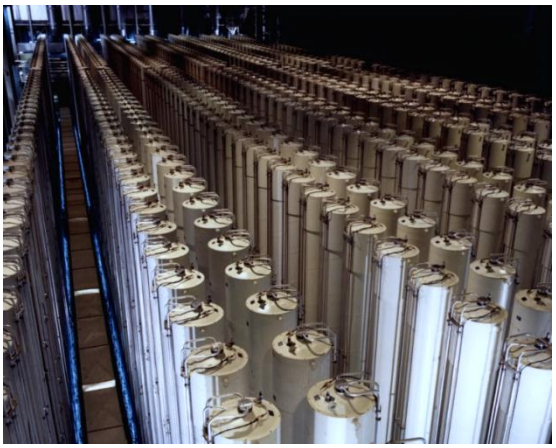
ENRICHMENT INDUSTRY IN THE WORLD



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1- Nuclear Fuel Cycle

The basics of Iran's vision for nuclear fuel cycle development

"In line with the realization of the 20 years vision document plan in 2015, Iran is a developed, progressed country, self-dependent in the nuclear fuel cycle knowledge, technology and industry, enjoying a competitive position on a global scale, capable of providing needed fuel for the country's nuclear reactors and export of relevant products plus services within the framework of international rules, regulations and national, global standards.

Vision of uranium enrichment section in the nuclear fuel cycle

The vision of Iran nuclear fuel cycle encompasses the uranium enrichment section as a key factor, to have access to advanced technologies and production of enriched uranium hexafluoride, on the economic – industrial scale, needed for the country's nuclear fuel demands.

The Mission assigned to the uranium enrichment section in the country's nuclear fuel cycle

The uranium enrichment section by having access to the technical knowledge and advanced technology as well as utilizing national, international capacities is able to produce the enriched uranium hexafluoride required for the fuel needs of the country's nuclear reactor. This section, by emphasizing on research and development as well as expert human resources, while preserving the fundamental values, has been capable of noticeable growth and helps maintain national integrity.

The first step in the fuel cycle process is the exploration of uranium assay deposits, estimating their content and exploration costs.

The level of pure uranium in uranium ore is very low and often does not exceed few hundred grams in a ton. Upon feasibility studies and economic cost estimates, the exploration and following that mineralization, concentration process of the uranium assays takes place.

At this point, the important step is the concentration and uranium processing in the fuel cycle which included washing, sedimentation, dissolving in acid and ion exchange. Through the mineralization and concentration operations of uranium assays, ammonium bicarbonate is obtained which results in yellow cake and finally upon heating in a furnace is turned to uranium oxide (U3O8). The (U3O8) product is then transferred to the uranium conversion facility for the next operation of the nuclear fuel cycle.

In the conversion facility, the remaining chemical impurities in the yellow cake is eliminated and the converted uranium is processed to desired chemical compound for the next step in the cycle and according to the needed fuel for enrichment, the due chemical processes are determined.

In case the fuel needs enrichment the uranium hexafluoride is needed on the industrial scale for which its production requires uranium dioxide reaction with Flouridicacid and preparation of uranium tetrafluoride-reaction with flour gas and obtaining the final product as uranium hexafluoride. The enriched product is sent to the fuel production facility while observing safety precautions. The unit used in this stage is called the separation unit. This quantity is related to the weight, the enrichment level of the primary material, the enriched matter and the waste material. The separation capacity of a production unit is shown with kilograms in a year (SWU) and its spending energy with kwh/kg SWU indicator.

In the fuel production facility, the uranium hexafluoride is prepared as the desired compound and then other fuel production stages are carried on. Primarily the product is converted to uranium dioxide and powder preparation and then to pellet dioxide synthesis.

The obtained pellets along with other needed instruments such as lower cover, alumin pellet (disk) and upper cover is placed in the fuel rods and upon injection of helium gas and welding is situated in the fuel assembly and transferred to the reactor.

As it was mentioned, having access to nuclear fuel requires uranium excavation, mineralization processing, enrichment and production of fuel rods to be used in the nuclear power plants. The cycle up to this point is called the first half of the nuclear fuel cycle. The second half includes waste radiation management from using all the fuel cycle phases, decommissioning of nuclear installations, storage, reprocessing, and maintenance or burying the spent fuel. Each of the fuel cycle stages has its own waste handling criteria which differ according to the level of the radioactivity and the volume procurement.

The figure 1 demonstrates the schematic picture of the nuclear fuel cycle.

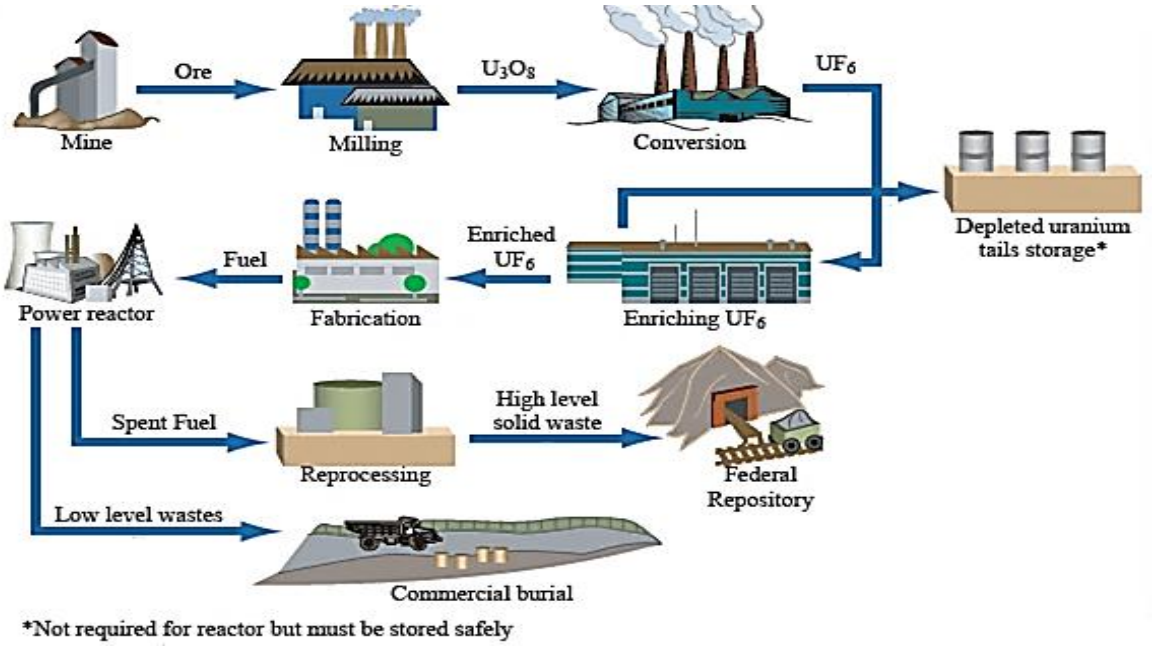

FIGURE 1: General scheme of nuclear fuel cycle

2- Enrichment industry in the world

In the nuclear fission reactors, the nuclear fission process is used to produce thermal energy. The heat produced is absorbed by cooling agents and with the help of turbines in the form of mechanical energy and finally converted to electrical energy by generator. Considering the qualities uranium possesses or combinations of this element in absorbing neutron and nucleus fission, the element is often used as fuel feed in nuclear reactors. The U235 is the most important fissionable isotope of uranium and because of its low concentration in raw natural uranium; enrichment process is carried on it.

Enriched uranium is a strategic material which it's processing demands complex technology and sophisticated knowledge.

Manufacturing the equipment needed for this technology is very demanding. Only few countries possess the information in this regard and the transfer of this knowledge is not possible.

2-1- Enrichment history in the world

Upon the discovery of radioactivity, isotopes were also identified in the beginning of the 20th century.

The word "isotope" was first used in 1913 in England by a scientist called SADI. In 1919, two scientists by the name of stone and lineman proposed isotopes separation through diffusion, distillation, gravity or centrifugal force and electromagnetic procedures.

Lab research was carried out on various separation methods from 1920 to 1930. The gas diffusion method was first used by stone in 1920 for separation of neon isotopes. Lab research on heat (thermal) diffusion first started in 1930 and first thermal diffusion tower was built in Germany in 1938 and the first vacuum gas centrifuge system was built in 1934.

The uranium enrichment history goes back to the Π world war, during which enriched uranium (more than 90%) was needed for making nuclear bombs.

Uranium is found in nature and consists of 3 isotopes, U^{234}, U^{235}, and U^{238}. Table 1 shows the density of different uranium isotopes in uranium ore as well as the content of proton, neutron and their half life span.

TABLE 1- Characteristics of uranium isotopes

Isotope name	Level of isotope in natural uranium (%)	No. protons	No. neutron	Half-life (year)
Uranium 238	90.284	92	146	4.46×10^{9}
Uranium 235	0.711	92	143	7.04×10^{9}
Uranium 234	0.0055	92	142	2.45×10^{5}

2-2- Deployments and necessity of enrichment process

Light water reactors used in the nuclear power plants such as pressurized water reactors (PWR) and boiled water reactors (BWR) need enriched uranium of 2-%5 uranium^{235} which is also called Low Enriched Uranium (LEU). The more the level of enrichment, the smaller will be the reactor used.

In the shipping transportation system uranium with enrichment level more than U^{235} %10 is used. Nuclear submarines, satellites and small research reactors mainly use uranium with %90 concentration of U^{235} and even higher.

It should be noted that following the proposal made by U.S.A in 1978 in the context of (RERTR3) for changing the research reactors fuel from HEU to LEU or low enriched uranium (fuel with less than %20) and the support rendered by IAEA to this plan, at present only few research reactors work with more than %20 enrichment.

Since separating of uranium isotopes with chemical procedures is not common due to technological limitations or economic feasibility, the separation takes place through physical methods.

Most of the separation procedures are based on small mass difference of the two uranium isotopes present in the UF6 molecules.

According to the gas synthetic theory, each molecule has an average (mean) kinetic energy, and hence, lighter molecules will have a faster speed while heavier ones have less speed. Isotope separation in other enrichment procedures is performed based on

differences in absorbing laser radiation by energy surfaces of a particular nuclide or small difference in their balanced nuclear reactions.

Centrifuge method came into focus in Germany since 1941 and gas diffusion procedure was used in England on a large scale. Since the end of 1943 U.S and England cooperated to establish a factory in United States.

During the Manhattan project in the United States four procedures including gas diffusion, heat diffusion, electromagnetism and gas centrifuge were used and finally, in 1944, the centrifuge method due to technical difficulties at that time was stopped, but improvement work to upgrade used material and increase efficiency continued until that since 1970 centrifuges were substituted for gas diffusion.

2-3- Different procedures used in uranium enrichment

Different processes are deployed for uranium enrichment, the most important of which are: Gas diffusion (spreading), centrifuge, isotopes separation by laser, ion exchange and etc…. table 2 depicts the different processes of uranium enrichment carried out in industrial or laboratory scales.

TABLE 2: Used methods in uranium enrichment

Basis of separation	Example
Pressure gradient	Gas centrifuge
	Separation factor
	Ucor process (S. Africa)
Penetration	Gas diffusion
	Mass diffusion
	Thermal diffusion
Chemical exchange	Excavation with solvent
	Ion exchange
Light stimulation (excitation)	Atomic-vapor-laser-isotope separation (AVLIS)
	Molecular-vapor-laser-isotope separation (MLIS)
	Separation of isotopes by laser excitation (SILEX)
	Electromagnetic isotope separation (EMIS)
Electro magnetic	Plasma separation process (PSP)

2-3-1- Countries active in separation process with the aerodynamic technique

- **GERMANY**

German scientists began research on this method in the 1950 s decade. In 1967 a research lab started work on descending separation process. In 1976 Germany and Brazil agreed to work jointly on this procedure and in the same year first factory began successful work on semi- industrial scale. The factory was transferred to Brazil in 1980. In 1989 all research work on this procedure was halted in Germany.

- **BRAZIL**

Upon signing an agreement between Brazil and Germany, Brazil started plans for building the first enrichment facility.

This country after 1980, in which the semi-industrial German factory was transferred, began its completion work until in 1985 and succeeded in this task, but in 1994 due to the high cost of production and some technical issues the factory was shut down.

- **SOUTH AFRICA**

In the republic of South Africa research on aerodynamic separation started in 1960. In 1964 a factory on lab level and scale was initiated and in 1974 the semi-industrial factory construction was completed.

This factory due to technical problems stopped functioning in 1979 and upon renovation began work again in 1981. In the year 1988 the first industrial plan was commissioned. Since this facility due to high energy consumption was not economically competitive with world market, stopped functioning in 1995.

2-3-2- Countries active in enrichment field with the gas diffusion process.

- **United States**

U.S.A built 3 enrichment facilities working with gas diffusion method until 1959. Such facilities provided more than 90% of the uranium needed in the west until 1976. At present only one gas diffusion enrichment factory is active in the U.S.A.

- **Former Soviet Union**

The building of the first enrichment facility with gas diffusion-system started in 1946 in Soviet Union. Three more factories were also built in this way between 1949 and 1964,

but due to the high energy consumption in such facilities and construction of centrifuges with higher output, enrichment in this manner stopped in 1991.

- **England**

England (U.K) began building the first enrichment facility with gas diffusion system in 1950 and was able to produce (LEU) in 1952. This factory also due to prevailing problems got out of service in 1982.

- **China**

China bought its preliminary equipment for gas diffusion from former Soviet Union and started the first factory in 1958 and completed it until 1961.

- **France**

Building of the first French gas diffusion facility for military purposes started in 1960 and its final phase was completed in 1967. The production of first (LEU) in this factory took place in 1964. France started its first gas diffusion factory, in the industrial scale, in 1974 and completed it up to 1974.

- **Argentina**

Argentina secretly built its first gas diffusion enrichment facility in 1974. This factory started functioning in 1987 and upon one time stop and general repair in 1994 was completely put out of service in 1997, but its gas diffusion unit after 20 years of stop has again been commissioned in 2011.

2-3-3- **Countries active in enrichment field with ion and chemical exchange procedure.**

- **France**

France began research on this method in 1968 and extended it after discovering a new chemical may to enrich uranium. Up to 1974 two enrichment facilities were initiated on lab scales. In 1984 also a semi-industrial factory was initiated, but France decided on halting this type of research and began research on enrichment through laser methods.

- **Japan**

Japan started research on this procedure in 1972 and completed its first facility in 1979 on a small scale and in 1982 succeeded to enrich uranium up to 2/2 percent. In 1984

through enhancing this procedure, the country was able to build a bigger facility and enrich uranium up to %3/2. The building of a factory on industrial scale remained in the agenda, but the Japanese authorities in 1992 decided to halt the activity.

- **United States**

This procedure was deployed by U.S in addition to France and Japan. In U.S also the process of excavation of liquid-liquid and exchange of solutions (UF_6) and $NOUF_6$ enriching uranium was used.

- **Iraq**

Iraq covertly gathered information relating to the French and Japanese devices and in 1991 claimed to have access to both technologies, although was never able to enrich in this manner.

2-3-4- Countries active in enrichment field by using laser technology

The table below indicates the list of countries active in this technology.

TABLE 3: the list of countries in enrichment field by using laser technology

Country name	Used technology	Time spent in the process	Reason for work stop
Australia	SILEX	1982-Present	
England	MLIS	1983-1994	Budget Halt
France	SILVA	1984-1996	Work on MLIS
France. Africa	MLIS	1996-97	France withdrawal
Japan	AVLIS	1982-2001	Japan cancels project
U.S.A	AVLIS	1984-1991	Budget stop
U.S.A. Australia	SILEX	1997-Present	---

2-3-5- Countries active in enrichment by electromagnetic techniques.

- **United States**

This method was first used in the U.S in 1944 for the production of the first nuclear weapon. In the Oak-Ridge project two models of calutrons were used for production of (HEU). In the first model or (α), the uranium that was first enriched by gas diffusion process to 8 percent of U^{235} increased it up to 12-%20 of U^{235}. The second type or (β)

enriched the product derived from model (a) up to around %90. This procedure after gas diffusion devices were put in the related agenda, was discontinued.

- **Former Soviet Union**

U.S.S.R was the first country to use its first calutron in 1934 for the production of (PU 239) and in 1946 started making calutrons similar to U.S calutrons which had not satisfactory results, because it had very low enrichment capacity. After Soviet Union in 1950 commissioned its first Gas diffusion factory, the activity on (EMIS) method was discontinued.

- **Iraq**

Iraq started its research on this procedure in 1979 and in 1982 started to build the related factory. The work was completed in 1990, but there were technical problems for production of enriched uranium. Before they were able to eliminate the problems the facility was completely destroyed in 1990.

2-3-6- Countries active in enrichment by plasma techniques

France and U.S.A are the two countries that have worked on this technology. U.S stopped its research in 1982 and France in 1990.

2-4- Common procedures for enrichment on industrial scale

Among the enrichment procedures mentioned for uranium enrichment only centrifuge and diffusion methods have been deployed to produce enriched uranium on industrial scale. In both methods uranium is used as (UF_6) gas for enrichment. UF_6 is a matter that is solid in room temperature and has high molecular weight. As seen in diagram phase figure, the UF_6 (sublimation) temperature is under its three different points. Progression (sublimation) temperature is a type of temperature in which the solid steam (vapor) pressure is equal to the atmospheric pressure. At the time that (UF_6) in atmospheric pressure is in a balanced form, solid (UF_6) without going through the liquid phase is directly turned to vapor (steam) or sublimation. In order to have liquid (UF_6) we need a pressure higher than (0/15 MPA) and temperature higher than 65 centigrade. The physical properties and (UF_6) phase changes are shown in

TABLE 4 physical properties and conditions of UF6 phase change

Physical state	Appearance	Density
Solid	White	5.0g/cm^3 in 20^{o}C
Transparent	Liquid	3.4g/cm^3 in 100^{o}C
Gas	Colorless	

TABLE 5: conditions of UF6 phase change

Sublimation point	56.4^{o}C in 0.101/pressure-mega Pascal
Triple point	64.02^{o}C in 0.152 pressure mega Pascal
Critical point	230.2^{o}C in 4.86 pressure mega Pascal

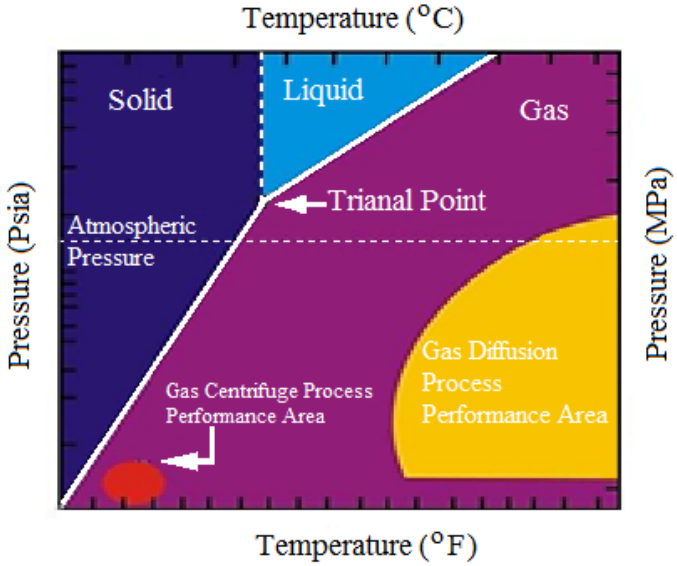

FIGURE 2: UF6 phase diagram

TABLE 6: Comparison between centrifuge and gas diffusion methods

Characteristics	Gas diffusion	Centrifuge gas
Enrichment level by one stage.	Low	High
Level of existing current in one stage	High	Low
Process pressure	Medium	Low
Material present inside centrifuge assembly	High	Low
Level of required cooler	High	Low
Consumption Ability	V. High	Low

Characteristics	Gas diffusion	Centrifuge gas
Level of needed smoothers	High	V. Low
Level of repair or equipment substitutes	Low	High
Needed personnel	Low	High

The following results have been obtained from comparing the 2 methods of gas diffusion and centrifuge processes.

1) The centrifuge main advantage as compared to gas diffusion is that it consumes 25 to 50 times less energy than diffusion system. The energy needed in the gas diffusion process in 2400-3000 kWh/SWU while in the centrifuge process is 50-100 kWh/SWU. Therefor if enrichment is done by gas diffusion system around %3-4 electricity is produced and if it is done by centrifuge method only %0/1 electricity produced is devoted to enrichment. For a specific separation capacity of energy required for enrichment by centrifuge system is %4 of spent energy by gas diffusion system.

2) Consumption of electrical energy in gas diffusion factories not only because of many existing compressors, but also due to gas friction in pipes beside other factors is a lot and approximately %5 of energy produced by light water reactors for its enrichment unit is required.

3) The cost of electricity in gas diffusion facilities absorbs around %60 of the total production expenses while this figure is only %6-7 of the electricity cost of total production in centrifuge facilities.

4) The disadvantages of centrifuge process include low enrichment capacity of each unit. The separation factor in the centrifuge assembly depends on the differences among the molecular mass of isotopes while in the gas diffusion system this factor depends on their proportions.

5) Although, the capacity of one centrifuge stage is less than one gas diffusion stage but its ability to separate the isotopes is more.

6) The space used by centrifuge process equipment is less than that of diffusion process and therefor expansion of a centrifuge facility is done in a less compact space.

7) In general, working with centrifuges is very difficult due to their high speed rotation and big sizes. Such factors make their balancing rather difficult.

8) The building and maintenance of proper membrane (coating) in a gas diffusion procedure is an important factor.

9) In the gas diffusion procedure the amount of present material inside the system is high. For example in order to produce one mole of (UF_6) with %90 enrichment around 42 million mole matter must rotate in the process.

10) In order to produce 10 million SWU, the operational cost of a centrifuge factory is around 25 to %30 less than a gas diffusion facility.

The figure below depicts the large (Georges base 1) enrichment site in France with the gas diffusion procedure. The 4 nuclear reactors in front of the picture with 3000 megawatt electricity power provide the energy needed for this site.

Figure 3: Georges base 1 enrichment site-France

The following table (7) depicts the gas diffusion enrichment facilities in the world with their capacities**.**

TABLE 7: Important the gas diffusion enrichment facilities in the world

Actual capacity	Nominal capacity	Date of commercial exploit	Country	Installations	Building company
6 ML	3.11 ML	Mid 60S to May 2013	U.S	Paducah GDP	USEC
9.5 ML	4.7 ML	1954 to May 2001	U.S	Portsmouth-GDP	USEC
5.8 ML	8.10 ML	1979 to mid-2012	France	Georges-Besse1	AREVA
1.1 ML	-	1980 to 1997	China	Lanzhou	CNNC

Actual capacity	Nominal capacity	Date of commercial exploit	Country	Installations	Building company
-	-	40s decade to 80s decade	Russia	ECP, UEIP…	TENEX
325000	-	60s decade to 1982	U.K	Capenhurst	U.K
20000	3 ML	1983 to 1989, 2011 to present	Argentina	Pilcaniyeu	Argentina

Commercial exploitation of the last industrial enrichment unit of gas diffusion system in the world (uses/Paducah-11.3 million SWU/yr) ended in May 2013 (this unit for the purposes of resources management, delivery of orders to customers and etc…. will be active in 2014).

Argentina also commissioned its gas diffusion enrichment unit after 20 years of halt in 2011 (CNEA/pilcaniyeu-20/000 SWU/YR).

2-5- Centrifuge procedure

Isotopes separation process by centrifuge device was first suggested by lineman and stone in 1919. The first successful experience of this procedure was performed by James and colleagues in 1938. In this way ultracentrifuges under vacuum condition were used to separate chlorine (Cl) isotopes in carbon tetrachloride (CCl4) compound.

Uranium isotopes separation by centrifuge device was first performed by Beams and colleagues in the University of Virginia. They were able to produce ½ KG of uranium with %4 enrichment. In that time, the biggest centrifuge built had a rotation speed of 206 meter in second and had an enrichment ability of one kilogram (SWU) in a year. After Π world war, when the success of gas diffusion technology was stabilized, the work on centrifuges in the U.S.A was halted.

Later on, in Russia, a team of German and Austrian scientists who were captured during the war helped expand the centrifuge enrichment technology. The head of this group after liberation transformed the technology to U.S and Europe, but research on this procedure were maintained until in 1960s decade that the centrifuge technology became comparable to gas diffusion technology. At present, the centrifuges are deployed on large scales in west of Europe, Russia and Japan.

2-6- Survey of organizations and countries active in uranium enrichment

At present, enrichment on large scale is only performed in Russia, France, U.S.A, U.K, Germany, Holland, Japan and China which are as follows: Japan nuclear fuel limited (JNFL), CNNC, AREVA, MINATOM, URENCO, and USEC.

- (CNNC) Stands for china national nuclear co. Consists of 2 centrifuge facilities with the capacity of one million SWU/year.
- (AREVA) a French co. has one gas diffusion factory in (TRICASTIN) (10.8 million SWU/YEAR) and a new site (GBII).
- Minatom-Russian federation organization has centrifuge factories in Angarsk, Ekaterinburg, and Krasnoyarsk and Tomsk locations.
- (USEC) has a gas diffusion facility in Kentucky State of U.S.A (PADOKA) with total 11/3 million SWA/YEAR capacities.
- JNFL-(Japan nuclear fuel limited)-has commissioned a facility with 1.1 million SWU/YEAR in 1992.
- URENCO-is a joint co. Of Germany, Holland and U.K which has factories in Germany, U.K Holland and U.S.A, all of centrifuge type, with total capacity.

The figure depicts the position of enrichment sites on the commercial scale in the world.

FIGURE 4: position of enrichment facilities in the world

It should be mentioned that the share of China and Japan in the global market of enrichment is low as compared to other countries and such countries mainly use these

products for domestic purposes. The 4 main enrichment organizations that have provided more than %90 of required enrichment in the year 2012 are as follows:

- AREVA
- TENEX
- URENCO
- USEC

The figure shows the share of each organization in the uranium enrichment world market (production more than domestic needs) in 2012. Although it seems that the four main provider of enriched fuel in the world are independent but (URENCO) and (AREVA) upon partnership in the (ETC) project have practically joined each other.

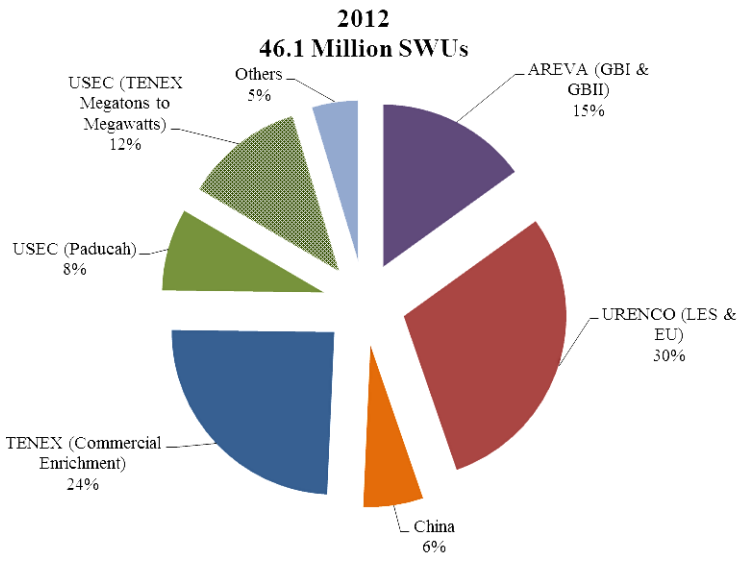

FIGURE 5: Share of organizations related to uranium enrichment in the world market in 2012

As it is noticed most of the share belongs to (URENCO) with %30 of total world market share. Following that (TENEX) with %24 holds the second rank. The estimate share of world enrichment capacity of production is shown in the figure.

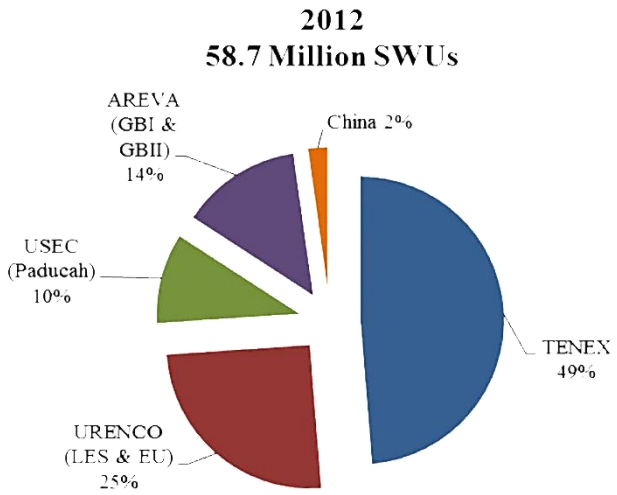

FIGURE 6: Estimate share of world enrichment capacity from the production point of view in 2012

The present partners of the enrichment industry have the ability to expand the level of production in a rather short time, around one year, with added capacity in the installations.

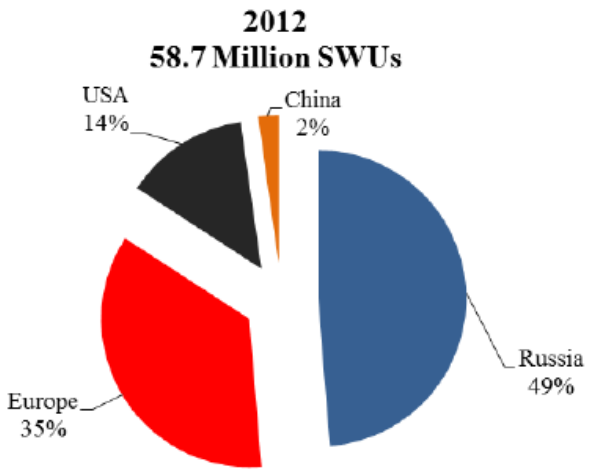

FIGURE 7: Global estimate share of enrichment capacity based on location in 2012

As it was indicated, uranium enrichment is only performed in limited number of countries and the rest of countries obtain their enriched uranium needs from the mentioned organizations.

The existing and predicted capacity for enrichment facilities with the centrifuge procedure and the share of nations possessing such technology is shown in

TABLE 8: Present and predicted capacity for enrichment facilities with centrifuge process in industrial scale: 1000SWU/yr

Country	Operator		2012	2015	2020
Russia	TENEX-ANFARSK-NOVOURALSK-ZELENO GORSK-SVERESK		25000	30000	37000
France	AREVA, George BESS Π		2500	7000	7500
U.S.A	URENCO, New Mexico		2200	4800	5700
	AREVA, Idaho Falls			1500	3300
Japan	JNFL, Rokkassho		150	150	1500
China	CNNC: Hanzhun-Lanzhou		1500	3000	8000
U.K Germany Holland	URENCO: Capenhurst-Gronau-Almelo	14700	13200		

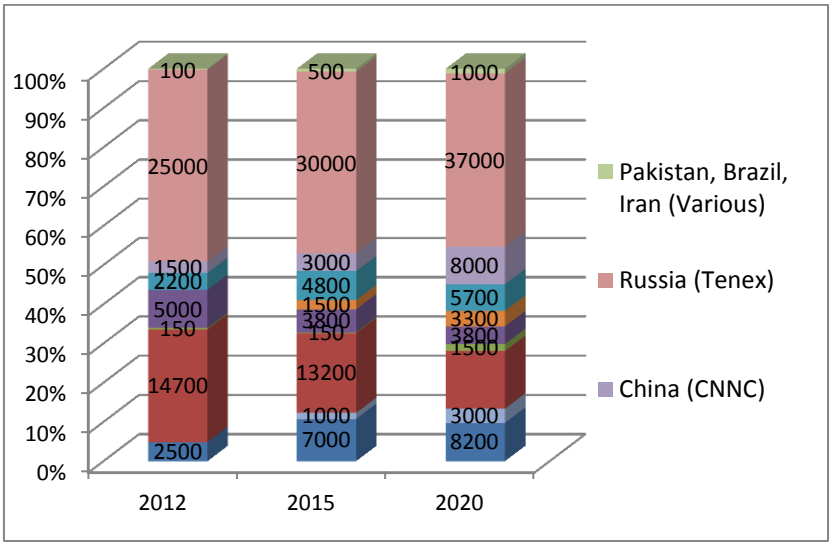

FIGURE 8: Expansion of uranium enrichment facilities until the year 2020 (1000 SWU/yr).

The main motive for enrichment is the demand to provide nuclear fuel for power plants. Therefore, survey of the number, capacity and position of nuclear power plants used and estimate of their productivity, provides a proper outlook for the required level of enrichment.

This survey could include designed power plants as well as expanding and the ones being constructed. The figure 9 shows the estimated needs for enrichment until 2025

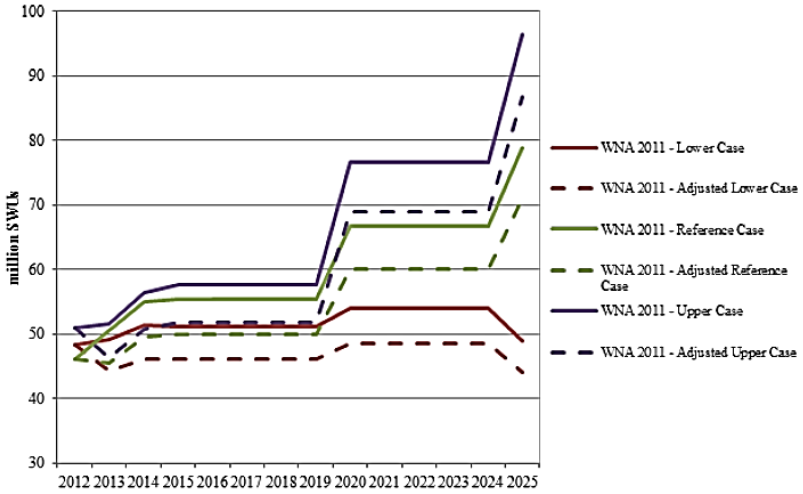

Figure 9: World demand for enrichment from 2012 to 2025

According to the statistics available until the end of 2012, 436 power plants were active in the world and it is expected that 550 plants will be operational within the next 15 years. The figure 10 shows the enrichment capacity in 2020.

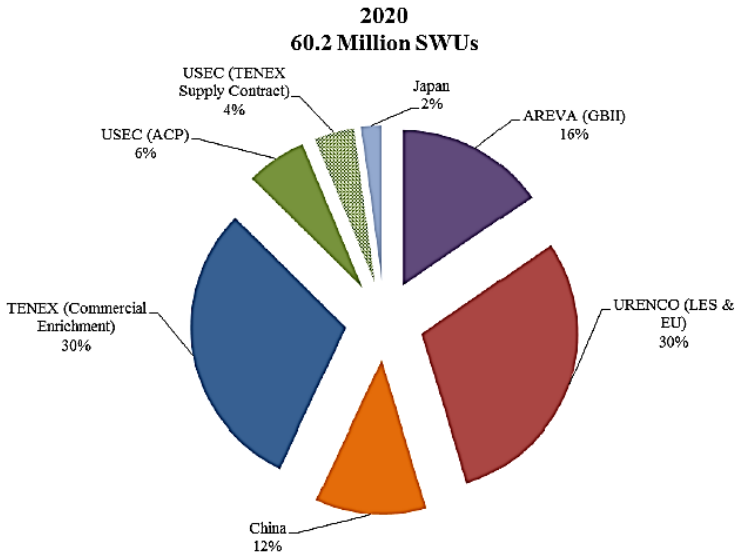

Figure 10: Estimated enrichment capacity for 2020

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