclear power plants.

- Uranium conversion facilities play an important role in the nuclear installations and can be influential in the industry and economy of any country. Numerous countries have done different activities in this respect, but only a few have been able to acquire sophisticated knowledge in this field.

Usually such facilities are designed in the following way for the production of three types of nuclear fuel as the following:

- Natural uranium dioxide powder
- Enriched uranium dioxide powder
- Metal fuels and natural uranium and highly enriched alloys
- As it can be seen, upon mixing the yellow cake with nitric acid, the uranium nitrate solution through purification, evaporation, solidification and sedimentation is changed to ammonium urinal carbonate (AUC).

The process of changing AUC to (UO_2) is very complicated and the reaction mechanism can also be performed in different ways. Usually a rotating reactor is used to perform the analysis reaction and finally the uranium dioxide is produced.

The obtained (UO_2) is sent to the fuel complexes for the purpose of producing fuel for heavy water power plants or gas graphite. Uranium metal is also produced through reduction to manganese (MG).

The production process of UF_4 is done by hydroflorination of UO_2 with hydrogenflouride (HF) gas.

To carry out this reaction it is necessary to use a two phase reactor. The gas (HF) and UO_2 enter the reactor in the opposite direction so as the proper temperature gradient and density is obtained for the production of (UF_4). The produced (UF_4) is discharged in a special container and is sent to the temporary storage location. The produced (UF_4) is reacted with (F_2) gas and uranium hexafluoride is produced.

This material is the final product of uranium processing facilities which is gathered is special designed cylinders and is sent to the enrichment factory. The (UF_6) production process is composed of three parts namely: fluorination, condensing and filtration of polluted gas.

- In figure 1 an example of an open nuclear fuel cycle is shown. As it can be noticed this cycle is composed of two parts. The first section which is shown is black color indicates part of the activities related to the nuclear fuel cycle including, uranium enrichment, conversion to dioxide and formation of complex and fuel packages.
- The second part shown in red depicts another part of the activities related to nuclear fuel cycle. Therefore to convert the yellow cake (YC) to different uranium compounds, all or part of the operation can be done in one place or separate places.

Nuclear Fuel Cycle

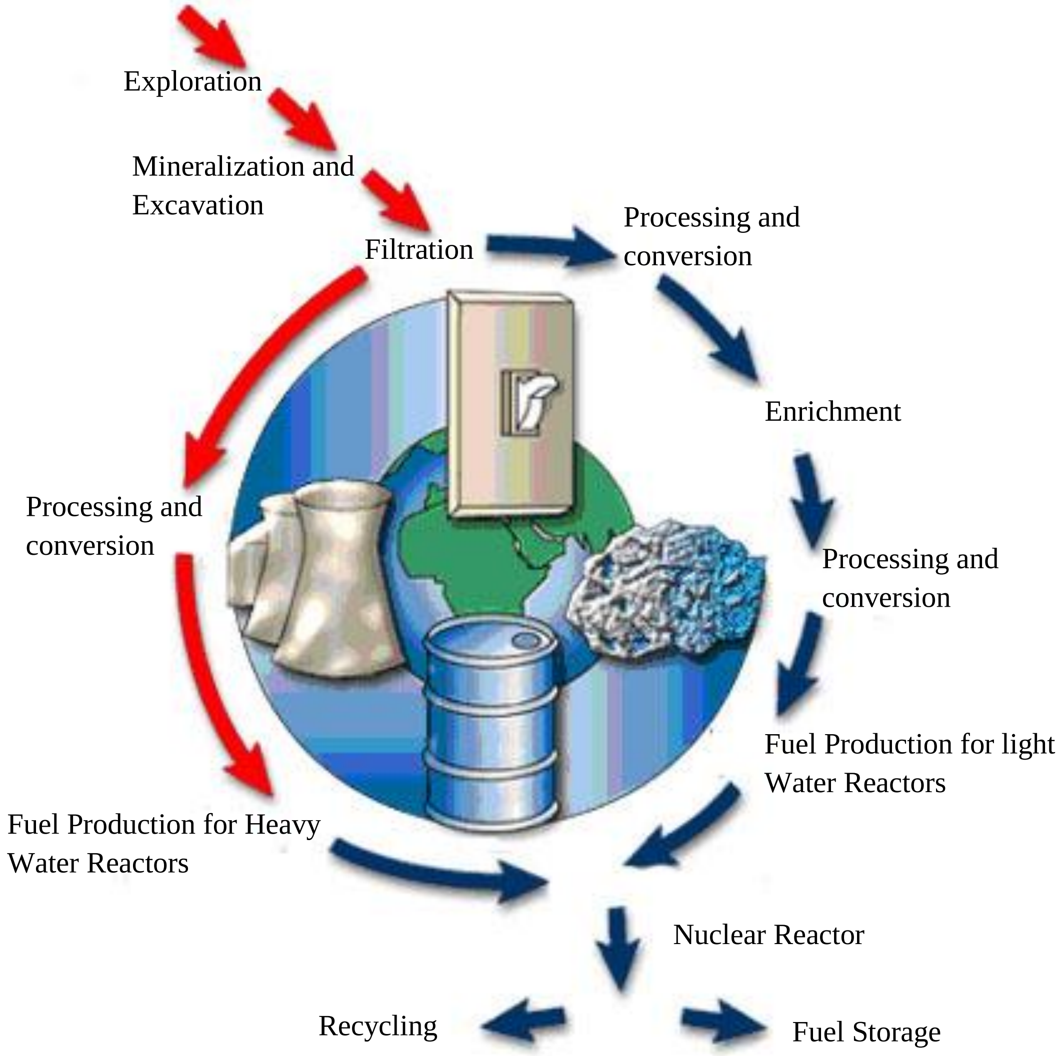

Figure 1: Open Nuclear Fuel cycle Complex Installation as Separated from each other

2-3) Uranium enrichment process

- Natural uranium which is obtained from processing contains only (0.711) percent of ^{235}U isotope and the rest includes ^{238}U and other isotopes.

To prepare feed fuel for most reactors including light water reactors (pressurized water PWR or boiled water reactor BWR) the level of isotope (^{235}U) in fuel must reach 3-4 percent. Therefor there is a need to increase the level of isotopes and the process of increasing (^{235}U) isotopes is called uranium enrichment.

- In general, the process of enrichment encompasses the following procedures.

- Gas centrifuge procedure

- Electromagnetic procedure

- Gas diffusion procedure

- Jet process procedure

- Ion exchange process procedure

-Enrichment with laser procedure

- The above procedures are performed in two industrial manners globally as the following:

- Gas diffusion procedure

- As shown in figure 2, if we consider a container (vessel) filled with gases and is in thermal balance with the environment. The kinetic energy of all present gas molecules in the container (vessel) will be equal, but the speed of lighter molecules will be faster than heavy ones.

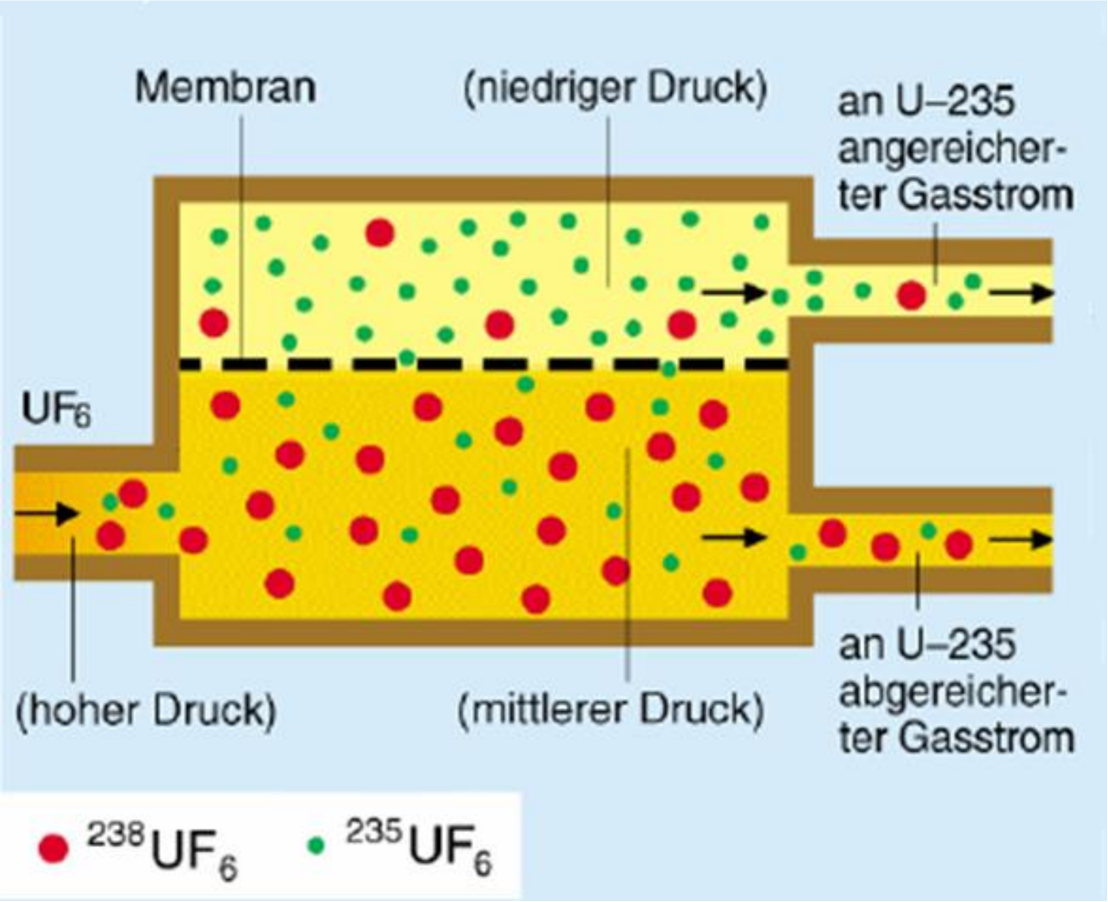

Figure 2: picture of Uranium (235) Isotope Separation Process in the Gas Diffusion Procedure

The lighter molecules will hit the container wall more than the heavy ones. If the vessel wall has very small poles that enables molecules to pass through one by one, and the gas flow is not possible in a massive way, then, the gas that passes through pores (holes) will contain more light molecules than heavy ones. In the gas diffusion process, the passage of molecules from the poles highly depends on the gas pressure and due to this reason, gas pressure at every phase must be increased. The consumption of electrical energy in the gas diffusion facilities, not only because of numerous compressors used, but due to the gas friction in the pipes and other factors is very high.

- Separation procedure by gas centrifuge system

- The use of centrifuge for separation of gas isotopes started since a century ago. The main container (vessel) of centrifuge system is placed in vaccume to prevent vibration movements and transfer of thermal flow and waves. This vessel rotates with a speed of nearly 60/000 revolution per minute by rotary engines.

- As it can be seen in figure (3) the feed material in the centrifuge device enters from the middle of the rotating axis and through movement along the axis and wall, in two different directions, causes isotope density discrepancy in the axis direction, and as a result, the light and heavier isotopes at two ends of the axis and near the centrifuge wall can be picked up.

- The centrifuge procedure is still considered important, and by deploying more resistant and quality material, has offered more output and become widely competitive economically. At present, U.K, Germany and Holland have established the (Urenco) co. to further expand this process in the international market and offer related enrichment services.

- Utilization of this technology has also been deployed in U.S, JAPAN, Australia and some other countries in the industrial, semi-industrial and lab scales.

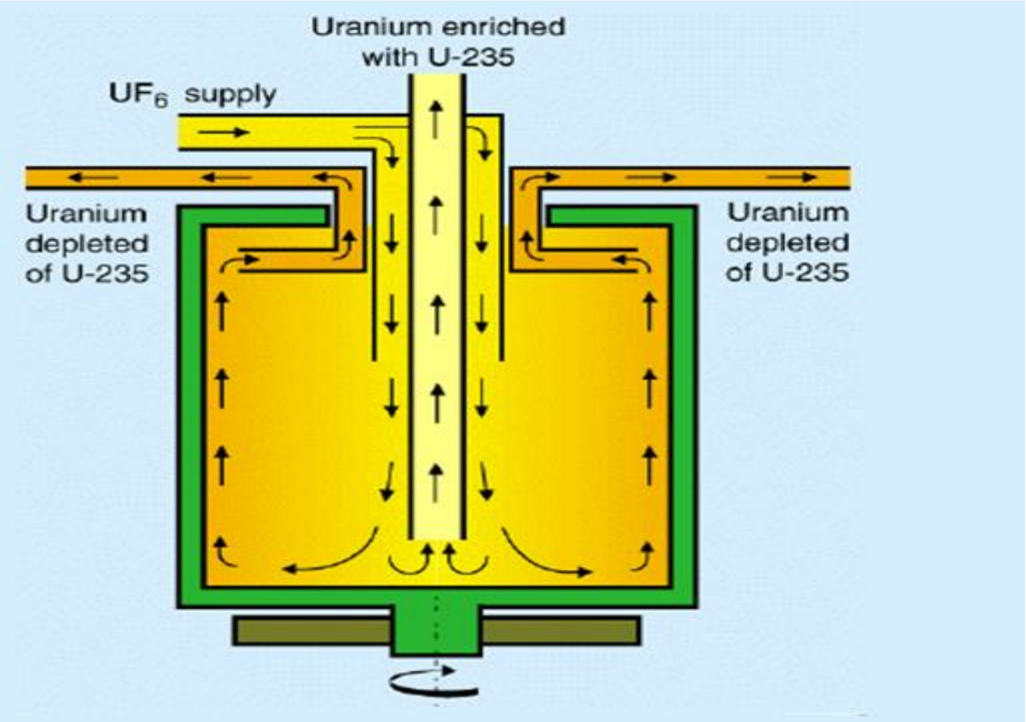

Figure 3: Picture of a centrifuge Machine for Separation of Uranium 235

2-4) Building process of fuel assembly and pellets.

- The fuel required for nuclear power plants vary according to the plant type. Usually, the fuel used for nuclear reactors for the generation of electricity in the world is divided into the following four categories:

- Metal and alloy fuels
- Ceramic fuels
- Scattered fuels
- Liquid fuels

- The metal and alloy fuels are usually used in military and research reactors while liquid and scattered fuels have their own particular applications. Ceramic fuels, in practice, are the most common type of fuels used in the nuclear power plants worldwide and most of the facilities involved in production of fuel assemblies are active in this field.

The ceramic fuels are divided into the following 3 subgroups:

1) Low enriched uranium oxide fuel, used for pressurized water reactors include: western (PWR) (BWR), Russian vver, reactors with High temperature gas cooling system of Germany, U.K, U.S.A , steam generating reactors with heavy water cooling system of Britain, (U.K) and water graphite Russian Reactors.

2) Natural uranium oxide fuel for British gas graphite reactors and Canadian pressurized heavy water reactors.

3) Mixed fuel of uranium and plutonium oxides.

- Fuel rod is a replaceable part in the reactor core. The fuel material is placed in it in the form of a pellet or other shapes inside a zirconium tube or stainless steel tube.

Diameter, length and appearance and shape of fuel rod is different in various reactors. In some reactors, the rods are replaced individually in reactors (gas reactors), while in some other are situated beside each other and form a structure called fuel complex. In some test reactors, the fuel is placed as plates and in some other is deployed as pellets (gas reactors with high temperature).

3) Global study of countries with open nuclear fuel cycle.

- According to the documents issued by (IAEA), the countries possessing nuclear knowledge technology and uranium processing are limited to 8 and those merely having uranium enrichment technology amount to 10 countries. The names of countries possessing the entire or part of the open nuclear fuel cycle are indicated in table (3). As it can be noticed in this table some of these countries are active and operating only in one part (fuel complex production), and some others in two sections (excavation and mineralization of uranium and production of fuel packs) and some others in three parts of the nuclear fuel cycle (except excavation and mineralization). All together only 5 countries are active in each of the four parts of the nuclear fuel cycle operations.

TABLE 3: Countries possessing all or part of open nuclear fuel cycle

	Spent fuel (AR+AFR) (THM)	**Recycling (THM)**	**Fuel pack And Complex ton uranium/year**	**Enrich mint 10^6 swu/a**	**UF6 Processing ton uranium -year**	**Excavation mineralization ton Uranium -year**
Argentina	**6500**	**--**	**150**	**0/02**	**62**	**120**
Armenia	**88**	**--**				**8200**
Australia						
Belgium	**2000**	**540**				
Brazil	**318**		**120**		**80**	**400**
Bulgaria	**1156**					
Canada	**32271**		**2702**		**12500**	**11830**

China	**420**		**100**	**11**	**400**	**740**
Czech republic	**936**					**680**
Finland	**2115**					
France	**25762**	**1600**	**1090**	**10/8**	**14350**	**600**
Germany	**14920**		**650**	**1/8**		
Hungary	**500**					
India	**3515**	**260**	**510/3**			**210**
Japan	**11521**	**120**	**1689/3**	**1/25**		
Kazakhstan	**30**					
South Korea	**8738**		**800**			
Lithuanian	**2101**					
Mexico	**984**					
Mongolia						**150**
Namibia						**4000**
Holland	**86**			**1/5**		

Niger						**2910**
Pakistan	**160**		**20**	**0/005**		**30**
Portugal						**170**
Rumania	**940**		**110**			**300**
Russia	**20928**	**401**	**2571/5**	**15**	**34000**	**3500**
Slovakia	**1050**					
Slovenia	**361**					
South Africa	**670**		**1**			**1700**
Spain	**3820**		**300**			**255**
Sweden	**6500**		**600**			
Switzerland	**904**					
Ukraine	**5150**					
England	**12000**	**2700**	**1950**	**1/3**	**6000**	
U.S.A	**62000**		**3900**	**18/7**	**12700**	**3761**
Uzbekistan						**2300**

4) Thorium fuel cycle

- Nuclear fuel must have three characteristic in the future. These criteria include utmost use of time in the reactor, assuring nonproliferation of nuclear weapons and simplicity in nuclear waste disposal. All the mentioned three factors can be found together in the thorium fuels. Therefore, it seems, that in a future not so distant, thorium fuels in the third and fourth generation of nuclear reactors will noticeably expand on a global scale. Due to this reason diverting attention to this issue is essential and inevitable.
- The thorium element is 3 to 4 times more abundant in nature than uranium with easy excavation possibility in many countries. Unlike natural uranium which is composed of two isotopes (^{238}U) as fertile and (^{235}U) as fissionable, natural thorium is only composed of (^{232}Th) fertile and without fissionable material. Thorium fuel cycle was considered and initiated since the middle of 1950 up to 1970 in line with preliminary advances in deploying nuclear energy in countries which lacked uranium fuel resources for their long term nuclear power plant extension plans, but possessed reasonable thorium reserves on the other hand.
- As it was indicated, due to the high fertility quality, it can be a proper choice for provision of nuclear energy in future power plants of the world. This element by absorbing one neutron is converted to uranium (233) radioisotope. Uranium 233 isotope has a high fissionability compared to uranium 235.
- Thorium fuel cycle cannot be independently surveyed, studied or evaluated without considering uranium fuel cycle. This is due to the fact that thorium by itself is not fissionable; therefore provision of a proper surrounding is needed to produce

fissionable radioisotope uranium (233) so that this element can be placed beside enriched uranium or plutonium in the thermal reactors.

- As pointed out, thorium fuel cycle is different from other uranium fuel cycles and in practice two conditions can be presumed for thorium fuel cycle as the following:

- Thorium open fuel cycle based on thorium (232) radiation in the proximity of mixed uranium and plutonium fuels and in place (instant) production of fissionable uranium 233 radioisotopes without chemical separation process in the pressurized light water reactors of (PWR) or (VVER) types.

- Closed thorium fuel cycle by chemical separation of uranium 233 radioisotopes from radiated thorium fuels and using it for manufacturing new fuel products.

- In both ways it is necessary to use thorium oxide in proximity of various uranium oxides with different degree of enrichment or plutonium. Since the deployment of thorium fuel packs and complex in the nuclear power-plants as compared to plutonium and uranium fuel packs enjoy similarity and are often compatible with regard to the design of reactor core and control rod mechanism and, hence, there is no need for noticeable alteration in the reactor, therefore it seems that deployment of nuclear fuel cycle in proximity of other nuclear fuel cycles in near future will be expanded globally.

- The reason for deploying thorium as fuel in the nuclear reactors

- In thermal reactors, thorium is much more fertile as compared to uranium because its surface section for absorbing heat is 3 times more absorbent than the surface section of uranium (7.4 barns for thorium x 2.7 barns for uranium.

- As shown in chart, thorium (232) by absorbing one neutron in thermal reactors can be converted to uranium (233) which is a fissionable radioisotope

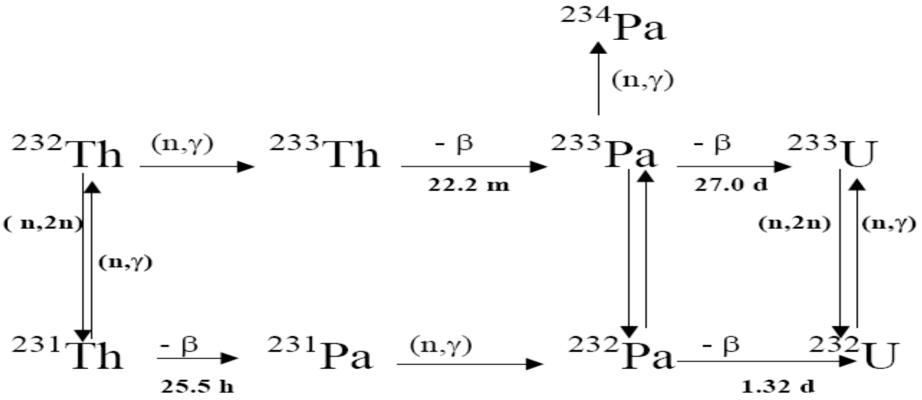

Chart 1: Picture of Fertilizing Thorium 233 for Production of fissionable Uranium 235

- In practice, in case of simultaneous use of produced uranium 233 as a result of absorbing neutron in fuel packs containing thorium, the obtained cycle is termed as open nuclear fuel cycle. On the contrary, in case of recycling the spent thorium fuel and extracting uranium 233 from it, then, this process is named as closed nuclear fuel cycle. Radioisotope 233 as uranium radioisotope 235 has adequate fission quality (525, 577, and 742 barn for ^{233}U, ^{235}U, ^{239}Pu). In addition the absorbing surface section of this isotope is much less than the absorbity of surface section of uranium 235.

- Thorium oxide is also much more stable and resistant than uranium oxide exposed to nuclear radiation. At the same time the thermo physical characteristics of this oxide is also much better compared to uranium oxides.

- Thorium oxide, on the long run, contrary to the uranium oxides (Uo3 and U308), does not show oxidation reactions, and hence, maintenance, storage or disposal of spent fuel of thorium is much less costly and simpler as compared to uranium fuels.