WFEO

World Federation of Engineering Organizations
Energy Committee

Series on
Feasibility of Current Energy Options

NUCLEAR POWER FEASIBILITY 2007

REVISION 1

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WORLD FEDERATION OF ENGINEERING ORGANIZATIONS

ENERGY COMMITTEE

NUCLEAR POWER FEASIBILITY

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REVISION 1

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FOREWORD

Nuclear power is a proven technology and has the potential to generate virtually limitless energy with no significant greenhouse gas emissions. Nuclear power can become one of the main options to contribute to substantial cuts in global greenhouse gas emissions.

Modern development of nuclear power technology and the established framework of international agreements and conventions are responding to the major political, economic and environmental issues -high capital costs, the risks posed by nuclear waste and accidents, and the proliferation of nuclear weaponry- that until recently hindered the expansion of nuclear power.

In response to such prospects, the WFEO Energy Standing Committee set up a Task Group to develop this Report on NUCLEAR POWER FEASIBILITY - 2007. This Report gathers information on the state-of-the-art of nuclear energy technology and its current technical and economic feasibility based on engineering criteria and technological maturity.

Members of the Task Group were appointed by WFEO Member Organizations.

This Report is being presented as a publication in the Energy Standing Committee Series on Feasibility of Current Energy Options. The Series is intended to give the viewpoint of the engineer on questions related to technical and economic feasibility of energy issues of significance to society. It aims at providing the engineer and decision-making officers with updated information regarding the state-of-the-art of different technologies that are being used or are under consideration for the supply of energy.

WFEO hopes this report will assist the engineering community, policy and decision makers, and the public to be aware of the conditions that make nuclear power utilization a feasible option for assuring sustainable development and mitigation of climate change effects.

Barry J. Grear AO
President, World Federation of Engineering Organizations
December 2007

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NUCLEAR POWER FEASIBILITY

1 INTRODUCTION

Nuclear power is a proven technology and has the potential to generate virtually limitless energy with no significant greenhouse gas emissions.

Modern development of nuclear power technology and the established framework of international agreements and conventions are responding to the major political, economic and environmental issues related to high capital costs, the risks posed by nuclear waste and accidents, and the proliferation of nuclear weaponry.

Nuclear power share of worldwide electricity production rose from less than 1 percent in 1960 to 16 percent in 1986, and that percentage has held essentially constant in the 21 years since 1986. Nuclear electricity generation has grown steadily at the same pace as overall global electricity generation. In December 2007, there were 439 operating nuclear reactors around the world, and 34 more under construction [1].

At the close of 2006, nuclear provided about 15 percent of total electricity worldwide. The US had 103 operating units. France was next with 59 and Japan followed with 55, plus one more under construction. Russia had 31 operating units, and seven more under construction [2]. Of the 30 countries with nuclear power, the percentage of electricity supplied by nuclear ranged widely: from a high of 78 percent in France; to 54 percent in Belgium; 39 percent in Republic of Korea; 37 percent in Switzerland; 30 percent in Japan; 19 percent in the USA; 16 percent in Russia; 4 percent in South Africa; and 2 percent in China.

Assuming that all nuclear capacity currently under construction or firmly in the development pipeline gets completed and attached to the grid, without any further capacity added, the nuclear installed capacity will grow from 370 GW(e) at the end of 2006 to 447 GW(e) in 2030. In a high projection -which adds reasonable and promising projects and plans- global nuclear capacity is estimated to rise up to 691 GW(e) in 2030. That would represent an average growth rate of about 2.5%/yr [3].

2 GENERAL CONSIDERATIONS

2.1 NUCLEAR ENERGY PHYSICS

2.1.1 Molecules, Atoms, Nuclei, Isotopes

Ordinary matter around us, whether solid, liquid or gaseous, is made of atoms. Almost the whole mass of an atom is gathered within its nucleus, an assembly of protons and neutrons (the «nucleons»), with the former carrying a positive electrical charge. A cloud of electrons is located around the nucleus. There are as many electrons as there are protons. Each electron, of very low mass, has a negative electric charge that is equal, in absolute terms, to the proton charge. The atom is therefore electrically neutral.

The chemical nature of an atom is determined by the number of protons in its nucleus. This number can range from 1 in the case of hydrogen to 92 for uranium. Two atoms that have the same number of protons but a different number of neutrons are known as the *isotopes* of a single chemical element. For instance, uranium has two main isotopes: uranium 238, ^{238}U, whose nucleus has 92 protons and 146 neutrons, and uranium 235, ^{235}U, whose nucleus has 92 protons and 143 neutrons.

Several atoms can join together a part of their electron cloud to form molecules (or crystals). Chemical energy, which only concerns electrons, is produced when atoms and molecules join together and separate. Nuclear energy, on the other hand, is released when the components of the nucleus assemble or disassemble through fusion, radioactivity and fission.

Some atoms, or rather their nuclei, can disintegrate (radioactivity or fission) or fuse together, processes which implicate the components of the nucleus: such is the origin of two nuclear energies, respectively called fission and fusion energy. Those nuclear energies are roughly 1 million times larger than chemical energy, which does not involve nucleons. For instance, the fission of one gram of uranium releases more energy than the combustion of one metric ton of oil.

2.1.2 Radioactivity

Some atomic nuclei are unstable: they spontaneously transmute themselves into other nuclei, with different properties. When this transformation occurs, the nucleus emits radiation, i.e. particles or electromagnetic rays. Such nuclei are called *radioactive*. The radioactivity of a given nucleus is specific: this radioactivity is characterized by the type of radiation emitted, its energy, and the rhythm governing the *decay* of the nucleus.

While it is impossible to predict at which precise time *one* radioactive nucleus will undergo decay, the amount of time necessary for half of a given nuclei population to have decayed is known with great statistical precision. This characteristic amount of time, noted $T_{1/2}$, is called half-life of the radioactive nucleus.

The main types of radiation emitted by radioactive nuclei are the following:

Alpha (α) radiation is the emission of a very energetic helium nucleus, made of two protons and two neutrons. α radioactive nuclei are mostly heavy nuclei, and often with

long or very long half-lives. For instance, uranium 238, ^{238}U, is α radioactive and its half-life is 4.5 billion years, about the age of our solar system (creation of the Sun and its planets.)

Beta (β^-) radiation is the simultaneous emission of one electron and one *neutrino*, a small particle of extremely tiny mass, the interaction of which with matter is too low. The kinetic energy of the electron can vary considerably: they are accordingly being called “hard” or “soft” beta rays.

Gamma (γ) radiation is the emission of photons by *excited* nuclei which get rid of their excess energy without changing their nature. A gamma ray is a form of electromagnetic radiation like visible light or X-rays, only more energetic. γ radioactivity can occur by itself, but if often occurs together with the α and β^- radiation.

2.1.3 Natural and Artificial Radioactivity

Radioactivity was discovered in 1896 by Henri Becquerel, as he realized that uranium salts spontaneously emitted invisible and penetrating rays, able to blacken photographic plates and to make air conductive of electricity. In 1898, Pierre and Marie Curie extracted from uranium ore two new elements, which emitted much more powerful radiation: the element *polonium*, and the element *radium,* of world renown. They coined the word **radioactivity** to describe this phenomenon.

Artificial radioactivity was discovered in 1934, by Irène Curie, Marie’s daughter, and her husband Frédéric Joliot. They irradiated a thin aluminum plate with α rays from a polonium source. They observed radiation as well as the creation of silicon and phosphorus. Following their example, researchers started to irradiate all known nuclei with various forms of radiation and to produce many other «artificial» radioactive nuclei.

Whether «natural» or «artificial», radioactive atoms emit the ***same*** forms of radiation, with identical effects on live beings. Protections against radiations are identical: keeping distance, limiting exposure time and using shielding materials.

2.1.4 Radiation Units: Becquerel, Gray and Sievert

The activity of a substance is the number of its atoms which undergo decay per unit of time. Activity is measured in ***becquerels***: 1 Bq = 1 decay per second (irrespective of the type of radiation). One becquerel is an extremely tiny unit.

The radiation ***dose*** measures the energy deposited by radiation in a substance per unit mass. Dose is expressed in ***grays***: 1 Gy = 1 joule/kilogram.

Some parts of the body are more sensitive to the effects of radiation than others, and some types of radiation are inherently more dangerous than others, even if they deposit the same level of energy. To take these characteristics into account, tissue weighting factors and radiation weighting factors have been developed. These can be combined with a measurement of absorbed dose of radiation to give an effective dose. To quantify the biological effects of a radiation absorbed by a living tissue, one uses the unit of ***equivalent dose*** which is the ***sievert*** Sv. The millisievert (mSv), one 1000th of a sievert, is the more usual unit for the sorts of exposures found in day-to-day life. For

instance, the average equivalent dose received from natural sources is about 2.4 mSv per year.

2.1.5 Origin of Nuclear Energy

Everyone is familiar with Einstein's formula $E = mc^2$, which is more accurately expressed as: $\boxed{\Delta E = - c^2 \times \Delta m}$, where c is the velocity of light (3×10^5 km/s).

This formula states that mass and energy are two forms of the same reality that can be interchanged under certain conditions, and that a slight variation in mass represents an enormous variation in energy. The total mass of a nucleus is thus lower than the sum of the masses of all the protons and all the neutrons that make it up, and the difference in mass is the *binding energy* of the nucleus, generally expressed in millions of electron volts or MeV.

The most stable combination of nucleons happens to be a medium-sized nucleus. This means that if two light nuclei can be fused to form a medium-sized nucleus, some binding energy will be released, and if a heavy nucleus can be split into two medium-sized nuclei, such energy will as well be liberated. These two phenomena are known respectively as *nuclear fusion* and *nuclear fission* (Fig. 1).

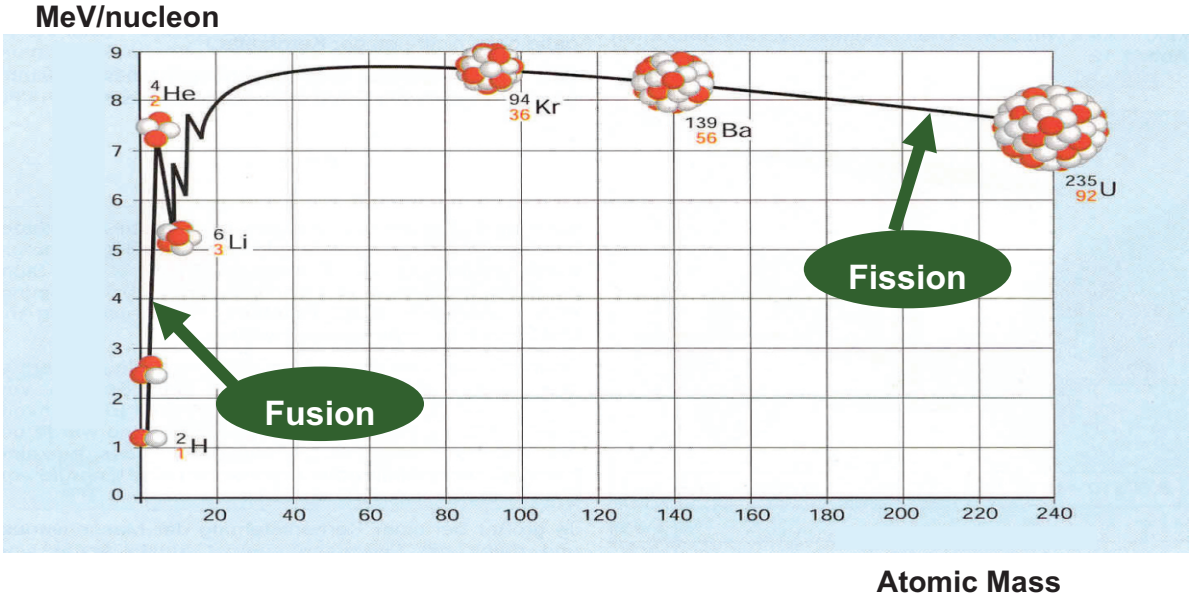


Figure 1
Fusion and Fission Processes

2.1.6 Nuclear Fission

Some heavy nuclei are ***fissile*** after having absorbed a neutron: the «composite» nucleus is too excited and gets rid of its extra energy through simple decay, like an oversized drop of water: it violently splits into two unequal fragments, while at the same time ejects two or three neutrons. This phenomenon is called ***fission***. The total mass of the fragments and neutrons is slightly smaller than the mass of the composite nucleus. Energy is therefore released. Most of the energy is released as kinetic energy

of the fragments. When the fragments slow down, this kinetic energy becomes heat. It is this heat which is transformed into electricity in nuclear plants.

Neutrons ejected during one fission can, in turn, be absorbed by other neighboring fissile nuclei, thus creating a **chain reaction**. If this chain reaction is left to develop exponentially, one gets a nuclear explosion. If the reaction is controlled and stabilized, one gets an energy source: this is what happens in a nuclear reactor.

Both fission fragments are almost always radioactive, and undergo successive radioactive decays. Together, fission fragments and their daughter elements are called **fission products**. Fission products constitute most of the high level radioactive waste.

The only readily fissile nucleus found in the Earth crust is an isotope of uranium, whose atomic mass is 235. This isotope constitutes 0.7% of natural uranium. On the other hand, when a nucleus of the other isotope of natural uranium, uranium 238, absorbs a neutron, it gets transmuted into fissile plutonium. This plutonium can, as well, generate energy in a nuclear reactor. Another naturally occurring isotope, thorium 232, can also, by absorbing a neutron, turn into a fissile isotope, uranium 233. Uranium 238 and thorium 232 are called ***fertile***.

Fission was discovered in late 1938 by the German research team led by Otto Hahn. In Chicago, USA, on December 2nd 1942, the first man made nuclear chain reaction was produced in the atomic pile CP1 designed and built under the leadership of Enrico Fermi. The use of nuclear fission to produce electricity in nuclear power plants dates from the mid 50s: 1954 for the Obninsk reactor in the Soviet Union, and 1956 for the Calder Hall plant (UK) in the western world.

Today all the nuclear power (over 2600 billion kWh per year) is produced by nuclear fission. Nuclear fission is also used to power military ships, mostly submarines and air carriers, in the USA, Russia, the UK, France and China. Russia operates six nuclear ice-breakers.

2.1.7 Nuclear Fusion

Nuclear fusion is the source of the energy radiated by the stars, including our Sun. The actual fusion reactions occurring within the stars cannot be achieved on Earth, but one can, at very high temperatures (100 millions K) fuse together the nuclei of two hydrogen isotopes, according to the reaction:

$$D + T \rightarrow He + n + 17.4\ MeV$$

where D, deuterium or ^{2}H, is made of one proton and one neutron, while T, tritium or ^{3}H, is made of one proton and two neutrons. Deuterium is a stable isotope of natural hydrogen, though in low concentration, but tritium is radioactive and decays with a half-life of 12 years. Tritium therefore must be produced, using the neutron emitted in the fusion reaction and one isotope of lithium:

$$^{6}Li + n \rightarrow T + He$$

Both D & T nuclei have a positive electric charge and repel each other. To overcome the electrostatic repulsion (the “Coulomb barrier”), they must be given high kinetic energy, hence the very high temperature, where atoms are fully dissociated in free ions and electrons and matter becomes a “plasma”.

Fusion was first achieved through the H-bomb, where the necessary energy to ignite the fusion reactions is supplied by an A-bomb. Controlled fusion is much more difficult to achieve.

The main method to force D and T nuclei to meet and undergo fusion is to vastly increase their velocity by thermal agitation. That means heating the “plasma” to 100 or 150 *million* degrees. Of course, one cannot let this ultra-hot plasma in contact with any material wall: it must be contained within some kind of magnetic bottle through a combination of electric field and extremely powerful magnets. This method is called ***Magnetic Containment Fusion (MCF)***.

The best experimental fusion device, the “Tokomak”, was invented in the mid 50s by a Russian team led by L. Artsimovitch. Inside a Tokomak, a very low density plasma D-T (100,000 times lower than the density of air at atmospheric pressure) is contained within a donut shaped metallic vessel by a series of magnetic coils and heated by Joule effect. Since their invention, tokomaks have undergone great improvements, and their performances have increased by several orders of magnitude.

Seven partners (European Union, Russia, Japan, USA, China, South Korea and India) have pooled their effort to develop together a reactor-size Tokomak called ITER (International Tokomak Experimental Reactor), located in Cadarache (France), which should produce its first plasma by the end of 2016 and carry its experiments at least over 15 more years.

ITER its expected to bring the physical demonstration of controlled MCF by producing, over several minutes, more energy from fusion reactions than will have been required to heat the plasma. The success of the ITER experimental program will not be enough. It will be necessary, in addition, to implement a complete program to develop materials suited for this technology, notably the materials facing the plasma which must withstand very high temperatures as well as an intense high energy neutron irradiation.

Fusion offers a tremendous prospect of very abundant energy, but there are still many hurdles to overcome before starting a first reactor prototype, not to mention commercial maturity.

3 NUCLEAR POWER PLANTS

A nuclear reactor produces energy in a controlled way by splitting the nuclei of elements such as uranium and plutonium present in its “fuel”.

In a nuclear power reactor, the heat released from continuous fission of the nuclei in the fuel is used to make steam. The steam is used to drive the turbines which produce electricity (as in fossil fuel power plants).

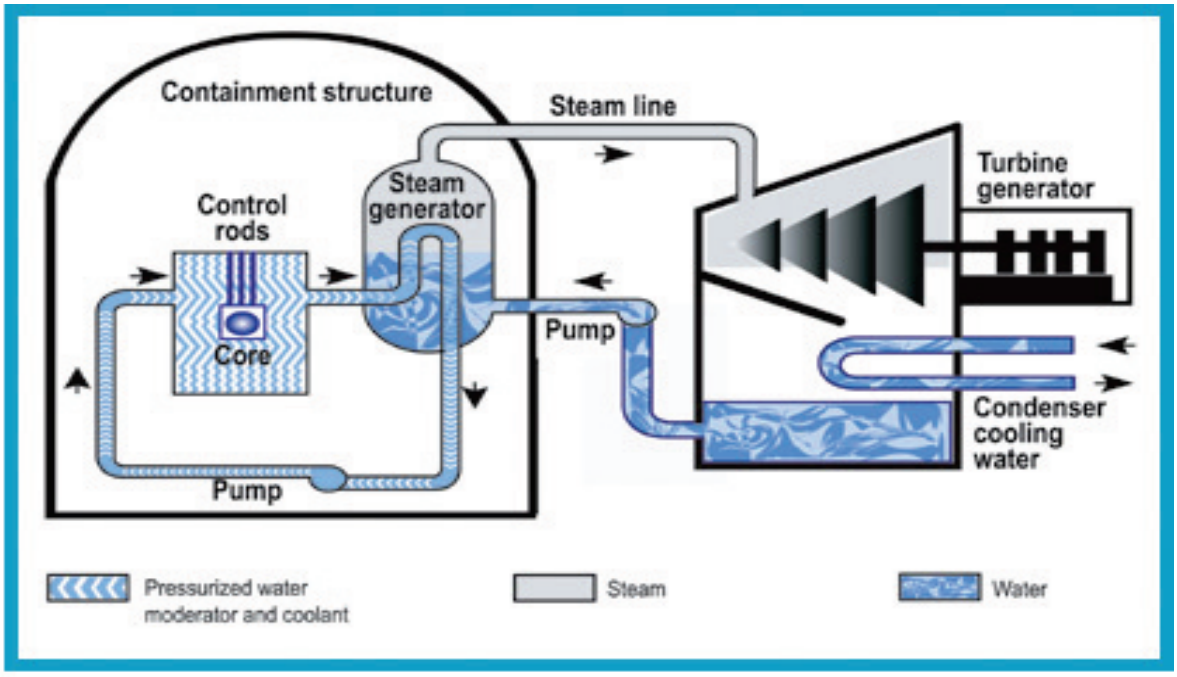


Figure 2
A schematic diagram of a typical Nuclear Power Plant

Fig.2 shows one of the most common types of a nuclear power plant, based on the Pressurized Light Water Reactor (PWR). It has the following components:

Fuel.
Pellets of uranium oxide UO_2 or mixed oxide MOX (UO_2, PuO_2) piled up in tubes form fuel rods. The rods are arranged into fuel assemblies in the reactor core.

Moderator.
This is material which slows down the neutrons released from fission so that they cause more fissions. In PWR, it is ordinary water, but it may be heavy water or graphite in other types of reactors. “Fast neutron” reactors do not have any moderator.

Control rods.
These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it. Secondary shutdown systems involve adding other neutron absorbers, usually in the primary cooling system.

Coolant.
A liquid or gas circulates through the core in a close loop (the primary circuit) so as to transfer the heat from it. In light water reactors the moderator functions also as coolant.

Pressure vessel.
A thick and sturdy steel vessel contains the reactor core and moderator/coolant. In other reactors, it may be a series of pressure tubes holding the fuel and conveying the coolant through the moderator.

Steam generator.
This is a specific heat exchanger where the heat from the reactor is transferred from the primary circuit to make steam for the turbine.

Containment.
There is a very resistant structure around the reactor core which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any major malfunction inside. It is typically a meter-thick concrete and steel structure, often double walled in modern plants.

Most reactors use “slow” or “thermal” neutrons to maintain the fission chain reaction, because they interact much more readily with the fissile nuclei. The most common moderator is ordinary water because the hydrogen nucleus, a single proton, is most efficient to slow the neutrons down. Reactors moderated (and cooled) by ordinary water are called LWR, for Light Water Reactor. Since light water absorbs neutrons and slows them, it is less efficient as a moderator than heavy water or graphite. In such reactors, the fuel cannot be made of natural uranium: it needs to be “enriched”. Natural uranium has the same isotopic composition as when it was mined (0.7% ^{235}U, over 99.2% ^{238}U). Enriched uranium has had the proportion of the fissile isotope (^{235}U) increased by a process called enrichment, commonly to 3.5 - 5.0%. During the irradiation in the power reactor, part of the ^{238}U nuclei absorbs neutrons and is transmuted into fissile plutonium ^{239}Pu, which compensates, but only partly, the fission of ^{235}U nuclei.

After a period of operation, these LWR need to be shut down for refueling, and the pressure vessel is opened up. In this case refueling is at intervals of 1-2 years, when 1/4 to 1/3 of the fuel assemblies are replaced with fresh ones. Practically all fuel is ceramic enriched uranium oxide (UO_2 with a melting point of 2,800°C). The fuel pellets (usually about 1 cm diameter and 1.5 cm long) are typically arranged in a long zirconium alloy (zircaloy) tube to form a fuel rod, the zirconium being hard, corrosion-resistant and permeable to neutrons. Up to 264 rods form a fuel assembly, which is an open lattice and can be lifted into and out of the reactor core. In the most common reactors these are about 3.5 - 4.0 meters long.

One distinguishes two families of LWR: the Pressurized Water Reactor (PWR, or VVR in its Russian version) and the Boiling Water Reactor BWR.

3.1 TYPES OF NUCLEAR POWER PLANTS

Table 1 shows the number and the capacity of the different types of power reactors in operation or under construction as of end of December 2007 [1]. Their characteristics are described below.

Type	Nr. Operating	GWe	Nr. under Construction	GWe
PWR + VVR	265	243.4	25	22.1
BWR	94	85.0	2	2.6
GCR	18	9.0		
HWR	44	22.4	4	1.3
RBMK	16	11.4	1	0.9
FBR	2	0.7	2	1.2
Total	**439**	**371.9**	**34**	**28.1**

(Source: IAEA PRIS-Dec 2007)

Table 1
Reactors in operation and under construction at end of Dec.07

3.1.1 The Pressurized Water Reactor PWR (or VVR)

In the PWR, the coolant in the primary circuit is maintained as a liquid through high pressure (typically 15 MPa) at a temperature close to 300°C. In the steam generator, the heat is used to boil water in a close loop “secondary circuit” and produce steam at a pressure around 7 MPa. This steam rotates a turbine coupled to an alternator which generates electricity.

The low pressure steam is then returned to liquid water in a “condenser” and recycled within the secondary circuit. The condenser is cooled by water pumped from a river or from the sea, or cooled by air in cooling towers. Initially developed to power nuclear submarines, the PWR (or VVR) has become the most popular reactor type.

3.1.2 The Boiling Water Reactor BWR

In the BWR, the water is allowed to boil in the core, and the primary steam, under 7 MPa, goes directly to the turbine. The overall design is simpler since there is no secondary circuit, but the large variation of moderator density along the core height calls for a more complicated core design.

3.1.3 The Heavy Water Reactor HWR (or CANDU)

One of the best possible moderators is heavy water D_2O, where D stands for deuterium, an isotope of hydrogen whose nucleus is composed of one proton and one neutron. Heavy water slows neutrons almost as efficiently as ordinary water but it does not absorb neutrons. Deuterium is found in seawater at very low concentration, but increasing its concentration is expensive and needs energy. Owing to its moderator efficiency, HWR can use natural uranium without enrichment.

Most HWR, the CANDU types initially developed in Canada, have horizontal pressure tubes (rather than a pressure vessel enclosing the reactor core). They can and must be refueled while still generating electricity by disconnecting individual pressure tubes. This is called on-line refueling.

3.1.4 The Graphite Moderated Water Cooled Reactor RBMK

Apart from ordinary and heavy water, the other moderator practically available is graphite. Graphite hardly absorbs any neutron but its nuclei are heavier and less efficient to slow them down. As a result, graphite moderated reactors have large sizes and low power density, and they must be refueled on-line.

In the RBMK, of soviet origin, the coolant is ordinary boiling water flowing in vertical pressure tubes. Fueled with slightly enriched uranium, RBMK were designed both to generate electricity and produce weapon-grade plutonium. The technology of RBMK safety relies too heavily on human control which is not up to modern operational standards. The worst nuclear accident in history occurred in a RBMK, the Chernobyl 4 reactor in Ukraine. However, nowadays, Russia is completing one unit with improved safety conditions.

3.1.5 The Gas Cooled Reactor GCR

Graphite moderated reactors can also be cooled by gases, usually carbon dioxide CO_2. Earlier GCRs, sometimes called Magnox, used natural uranium as metal rods. More modern GCRs, called AGRs, used slightly enriched uranium as oxide pellets. The last remaining GCRs all operate in the United Kingdom and all should be decommissioned by 2020. The modern helium cooled and graphite moderated High Temperature Reactor (HTR, PBMR) is somehow a successor of the GCRs.

3.1.6 The Fast Breeder Reactor FBR

While slow neutrons interact more efficiently with fissile nuclei, fast neutrons are able to extract energy from uranium 238. Present thermal neutron reactors use at best 1% of the potential energy of natural uranium. FBRs can extract almost 100% of this potential energy, by transmuting “fertile” ^{238}U into ^{239}Pu through successive recycles.

To avoid slowing down the neutron population, FBRs cannot use water as coolant: they use molten metals like sodium. In the future, helium gas will also be used as coolant. The FBR technology is highly sophisticated, which results in higher capital costs: only prototypes have operated till now.

3.2 GENERATION IV

Nuclear reactor technologies are often described in terms of “generations”.

Generation I reactors were the early prototypes of the pioneer era. Many different types of reactor were designed and tested, with a rapid escalation in size and no standardization. With embryonic regulations still under development, these reactors were built very quickly and many would not be licensed today. All those Generation I plants are now decommissioned and several have been completely dismantled.

Generation II reactors are those operating today, as described on Table 1: they supply 16% of the world's electricity (some 2,600 TWh).

Generation III reactors are:

- being built today, ABWR in Taiwan and EPR in Finland and France (Fig. 3), or
- just ordered, AP 1000 in China (Fig. 4), or
- still waiting for their first order, ESBWR (Fig. 5), SWR and ACR 1000 (Fig. 6).

Figure 3
EPR Layout

All of them are water moderated, and exhibit some kind of technological continuity with Generation II LWRs and HWRs[1]. What makes them differ from Generation II reactors comes from the fact that they were designed after the Chernobyl accident. There were few technical lessons to be learned from this accident, very specific to the RBMK design, but one: any new massive release of radioactivity in the environment is unacceptable. Generation III reactors are designed so that even a full core meltdown, an extremely improbable event, would not result in such a release.

[1] The ACR is moderated with heavy water, but cooled with ordinary water, and must use slightly enriched uranium

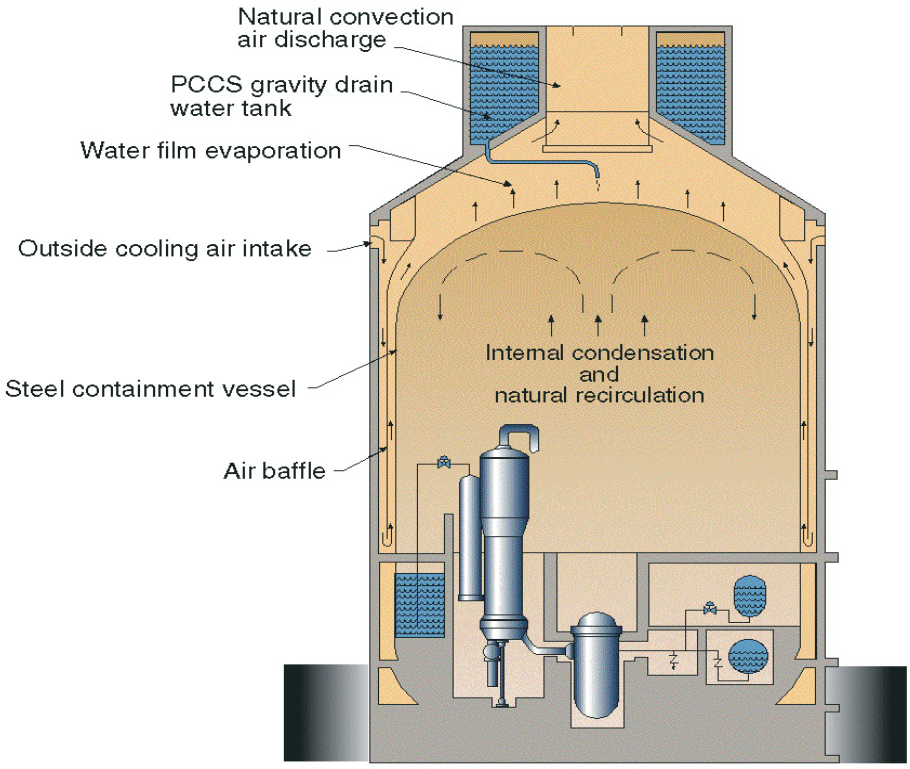


Figure 4
Schematic diagram of the AP 1000

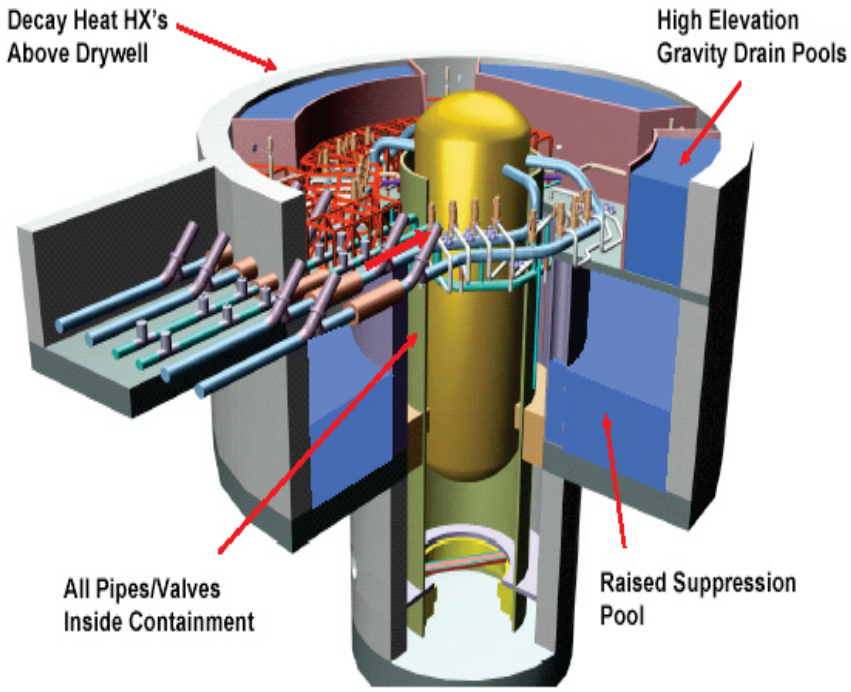


Figure 5
Features of the ESBWR

While Generation III reactors are starting their deployment, R&D is being carried out in a multinational framework to prepare Generation IV, to be commercially available around 2040.

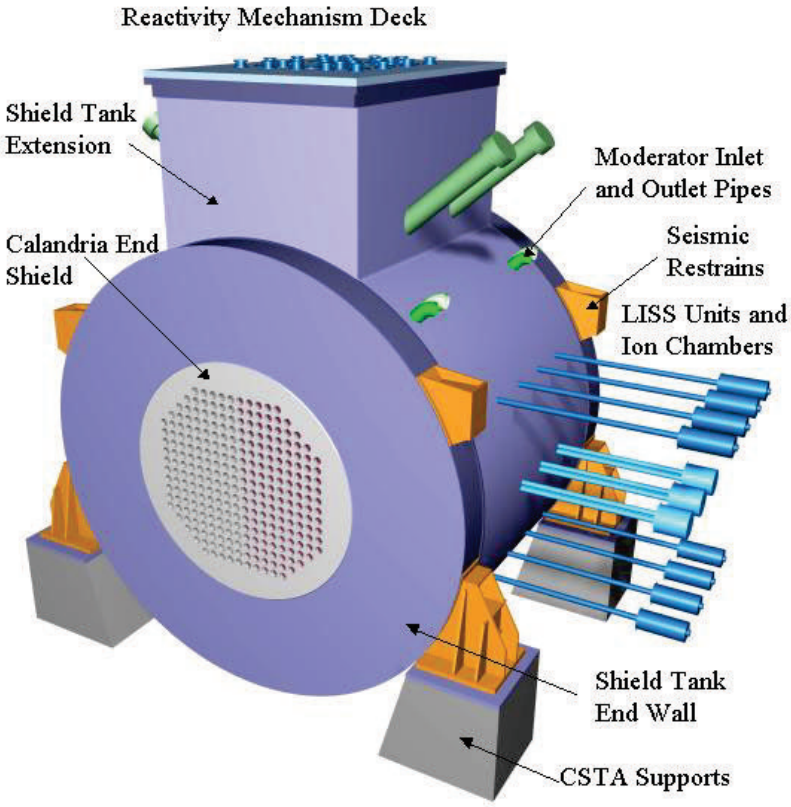


Figure 6
The ACR 1000 Characteristics

Generation 4 reactors will have to overcome the main limitations of present day designs, in order to make nuclear power really sustainable:

- Make better use of the fissile material resources,
- Reduce the long-term radio-toxicity of radioactive waste,
- Offer better protection against terrorism and proliferation,
- Reduce capital costs (notably through shorter construction times),
- Be able to offer other services than electricity (desalination, process heat, hydrogen, etc.)

Six designs are being considered as potential candidates for this Generation IV: three types of FBRs (sodium cooled, lead-alloy cooled and gas cooled), one reactor cooled by supercritical water, one high temperature gas cooled reactor and one reactor fueled and cooled by a molten salt. In order to have some of these designs commercially available by 2040, prototypes should operate around 2020.

4 THE FUEL CYCLE AND ITS DIFFERENT STAGES

The term nuclear fuel is applied to an element that can produce heat through the fission of the heavy atoms it contains. Uranium ore does not provide nuclear fuel directly. In order for heavy nuclei to generate usable heat through fission, they must undergo a *fuel cycle* consisting of many industrial stages. Fuel cycles depend on the type of reactor and the choice of fissile and fertile isotope pairings.

4.1 THE LWR FUEL CYCLE

The LWR fuel cycle is outlined in Fig. 7.

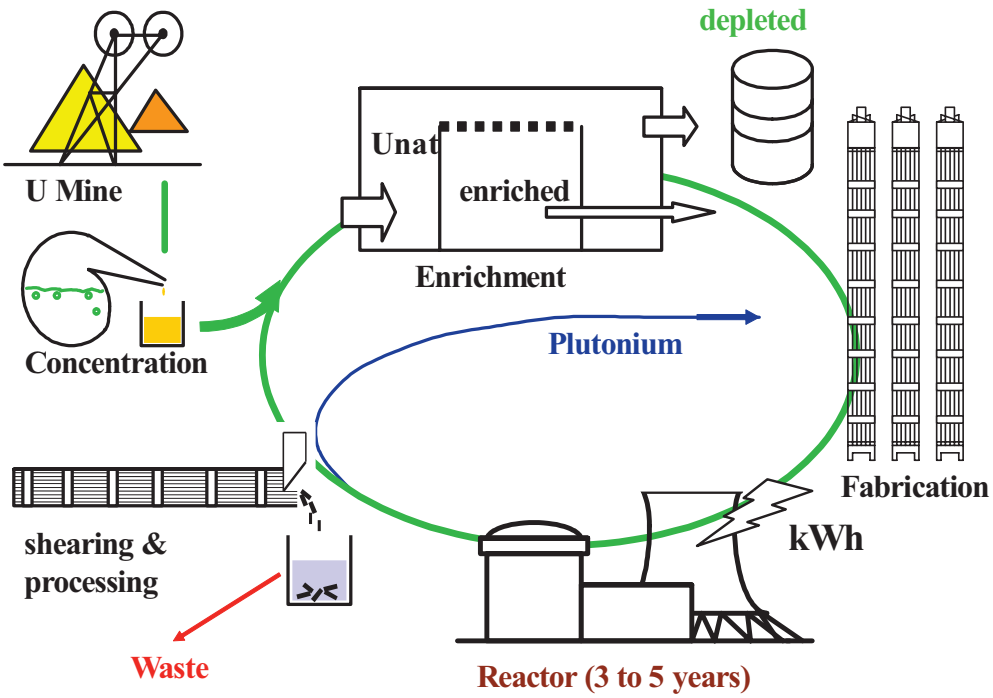


Figure 7
LWR Fuel Cycle

The typical PWR fuel cycle is made up of the following stages:

- **Extraction** of uranium ore from underground mines, open quarries or in-situ leaching,
- **Concentration** of the ore (which often contains less than 1% uranium) on the extraction site (production of *yellow cake*),
- **Conversion** of uranium concentrates into uranium hexafluoride, UF_6, which is solid at ambient temperature and turns into vapor at moderately high temperatures,
- Isotope **enrichment** of UF_6 to increase the concentration of fissile ^{235}U nuclei, as it is too low in natural uranium,
- Fuel **manufacture** (i.e. conversion of the fluoride into enriched uranium oxide, UO_2; pellet manufacture; pellet sintering; fuel rod manufacture, and assembling the rods into bundles),

- **Production** of electricity in the reactor for about 4 years,
- Temporary **storage** of the spent fuel under water,
- Spent fuel **management** and eventually **recycling** of recoverable materials.

There are many inspections and some transportation between each of the above stages. Each stage is a complete industrial process by itself, as shown above.

Each installation involved in the fuel cycle, i.e. enrichment, manufacturing or reprocessing, is large enough to produce fuel for 20 to 30 large reactors. The fuel cycle is international by its very nature.

4.1.1 Once-Through Cycle and Closed Cycle

The last stage – spent fuel management – is different for the *closed cycle*, set out in the diagram above and adopted in France, and the *once-through cycle*, adopted notably in the U.S. and other European countries.

The once-through cycle –which in fact is not a cycle at all– ends with the final disposal of the spent fuel, in this case written off as plain waste.

The closed cycle includes the following sub-stages:
- Chemically **processing** the spent fuel to recover any remaining fissile and fertile materials for recycling purposes,
- **Recycling** the plutonium into MOX fuels and enriching residual uranium,
- **Conditioning** waste, in particular, vitrifying high-level radioactive waste left over from fission,
- **Final disposal** of conditioned waste.

Many countries have not really made their choice between the two cycles and keep their spent fuel in interim storage, waiting for a final decision.

4.1.2 Uranium Prospecting and Resources

Uranium is the heaviest natural element remaining on earth. Its nucleus is surrounded by 92 electrons. It is composed mainly of two isotopes, ^{235}U and ^{238}U.

Isotope	Half-life (years)	Current relative abundance on earth (as % U total)
235	713 million	0.720
238	4.47 billion	99.275

Table 2
Isotopic Composition of Natural Uranium

Chemically speaking, uranium is similar to chromium and tungsten. It is an element with a clear affinity for oxygen and is found in at least two hundred minerals. The Earth's crust contains on average 3g of uranium per ton. Uranium is found in all rocks and soils and in particularly high concentrations in phosphates and certain types of granite or igneous rock. It can also be found in granite and sedimentary ground, and even in water.

Radiometric prospecting is the geophysical method used specifically for uranium detection as it is based on radioactivity. In actual fact, radium is detected more readily. Radium is a daughter product of uranium and its radiation is more penetrating. Radiometric prospecting can be performed on foot, from a land vehicle or by aircraft for large grids and regions where access is difficult.

Although correctly interpreted radiometric measurements can be used to detect uranium ore deposits, they give little information as to the quantity or concentration of the ore. Additional information can be obtained using electrical, electromagnetic and magnetic devices, and by geochemical surveys.

World identified resources recoverable at a cost of less than 130 $/kg uranium amount to some 4.7 million tons [4]. It must be pointed out that, during the 80s and 90s, the market price of uranium was so low as to completely discourage any exploratory effort. With uranium prices having soared in the last few years, world uranium prospecting has been drastically resumed and those figures can be expected to be revised upwardly.

Table 3 shows the distribution of world reserves among the main producers. Most of the uranium produced in the world currently comes from Canada, followed by Australia and Niger. Extremely large high-grade deposits are still to be mined in Australia and Canada. Other lower-grade or less easily reached deposits represent considerable potential reserves. It can be seen that some of today's large consumers, e.g. Japan and the European countries, or potentially large consumers, e.g. China or India, are particularly poorly endowed with this natural resource.

Country	% of World Reserves
Australia	24
Kazakhstan	12
Canada	9
South Africa	7
USA	7
Namibia	6
Niger	5
Russian Federation	4
Uzbekistan	3

Table 3
Breakdown of World Uranium Identified Reserves (< $ 130/kgU)

Currently, a question is repeatedly posed: can these reserves be described as extensive? For the sake of comparison, some 2 million tons of uranium have been produced since the dawn of the nuclear industry; 1.2 million tons of this amount were consumed in civil reactors, and the rest went into stockpiles.

At the present rate of consumption (67,000 tons in 2005), "cheap" reserves should last between 50 and 100 years. Mining less rich deposits could bring this number well above 200 years. But it must be borne in mind that a growing nuclear fleet will

significantly expand the consumption of the year 2005. Beyond that, the millions of tons of uranium contained in phosphates (and perhaps the billions of tons contained in the oceans) could then be tapped. More important, the “breeders” technology has been already developed, though not yet economically competitive it can extract roughly 50 to 60 times more energy from a given amount of uranium than present LWRs. These breeders can also use the huge existing stockpiles of depleted uranium. With the breeders, there is enough uranium for many centuries under any credible scenario of nuclear development. Breeding could also allow using thorium as a fuel, which is more abundant than uranium probably by a factor of two or three.

4.1.3 Uranium Extraction and Conversion

At the yellow cake stage, the uranium must first be converted into uranium hexafluoride or UF_6 (gaseous) to undergo isotope enrichment. The first step is to purify the yellow cake to rid it of neutron-absorbing elements such as boron or cadmium, or other elements that form volatile fluorides liable to contaminate the uranium hexafluoride produced at a later stage.

The purified uranyl nitrate solution is then converted into uranium oxide powder, UO_3, and then into UO_2. The oxide powder, UO_2, is then fluorinated by hydrofluoric acid. The uranium tetrafluoride, UF_4, thus obtained is converted into uranium hexafluoride UF_6 by fluorinating it again with gaseous fluorine. The uranium hexafluoride is then transferred to the enrichment plant in solid form in pressurized containers.

4.1.4 Uranium Enrichment

Uranium enrichment has been closely linked with the use of light water nuclear reactors, which are the most widespread among nuclear reactors today. The fuel for these reactors must be enriched from 0.7% to around 4% in ^{235}U.

The physical properties of a pure element depend on its isotopic composition, but these differences in properties are generally slight and not easy to exploit for the purposes of isotope separation. The chemical properties of elements generally depend very little on the isotope considered, which makes isotope separation all the more difficult by chemical means. The processes implemented use the difference in the mass of the isotopes to be separated, either directly (mass spectrometry and centrifugation), or indirectly (gas diffusion).

a) Cascades

All current separation methods have a small or very small elementary separating power, which calls for the use of a cascade design, where each elementary step is repeated until the required degree of enrichment Np is obtained (Fig. 8). The cascade is often made up of two parts, the larger of them being devoted to the actual enrichment. Other stages are also used to deplete the residues in order to optimize the separation performance of the cascade. In Fig. 8, each rectangle represents an elementary separation step. P (product), W (waste), F (feed) represent flows, and Np, Nw and Nf the isotopic abundance.

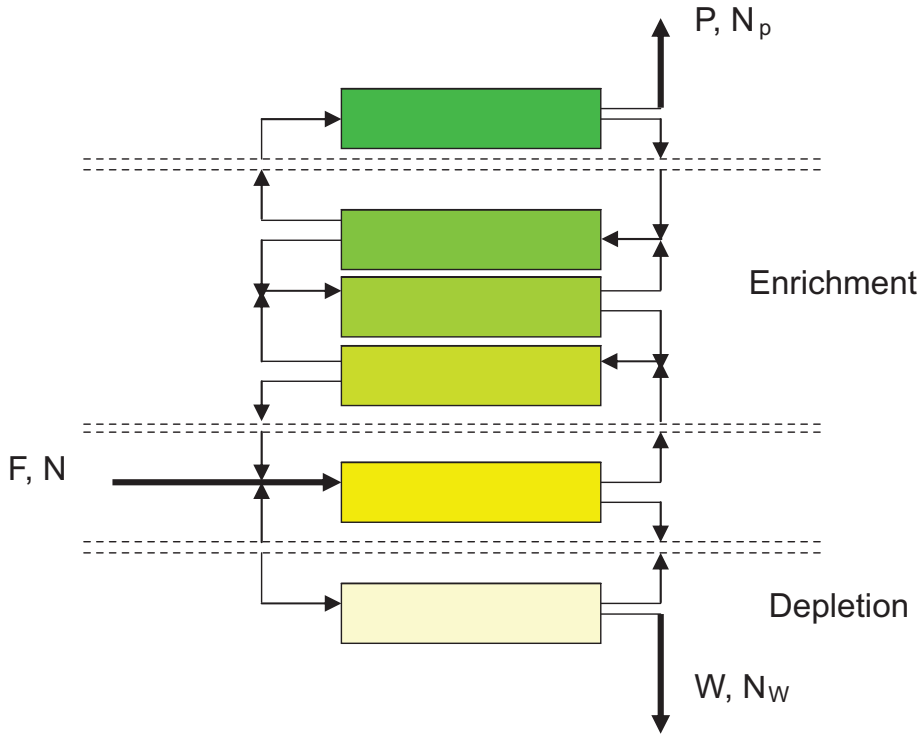


Figure 8
Example of a cascade

The degree of depletion chosen depends on economic optimization taking into account the price of natural uranium and the cost of enrichment. The higher the value of Nw, the easier the enrichment process, but the greater the consumption of raw materials. In order to achieve successful economic optimization, the notion of separative work unit (SWU) is introduced. This is a unit of measurement combining isotope abundance and the three flow rates. Fig. 9 illustrates the typical values of these parameters for civil uranium enrichment.

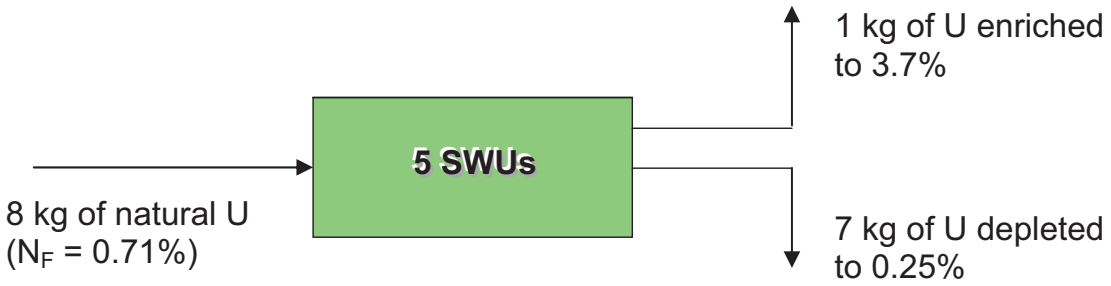


Figure 9
Material Enrichment Flows and SWUs

The SWU is also the commercial unit of measurement used for enrichment. The "typical" 900 MWe reactor consumes about 100,000 SWU/year, at a rate of 5 SWU/kg U, enriched to 3.7% from natural uranium.

b) Gaseous diffusion

Gaseous diffusion was the first uranium isotope enrichment process to be used on a large industrial scale. The gaseous diffusion process for uranium enrichment uses a gaseous compound of uranium, uranium hexafluoride (UF_6). The molecules of $^{235}UF_6$ (mass 349) travel faster than those of $^{238}UF_6$ (mass 352) and, over the same period of time, produce a greater number of impacts on the walls of the recipient containing them. Given these conditions, if gaseous UF_6 is diffused through a porous wall, then the ^{235}U enrichment of a fraction of the gas downstream from the barrier will be slightly higher than for the total gas upstream from the barrier at the start. The elementary effect is small since the enrichment factor for UF_6 is low, in practice around 1.002. This means that a cascade must have a large number of separative units (1,400 in the Eurodif plant). Such a plant is large and remarkably visible and cannot be used for enriching uranium beyond its design level.

This process will no longer be adopted for future plants mainly because of its considerable power consumption. All recent plants use the process described below, the centrifuge process.

c) Centrifuge Process

This process involves rotating a cylinder containing UF_6 gas at very high speed (Fig. 10).

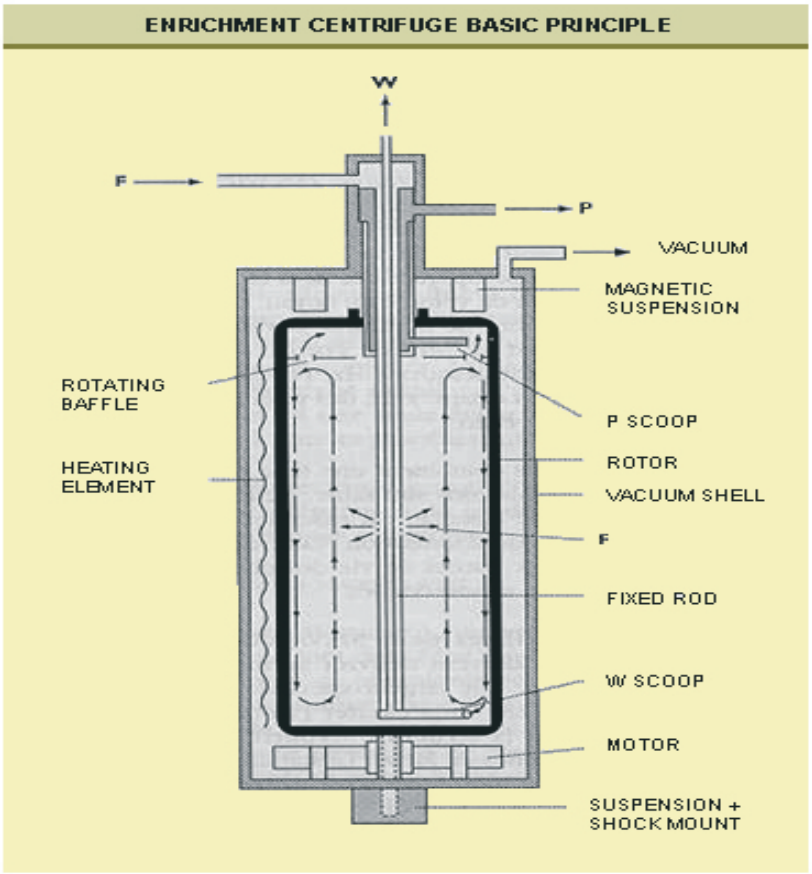


Figure 10
Uranium Enrichment Centrifuge

The heaviest molecules gather at the edge of the cylinder, while the lightest ones mostly migrate towards the center. The typical enrichment factor for this process is 1.3, a much higher value than that obtained with gaseous diffusion. Depleted and enriched fractions are caught by scoops – small tubes fitted at both ends of the cylinder at carefully optimized distances from the wall. As the gas is fed in and caught by the scoops, a counter-current forms along the rotational axis of the cylinder – which is vertical – and transforms the radial isotopic gradient into an axial gradient. With this optimized axial current, a centrifuge works rather like a distillation column: the current flowing upwards is gradually enriched with U 235 while the downward current is depleted.

The cost structure of a centrifuge plant is dominated by high investment costs and extremely low operating costs. Centrifuges are highly reliable in the case of models that have reached technological maturity. The power consumption of centrifuge plants is very low. Those plants can be unobtrusive and could, if un-safeguarded, be used to produce highly enriched weapon-grade uranium.

d) Laser process

Laser enrichment processes have been the focus of interest since the 70s. Being isotope-specific rather than statistical, these processes promise lower energy inputs, lower capital costs and lower tails assays. However, technological problems, mostly linked to materials behaviour and lifetime, have kept those processes at the experimental stage in the USA (AVLIS), France (SILVA) and Japan.

A promising laser process to be developed is SILEX, an Australian concept which is molecular and utilises UF_6. In 2006, GE Energy (now GE-Hitachi) entered a partnership to develop the SILEX process renamed “Global Laser Enrichment”. In August 2007, GE-Hitachi announced it planned "to complete a test loop program at the end of 2008 which, if successful, would open the way for the first commercial enrichment plant to be constructed."

4.1.5 Fuel Manufacture

Nuclear fuel design objectives are based on the following criteria:

- Providing the power required by the reactor for the entire duration of the planned cycles, while adapting to the power variations imposed by the grid.
- Containing fission products under normal, incident and accident operating conditions within design limits.
- Achieving the lowest possible cycle cost by optimizing the use of available fissile material.

The above objectives generate technical and technological requirements, the most important of which are:

- High power density.
- High level of reliability combined with a long lifetime: the fuel assembly, its structure and the rods making it up must withstand without failure throughout its time in the reactor, currently 4 to 5 years, with a target of 6 years by 2010.
- Leak tightness: in incident and accident situations, nuclear materials must remain perfectly contained for safety reasons. The fuel rod cladding forms the first

containment barrier (the other two are the primary system and the containment building).
- Under extreme accident conditions, even if cladding failures are unavoidable and the fuel assembly is deformed, it must still be possible to cool the fuel.
- In spite of these performance requirements, the fuel design must remain simple: this need for simplicity applies to all stages, i.e. manufacturing, handling, transportation, repair, and, after use, storage. In most cases, particularly in France, it must also be suitable for "reprocessing".

In addition, the materials chosen for the structure of the assembly and cladding must take into account their resistance to irradiation and corrosion.

The fuel assembly of a light water reactor is always made up of rods containing the nuclear material. These rods are arranged in a square grid in a structure designed principally to provide mechanical support for the fuel rods.

In a pressurized water reactor, this structure is open and the coolant can flow across the assemblies. On the other hand, in a boiling water reactor the structure is closed and each set of fuel rods is enclosed in a casing which prevents cross flows.

One preliminary step of the fuel fabrication process involves defluorinating the uranium hexafluoride (UF_6) to convert it into oxide (UO_2).

The actual fuel manufacturing process then includes the following steps:
- Manufacturing the materials, chiefly zirconium alloys, and parts, tube cladding and structural parts.
- Preparing fuel pellet powder (UO_2) or (UO_2 and PuO_2), including powder recovered from previous manufacturing runs.
- Pellet manufacture: shaping cylindrical pellets and "sintering" them, i.e. baking the pellet ceramics.
- Rod manufacture: inserting the pellets and sealing the rods.
- Assembly and storage.

Each of these steps includes controls on the compliance of physical criteria (geometry, density, and appearance), chemical criteria (exact degree of oxidation, impurities, etc.), and isotope criteria (^{235}U abundance, and plutonium abundance). Quality assurance requirements also impose maximum traceability of materials, equipment and operations so that the history of each element can be reconstructed and its origin guaranteed.

4.1.6 Spent Fuel Management

While the fuel assembly produces energy in the reactor core, the fuel loses fissile elements and accumulates poisons; it becomes less and less reactive, until it finally stops producing energy. It is at this stage that it becomes "spent" and must be replaced with fresh fuel in the core.

When spent fuel is removed from the core, it is still composed of roughly 95% uranium, much less enriched than it was initially and slightly "poisoned" by other non-fissile isotopes, about 1% plutonium, various fission products and a few minor actinides. It

has served its purpose. It must now be disposed of in a way that protects the public from the radioactive products it contains.

The residual uranium and plutonium can be extracted and *recycled* to produce more energy. The savings obtained from this recycling operation depends, of course, on the market price of the fresh fissile material it saves.

Most fission products are highly radioactive. Although this makes them very hazardous, it also means that they decay rapidly. For example, if they have a half-life of 30 years, which is the case for two of the most abundant isotopes, it means that only one-thousandth of them remains after 300 years, and practically all of them have disappeared after a thousand years.

At the other end of the spectrum, some elements have such a long half-life that they are not very radioactive and thus present little danger. Between these two extremes are the elements that present the greatest problem, as they are quite radioactive and have a significant half-life. Most actinides, in particular plutonium, fall into this category.

A spent fuel assembly has not only lost its capacity to produce energy; but its weakened structures also contain a complex blend of radioactive products with extremely varied physical and chemical forms and radioactive half-lives. It has to be safely disposed of.

One solution is to store the spent fuel as it is, by encasing and burying it deep underground in a stable geological formation. This implies demonstrating the durability of the additional barriers encasing it, since the assembly itself does not represent an optimal barrier. This solution also means virtually giving up any hope of taking advantage, even in the distant future, of the potential energy it still contains. Sweden has opted for this solution and the United States held it with priority in its nuclear power strategic planning of previous years.

Another solution involves *reprocessing* the spent fuel. This means chemically separating its different components to manage each different category in a specific manner. The fact that the material handled is highly radioactive makes this a heavy and costly operation. Uranium, plutonium (perhaps, in the future, minor actinides too), and all highly radioactive fission products are separated in this way. Once isolated, they can be stored in the most suitable way, bearing in mind that most of their radioactivity will have disappeared in a few centuries. They are incorporated within a glass matrix, the composition of which is specially designed to house this complex mixture. The glass is very slow to corrode and will hardly release any radioactive product it incorporates.

Reprocessing/recycling significantly reduces the amount of spent fuel stored in pools awaiting final disposal.

4.2 REPROCESSING

Spent fuel processing operations are aimed at recovering the materials that can be recycled – uranium and plutonium – and conditioning the "final" waste as effectively as possible.

When it is received for reprocessing, the spent fuel has already been stored in the spent fuel pool between six months and a year for allowing some of its activity to decrease substantially (i.e. "cooling"). This cooling continues in one of the pools at the reprocessing plant and the fuel is not to be reprocessed for some years: currently, the average figure is close to 8 years. The decrease in radioactivity is quite significant in the first few years and considerably simplifies subsequent operations.

Shearing machines are used to cut off the end-pieces from the fuel, which are then sent to be rinsed, and to cut up the fuel rods into segments which drop into a dissolver via a feed spout. All the off-gases released during the shearing are extensively filtered and controlled before discharge.

The dissolver is a wheel fitted with buckets. It rotates 30° at a time, completing a full revolution within 8 hours, thereby ensuring continuous operation. At the end of its travel, i.e. about every 2nd hour, each bucket empties its contents through a funnel to a helical ramp where the hulls are rinsed. End-pieces are rinsed in acid, then in water, and go to join the hulls in a storage drum ready for compacting. Compacting reduces the volume of waste to a quarter of its initial value.

The solution is fed off-line to a centrifuge to separate the insoluble particles from the clarified solution. After clarification, the typical solution obtained from dissolution contains 200 g/l of uranium, 2.5 g/l of plutonium and 3.5 moles/l of nitric acid. It also contains 6 to 7 g/l of fission products. It then undergoes several extraction stages.

First cycle extractions are at the heart of the process for they are used to separate and purify U and Pu, which can be recycled. All is done using a single solvent, tri-butyl-phosphate (or TBP), diluted in a hydrocarbon similar to kerosene. The separation stage is divided into two phases: mixing and settling. In the mixing phase, a uranium- and plutonium-rich aqueous solution of fission products is stirred with the organic phase and forms an emulsion. During this phase, the uranium and plutonium show a preference for the organic compound, while the fission products and minor actinides have the opposite tendency. The second phase, settling, involves separating the emulsion components. This operation is repeated several times in counter-flow and the U and Pu are thus extracted in the TBP.

The method selected to separate the plutonium from the uranium is by selective re-extraction of the plutonium. This is done by reducing the plutonium, after which it returns to the aqueous phase. To re-extract the uranium, water containing a small quantity of nitric acid is used.

At the end of the first cycle, the plutonium and uranium have been separated not only from the fission products, but also from each other. A second cycle is carried out to obtain the degree of purity required for their recycling as fuels. Once separated, the uranium is recovered as uranyl nitrate. After re-enrichment, similarly to what was done with natural uranium, some of this uranium is recycled while the rest is stored. The plutonium is transformed into Pu oxide and used to make MOX fuel.

4.3 VITRIFICATION

Vitrification is the process used to condition all fission products and actinides in a glass matrix. This glass matrix will contain almost all the fuel radioactivity (about 99.5%). It constitutes a *final* waste, meaning waste that has been stabilized and that contains no longer any reusable elements.

After suitable preparation, the fission products solution is fed into the “calciner”, which is a rotating tube whose outer shell is heated to about 600 °C. The water evaporates, the nitrates are partially broken down, and the load becomes a solid calcine. It then drops into the melting furnace together with the glass frit, the basic compound allowing fission products to be incorporated. It is composed primarily of silica, boron, aluminum and sodium oxides. When the furnace is full, melting is continued for several hours to refine the glass.

The melting furnace is then emptied. Each heat process represents 200 kg of glass, and two heats are required to fill a 150-liter glass canister (180 liters overall volume). This glass canister contains on average 84 kg of fission products and actinides and represents the waste for supplying the equivalent of 360 million kWh of electrical power consumption (by comparison, a French family of four people consumes in average 10,000 kWh/year including electrical heating).

The end product is left to cool for 24 hours, then inspected to ensure that the surface of the canister is not contaminated before being stored. It will not be removed from storage until it is ready to be sent to its final disposal site.

5 RADIOACTIVE WASTE MANAGEMENT

High Level Waste – HLW disposal is certainly a question about which the perception of the specialists, aware of the progress achieved in the last two decades, differs deeply from the perception of the public-at-large and the media who, in general, are convinced it constitutes an insoluble problem. In order to bridge part of this gap, up-to-date information on the status of HLW disposal across the world is being provided in the following sections [5].

5.1 RADIOACTIVE WASTE CATEGORIES

Each country has its own classification of radioactive waste. A simple definition would be: A radioactive substance is material that contains radioactive nuclei in amount or concentration high enough to motivate radiation protection measures. A radioactive waste is a radioactive substance resulting from a process of human activity and which has no foreseen use in the present technical and economic context and must be disposed of without harming people and environment. Three broad categories are being characterized: Low level waste LLW, intermediate level waste with long lived isotopes LL-ILW and high level waste HLW [6].

LLW constitutes the bulk of the radioactive waste in volume and in mass, although it contains only a small fraction of the total waste radioactivity. The origin of LLW is quite diverse: nuclear power, medicine, research, industry, etc. Many countries have licensed operating LLW disposal sites, usually surface storage sites which accept conditioned (immobilized) waste packages with such specifications as to assure that within two or three centuries, given the short radioactive period of most isotopes, the radioactivity of the disposal site will be of the same order of magnitude than the natural background radioactivity.

LL-ILW and HLW originate almost exclusively from nuclear reactors and their fuel cycle facilities, as well as defense facilities of countries that have developed nuclear weapons. Though quite limited in volume, they constitute the bulk of the waste radioactivity. For those countries with no weapon activities and which do not reprocess their spent fuel, all their HLW and LL-ILW is inside their spent fuel assemblies which for them constitute the ultimate waste. In the following sections, only these two categories of waste will be considered.

5.2 RADIOACTVE WASTE DISPOSAL

Despite all the fear it inspires, radiation has two positive characteristics:

- It is easy to detect at levels far below the detection threshold of any noxious substance (one can detect a single disintegration when one cannot detect a given chemical unless billions of molecules are present);
- When detected, it is easy to protect oneself from radiation by a combination of three measures: keeping distance, limiting exposure time and providing shielding.

5.2.1 Containment, Storage, Transmutation

The problem of radioactive waste disposal is therefore only a problem of **containment**: making sure the radioactive species will stay where they were located, or that the migration time from their original site to the biosphere will be long enough for the radioactivity to have decayed much below currently acceptable limits.

The problem is exactly the same for the containment of the radioactive elements within a nuclear reactor, but in the case of HLW the volumetric activity is far smaller, while the containment time must be far longer. The solution, therefore, is basically the same: containment by multiple imbedded barriers. The first barrier is the matrix which contains the radioactive elements, then there is the waste packaging, and then additional barriers are added according to the chosen disposal method.

The basic choice is between long term surface (or subsurface) storage and deep geological disposal. Transmutation of the longest lived elements might in the future be a preliminary operation in either method.

In **surface storage** –sometimes called interim storage, the conditioned waste packages are stored in engineered facilities for a given period of time, to be retrieved from the facility at the end of the specified period. The facility may be located at ground level (surface facility) or shallowly buried (subsurface facility) in order to improve its physical protection against external aggression. Both surface and subsurface storage facilities must be kept under full surveillance and monitoring during the specified period, and one must demonstrate that the waste package can actually be retrieved if the decision is made to do so. Interim storage provides a satisfactory medium term solution, but it still leaves to our successors the burden of implementing a permanent disposal solution.

In **deep geologic disposal**, the stratum itself constitutes the ultimate barrier against the migration of radioactive elements: once full, the disposal facility will be sealed off and one does not intend to retrieve the waste packages. This concept was put forward by the US National Academy of Sciences as early as 1957, upon request of the U.S. Atomic Energy Commission. However, in order to facilitate public acceptance, the concept is being refined into “reversible” geological disposal. In a reversible geological disposal, waste packages are intended to stay, but the possibility to reverse the decision and retrieve them is kept open for a significant period of time, ranging from one to a few centuries. In this way, even if it is meant to be a definitive solution, the best which can be implemented today, it does not preclude the possibility for our successors of finding an even better solution. For practical reasons, HLW will be held in a surface storage facility for a number of years before being sent to geological disposal. This allows all but the longer half-life radionuclides to decay and, thus, the heat source itself is substantially cooled down.

During the first few centuries, most of the radioactivity of the waste comes from the decay of fission products; thereafter, the longer lived actinides (uranium, neptunium, plutonium, americium and curium) take over. When the spent fuel is reprocessed, recovered uranium and plutonium remain in the nuclear cycle and only traces of them, together with the fission products and the “minor” actinides are vitrified to constitute HLW packages. The radioactivity of vitrified HLW decays much more rapidly than the

radioactivity of non-reprocessed spent fuel. If one pushes the reprocessing one step further to recover the minor actinides (“partitioning”), curium could be conditioned to decay by itself while neptunium and americium could undergo fission in nuclear reactors to become “ordinary” fission products (“transmutation”). The radioactivity of the resulting HLW packages would decay even faster, and the necessary containment time within the disposal facility would be reduced. This is called **P&T**, for **partitioning and transmutation**.

Implementing P&T would not eliminate the need for ultimate disposal, but it would alleviate some design constraints on the disposal facility. Partitioning has been developed at laboratory scale, and significant results have recently been obtained. Transmutation has been demonstrated experimentally, but present Light Water Reactors would be poor “transmuters”. The high neutron fluxes inside the core of a Fast Neutron Reactor would be much more efficient. Furthermore, a metal-fuelled Fast Neutron Reactor with integral reprocessing and fabrication facilities promises both high P&T efficiency and very low levels of trace actinide materials in the waste stream. P&T is therefore a possible useful *future* sophistication of the basic two methods above described.

5.2.2 Current Radioactive Waste Disposal Programs

As shown on Table 4, which is not exhaustive, many advances on radioactive waste disposal were achieved throughout the world during the last two decades.

Almost all countries using nuclear power have studied geological disposal, through underground labs or “natural analogues”, and taken part in international round robin computer simulations. Main results show that glass and concrete, the most extensively studied matrices for HLW and LLW containment respectively, are remarkably durable. High integrity copper containers have also been developed for the geological disposal of spent fuel. If the proper site and the proper stratum are selected, the geological barrier is very efficient at preventing radioactive nuclides migration.

While no demonstration of the behavior of a geological disposal facility can be fully rigorous and definitive, given the timescales involved, there are now many converging indices that the mechanisms governing the disposal evolution in time are understood and mastered, and that those mechanisms will induce minimal environmental impacts.

USA	LL-ILW	Since 1998, a disposal site is actually operating near Carlsbad (New Mexico, the WIPP, a non-reversible geological disposal in a salt bed, devoted to transuranic Defense waste disposal.
	Spent Fuel	A disposal site for spent fuel in volcanic tuff (Yucca Mountain, Nevada) has been selected in 2002, with Congress approval despite State opposition. Licensing is in progress. Preliminary consideration is being given to reprocessing the spent fuel in order to increase the site capacity.
Finland	Spent Fuel	Decision was taken in 2001 to build a reversible geological disposal in granite near Olkiluoto. The site should open around 2015. An underground laboratory ONKALO is under construction.
Sweden	Spent Fuel	Site selection is almost completed for a reversible geological disposal in granite. Target date for operation is 2015. An underground lab has been operating in Aspö since 1994.
Switzerland	HLW	Two underground labs in granite (Grimsel) and clay (Mont Terri) are in operation. The Swiss law stipulates a geological disposal should open before 2040.
Belgium	HLW	Many experiments have been carried out since 1984 in the Mol underground lab (in clay). Decision for a geological disposal site is expected in 2030.
Japan	HLW	The law voted in 2000 foresees a geological disposal operational by 2040. JAEA has started construction of two underground labs.
France	HLW	One underground lab in clay is operating. The law voted in 2006 plans for a reversible geologic disposal in 2015-2020 and calls for interim storage and continued R&D on P&T.
Germany	HLW	Extensive R&D was carried out in the 70s on geological disposal in a salt dome near Gorleben. A 10 year moratorium has been decreed in 2000.
Spain	Spent Fuel	No search for a disposal site. A centralized storage is foreseen for 2010.
Netherlands	HLW	Long-term storage in the HABOG facility.
Canada	Spent Fuel	Storage was considered in 1998 “technically acceptable, but not socially”. Disposal policy is still under study by the government.
UK	LL-ILW	Disposal policy under consideration.

Table 4
World Radioactive Waste Disposal Programs

6 URANIUM & PLUTONIUM RECYCLING

When a uranium-based fuel (natural or slightly enriched) produces energy in a nuclear reactor, some of the neutrons produced by fission are captured by ^{238}U nuclei which are transformed into ^{239}Pu by two successive beta disintegrations. Like ^{235}U, ^{239}Pu is fissile. Some of it undergoes fission, thus generating energy, while another part captures a neutron to form ^{240}Pu, which in turn can also capture a neutron to form ^{241}Pu, another fissile isotope. Subsequent captures will lead to the formation of ^{242}Pu, and then americium and curium and so on. Plutonium is therefore an unavoidable by-product of uranium fission.

The plutonium produced in fuels is a mixture of isotopes, with atomic mass ranging from 238 to 242. The relative proportions of these isotopes depend on initial fuel composition and on how long the fuel was irradiated in the reactor. The fissile "quality" of this plutonium depends, of course, on these proportions, as even-numbered isotopes (^{238}Pu, ^{240}Pu and ^{242}Pu) are not fissile in light water reactors.

For example, PWR fuel initially made from uranium enriched with 4% ^{235}U will contain about 1% plutonium at the end of its life, this plutonium being made up of 65% fissile ^{239}Pu and ^{241}Pu isotopes. Towards the end of its life span, more power is released in the almost spent fuel by plutonium fission than by ^{235}U fission. It has practically become a MOX fuel, as will be explained below.

If the spent fuel is disposed of without processing it, all the plutonium will end up in final high-level waste. By separating out the plutonium through reprocessing, elimination of what would have been the most radioactive ingredient of the spent fuel a thousand years from now was achieved. In fact, it is the residual plutonium concentration in the glass that would represent the main source of radioactivity at that point in the future.

Yet this plutonium (and, as a matter of fact, the residual enriched uranium which still makes up 95% of the spent fuel) represents a great deal of potential energy. Complete fission of one gram of plutonium generates more heat than complete combustion of one ton of oil.

Plutonium can either be specifically conditioned to be buried, or –as is the case in France today– it can be recycled and manufactured into fuel known as MOX fuel. Uranium is stored in a chemically stable form until its recycling becomes an economically viable option. In France, some reprocessed uranium is recycled, after re-enrichment, in two specially authorized reactors.

Recycling saves enriched uranium, though the amount of money saved depends on the market price of the material, as the special precautions required for handling plutonium make it more expensive to manufacture MOX fuels than enriched-uranium fuels. On the other hand, recycling avoids the ever increasing quantities of plutonium inside the wastes which, as seen before, complicate waste management. Recycling also paves the way for effectively reclaiming the energy resources that this plutonium represents[2]. More effective management for the future may be worth a reasonable

[2] Here reference is made to the Fast Breeders, which optimize the use of uranium.

extra cost –especially since it does not affect the competitiveness of nuclear energy in relation to other sources of energy.

Plutonium could be recycled under optimum conditions in fast neutron (breeder) reactors by using it to burn all the depleted uranium left over from enrichment operations. However, only a few prototypes of such reactors are currently in existence, and large-scale deployment is not expected in the near future.

Today, plutonium is recycled in light water reactors –PWRs and BWRs– which are the most common nuclear power reactors in the world. This makes enriched uranium savings possible, by replacing it with plutonium, and prevents plutonium from ending up in final waste or piling up "on the shelf" after being separated during spent fuel reprocessing. The plutonium is recycled as MOX fuel.

6.1 MIXED OXIDE FUEL - MOX

MOX fuel is a mixture of plutonium and uranium oxides. Depleted uranium is generally used since plutonium is intended as a substitute for ^{235}U. Viewed from the outside, MOX fuel for PWRs or BWRs is identical to the enriched-uranium fuel it replaces – same assembly structure, same spacing, same rods, claddings, grids, and springs. The pellets enclosed in the claddings are of the same size – the only difference is their composition, and therefore, their manufacturing process.

In the core of a light water reactor, one needs twice the amount of plutonium to obtain the energy equivalence of a ^{235}U enriched fuel. A mixture containing about 8% plutonium and 92% depleted uranium is needed to replace 4% enriched uranium. At the end of its life span, MOX fuel will contain only about 4% plutonium[3].

MOX recycling began on an experimental basis in Belgium in the early 1960s. It was then industrialized in Belgium, Germany and Switzerland, followed by France as from 1985. Japan is now preparing to allow MOX fuel in its BWRs and PWRs.

In France, EdF decided to recycle its plutonium gradually in most of its 900 MWe reactors, by operating them on 30% MOX fuel (meaning that for each refueling operation, MOX fuel is used in about one third of fresh fuel assemblies). Out of 28 reactors which could technically do so, 20 now use MOX fuel. By operating 20 reactors on one-third MOX fuel, all the plutonium extracted from the EdF fuel reprocessed at the La Hague plant can be recycled. The "plutonium account" of a "moxified" PWR is balanced, i.e. its MOX assemblies consume as much plutonium as its enriched-uranium assemblies produce.

[3] As the initial plutonium undergoes fission, more of it is formed through capture in the depleted uranium. Some of this secondary plutonium is burned on site. The final concentration of 4% results from these three phenomena. The plutonium contained in spent MOX fuel is less fissile than the plutonium initially used in the fuel.

7 NUCLEAR POWER SAFETY AND RADIATION PROTECTION

The radioactivity of uranium has potential health impacts when it is used to produce electricity. Ionizing radiation is produced when the nucleus of an atom disintegrates, releasing energy in the form of energetic particle waves of electromagnetic radiation.

The generation of electrical energy is now the major use of the nuclear fuel cycle. All industrial activities involve some risk to human health and safety. No means of generating electricity is risk-free. In normal operation, a nuclear power plant releases very little pollution, chemical or radioactive. Paradoxically, it releases less radioactivity than a coal fired power plant. The choice of any technology or mixture of technologies will inevitably be a matter of balancing different costs, benefits, and risks.

While considerable technical and management advance has been achieved over the last few decades with the safety of nuclear power installations, little advance has been achieved in the area of social acceptability.

7.1 RADIATION PROTECTION

Radiation exposure can arise from sources outside the body (external exposure) or from radioactive material inside the body (internal exposure). Radioactive material can enter the body by inhalation or ingestion in water or food.

People are continuously exposed to natural background radiation although this may vary substantially from place to place. The worldwide average is 2.4 mSv/year, with maximum values above 12 mSv/year depending on local geology and altitude [4]. There is no evidence that this variation leads to any differences in terms of human health. Evidence is emerging that the small background radiation exposure experienced by human beings may have a beneficial effect. The dose rate expected for individual members of the public from nuclear power generation is very low, on average 0.005 mSv/year for people resident within 50 km of a pressurized water reactor power station. To place radiation exposure to the public in perspective, a person taking a return flight from Sydney to London would receive the same dose (approximately 0.25 mSv) as someone living 50 years in the vicinity of such a power reactor.

7.2 NUCLEAR POWER SAFETY

The International Commission for Radiation Protection (ICRP) issues recommended guidelines on safety standards after ongoing review of the emerging scientific information from around the world. The standards are used as the basis of design criteria for all aspects of nuclear power plant radiation exposure for both workers and the general public. The following levels of exposure to ionizing radiation are the generally recommended limits above background levels:

- 1 mSv/year above natural background radiation for the general public;
- 100 μSv over five years for occupational exposure.

Ionizing radiation exposure can only be detected and measured by instruments as the body has no natural detection mechanism for other than extreme situations.

[4] Doses as high as 300 mSv/year have been consistently measured in some district of the Ramsar Caspian Sea resort (Iran).

The fundamental safety requirement for all nuclear power stations is to ensure that no radioactive material or ionizing radiation from the area of the heat producing nuclear reaction is transmitted to any location at a level adversely impacting human safety or the environment. This isolation requirement is achieved in a number of linked ways:

- Control of the nuclear reaction, most commonly by neutron absorbing control rods inserted partially or wholly (for shutdown) into the reactor core. The control rods are moved automatically through the station instrument and computer control systems. The control system monitors all operating parameters to maintain defined operating power levels or to shut the reactor down in the case of any emergency condition.
- Removal of heat generated in the fuel from the nuclear reaction, typically achieved by a cooling water circuit for a nuclear power station.
- An engineering design which ensures that all radioactive products or components are isolated or contained in locations away from possible harmful contact.

In a modern nuclear power station design, the isolation barriers start with fuel metallurgy designed to hold or contain radioactive products both internally and within a surrounding metal barrier. A fuel element is now typically a string of ceramic uranium oxide pellets that are held in a sealed metal tube. The second isolation barrier is a fully enclosed reactor heat transfer system -most commonly water- in a steel pressure vessel, pumps, heat exchangers, and associated pipe work. The third isolation barrier is an enclosing building designed to be leak tight in the event of any release of pressure from the reactor cooling system. The reactor containment building may itself consist of a number of layered barriers and is generally now designed to withstand external breach by an aircraft crash.

The ongoing integrity and effectiveness of the engineered safety isolations noted above is maintained over the life cycle of a modern nuclear power station principally by thoroughly managed design, construction, operation, and maintenance processes taking into account all of the experience and lessons from the past.

A key part of the design is the incorporation of systems capable of monitoring and assessing all plant operating conditions or any deviation from operating limits, and initiating immediate action to correct any deviation ultimately by shutting the reactor down. The ongoing development and reliability of modern computer-based systems now allows a much wider range of monitoring, assessment, and control systems to be incorporated supporting plant operators with overall control information than was available for past designs. Even given the sophistication and reliability of modern control systems, it is normal to allow at least three levels of isolated redundancy within the design and installation.

7.3 NUCLEAR POWER PLANT ACCIDENTS

General community concern most likely remains related to the potential risk of a single serious accident similar to those at Chernobyl and Three Mile Island nuclear power stations.

The Three Mile Island accident in March 1979, while a large financial cost to the company involved, injured no one and led indirectly to the release of only minor amounts of radioactive elements which after extensive expert review, had no measurable impact on health. Resulting from human error, it demonstrated the robustness of the reactor design and the value of containment structures required in all Western nuclear power plants when an operational failure caused severe damage to the reactor core.

The Chernobyl accident in April 1986, a typical case of lack of safety culture, caused the deaths of less than 50 workers [7] and emergency staff and released radioactive gas and dust high into the atmosphere. Over the time since the accident, there have been approximately 2,000 thyroid cancers in children (mostly in Belarus and Ukraine) and the Chernobyl Forum considers likely that a maximum of up to 4000 premature deaths from radiation may eventually occur among the 600,000 most irradiated people. The design of the reactor was inherently unstable and there was no containment structure, a common feature of most Western designs. The accident occurred at shutdown power levels as staff was testing safety performance parameters, outside the prescribed operating limits for the reactor and in violation of existing regulations for the safe operation of the reactor.

There was a twofold reaction to the accidents. Public opinion forced a slowdown or hold on the power reactor construction programs by governments around the world and the responsible technical/safety regulators undertook a wide range of design and operational reviews based on the outcome of the accident investigations. Public concerns based on real or imagined information remains strong. Over the decades since the accidents the international technical and regulatory community has moved forward to the point where engineering design, equipment development and operational practice has made very considerable advances to enhance general safety for both existing and new designs of nuclear based electricity generating capacity.

7.4 SAFETY CULTURE

Above all of the engineered safety features that might be incorporated in design, construction, and operation of modern nuclear power stations, or any similar facility requiring high reliability of operation, the experience of the past shows that the safety culture of the controlling organization is of paramount importance.

The overall safety culture of the organization reflects on every aspect of nuclear plant design construction and operation through the balance of factors and sometimes conflicting interests that need to be managed. Factors such as time, finance, customer issues, staffing levels, operating principles, and maintenance philosophy can all have an influence on how safety matters are viewed and resolved within the controlling organization.

An uncompromising focus on safety leadership and safety responsibility at the most senior executive levels and down through all levels of line management has proven to be the most important directing influence in the development of best practice safety culture for any organization. Safety monitoring or advisory or training roles within the organization are important but ultimately these roles can only support executive management responsibilities and not act as a substitute or alternate. Experience has

shown that large safety divisions in high reliability organizations can be counterproductive with many management and staff abrogating responsibility for safety to the safety division or at best allowing confusion of responsibility. The ultimate and most desirable outcome is that all staff accept personal and collective responsibility for safety leadership within their sphere of influence and to the best of their ability.

There are now many excellent (and poor) safety culture examples documented across the nuclear power sector, across countries, and across all other industries to provide both benchmark examples and guidance for the highly effective and safe operation of nuclear power plants. Extensive investigations of a number of serious accidents particularly in the international oil and gas industry have highlighted the need for effective management of organization safety culture covering all levels of operation. The key areas of attention for the development and ongoing maintenance of an excellent safety culture include; owner and management commitment, workforce empowerment, workforce hiring and training methods, pre-project planning and risk mitigation, and prompt accident and near-miss investigation with timely implementation of improvement recommendations.

7.5 INTERNATIONAL REGIME FOR NUCLEAR SAFETY

After the accident at Chernobyl a truly international nuclear safety regime was fully developed. This regime is based on binding international conventions, internationally accepted safety standards, and an extensive system of peer reviews. IAEA safety standards are periodically revised and updated to reflect the state of the art for nuclear safety, and to include new areas, such as the nuclear fuel cycle; modern techniques such as human/machine interaction, and assessment of the probability of occurrence of certain postulated accidents. These standards are now accepted worldwide and although not obligatory, have been adopted by several countries on a voluntary basis, and used as the basis of national regulations in numerous other member States.

The International Atomic Energy Agency Convention on Nuclear Safety is an agreement that sets out the guiding principles under which the international community accepts responsibility for the safety of all nuclear related installations under their various jurisdictions. The objectives of the Convention are:

- To achieve and maintain a high level of nuclear safety worldwide through the enhancement of national measures and international cooperation including, where appropriate, safety related technical cooperation;
- To establish and maintain effective defenses in nuclear installations against potential radiological hazards in order to protect individuals, society, and the environment from harmful effects of ionizing radiation from such installations;
- To prevent accidents with radiological consequences and to mitigate such consequences should they occur.

The Convention, adopted in June 1994, has 59 parties and 65 signatories as of May 2006. The scope of the Convention defines a wide range of provisions that apply to the safety of nuclear installations. There are provisions to cover; the implementation of an appropriate legal, regulatory, and reporting framework; the review upgrading or closing of existing nuclear installations; the focus on nuclear safety as a priority, ensuring adequate financial and human resources to support appropriate safety levels; keeping

radiation exposure as low as reasonably achievable, and providing and testing emergency plans.

Safety requirements for location, design, construction, and operation are also covered in the Convention. There is provision for joint review and information sharing by the contracting parties to the Convention and for the ongoing management review of the Convention processes and documentation.

Supporting the implementation of all aspects of the Convention is a wealth of documentation and training resources incorporating the research and experience of members of the International Atomic Energy Agency. The extent of knowledge is huge and most of the information can be traced back to origins in the large research programs carried out in the mid to late 20th-century.

The extent of information available ensures that all elements of nuclear safety and radiation protection engineering for new or existing installations can be adequately covered. Ionizing radiation and its health impacts are well understood and there are established international safety standards that can be utilized for all operational practice.

On a comparative basis the safety record of the nuclear industry is orders of magnitude better than coal or oil or natural gas generation of electrical energy. The reasons for this outcome can be traced back to both the level of investment in safety related plant engineering and well understood international safety standards and regulation. Comprehensive incident reporting and dissemination of resulting information under the guidance of the IAEA has resulted in a worldwide culture of safety driven continuous improvement for both existing nuclear power station operations and new designs.

8 NUCLEAR POWER AND CLIMATE CHANGE

In February 2007, the Intergovernmental Panel on Climate Change IPCC Group 1, in charge of synthesizing the scientific evidence, published its executive Summary [8] stating that:

- Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system. These changes are expressed in terms of radiative forcing which is used to compare how a range of human and natural factors drive warming or cooling influences on global climate. Since the Third Assessment Report (TAR) issued in 2001 [9], new observations and related modelling of greenhouse gases, solar activity, land surface properties and some aspects of aerosols have led to improvements in the quantitative estimates of radiative forcing.
- Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change (Fig. 11), while those of methane and nitrous oxide are primarily due to agriculture.
- The understanding of anthropogenic warming and cooling influences on climate has improved since the Third Assessment Report (TAR), leading to very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W/m^2.
- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.

Changes in Greenhouse Gases from Ice-Core and Modern Data

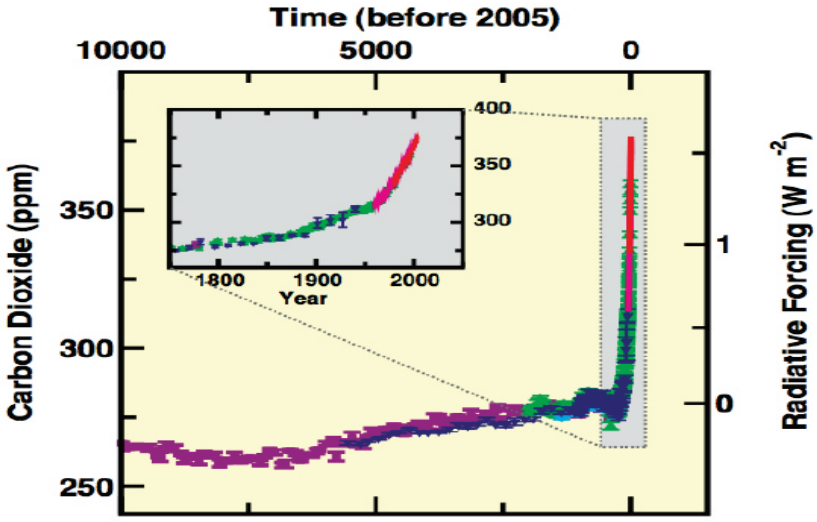


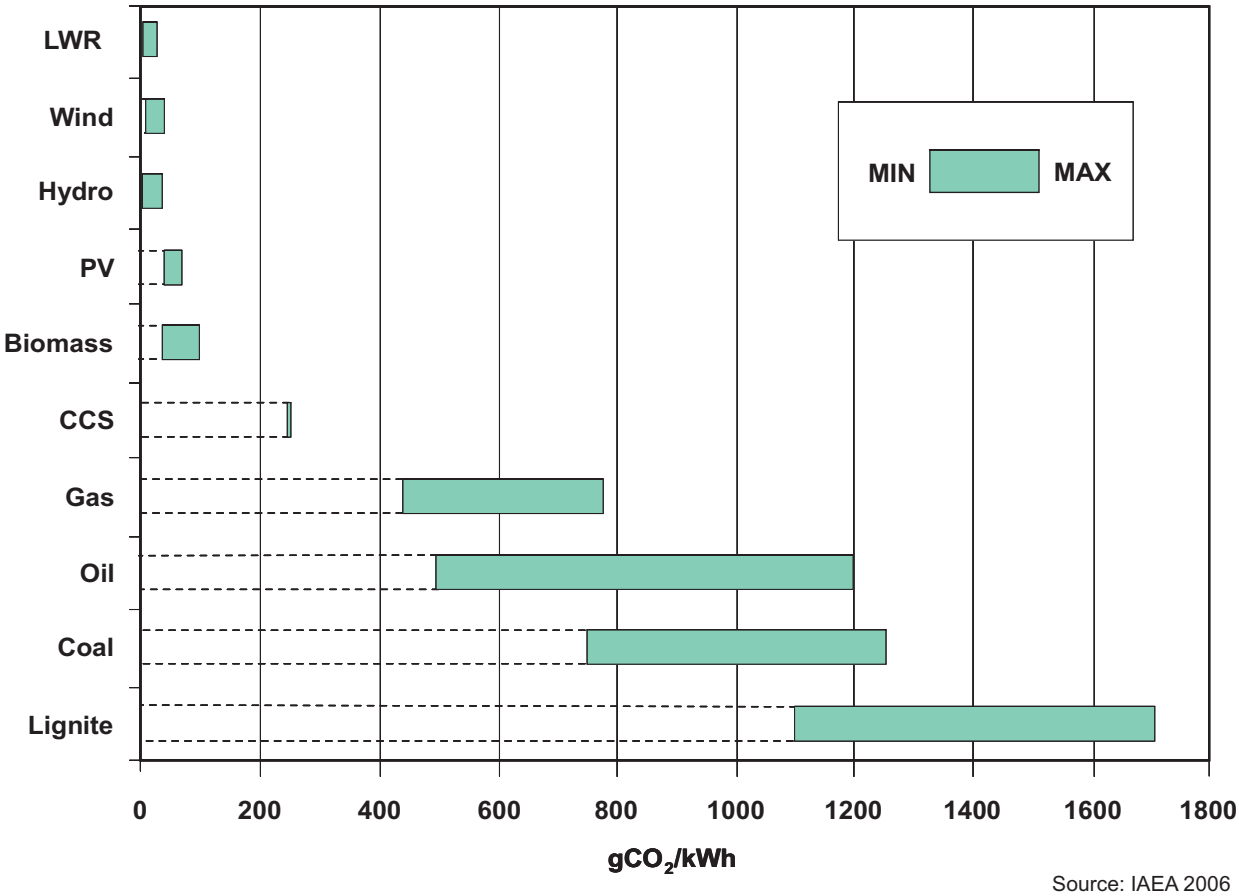
Figure 11
Variation of CO_2 Atmospheric Concentration

Society is therefore faced with a terrible dilemma: more energy is needed to allow for the human development of vast regions of the world, but reduction of CO_2 emissions for fear of endangering the planet's climatic equilibrium is also urgent, while, today, 80% of the world primary energy is supplied by the combustion of oil (35%), coal (24%) and gas (21%), followed by the uncontrolled release of the CO_2 [10].

There is no single way out of this dilemma; it will be necessary to implement every available measure, like:

- Using rationally the energy resources (the so-called energy conservation) and increasing their use efficiency;
- Reducing the share of fossil fuel in the energy supply matrix and increasing the share of sources emitting few greenhouse effect gases GHG (renewable and nuclear energies);
- Capturing and storing CO_2 wherever practicable.

Nuclear power and renewable energy sources emit very few GHG as shown on Fig. 12 [11].



Source: IAEA 2006

Figure 12
Life-cycle emissions of GHG (in equivalent g CO_2)
to generate 1 kilowatt-hour of electricity.

9 INTERNATIONAL REGIME OF NON-PROLIFERATION

The term "proliferation" refers to the rise in the number of States in possession of nuclear weapons. It is sometimes extended to describe the misappropriation of weapons or fissile material by sub-national groups[5]. The term "nonproliferation", on the other hand, refers to the political or technical means implemented to combat proliferation [12].

9.1 HISTORICAL BACKGROUND

The first atomic explosion was achieved July 16, 1945 in the desert of New Mexico (USA). The following months, two A-bombs destroyed the Japanese cities of Hiroshima and Nagasaki, leading to the end of World War II. No atomic weapon has ever since been used in war. The United Stated first tried to protect its military nuclear monopoly by refusing any transfer of civil nuclear technology. After proliferation occurred with the USSR (1949), President Eisenhower changed this policy and allowed other countries access to reactor technology in exchange for their commitment to using the technology for civil applications only. During the Cold War, the United Kingdom (1952), then France (1960), and lastly China (1964), joined the Nuclear Weapon States (NWS).

In 1968, the Non-Proliferation Treaty, **NPT**, attempted to freeze the situation by recognizing five NWS (USA, USSR, UK, France and China) but no more. Other parties to the NPT (NNWS) took the commitment to never try to acquire nuclear weapons. In exchange, the NWS committed to reduce their arsenal and give free rein to civil technology transfers, in addition to support militarily any NNWS party if menaced with nuclear weapons. The International Atomic Energy Agency, IAEA, was entrusted with the task of overseeing the peaceful use of nuclear materials in compliance with the NPT obligations. Under IAEA control, technology transfer agreements multiplied rapidly, each exporter imposing on the recipient its own conditions for the use of the technologies, facilities, and materials exported. The NPT entered into force in 1970.

In 1974, India, which had not signed the NPT, carried out a "peaceful explosion", using plutonium produced in a heavy water reactor supplied by Canada. Exporting nations then formed the “London Club” which later became the Nuclear Suppliers Group (NSG) to regulate "sensitive" exports.

In 1991, a similar shock was felt with the discovery of the extensive clandestine nuclear program of Iraq, a country that had signed and ratified the NPT. As a result, the powers and inspection capabilities of the IAEA were reinforced.

With the end of the Cold War and the disintegration of the USSR, the Russian Federation became sole inheritor of the former nation's NWS status. In 1991, after abrogating the apartheid, South Africa, having dismantled its handful of nuclear weapons, joined the NPT. Argentina and Brazil both stopped their military developments, ratified the Tlatelolco Treaty that, in the 60s, created the Latin American Nuclear Weapons Free Zone, with obligations somewhat similar to those of the NPT,

[5] This does not cover the issue of “dirty bombs”, i.e. the dissemination of radioactive products by a conventional explosive. On the one hand, a dirty bomb may be used by terrorists to create panic but it would not kill many people, and on the other hand, the major risk does not come from materials used in the nuclear power sector but rather from the many radioactive sources in various industries, hospitals, etc.

and entered the NPT. After decades of increasing their arsenals, all NWS but China started drastic reductions. Negotiations were carried out towards a Comprehensive Test Ban Treaty CTBT and a “cut-off” convention to stop producing fissile materials for military purposes. On the other hand, Pakistan, India's rival since the 1948 partition, carried out its "peaceful explosion" in 1999.

A third serious crisis erupted in 2003. On the one hand, North Korea withdrew from the NPT, and on the other hand it was discovered that, apparently unbeknownst to its own government, Dr A. Q. Khan, the “father of the Pakistani bomb”, had established a black market of military nuclear technology with Libya, North Korea and Iran. This, in turn, led to the discovery that Iran, a NPT Party, had been carrying out a clandestine undeclared and un-safeguarded program of uranium enrichment. This triggered a crisis still going on nowadays, although the IAEA Director General has consistently said there is "no evidence" Iran has ever maintained a program of developing nuclear weapons.

In the fall of 2006, North Korea performed some kind of atomic test, but it appears that it will resume its re-entry into the NPT regime.

The NPT, backed up by IAEA inspections, now forms the universally acknowledged basis for all nuclear commerce. As of today, only three countries are not Parties to the NPT: India, Israel and Pakistan.

The non-proliferation regime has proven highly successful. Back in the 60s, it was widely forecasted that by 2000 there would be at least 30 countries possessing nuclear weapons: as a matter of fact, only 3 or 4 additional countries have crossed the threshold.

The Regime is robust because it has proven to be adaptable: after each crisis, a response has been –sometimes slowly– implemented:

- After 1974, it was the establishment of the NSG and the definition of the “trigger list” of suspicious or “dual” items not to be freely exported.
- After 1991, it was the Additional Protocol and the adoption by the NSG of the “full scope safeguards[6]”.
- NPT parties are still in the throes of adopting suitable measures to cope with the consequences of the North Korea and Iran crises. It appears likely that some restrictions or specific limitations will be required for “sensitive technologies”.

9.2 CIVIL NUCLEAR INDUSTRY AND PROLIFERATION

The first application of nuclear fission was the atom bomb, and not nuclear power. Fission cannot unfortunately be "un-invented", and there will always be some risk that a State or a large sub-national group would decide to make nuclear weapons, to devote to that purpose the required financial and technical efforts, and to bear the political consequences.

[6] Under this rule, no nuclear material or facility can be transferred unless the recipient country has put all its nuclear facilities under IAEA safeguards.

On the other hand, no country opting for proliferation has yet done so by misappropriating materials or facilities covered by commitments to peaceful use and under IAEA safeguards.

Bearing that in mind, the real question is this: does the development of nuclear energy for civil applications increase or reduce the risks of nuclear weapons proliferation? Although possessing a civil nuclear facility within its borders may give a State quicker access to the necessary fissile materials, a civil nuclear industry also means international agreements and treaties, commitments not to misappropriate materials, and international inspections with highly sensitive and effective measuring devices. It would make it much more difficult to carry out a clandestine program as it can be witnessed from the North Korean and Iranian experiences.

9.2.1 “Proliferating" Technologies

Most nuclear technologies are not “sensitive” in terms of nuclear weapons development. LWRs produce plutonium of poor “military” quality and are easy to control since they must be shut down to unload the fuel. On-line refueling reactors (Magnox, AGR, Candu, and RBMK) have the intrinsic capability to easily produce weapon-grade plutonium, and must and can therefore be more carefully controlled and safeguarded.

The most sensitive technologies are today the centrifuge enrichment and the spent fuel reprocessing (if associated with low burnup fuel).

Proliferation is essentially a matter of political will, not technology. It is difficult to determine exactly how "proliferating" a technology is. Different factors must be taken into account, like ease of access to pure concentrated fissile material, detectability, throughput, etc.

10 COST OF ENERGY GENERATED BY NUCLEAR-POWER

Nuclear power can only meaningfully be compared to the other main sources of base load electricity. In places where hydropower it can generate base load electricity, the cost is so site-dependent that any comparison is very specific.

Nuclear power is capital intensive but cheap to operate: its competitiveness depends heavily on the mode of financing and the cost of money, and very little on the fuel cost. The cost of electricity generated by nuclear power is quite insensitive to the variations of uranium prices in the international market -a cost that for other options depends considerably from the hypotheses on the future prices of the fuel over the plant lifetime. As a result, projected kWh costs for comparison purposes can widely differ from one country to another and from one study to another.

In 2005, the Nuclear Energy Agency of OECD, together with the International Energy Agency, updated their projected costs of nuclear electricity production, for plants to be commissioned between 2010 and 2015 [13]. It is still the most recent exhaustive cost comparison available today. The costs calculated were *busbar* costs at the station, without costs of transmission and distribution. The calculations were based on the levelised lifetime costs approach, assuming an 85% load factor over 40 years of economic lifetime and discount rates of 5% and 10% (only Japan uses substantially lower discount rates). The nuclear costs include refurbishing and decommissioning, but *the savings to society of avoiding CO_2 emissions were not included*. Table 5 summarizes the results.

Technology	Overnight Investment $/kWh	Levelised lifetime cost ($/MWh)	
		Discount rate	
		5%	10%
Coal	1000 - 1500	25 - 50	36 - 60
Gas	400 - 800	37 - 60	40 - 63
Nuclear	1000 - 2000	21 – 31*	30 – 50*

* except Japan

Source: OECD NEA - IEA, Projected Costs of Generating Electricity, 2005 Update

Table 5
Generation costs of different technologies

When all uncertainties are taken into account, the study suggests that none of the three main electricity generating technologies can be expected to be the cheapest in all situations, but that nuclear power is often competitive. If some cost had been included for CO2 emissions, the competitiveness of nuclear power would have been even more significant.

As for “Generation 3” nuclear power plants, some -like the EPR- are now under construction. Indicative values from three different European countries are shown in Table 6.

COUNTRY	FINLAND	FRANCE	GERMANY
Net capacity (MWe)	1500	1590	1590
Overnight cost (€/kW)	1656	1360 (1)	1550
Operation & Maintenance cost (€/kW)	40.0	40.3	56.8
Fuel cycle cost (€/MWh)	4.3	4.6	4.2
Total (€/MWh) *(10% discount rate)*	**36.7**	**34.0**	**36.7**

(1) For a series of 10 EPR including the 1st of a kind

Source: OECD NEA - IEA, Projected Costs of Generating Electricity, 2005 Update

Table 6
Estimated EPR generation cost

Since 2005, many parameters have changed: oil, gas and uranium prices have escalated. Not only fuel prices are higher, though in the case of nuclear power their influence in the final kWh cost is much lower, but also the prices of steel and concrete which will impact investment costs. That is why comparisons tend to be parametric in accordance to oil and gas prices.

11 NUCLEAR POWER WORLDWIDE: STATUS AND OUTLOOK

Nuclear power share of worldwide electricity production rose from less than 1 percent in 1960 to 16 percent in 1986, and that percentage has held essentially constant in the 21 years since 1986. Nuclear electricity generation has grown steadily at the same pace as overall global electricity generation. Table 7 shows the current nuclear power generation status among countries [2].

	NUCLEAR ELECTRICITY GENERATION 2006		REACTORS OPERABLE May 2007		REACTORS UNDER CONSTRUCTION May 2007		REACTORS PLANNED May 2007	
	billion kWh	% e	No.	MWe	No.	MWe	No.	MWe
Argentina	7.2	6.9	2	935	1	692	0	0
Armenia	2.4	42	1	376	0	0	0	0
Belgium	44.3	54	7	5728	0	0	0	0
Brazil	13.0	3.3	2	1901	0	0	1	1245
Bulgaria	18.1	44	2	1906	0	0	2	1900
Canada*	92.4	16	18	12595	2	1540	4	4000
China	51.8	1.9	11	8587	4	3170	23	24500
Czech Republic	24.5	31	6	3472	0	0	0	0
Egypt	0	0	0	0	0	0	0	0
Finland	22.0	28	4	2696	1	1600	0	0
France	428.7	78	59	63473	0	0	1	1630
Germany	158.7	32	17	20303	0	0	0	0
Hungary	12.5	38	4	1773	0	0	0	0
India	15.6	2.6	17	3779	6	2976	4	2800
Iran	0	0	0	0	1	915	2	1900
Japan	291.5	30	55	47700	2	2285	11	14945
Korea DPR (North)	0	0	0	0	0	0	1	950
Korea RO (South)	141.2	39	20	17533	1	950	7	8250
Lithuania	8.0	69	1	1185	0	0	0	0
Mexico	10.4	4.9	2	1310	0	0	0	0
Netherlands	3.3	3.5	1	485	0	0	0	0
Pakistan	2.6	2.7	2	400	1	300	2	600
Romania	5.2	9.0	1	655	1	655	0	0
Russia	144.3	16	31	21743	5	2720	8	9600
Slovakia	16.6	57	5	2064	2	840	0	0
Slovenia	5.3	40	1	696	0	0	0	0
South Africa	10.1	4.4	2	1842	0	0	1	165
Spain	57.4	20	8	7442	0	0	0	0
Sweden	65.1	48	10	9076	0	0	0	0
Switzerland	26.4	37	5	3220	0	0	0	0
Turkey	0	0	0	0	0	0	3	4500
Ukraine	84.8	48	15	13168	0	0	2	1900
United Kingdom	69.2	18	19	10982	0	0	0	0
USA	787.2	19	103	98254	1	1200	2	2716
WORLD	**2,658**	**16**	**437**	**370,163**	**30**	**22,443**	**74**	**81,601**

Source: WNA Reactor data

Table 7
World Nuclear Power Reactors

At the close of 2006, nuclear provided about 15 percent of total electricity worldwide [3].

11.1 CURRENT STATUS

Present nuclear power plant expansion is centered in Asia: 19 of the 34 units under construction at the end of 2007, and 30 of the last 40 reactors to have been connected to the grid, were in Asia.

India currently gets less than 3% of its electricity from nuclear, but at the end of 2006 it had one-quarter of the nuclear construction (7 units) of the world reactors that were under construction at that time. India plans are even more impressive: an 8-fold increase by 2022 to 10 percent of the electricity supply and a 75-fold increase by 2052 to reach 26 percent of the electricity supply. A 75-fold increase works out to an average of 9.4 percent/yr, about the same average of the global nuclear growth from 1970 through 2004.

China is experiencing a huge energy growth and is trying to expand every source it can, including nuclear power. It has four reactors under construction and plans a nearly five-fold expansion by just 2020. Because China is growing so fast this would still amount to only 4 percent of total electricity.

Russia had 31 operating reactors, five under construction and significant expansion plans. There is discussion in Russia of becoming a full fuel-service provider, including services like leasing fuel, reprocessing spent fuel for other countries, and even leasing reactors.

Japan had 55 reactors in operation, one under construction, and plans to increase the nuclear power share of electricity from 30 percent in 2006 to more than 40 percent within the next decade.

South Korea connected last year its 20th nuclear power unit, has another under construction, and has broken ground to start building two more. Nuclear power already supplies 39 percent of its electricity.

Although Europe had 166 reactors in operation and six under construction, there are nuclear phase-out countries like Germany and Belgium, and several nuclear prohibition countries like Austria, Italy, Denmark and Ireland. On the other hand, nuclear expansion programs exist in Finland, France, Bulgaria and Ukraine. Finland started construction of Olkiluoto-3 in 2005, the first new Western European construction since 1991. France started a new plant in 2007.

Several countries with nuclear power are still pondering future plans. The UK, with 19 operating plants, many of which are relatively old, has been uncertain until recently. Although a final policy decision on nuclear power will await the results of a public consultation now underway, a White Paper on energy published in May 2007 concluded that "...having reviewed the evidence and information available we believe that the advantages [of new nuclear power] outweigh the disadvantages and that the disadvantages can be effectively managed. On this basis, the Government preliminary view is that it is in the public interest to give the private sector the option of investing in new nuclear power stations."

The US had 103 reactors providing 19 percent of the country electricity. For the last few decades the main developments have been improved capacity factors, power increases at existing plants and license renewals. Currently 48 reactors have already received 20-year renewals, so their licensed lifetimes will reach 60 years. Altogether three-quarters of the US reactors either have already license renewals, have applied for them, or have stated their intention to apply. There have been announced intentions for about 30 new reactors and the Nuclear Regulatory Commission is now reviewing four Early Site Permit applications.

11.2 OUTLOOK FOR 2030

The IAEA makes two annual projections concerning the growth of nuclear power, a low and a high. The low projection assumes that all nuclear capacity that is currently under construction or firmly in the development pipeline gets completed and attached to the grid, but no other capacity is added. In this low projection, there would be growth in capacity from 370 GW(e) at the end of 2006 to 447 GW(e) in 2030 (Fig. 13).

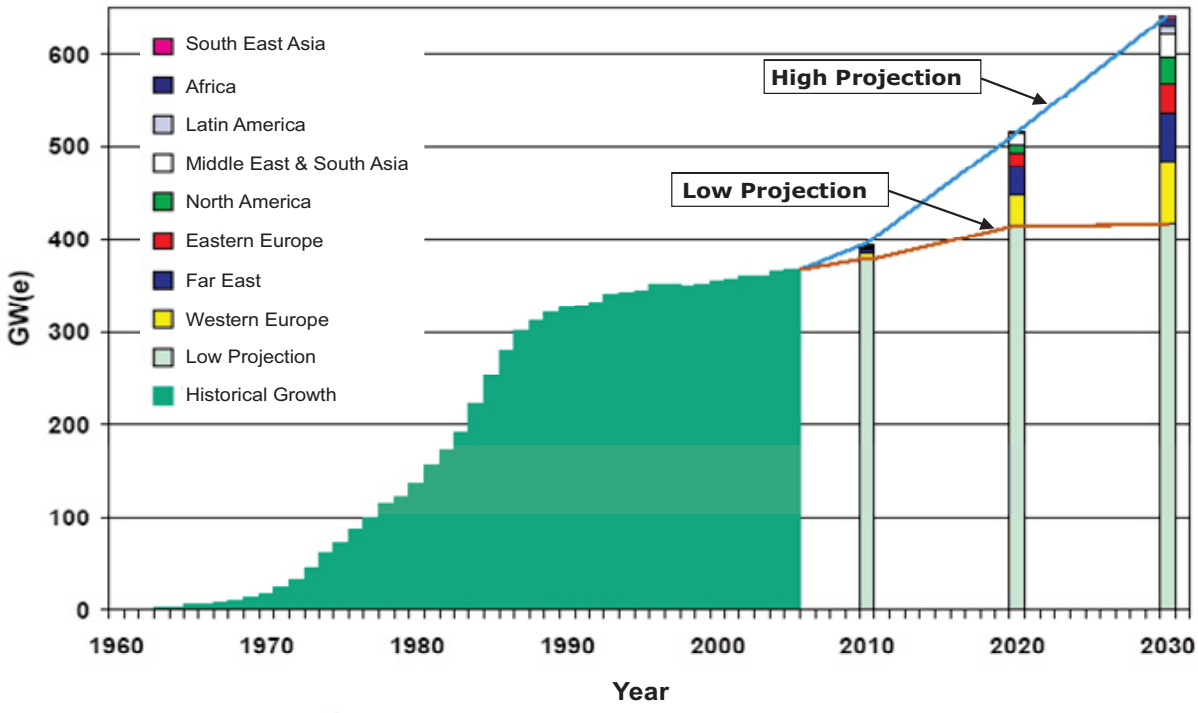


Figure 13
Projection of Installed Nuclear Power Capacity Worldwide

In the IAEA high projection -which adds in additional reasonable and promising projects and plans- global nuclear capacity is estimated to rise to 691 GW(e) in 2030. That would be an average growth rate of about 2.5%/yr.

It should be pointed out that the projections of the World Nuclear Association - WNA are in agreement with those of the IAEA (Fig. 14).

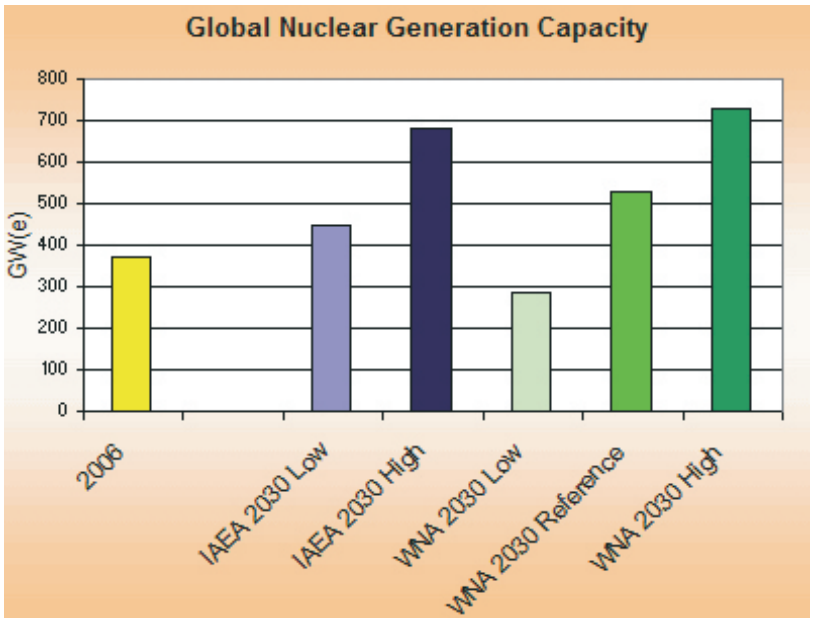


Figure 14
Comparison of IAEA and WNA Projections

12 INFRASTRUCTURE REQUIREMENTS

Nuclear power is a demanding technology which cannot be safely implemented without minimum technical, scientific and organisational infrastructures. Some are detailed below.

a) Grid requirements

Whether planned or unplanned, the shutdown of a power source causes a jolt on the grid. By a rule of thumb, it is unadvisable to have on any grid a node exceeding one tenth of the total grid capacity. Nuclear power plants (NPP) are big in order to be economical: each unit rates typically 1000 MWe or more. Nuclear power, therefore, makes little sense on grids below 10 GWe (of course, the size of an interconnected grid may far exceed the size of a given national grid). This will not be the case if development of medium size modular reactors -with a fraction of 1,000 MWe unit capacity- becomes proven technology.

b) Initial reactor supply and operation

In most cases, the first NPP is acquired under a turnkey contract, from an external supplier. To protect itself, this supplier will require the receiving country to be a part to the Paris or Vienna Convention on nuclear liabilities. A BOT (Build, Operate, and Transfer) contract may help introduce a newcomer state to nuclear power by providing a transition period during which the plant is actually operated by the supplier with the future domestic operators being properly trained.

Operator training is absolutely essential, including basic nuclear education, safety, radiation protection, plant operation and training on a plant simulator for accident management. The training is often offered by the vendor, but international organisations like the IAEA and WANO can help.

Maintenance personnel must also receive a proper training, especially in radiation protection.

When a country develops a nuclear programme, usually the construction of the plants is made with local resources, assuming the proper manpower and infrastructure are available.

c) Fuel Supply

Complete fuel supply services are easily available. Acquiring domestic fuel cycle facilities makes only sense when a sizeable nuclear programme is already in operation.

d) International Regime

As explained before, any newcomer must enter the international regime on Non-proliferation (NPT, Safeguards Agreement, and Additional Protocol) and on Safety.

e) National Organisation

A prerequisite to acquiring and operating nuclear facilities is the establishment of a National Safety Authority, technically competent and fully independent from the Operator of the facility. This Authority must have the actual power to shutdown any facility it no longer deems fully sure and secure. Usually, the same Authority is also in charge of radiation protection.

The proper management of the wide scope of activities to be planned and implemented for the first nuclear power plant project in a country represents a major challenge for the involved government, utility, regulatory, supplier and other supportive organizations (Figure 15). Experience has shown that the time frame from the initial policy decision by the State to the operation of the first nuclear power plant is at least 10 to 15 years [14], [15].

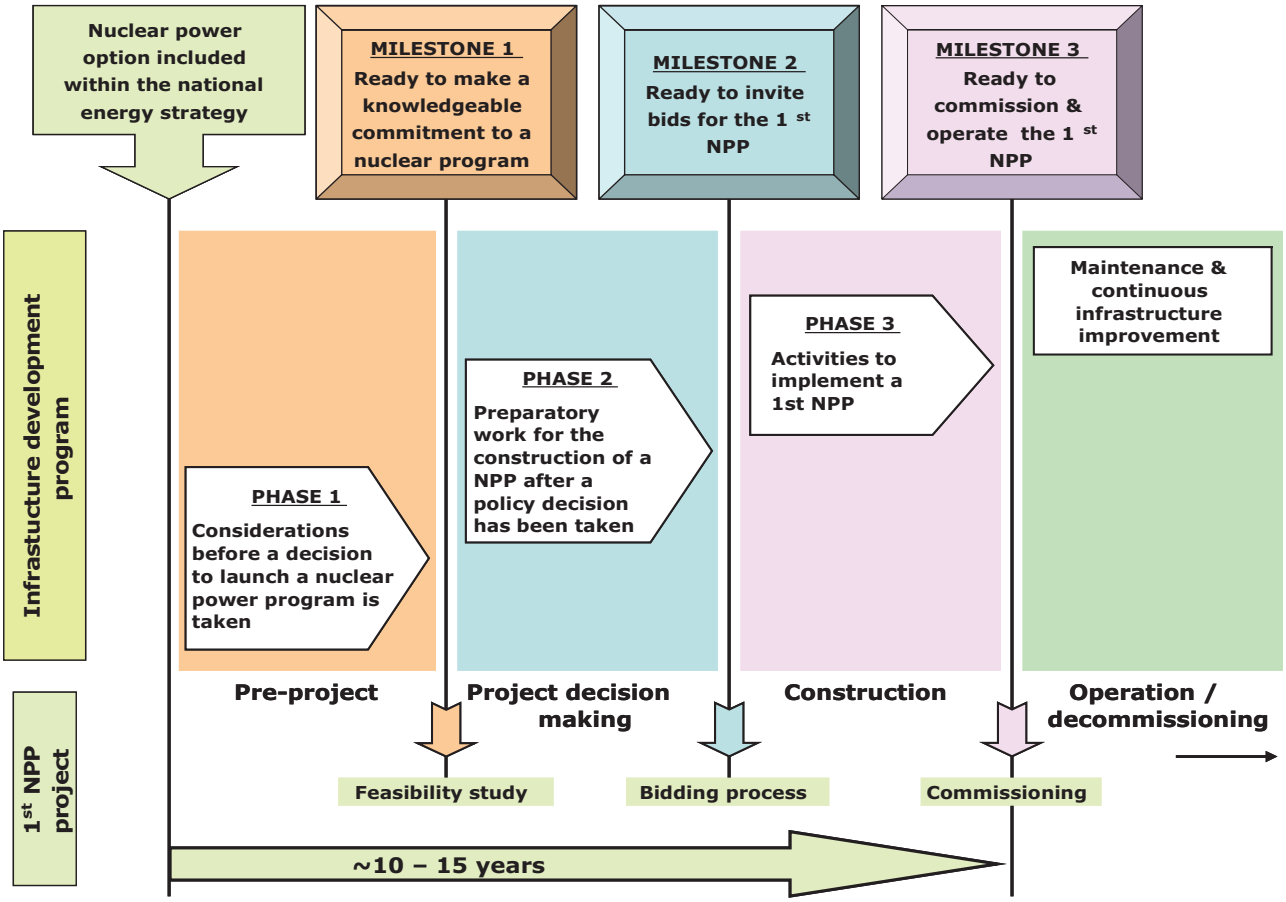


Figure 15
Infrastructure Development Program

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