NUCLEAR POWER

The first encounter

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Preface

This text has been worked out for people who would like to get familiar with rudiments of nuclear power. We tried to use as plain language and to keep individual sections as autonomous as possible to make the topics comprehensible without necessity to study the entire text. Be however warned that unless you are already acquainted with nuclear reactors & power industry basics, we do not recommend to read the text randomly. Some fragments of the brochure "Meet the radioactivity", in Polish (The Andrzej Sołtan Institute for Nuclear Problems, Świerk, November 2010) have been used by consent of its authors (L. Dobrzyński, E. Droste, R. Wołkiewicz, Ł. Adamowski, W. Trojanowski).

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Is Poland in need of nuclear power?

The question asked in the title of this chapter is a sample formulation of the probably key doubt expressed in majority of discussions held in Poland on nuclear power, namely whether nuclear power technology is already not obsolete. Is there any point in a project to put the first nuclear power plant (NPP) in Poland into operation around 2023? Maybe we will be better off if we'd rather concentrate our efforts to secure country power balance on wind, solar, and/or biomass renewable sources?

In line with the title of this brochure it is just "the first encounter". Therefore there is no place here to extensively analyse the above issues and to offer any exhaustive answers. We shall try to discuss the issues more extensively in the planned next brochure. However, we must be first of all aware of the fact that a significant fraction of the so-far operated power units in Polish power plants are approaching their lifetime and they will have to be soon replaced with some other power sources, see the *"Financing of power industry projects in Poland"*, in Polish, report by ING Bank Śląski and Price Waterhouse Coopers, May 2011,*http://www.pwc.pl/pl_PL/pl/publikacje/ING-finansowanie-inwest.pdf*. Some estimates suggest that the fraction may be as much as 10 GW out of the 36 GW total power installed in Poland. *"The Poland's energy policies till 2030"* government forecast estimates that 44 GW should be installed in Poland before 2020. All in all, a relatively huge demand for new power sources in the coming decade will probably force Polish power industry companies to spend sums on the order of 170 billion PLN (about 40 billion €), not taking into account any investment outlays necessary to implement nuclear power programme, see *"Power industry investments: good and evil powers"*, in Polish, *http://www.wnp.pl*, an article by Dariusz Ciepiela published on June 12, 2012.

As we all know (or at least as majority of Poles is convinced)"Poland is going by coal". Power industry in Poland is mainly coal-based, indeed. We can realistically consider a possibility to develop new coal-fired power units, similar to the 858 MW one recently put into operation in the Bełchatów power plant, or the units to be put into operation before 2017 in the Opole and Turów plants. However, cost-effectiveness of such coal-fired units will strongly depend on European Union decisions in the matter of fees related to carbon dioxide emissions. It looks like those fees are going to make cost of electricity generated in coal-fired power plants prohibitively high, unless a cost-effective CCS (Carbon Capture & Storage) technology is developed and deployed. Such technology is yet to be mastered in Poland.

Natural gas-fired power plants are relatively easy to quickly develop. A number of such plants totalling about 4.5 GW power are currently planned for the nearest decade (compare that figure with the estimated power deficit of about 15 GW expected within the decade). The above mentioned cost-effectiveness uncertainty is identical as in the case of the coal-fired plants.

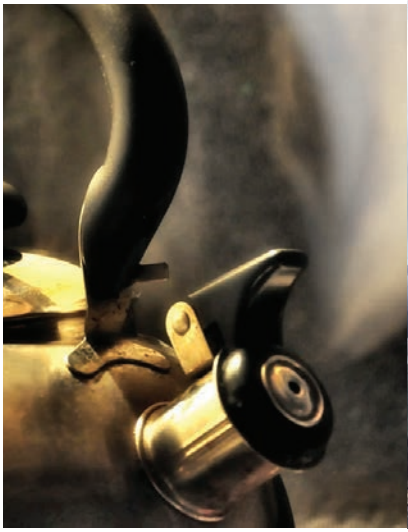
Perhaps our power balance can then be saved by "green energy" discussed in Chapter 5 of this brochure? Forecasts presented in the above mentioned government document say that all renewable energy sources might cover 15% of our demand (i.e. about 7 GW) in 2020. However, cost-effectiveness of green energy strongly depends on various regulations in force. Nowadays such sources are very rarely economically feasible without government subsidies. Besides, wind and/or solar energy is available only periodically and only in limited amounts, so that other independent power sources are needed to supply national grid in peak hours and/or periods during which the green energy is unavailable. Unclear economic feasibility of the technology dictates some caution in accepting the 7 GW forecast as a realistic, attainable goal. It may be worth to cite here James Lovelock's opinion: "Idea of the Greens that renewable energy sources will ever replace decommissioned nuclear power plants and will be able to cover rising demand for energy is a romantic nonsense" (Readers Digest, March 2005).

In the outlined situation, nuclear power seems to be just indispensable for Poland, even if the first nuclear power plant in Poland is to be put into operation after 2020. Nuclear power is environmentally clean and capable to produce the cheapest electricity for the final user in comparison to all competing technologies. The argument that the technology is obsolete is just silly. It may be used only by a person who knows nothing about recently achieved tremendous progress in technology of nuclear reactors. Also Poland's power safety and independence on imported energy carriers are important arguments in favour of that technique. Finally, we will try to show here that additional benefits for the national economy originating from development of that new economy sector are difficult to be over-estimated. All that should definitely outweigh the often irrational fear against nuclear power felt by a large part of Polish society.

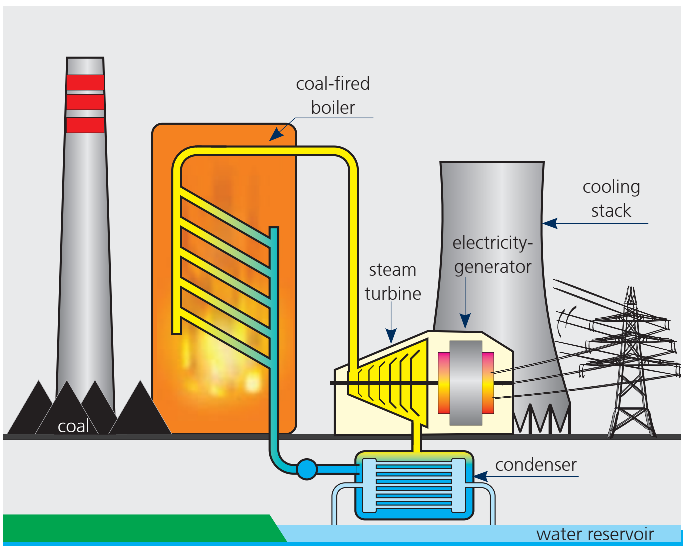
1. Introduction

Earth population is continually growing at a rate that cannot be compensated by still possible improvements in

energy saving techniques. Abundance of electric energy has helped to systematically lengthen average life expectancy: inhabitants of countries in which more electric energy is



consumed statistically live longer. However, it is comfort of living that critically depends on abundance of electric energy. The comfort must include some sense of personal safety, an extremely important factor in the nuclear power context. Therefore, capacity of the installed power plants must also be growing.



Layout of a coal-fired power plant

Where does electric power necessary to keep our standard of living come from? The obvious answer is: from fossil fuel (coal, oil, gas). Less obvious sources include renewable[1] or "green" energy such as hydro-energy, solar energy, wind energy, biomass. Every technology must be cost-effective to be practically useful since price paid for comfort may not be prohibitively high.

People have been uninterruptedly using fire since it was invented. Fire produces heat and helps to cook meals that are often based on boiling water. If water is boiling inside a kettle, steam is getting out of its spout or from under its lid.

Steam is carrying thermal energy: the higher the steam temperature is, the more energy it is carrying. Perhaps that energy could be used to do some work for us (or more precisely: instead of us)? For example, could it drive a power generator? Not directly. However, you can let the steam into a steam turbine, which – rotated by it - can drive an electricity generator.

In this brochure we will be presenting various ways to convert thermal energy contained within steam into electric current. But that's not all, dear reader. We will also show you tricks of the trade of nuclear power technology. Of course the principal difference in relation to the conventional coal-fired technology is the used fuel. However, different fuel is by no means the only difference.

You must have heard that many people oppose nuclear power, some are even ready to devote plenty of their time to fight that technology. Are they motivated by a sheer fear against unknown or else by some deeper knowledge? Since the answer is not clear, in this brochure we are presenting our – scientifically grounded – opinion on nuclear power.

We are not hypocrites to conceal that we are strong supporters of nuclear power. Just like motives of ecologists, our motives include concern for Earth and for their inhabitants, including mankind. That concern is by no means less passionate than that of those who fight against that technology, supposedly (as they believe) harmful to natural environment that all of us live in. However, we know the technology does not harm the environment and would like to share that knowledge with you.

Nuclear reactions that are the physical phenomena behind nuclear power have not been invented by man. They are among numerous natural processes running in the Nature. Life on Earth were not possible if physical parameters prevailing on the planet were unfavourable. Temperature is one of the more important of those parameters. The temperature was favourable among others due to huge amounts of heat liberated in nuclear reactions running within the Earth's crust and mantle since it was born. The heat was compensating heat continually radiated from Earth into the outer Space.

Nuclear reactors have been only re-invented by man. Mother Nature created nuclear reactors billions of years ago. Residues of one of those natural reactors may be

[1] The "renewable energy" term is pretty unfortunate since it may be misunderstood as a contradiction to (known from school) indestructibility of physical energy. Physics teaches that energy may neither be created nor destructed, it may only be converted from one form to another. However, the term has been already widely accepted in the "renewable energy sources" meaning.

studied nowadays in Oklo, Gabon (South Africa); such studies may be very instructive. We will be talking much about nuclear reactors in this brochure. In Chapter 7 we will be talking more about residues of natural reactors.

Before we move on to social and economic aspects, let us briefly show where does nuclear energy come from and what are its features that distinguish it from energy liberated in ordinary burning processes, e.g. coal combustion.

2. Nuclei and energy they hold

2.1. Structure of a nucleus

Atomic nucleus is a very tiny fragment of the entire atom. If dimensions of atoms are difficult to imagine (you can line up about 50 million atoms along 1 cm), dimensions of nuclei are completely unimaginable: they are several tens of thousands times smaller than atoms. Atomic nucleus is merely an "insignificant dot" within the atom. Nuclei carry positive electric charges, clouds of electrons orbiting at atom peripheries carry equivalent negative electric charges. Atom in its entirety is electrically neutral, negative charges of orbiting electrons are compensated by positive charges inside its nucleus. Atom of each chemical element has some strictly determined number of electrons. That number is known as **atomic number** and is traditionally denoted as Z.

As small as it is, nucleus still has some internal structure: it is composed of **nucleons**. There are two nucleon kinds: electrically **neutral neutrons** and positively-charged **protons**. To compensate electric charge, the number of protons must be identical with the number of electrons. Therefore each chemical element has strictly determined number of protons in nuclei of atoms it is composed of.

How about number of neutrons? Well, nuclei with the same number of protons (i.e. nuclei of the same element) may have various numbers of neutrons. Such varieties are known as **isotopes** of the element. Some of the isotopes are stable, some are not. The latter are known as radioisotopes. Radioisotopes spontaneously disintegrate (decay) after some **half-life time $T_{1/2}$** characteristic for any given radioisotope. Our planet, we ourselves, our food is composed mostly of stable isotopes since practically all atoms of short-lived radioisotopes (i.e. isotopes of which $T_{1/2}$ is short in comparison to Earth age) have already decayed. We can artificially produce such radioisotopes in a lab by means of some suitable nuclear reactions.

Therefore one has to specify two pieces of information to unambiguously identify an isotope. Traditionally one is element chemical symbol (sometimes accompanied by Z = number of protons), while the other is total number of protons and neutrons known as the **mass number** denoted A = Z + number of neutrons. If X denotes element chemical symbol, notation ${}^{A}_{Z}X$ or ${}^{A}X$ is traditionally used. Mass number gives practically total mass of the atom since mass of a neutron is practically identical as mass of a proton, and each of them (nucleon) is approximately 1840 times more heavy than an electron. Nucleon masses are specified in **atom mass units**[2] abbreviated "u". 1 u is defined as 1/12 mass of the ${}^{12}C$ isotope (6 protons and 6 neutrons). For example, three H isotopes exist: hydrogen, deuterium and tritium (${}^{1}H$, ${}^{2}H$ and ${}^{3}H$, respectively). Hydrogen nuclei are just protons. Deuterium nuclei are proton + neutron pairs. Each tritium nucleus is composed of one proton and two neutrons. Each hydrogen isotope has one proton (if the number of protons were different, it would be an isotope of a different element). All three hydrogen isotopes occur in the environment, although their abundances are largely different. Tritium is a radioisotope.

A very important role in nuclear power is played by uranium (chemical symbol U, Z=92). Natural uranium was discovered in Earth crust already in 18th century, i.e. more than 100 years before radioactivity was discovered by Becquerel. Uranium has there isotopes of mass numbers 238, 235 and 234 (99.27%, 0.72% and 0.0055% natural abundance, respectively). They are denoted usually as ${}^{238}U$, ${}^{235}U$, and ${}^{234}U$. Their very different abundances result from very different half-life times: the most abundant ${}^{238}U$ isotope has $T_{1/2}$ = 4.5 billion years, the least abundant ${}^{234}U$ isotope has $T_{1/2}$ = 250 thousand years. The other isotopes are constantly replenished by slowly decaying ${}^{238}U$.

2.2. Binding energy

Why some isotopes exist while others do not? Binding energy is the answer. If the famous anecdote about Newton and an apple is true, the apple fell on Newton's head because Earth was accelerating it (just like all other masses) towards its centre. In the energy language it may be expressed as follows: apple's energy on the Earth's surface is lower than energy of the raised apple since work done when raising it against Earth's gravity force had been accumulated in it as the so-called potential energy. Apple (as any other physical system) is constantly trying to reach its lowest energy state and is falling down as soon as it can.

If some isotopes produced during Earth birth are not observed in the Nature, it means that they had a too high energy to survive till our times. Such energetic isotopes have emitted part of their energy and disappeared. Radiation is the simplest way a nucleus may get rid of a surplus of its energy. Radiation may be corpuscular (emission of a particle) or electromagnetic (emission of a photon similar to visible light but of a higher energy). In case of a corpuscular emission we are talking about radioactive decay.

If decays of nuclei of an element result in any modification of the number of protons, that element is automatically changed into another. The resulting nuclei have in general other masses, too. You might think that sum of masses of all reaction products plus sum of masses of all emitted particles (and equivalent mass of all emitted photons) sum up exactly to the mass of the decayed nucleus. However, that sum is always lesser. The difference is known as mass defect. **Mass defect** is a crucial phenomenon from the nuclear power point of view. Let us illustrate it using the ${}^{200}Hg$ mercury nucleus (80 protons and 120 neutrons) example. ${}^{200}Hg$ measured mass is only 199.924 u even if 80 protons and 120 neutrons should weigh together $80m_p+120m_n$ = 201.622 u. It turns out that the bound nucleus weighs 1.698 u less than sum of its constituents. Isn't that strange? Imagine for contrast that 5 apples each of 200 g would weigh together only 999.5 g rather than expected 1 kg.

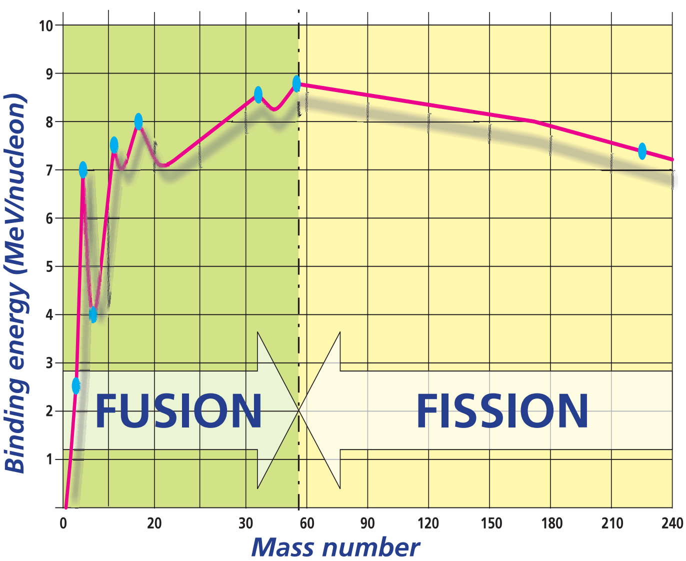
[2] 1u (atomic mass unit) = 1.66054 x 10^{-27} kg. Proton mass m_p = 1.0072765 u. Neutron mass m_n = 1.008665 u. Electron mass m = 0.00054858 u. Since mass is equivalent to energy ($E = mc^2$), one can also say that 1u = 931.4943 MeV = 931.4943 million electronvolts. 1 eV is the energy acquired by an electron accelerated by potential difference 1 V. 1 eV = about 1.6 x10^{-19} J.

According to the famous $E = mc^2$ Einstein formula, less mass m means less energy E (the constant is the velocity of light). Mass defect means that 80 protons and 120 neutrons bound within each ^{200}Hg nucleus have smaller energy that collection of 80 free protons and 120 free neutrons. However, energy may neither be created nor destructed, the **energy conservation principle** is one of the most basic principles of physics. Therefore mass deficit Δm appears as the so-called binding energy $(\Delta m)c^2$. You would have to supply back that energy to ^{200}Hg nucleus to liberate all its 80 protons and 120 neutrons into a collection of free 80 free protons and 120 free neutrons.

Some binding energy must be liberated also in spontaneous radioactive decays or else the decaying isotope would not be radioactive. Energy liberated in nuclear power plants is just the binding energy. In particular we practically use binding energy liberated in the nuclei **fission** processes, which will be discussed in Chapter 3.

Binding energy is specified in MeV/nucleon. Coming back to our ^{200}Hg example: mass deficit of about 1.7 u is equivalent to energy 1581.2 MeV (see footnote 2). Therefore ^{200}Hg nucleus binding energy is 1581.2/200 = 7.906 MeV/nucleon. That amount of energy would be liberated if we could bind just one free proton or neutron to the mercury nucleus. Is it a small or a large energy? It is tremendously large! Just compare almost 8 million eV to 4 eV liberated during chemical reaction of oxidization (combustion) a single coal atom. By the way: mass deficit effects accompany also chemical reactions, but are immeasurably small[3].

The chart depicts binding energy vs. isotope mass number. As you can see, the energy reaches maximum around A=55. It follows that some energy is liberated when heavy isotopes are transformed into some lighter ones. Besides radioactive decays, transformations of that kind include also cases when heavy nuclei split into some lighter **fragments**, which process is referred to as **fission**. Energy liberated during radioactive decays is too small to be useful in nuclear power, but it is nevertheless used in special applications e.g. spacecraft on board electricity generators. On the other hand, the fission reaction is the workhorse of the terrestrial nuclear power applications.



[3] Mass of a water molecule is 18.0156 u (1.6 x10[10] eV), while average chemical binding energy is 9.4 eV. Chemical mass deficit effects are then less that 1 part per billion.

Even more energy is liberated when very light isotopes combine into some heavier ones. That latter process known as **thermonuclear fusion** is seen as a basis for the technology of the future: **thermonuclear power**.

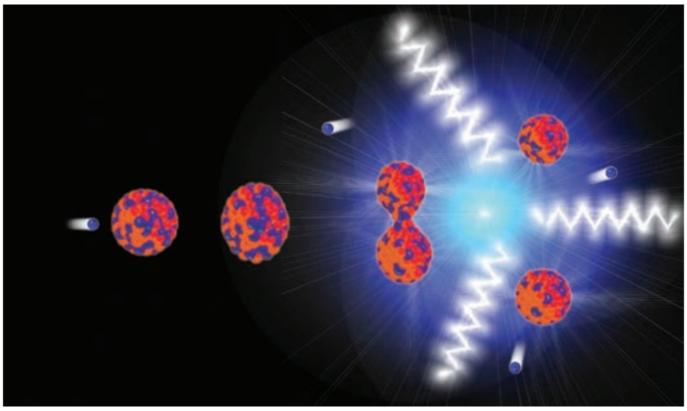
For now we are going to focus our attention on nuclear energy produced in "conventional" (i.e. fission-based) nuclear power plants.

3. Fission reaction

Fission reaction is a process in which nucleus of a heavy element (A>200) spontaneously or in reaction to some stimulation splits into two fragments of comparable masses (in rare instances the number of fragments is higher). Part of the liberated energy is carried away by particles (e.g. neutrons) or photons (e.g. gamma rays, γ) emitted within the reaction. Fission reaction employed in typical nuclear reactors is the reaction induced in ^{235}U nuclei by **thermal neutrons** i.e. neutrons of typical kinetic energy 0.0253 eV and movement velocity 2200 m/s comparable with energy/movement velocity of air molecules at room temperature. That fission reaction may be written down as:

$$n + {}^{235}U \rightarrow {}^{236}U^* \rightarrow X + Y + \text{neutrons} + \gamma + \text{liberated energy}$$

The asterisk* denotes that the ^{236}U nucleus is excited i.e. has more energy than it can steadily hold.



Thermal neutron (depicted in the figure as a small dark blue sphere approaching from left) hits the ^{235}U nucleus and is absorbed to transform it into a ^{236}U excited nucleus. To get rid of surplus of energy, the latter splits into two some lighter nuclei (X and Y fission fragments). The fragments may include such nuclei as ^{90}Kr, ^{97}Zr, ^{99}Mo, ^{137}Te, ^{140}Xe, ^{143}Ba, and/or others. The process is accompanied by emission of gamma radiation. Depending on mass of the produced fragments X and Y, from 0 up to 8 neutrons are also liberated. In some circumstances those neutrons may initiate subsequent fissions of the surrounding ^{235}U nuclei. The liberated energy is sum of kinetic/excitation energy of individual reaction products (X, Y, n and γ).

The process of splitting the excited ^{238}U nuclei may be imagined as strong oscillations during which the nucleus undergoes various deformations. In particular the nucleus may experience elongation along one of its spatial axes, so that a thin "neck" may appear between extreme massive parts. If both parts become distant enough, short-range nuclear forces will rapidly lose their power to keep the nucleons together, while not-so-short-range electric forces will continue to repel positive charges in both parts of the about-to-split nucleus. In time shorter than 10^{-15} s the nucleus will indeed split into two smaller droplets of a comparable mass just like a large droplet of water or mercury.

Binding energy in uranium is 7.59 MeV/nucleon. Binding energy in the produced fission fragments is about 0.9 MeV/nucleon larger. Therefore energy liberated in a single ^{235}U fission reaction is equal to 236 nucleons x 0.9 MeV/nucleon i.e. about 200 MeV. That energy is about 50 million times larger than energy liberated during oxidization (combustion) of a single carbon atom in coal. The corresponding mass defect amounts to just about 1/1 000 of the ^{236}U nucleus total mass. Taking into account different atomic masses, one can calculate that energy liberated during combustion of 1 kg of coal is 2.5 million times lower than energy liberated during fission of 1 kg of uranium. That's why a conventional coal-fired power plant may annually need many thousands of tons of coal, while a comparable power nuclear plant will get by on several tens of kilograms of uranium.

Shares of various types of energy in total fission energy is shown in the table.

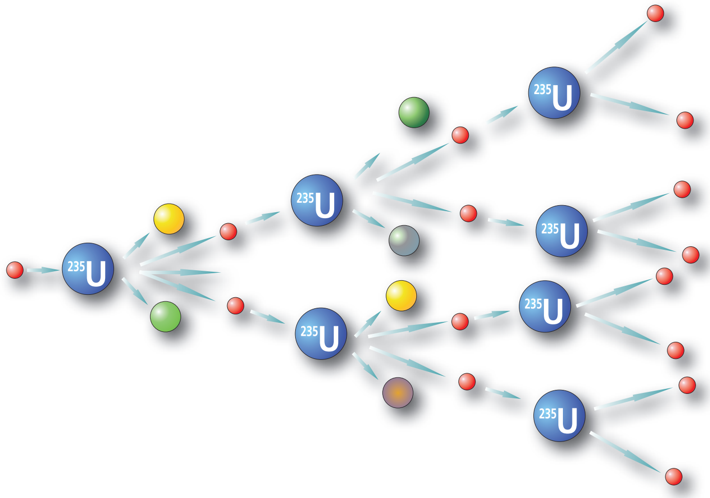
Type of energy	Amount [MeV]
Kinetic energy carried away by fission fragments (X, Y)	167
Kinetic energy carried away by neutrons	5
Radioactive decays of X,Y fission fragments[4]	17
Gamma radiation	7
TOTAL	**196**

The fact that huge amounts of energy can be liberated from very limited masses could not remain unnoticed by military people. They quickly developed atom bombs (a-bombs) of a devastating explosive power. Energy liberated in one fission is about 18 million times larger than energy liberated in explosion of one molecule of the TNT conventional explosive ($(NO_2)_3C_6H_2CH_3$). However, not every uranium nucleus hit by thermal neutron must undergo fission: only 6% of energy available in uranium built into the first a-bomb was actually liberated. By the way, devastating action of an a-bomb is to a much larger extent related to heat wave and blast than to ionizing radiation produced by its explosion.

^{235}U is the sole natural isotope fissionable by thermal neutrons. However, uranium ores are composed mainly of ^{238}U isotope, ^{235}U abundance is only 0.72%. Therefore to be useful for nuclear power, research, or military applications, natural uranium must be enriched. ^{235}U content is many times higher in **enriched** uranium than in mined natural uranium.

4. Chain reaction

On the average, 2.5 neutrons is produced in each act of uranium nucleus fission. For clarity let us assume that only two neutrons (red small circles in the figure) are produced in each fission, and each of them is absorbed by some other ^{235}U nuclei to give rise to their fissions, too. So the third generation counts 4 neutrons, the fourth generation – 8 neutrons, and so on. Fragments (yellow and green larger circles) produced in individual fission acts may have slightly different masses since nature of the fission process is random. Therefore we can only talk about probability of producing some given isotopes. However, self-sustainability of the reaction is its most important feature. Such reactions are known as "chain reactions".



The number of neutrons in successive generations rises exponentially, just like the number of rice grains in the famous story about Persian shah asked for remuneration for some work to be paid in rice. The worker asked to pay him with rice in the amount calculated as follows: put 2 rice grains on the first chessboard square, 4 grains on the second square, 8 on the third square etc. until the entire chessboard is packed with rice. However, it soon turned out that there was not enough rice in the entire shah empire to satisfy worker's request. It is not easy to imagine how much is 2^{64} grains that should be put on the last chessboard square. However, assuming that mass of a single rice grain is about 0.02 g, the asked-for rice would weigh about 400 billion tonnes!

[4] All possible fission fragments are radioactive.

Pay attention that exponentially growing number of neutrons in a chain reaction means also that liberated energy (about 200 MeV per single fission) accumulates in a flash into a tremendous heat wave. Energy liberated if all nuclei of 1 g of ^{235}U isotope split would amount to $(6.023 \cdot 10^{23}/235) \cdot 200$ MeV $= 5.125 \cdot 10^{23}$ MeV $= 8.2 \cdot 10^{10}$J[5]. Such energy would be liberated if 100 000 tonnes (e.g. a Nimitz-class aircraft super-carrier) were dropped from the height of 82 m and hit Earth surface. Energy liberated by a-bombs dropped in 1945 on Hiroshima and Nagasaki corresponded to explosion of about 20 000 tonnes of TNT, or to fission of about 1 kg of ^{235}U.

Simple calculations are enough to show that if a nuclear power unit is to be operated at the 1 000 MW thermal power level (10^9 J/s), only about 0.012g ^{235}U isotope must split each second. It follows that such an unit would consume only about 1 kg of that isotope per day, or only about 365 kg per year. ^{235}U abundance is only 0.72%, so we would need about 50.7 tonnes of natural uranium to run a 1 000 MW power unit all year round. Taking into account that not all neutrons give rise to fission, that mass would rather be about 61.1 tonnes. It is truly not much in comparison to hundreds of rail cars of coal needed to run 1 000 MW conventional power unit per year. Necessary volumes are also (relatively) tiny: 1 tonne of metallic uranium is a cube of side length 37 cm.

5. Nuclear power industry

Our civilization is already nowadays consuming huge amounts of energy and the developing technology is demanding ever more. All available socio-economic data show that GNP is positively correlated with both energy production output and amount of consumed energy. The data indicate also that life expectancy increases with energy consumption. Majority of energy consumed in the world is produced by combustion of biomass (mainly timber) and fossil fuel (coal, oil, natural gas). However, most probably natural energy carriers will in some not-so-distant future become exhausted or their price will skyrocket. Current estimates are that the time left is between 50 and 150 years. Sooner or later mankind will be in need of energy from some alternate sources. Is nuclear power a possible solution to the problem?

To be able to use energy from any natural source (like geothermal sources, wind or solar radiation) one has to develop some systems to convert it into the most convenient form i.e. into electricity. Such systems can cost quite a lot, especially if you consider cost normalized to unit power (natural energy is dispersed), as well as costs of some more reliable back-up power systems that could replace wind generators when there is no wind or could replace biomass power plants when biomass deliveries shrink because of a local crop failure.

Water reservoirs may be important and cheap sources of hydro-energy. In some countries hydro-energy is even basic energy. However, in many other countries profile of the terrain and number of rivers flowing through the country limit such opportunities that have been already fully exploited in some places. Our country is among the latter countries and it is irrational to expect that hydro-energy will be the energy of the future in Poland.

[5] $6.023 \cdot 10^{23}$ (the Avogadro constant) is the number of atoms/molecules contained in 1 mole (i.e. in mass of a substance in grams equal to its mass number A)

Mining/drilling operations indispensable to supply classical power industry with fossil fuel are quite risky, just to mention accidents in coal mines that occurred in 2010 in China and Ukraine, or pollution of Mexican Gulf waters with crude oil flowing out of the damaged "Deep Horizon" BP rig for three months in 2010.

Perhaps people invent in the future some other efficient, easily accessible sources of cheap energy. However, in no case can we expect them to enter common applications in a period shorter than about 50 years after their invention. That period is comparable to the time in which currently identified fossil fuel resources will start to be depleted. So, we have to make important decisions in that matter, and to make them fast!

Nuclear energy is a very efficient source of power already to-day practically available to mankind. True, it requires huge investments. However, there is no other, more promising energy source for the future.

Even if investment outlays necessary to develop a nuclear power plant are very high, price of plant-produced electricity that the consumers must be charged with turns out to be relatively low. Gross cost of electricity produced in NPPs (including costs of necessary safeguards, systems to protect fissionable materials against uncontrolled spreading, radioactive waste management, and total decommissioning of the plant down to the so-called "green grass" level after its lifetime is over) are among the lowest in the whole power industry.

Estimates of gross cost of electricity shown in the below table[6] were presented by the Agencja Rynku Energii S.A. company in December 2009.

Plant type	Cost of 1 kWh (PLN)	Drawbacks
Hard coal-fired with a system to remove SO_x/NO_x from flue gases	0.36	Air pollution
Hard coal-fired with a system to remove SO_x/NO_x from flue gases and a system to remove and store CO_2	0.36	Large quantity of ash
Brown-coal-fired with systems to remove SO_x/NO_x from flue gases	0.36	Air pollution
Brown-coal-fired with systems to remove SO_x/NO_x from flue gases and a system to remove and store CO_2	0.34	Large quantity of ash
Nuclear power with 3rd generation PWR reactors	0.29	Radioactive waste
Natural-gas-fired	0.37	Uncertainty regarding fuel cost
Fired by gas from an integrated hard coal gasification facility	0.40	Air pollution
Fired by gas from an integrated hard coal gasification facility, equipped with a system to remove and store CO_2	0.34	
Fired by gas from an integrated brown coal gasification facility	0.40	Air pollution
Fired by gas from an integrated brown coal gasification facility, equipped with a system to remove and store CO_2	0.32	
Terrestrial wind generators	0.43	A costly back up system necessary
Sea wind generators	0.44	A costly back up system necessary

[6] Estimates of the averaged costs to produce electric energy in power plants to be put into operation in Poland before 2020 published by Agencja Rynku Energii S.A.in the "Electricity produced in nuclear/coal-fired/gas-fired power plants and from renewable sources: cost comparison" report in December 2009.

Besides, nuclear power may be capable to satisfy mankind's hunger for energy for thousand years ahead. Currently about 14% of electric energy produced in the world is supplied by nuclear power *http://www.nei.org/resourcesandstats/nuclear_statistics/worldstatistics*. Breakdown of data on nuclear power in individual countries is shown in the table below after data published in May 2012 at the *http://pris.iaea.org/PRIS* Website.

Item	Country	Share of nuclear power (%)	Number of power units	Power (MW)
1	France	77.71	58	63.130
3	Slovakia	54.02	4	1.816
4	Ukraine	57.20	15	13.107
5	Hungary	43.25	4	1.889
6	Slovenia	42.04	10	9.014
7	Switzerland	40.85	5	3.263
8	Sweden	39.62	10	9.326
9	South Korea	34.64	23	20.671
10	Armenia	33.17	1	375
11	Czech Republic	32.96	6	3.766
12	Bulgaria	32.58	2	1.906
13	Finland	31.58	4	2.736
14	Spain	19.48	8	7.567
15	USA	19.25	104	101.465
16	Taiwan	19.02	6	5.018
17	Romunia	18.98	2	1.300
18	Japan	18.14	50	44.215
19	UK	17.82	17	9.703
20	Germany	17.79	9	12.068
21	Russia	17.59	33	23.643
22	Canada	15.33	18	12.604
23	South Africa	5.19	2	1.830
24	Argentine	4.97	2	935
25	Pakistan	3.77	3	725
26	India	3.68	20	4.391
27	The Netherlands	3.60	1	482
28	Mexico	3.55	2	1.300
29	Brazil	3.17	2	1.884
30	China	1.85	16	11.816
31	Iran	0.04	1	915

Nuclear power saves environment against pollution since neither flue gases nor carbon dioxide are produced in NPPs. Therefore it does not contribute to the so-called global warming effect. **Each 22 tonnes of uranium "burned" in nuclear reactors prevent emission of about million (sic!) tonnes of carbon dioxide that would accompany combustion of coal if equivalent amount of electricity would have to be produced in classical power plants.**

Emerging market countries do not disregard opportunities brought about by nuclear power. Programmes to develop nuclear power industry are most impressive in countries, in which shortages of power are most acute e.g. in China and India. As of March 2012, 14 nuclear power reactors were operational, 26 under development, and 28 planned in China. According to Chinese government plans, nuclear power plants should supply about 10% of energy consumed in China in 2025. We in Poland hope to put into operation two power units of the first nuclear power plant of combined power 3 000 MWe till that time.

What about consumption of various fuels? Yearly fuel consumption of a 1 000 MWe power plant and equivalent size power plants operated according to other technologies is shown below (data after the *Energy, Powering Your World* CERN report, 2000).

Energy source	Yearly fuel consumption/ requirements for power capacity 1 GWe	Compare with
Biomass (timber)	2 000 km^2 of cultivated land	About 1/4 area of Crete (Greek island)
Wind	2 700 wind turbines each of 1.5 MW power	486 km^2,.about area of the Polish capital, City of Warsaw
Sun (photovoltaic)	23 km^2 photovoltaic panels (on Earth equator)	2 555 soccer sport grounds
Biogas	20 000 000 pigs	1/8 of whole pig population in EU countries in 2011
Gas	1.2 km^3	470 Cheops pyramids
Oil	1 400 000 tonnes	10 000 000 barrels, 100 super-tankers
Coal	2 500 000 tonnes	26 260 rail cars
Nuclear power (fission)	20 tonnes of enriched uranium i.e. 160 tonnes of uranium ore	2 rail cars of ore
Thermonuclear power (fusion)	100 kg D + 150 kg T	2 850 m^3 of sea water and 10 tonnes of lithium ore

Within that context it may be worth to quote heating values for various fuels.

Fuel	Heating value [MJ/kg*]	Yearly consumption per capita in Poland 2000
Timber	16	
Brown coal	9	1.6 t
Hard coal	13 ÷ 30**	2.2 t
Natural gas	45	about 350 m^3
Crude oil	45-46	about 0.5 t
Natural uranium	500 000	

* 1 MJ = 0.278 kWh
** depending on coal quality

Thermonuclear power (fusion) technology has been discussed for several years. Even if the technology is very efficient in the fuel heating value sense, its practical utilization is a matter of a distant future.

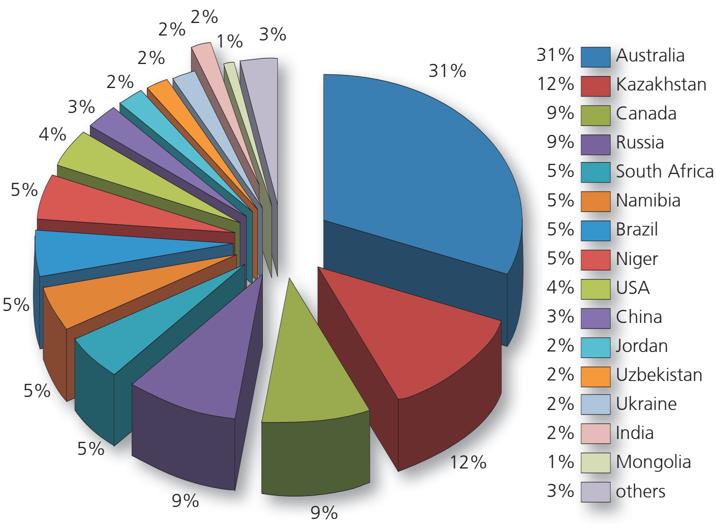
6. World uranium reserves and fuel independence

Since uranium ore is a natural raw material, the question of size of world uranium reserves in Earth crest is also natural. How long these reserves might be used to supply world nuclear power industry?

Contrary to all appearances the answer is not straightforward at all. Firstly, one has to adopt some method of uranium utilization. Here, the current technology is the most obvious choice. Secondly, available reserves depend on acceptable uranium ore price. As the reserves will be depleting, the price will undoubtedly be rising. Currently uranium ore prices are fluctuating around 100 USD/kg. Taking into account current delivery prices and current methods of utilizationin NPPs, uranium reserves will get depleted by 100 - 300 years. It might seem a pretty gloomy picture if looked at from the global power supply perspective.

However, it's not as bad. As uranium prices will be rising, the world will be switching to other types of nuclear reactors that currently are not sufficiently cost-effective, first of all to the so-called **breeders** and/or thorium-based "fast" reactors. Global reserves of thorium are much richer than global reserves of uranium. In that perspective nuclear power might be capable to satisfy global demand for energy even for millions of years.

The fuel independence issue is another often raised problem. In that aspect situation is favourable for nuclear power. Uranium is offered for sale by vendors from many different countries (world reserves by country are shown in the figure below).

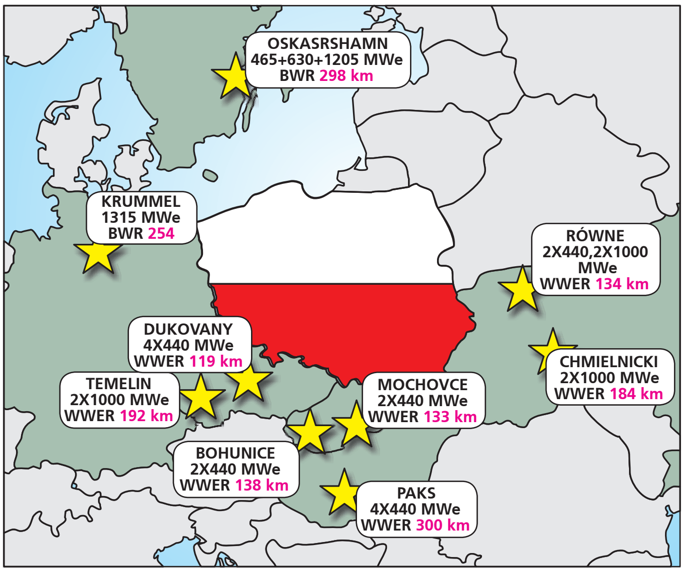


World uranium reserves by country[7]

Taking into account only uranium extractable at a cost below 130 USD/kg, deposits identified on territories of the 4 largest potentates (Australia/Kazakhstan/Canada/Russia) amount to 1 700/650/485/480 thousand tonnes, respectively. Total global reserves amount to about 5 400 thousand tonnes. Uranium may be extracted as cheaply as 80 USD/kg in some mines located in Canada, Australia, Brazil and South Africa. New deposits of uranium were found in Sweden at the end of July 2010, potentially the deposits may be the richest in the world. Since import is possible from many countries, there is no hazard of becoming dependent on any single supplier.

24 nuclear power units of combined installed electric power of about 16 GWe[8] are currently operated in 9 power plants located within about 300 km distance from Poland's borders, see map after the *http://www.elektrownia-jadrowa.pl* webpage (the Lithuanian NPP was shut down in March 2012).

Poland is only getting ready to develop its first NPP by 2023.



7. Nuclear reactors

7.1. Reactor core

Operation of a nuclear reactor may be described in a relatively simple way: it is just a device to control rate of chain reaction (fissions) running in uranium. Loss of such control i.e. allowing a spontaneous chain reaction would instantly liberate a huge energy that would give rise to a (nuclear) explosion.

Rate and other parameters of a running chain reaction depend on shape of the uranium solid and energy of neutrons that hit uranium nuclei causing their fissions. In case of an ideal sphere made of a relatively small amount of metallic uranium majority of neutrons escapes the sphere and chain reaction cannot sustain. Such reaction is referred to as **sub-critical**[9]. The larger sphere radius, the lower number of escaping neutrons. For a sufficiently large radius the chain reaction becomes critical. Respective mass of uranium is referred to as **critical mass**. For the ^{235}U isotope it is about 50 kg of uranium (sphere of about 17 cm diameter). Within larger masses the reaction runs in the super-critical mode eventually leading to an explosion. The first a-bomb was

[7]after Red Book OECD/NEA-IAEA (2009)

[8]Thermal power GWth of a power plant (both conventional and nuclear) is usually 3 times larger than its electric power GWe.

[9]Chain reaction may run in three different modes:
- sub-critical: majority of liberated neutrons fail to split other nuclei, the number of neutrons is dropping with time, the reaction is extinguishing
- critical: exactly one neutron out of all fission-liberated ones splits another nuclei, the number of neutrons is more or less constant with time, the reaction is running steadily, and
- super-critical: more than one fission-liberated neutron split other nuclei, the number of neutrons is increasing with time, the reaction is developing.

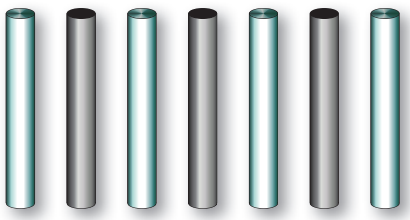
just a device in which two sub-critical masses of fissionable uranium were suddenly joined into a larger super-critical mass.

Notice that it is enough to split a super-critical mass into two sub-critical masses located at a distance away to prevent the **super-critical** chain reaction.

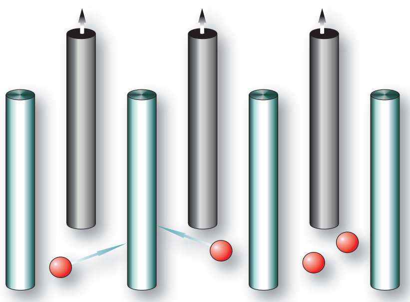
In every nuclear reactor uncontrolled chain reaction is prevented two ways.

Firstly, uranium fuel is hermetically sealed in fuel elements, in portions in each element much less that the critical mass. Each fuel element contains much more ^{238}U isotope that ^{235}U. The former isotope absorbs neutrons preventing any chain reaction inside of the element.

Secondly, fuel elements inside reactor (light blue on the figure) are separated not only by some distance, but also by some **control rods** (grey on the figure) made of a material strongly absorbing neutrons, e.g. boron carbide (boron absorbs neutrons very strongly). Unless control rods are lifted up, neutrons (red circles on the figure) emitted from one fuel element do not reach neighbouring elements and may not contribute to chain reaction. Grid of equidistant fuel elements and control rods is the heart of any nuclear reactor referred to as **rector core**.



Shut down reactor



Control rods lifted up to run the reactor

Each nuclear reactor is normally operated in the so-called **critical state**, in which exactly one neutron out of all fission-liberated ones (2.5 on the average) splits another nuclei, while others are absorbed by various reactor elements (including control rods). In such conditions the number of neutrons is more or less constant with time, the chain reaction is running steadily at some adjusted power level (is stationary). That critical state may be relatively easily maintained thanks to the so-called **delayed neutrons** produced in some fission acts. About 0.65% of neutrons from fissions of ^{235}U nuclei are delayed by more than 0.05 s. The delay may reach even 1 minute, while the average value is several seconds. Presence of delayed neutrons makes the control rod management a relatively easy task. If there were no such neutrons, control rod would have to react to fluctuations of instantaneous number of neutrons with the time constant of the order of 1/1000 second. There are no equally fast mechanical systems.

Operation of a nuclear reactor is organized in such a way that it is sub-critical without delayed neutrons (more neutrons absorbed than produced in fissions). On the contrary, an a-bomb is a super-critical device - the chain reaction develops spontaneously in an uncontrolled way.

^{235}U nuclei are most readily split by **thermal neutrons**[10] of a kinetic energy comparable to energy of thermal vibrations at room temperature (a fraction of one electron volt). However, **fission neutrons** have energies on the order of one million electron volts. Probability that such highly energetic neutrons will initiate next fissions is small. To use as much neutrons as possible we have to deprive fission neutrons most of their energy.

7.2. Neutron moderator/reflector

May be "to deprive fission neutrons most of their energy" seems as a complicated task, but in fact is easy. You just need a substance that absorbs very little of the incident neutron flux but radically slows each neutron down. Such a medium is known as **neutron moderator**.

Neutron moderator principle of operation is known from the billiards table. A ball that hits head-on another identical ball stops while the hit ball carries away the whole movement momentum.If the hit is not exactly head-on, the hitting ball slows down significantly rather than stopping completely.

Single protons are almost "identical balls" for neutrons. Hydrogen is the element whose nuclei are single protons. We need then a substance with plenty of hydrogen, such as

water. Not going too much into details, let's say than other good moderators include also beryllium and graphite. The used moderator is one of the more important constructional feature of any reactor.

To increase fission chances, reactor core is surrounded also by **neutron reflector**, i.e. material that reflects back neutrons trying to escape the core.

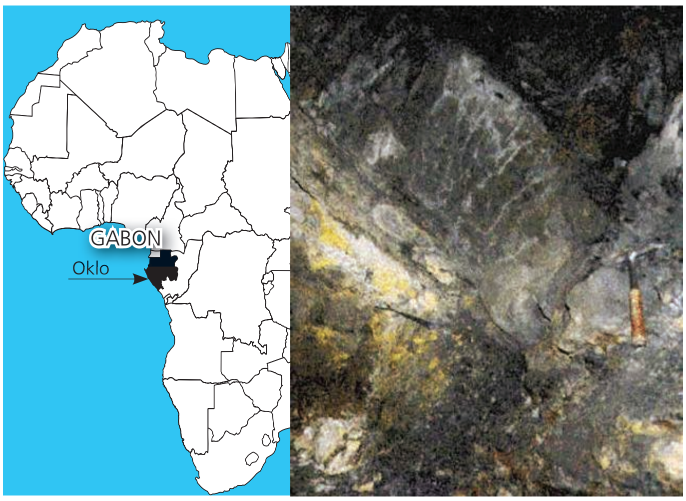
[10] On the other hand mainly fission neutrons of energy on the order on 1 MeV are employed in a-bombs.

7.3. Reactor core cooling system

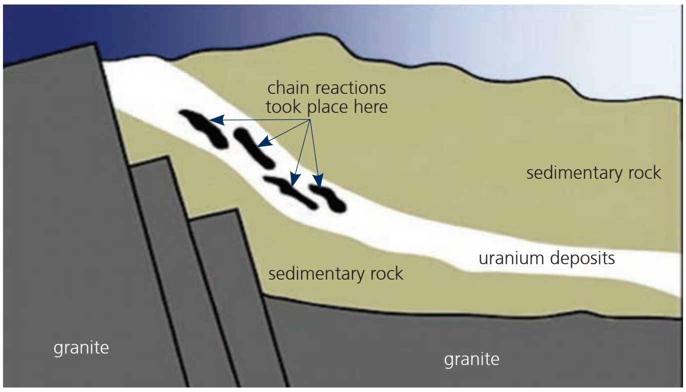
Large amount of heat generated during reactor operation may rise temperature of fuel elements and control rods above 2 000°C. Unless the core is intensely cooled down, the elements and the rods can quickly become damaged from overheating (in an extreme case can become molten down). Therefore each reactor core is first of all immersed in a pretty large water pool, and secondly cooled down dynamically by streams of a flowing coolant (usually also water). In fact, all more serious accidents that ever happened during operation of commercial reactors resulted from core overheating. Therefore, an effective and reliable cooling system is the basic prerequisite of good operational safety of any reactor.

7.4. Natural nuclear reactors

We have already mentioned in "Introduction" that Mother Nature was ahead of the man's atom epoch (that began in 20th century) by some 2 billion years. Uranium deposits found in Oklo (Gabon, Africa) contain places in which concentration of the ^{235}U fissionable isotope in natural uranium is lower than standard 0.72%. Natural uranium located in those places is **depleted**. It means that the fissionable isotope has been somehow used up. How it may happen? Well, some rich uranium deposits were surrounded by water in a so favourable layout that fission neutrons moderated by water to thermal energies were able to sustain chain reaction in neighbouring ^{235}U nuclei. Fission-generated heat vaporized the surrounding water and the "reactor" ceased to work. After some time new water dripped into surroundings of the deposits and the "reactor" resumed work. The cycle was repeated until natural uranium in the deposits got depleted below the ^{235}U level needed in those particular circumstances to sustain chain reaction. From that moment on the deposits never behaved as a natural reactor any more. Nowadays we can find in the Oklo deposits not only depleted uranium but also some products of the fission reactions once running at the site i.e. nuclear waste according to the present-day terminology. It should be an important lesson for all opponents of nuclear power: even after billions of years most waste remained at the site rather than became dispersed over large territories. Of course majority of the radioactive waste was too-short-lived to survive till our era, those isotopes just decayed.



Yellowish strips of uranium deposits of different depletion level are visible in several places inside cracked black rock

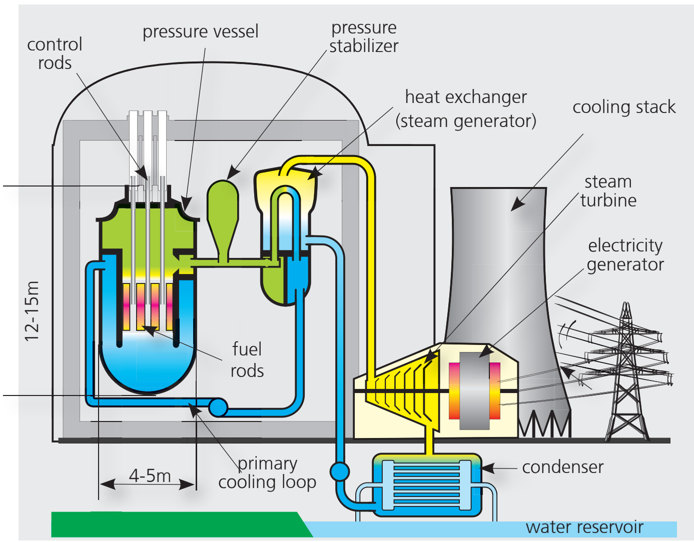


8. Nuclear power reactors and their safety features

8.1. Reactor types

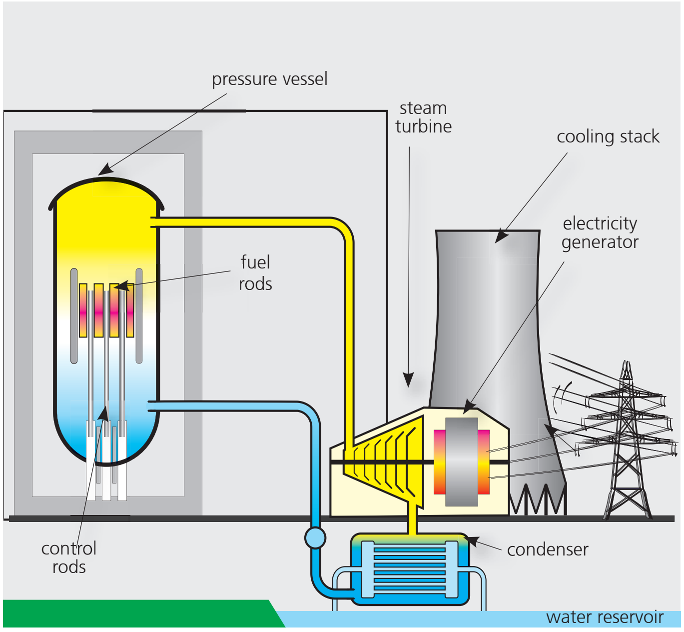
Contrary to common opinions, general layout of a nuclear power plant (NPP) does not differ much from general layout of a conventional power plant. Of course source of heat necessary to produce steam is not any coal/oil/gas-fired boiler, but a nuclear reactor.

Two light water reactor types are most popular in present-day NPPs:
(i) Pressurized Water Reactors (PWR) and (ii) Boiling Water Reactors (BWR).



Layout of a Pressurized Water Reactor NPP

Water inside PWR reactor core primary cooling loop heats up to a temperature of about 330°C. However, a relatively high pressure (about 150 times atmospheric pressure) maintained inside that loop prevents water against boiling. The pressure is stabilized by means of a pressure stabilizer: its vessel is additionally heated up if the pressure has dropped too low, or the vessel drop off valve is opened if the pressure has risen too high. If the pressure needs to be lowered even more, some cold water is injected into the stabilizer. In heat exchanger (**steam generator**) the primary loop water heats up water circulating the secondary loop (maintained at a much lower pressure) to a temperature sufficiently high to convert it into high pressure steam suitable to drive steam turbine coupled with electricity generator. Used (depressurized) steam is condensed in a condenser and the water is pumped again into the heat exchanger. The steam condensation process is assisted by cold water stored in a reservoir.



Layout of Boiling Water Reactor NPP

BWR reactor directly produces steam necessary to drive the power unit steam turbine. The steam collects at the top of the reactor pressure vessel. Since the chain reaction runs predominantly at the bottom part of the BWR reactor core where there is enough water molecules to efficiently slow down (moderate) fast neutrons, control rods must be inserted from below (besides, they would not survive long if operated in hot & wet steam environment). Before entering the turbine, the hot and wet steam (about 76 times atmospheric pressure, 285^{0}C) is dried. BWR reactors are simpler to build than PWR ones (single cooling loop rather than two loops), but require some shielding of their turbines because turbine working medium is contaminated with short-lived activation products from the reactor core (mainly ^{16}N that decays in seconds, so the turbine chamber may be entered already about 2 minutes after turbine shut-down).

Other than light water-moderated/water-cooled reactor types are also possible, to name for example gas-cooled reactors, liquid-metal-cooled reactors, or reactors employing heavy water as the moderator. However, we are not going to discuss those mostly experimental types in this popular brochure. Let us just say that about 2/3 of total 370 GWe electric power delivered in 2011 by NPPs all over the world were produced by PWR reactors, and about 20% by BWR reactors.

Regardless of reactor type, the most important issue that must be scrutinized in detail is reactor safety.

8.2. Safety systems

Hazards related to operation of nuclear facilities have been analysed with utmost care since the time first such facilities appeared. Steps taken to protect personnel and population against consequences of possible failures are grounded on an assumption that risks of running NPPs must not be higher than then risks associated with other electric power generation technologies. 50 years of practice have also enabled us to acquire vast experience in all matters related to radioactive waste management.

General safety principles that must be observed during development and operation of any nuclear facility include[11]:

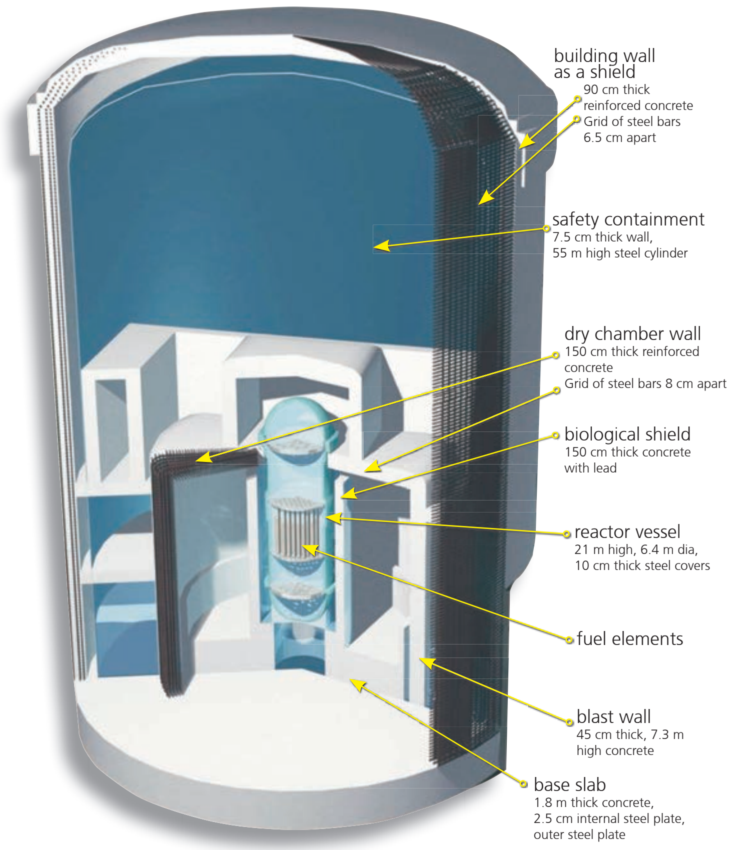
- Design of each individual facility must guarantee its reliable, continuous and easy operation, in which an overriding rule is "first of all to prevent accidents". One of the most basic rule inculcated to all NPP employees is that safety is more important than any electricity production schedule.
- Design must follow the "defence in depth" principle: multitude of defence levels, multiple barriers preventing release of radioactive materials. Probability of each failure (or combinations of failures) that could give rise to any serious consequences must be reasonably minimized.
- Technical solutions neither practically verified in other previously operated facilities nor experimentally verified must not be used.
- Design and operational instructions of each individual facility must take into account operators' mistakes potentially possible at every stage of operation of the facility.
- Design must keep exposition of facility personnel to ionizing radiation and risk of releasing radioactive materials into the environment as low as reasonably possible.

Multiple safety barriers built into nuclear reactors are depicted on the next figure, where a typical BWR reactor is shown as an example. The first barrier looking from inside is built into fuel elements themselves (element construction is optimized to stop fission fragments and to prevent their leaking outside). The so-called reactor "safety containment" and reactor building reinforced concrete walls are the outer barriers.

Reactor designers strictly adhere to the safety system redundancy principle. Each redundant safety system must be based on another physical law/principle (such as gravitation, convection, pressure difference etc.) so that no single failure could make them all simultaneously inoperative. Safety systems based on such simple physical phenomena are known as **passive safety systems**. Currently developed 3rd generation reactors are fully equipped with such passive systems and are therefore extremely reliable: calculated probability of reactor core overheating is less than once per one hundred thousand years of operation. No other industry meets so stringent safety requirements. Reactor safety is no more any problem in state-of-the art constructions. Undoubtedly, the to-be-deployed in Poland reactors will meet those high safety standards regardless of which vendor will be selected to deliver them.

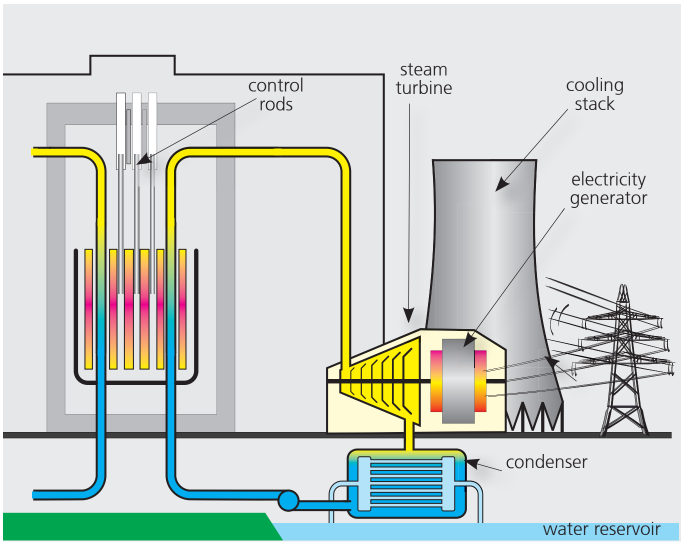
In that context the question of the catastrophic Chernobyl accident that occurred in 1986 may naturally be asked. Not going into intricate details, it must be pointed out that the RBMK-type reactors were designed with military applications in mind (although the one deployed in Chernobyl was not used for such purposes, as far as we know). Their construction would not be approved as safe to operate (even that time) in any other country than former Soviet Union. The Chernobyl accident resulted also from numerous mistakes made by operators of the reactor. Ukrainian and Lithuanian RBMK reactors have been afterwards decommissioned. Nevertheless, a few reactors of similar construction with some of their safety features corrected are still operated in Russia.

[11] After A. Strupczewski, Let us not fear nuclear power, in Polish, COSiW, Warszawa 2010.



Multiple safety barriers built into nuclear reactors (a typical BWR reactor is shown as an example)
www.nei.org/resourcesandstats/Documentlibrary/Safety-and-Security/graphicsandcharts/multiplelayersofsafetyatnuclearpowerplants

It must be pointed out that no nuclear reactor can ever explode like an a-bomb. During all past accidents (like those in Chernobyl or Fukushima) we witnessed chemical explosion of steam and hydrogen.



Layaut of a RBMK reactor NPP

Rate of work-related accidents may be a measure of overall safety of nuclear power industry. For example, in US rate of accidents that force some limitation of access of the worker to work or force him/her to change occupation altogether is much lower in nuclear power industry than in housing construction industry.

Vulnerability of NPPs to terrorist attacks (e.g. consequences of an airplane strike into reactor building) is another often raised issue. However, present day safety standards applied to reactor building walls sufficiently protect such facilities. It was experimentally verified that building damage caused by a striking airplane was insignificant while the airplane got totally disintegrated. Alike, no other terrorist attack can seriously put any reactor in jeopardy since nuclear facilities are designed and constructed with exceptional care regarding physical security.

8.3. Power reactors of to-day and of to-morrow

Germany, Italy, Japan and Switzerland have verified their approach to nuclear power after the Fukushima accident in March 2011. Germans intend to decommission their plants before 2022, Japanese – before 2030, Swiss – before 2034. However, governments of as much as 60 countries asked in 2011 International Atomic Energy Agency to consult their programmes to develop new NPPs. US have not been developing new power plants since the Three Miles Island accident in 1979. However, US Nuclear Regulatory Commission issued in 2011 their first new licences for reactors. Countries, in which new NPPs are to be commissioned still in 2012 include Belarus, Bangladesh, Arab Emirates, Turkey, and Vietnam.

According to World Nuclear Association, 436 power reactors were operated in the world as of 2011. 63 power reactors are under development, 152 are planned for the nearest decade, 350 are planned for a more distant future. As you can see, nuclear power industry is currently being rather revived in spite of unanimously negative decisions of the above mentioned 4 countries. Respective figures for EU/China/India are: 13/14/20 operational, 4/27/6 under development, 16/51/17 planned power reactors. Of course some currently operated reactors will have to be decommissioned in the coming decades, so total output of nuclear power industry will not grow as much as the number of new reactors might suggest.

Why nuclear power industry seems to be revived in spite of the Fukushima accident (even Japanese themselves do not back up)[12]? The answer is quite simple: it's just a matter of costs. After the Chernobyl accident the Swedish government declared that Sweden would close down their nuclear power programme. However, to-day they rather are expanding their nuclear power industry. Nuclear power is just competitively cheap and has several advantages from the environment protection point of view.

9. Can we safely live with reactor-emitted radiation?

9.1. Nuclear power plant accidents

Operation of every nuclear facility – as any industrial facility – is accompanied by some small probability risks, including risk of reactor failure, risk of liberating radioactive substances to the atmosphere, risk of environment pollution in result of incorrect nuclear waste management, or risk of spreading fissionable/radioactive materials. It is difficult to assess exposition of individuals on consequences of such accidents since the involved risks do not belong to the category of voluntarily accepted risks such as the risk of participating in a traffic accident you are accepting at the

[12] Two new reactors are to be commissioned soon in Japan.

moment you get on a car to travel a highway. The involved risks may be estimated by number of death casualties per unit of produced energy. That ratio estimated for coal mining or oil/gas drilling industry plus conventional power generation industry plus consequences of air pollution resulting from combustion of fossil fuels is about 40 times higher than the ratio estimated for uranium mining industry plus nuclear power generation industry including waste management and decommissioning of totally depreciated plants.

Death casualties following large industrial catastrophes of the 20th century were counted in thousands. Overtopping of the Vaiont Dam (Italy, 1963) claimed 2 000 casualties; poisonous chemicals leaking from a Bhopal (India) pesticide plant in 1984 instantly killed several thousand people, number of aggregated casualties reached 200 000; failure of the Baiqiao Dam (China, 1975) was a cause of death of 171 000 people. For comparison, the worst disaster in the entire history of nuclear power, namely fire of the Chernobyl reactor (1986), claimed lives of 31 rescuers, including 28 who died within a few days because they were exposed to lethal doses of radiation. Another 19 members of the rescue team died before 2010, several children died of thyroid cancer. About 6 700 new thyroid cancer cases were noted, however none of them turned out to be mortal.

Natural disasters may sometimes claim much more human lives. Tsunami on the Indian Ocean in 2005 claimed lives of about 300 000 people. Tsunami that destroyed the Fukushima NPP in March 2011 claimed lives of about 20 000 people. However, much less is talked about those casualties than about the destroyed reactors and the increased radiation level in the area around the plant even if nobody was injured nor lost their life because of the nuclear power accident itself or the aftermath radiation.

Some estimate that the entire US nuclear power programme has increased the radiation risk by amount comparable to consequences of a hypothetical rise of car speed limit from 80 to 81 km/h.

9.2. Radiation hazards A few words on radiophobia

Ionizing radiation (alpha, beta, gamma, X-rays, neutrons) may indeed be dangerous for human health since it is capable to produce free radicals following radiolysis of water molecules. Free radicals may change cell chemistry and/or genetic information stored in DNA. In severe cases cells may degenerate to cancer cells, including fatal cancers. Tens of years of "black PR"on such notions as atom, isotope, ionizing radiation etc. effected many societies who have established more or less intense radiophobia, consisting in an irrational fear against ionizing radiation. Such a fear is easy to induce and easily persists since ionizing radiation cannot be seen, felt, tasted etc. - nevertheless it may indeed be dangerous. The reasons for such situation include:

- We have been understanding ionizing radiation for just about 100 years. There were times when people feared comets and Sun eclipses, but nobody fears them now, several hundred years after they have been explained. People generally fear unknown.

- Poor general education.

- Nations vividly remember that a-bombs dropped in 1945 during World War II on Hiroshima and Nagasaki killed about 200 000 people and almost completely destroyed both cities. However, the fact that radiation-based nuclear medicine methods have saved millions of human lives since then is ignored.

- Lack of knowledge that people are constantly exposed to small doses of natural (background) radiation, which does not do any harm. As a matter of fact there are theories that such small doses are beneficiary to human immunologic system. Radiation is not dangerous unless doses are a couple of orders of magnitude higher.

Biological effects of ionizing radiation depend not only on the **absorbed dose** measured in **greys** (1 Gy = 1 J/kg), but also on "quality of radiation" i.e. radiation type (not every type ionizing radiation ionizes matter identically). To account for biological effects, each radiation type has been assigned some factor indicating how much it is biologically more effective than the gamma radiation (for which the factor is by definition equal to 1). Absorbed dose multiplied by that factor is referred to as **equivalent radiation dose**. The latter is measured in siverts (1 Sv = 1 J/kg)[13].

Average background radiation level on Earth (cosmic rays, crest-originated radiation, natural radioactive isotopes in our bodies) amounts to about 3 mSv/y, equivalent to about 15 000 particles/photons crossing our body in each second. Nobody can claim that "massive attack" does any harm to us, our life expectancy has been steadily rising. Well, radioactive isotopes emitted to the atmosphere by every operated NPP rise radiation level around the plant by 0.01 mSv/y i.e. by 0.3% of the background radiation. Can such an increase do any harm to people living nearby? Not at all. From time to time someone is publishing an alarming report that the number of (for example) leukaemia in children living nearby a NPP has risen. Such reports must be treated very sceptically as not confirmed by any analyses conducted by serious scientific societies such as COMARE.

Of course the situation changes radically if any of the NPP reactors seriously fails. Insufficient cooling of reactor core may give rise to production of hot wet steam which chemically reacts with zirconium cladding of fuel elements to produce zirconium dioxide and free hydrogen. Both high-pressure steam and hydrogen-oxygen mixtures may explode. Just that scenario was realized both in Chernobyl in 1986 and in Fukushima in 2011. Sudden rise of the temperature may melt the reactor core down, while an explosion means dispersion of huge amounts of radioisotopes into the atmosphere. People residing close to the explosion site may receive in a short time doses on the order of several Sv which may kill them within a few days. Just that happened to 28 members of rescue team who strived to put down fire in the Chernobyl power plant. However, nobody was harmed (not to mention death casualties) by radiation emitted during the Fukushima accident.

Atmospheric currents may transport large quantities of radioisotopes liberated from a damaged reactor to large

[13] Both units, grey and sievert, measure the same physical quantity: energy deposited by ionizing radiation per unit mass of the matter it interacted with. The difference is however in biological effects of the radiation. X [J/kg] deposited by alpha radiation will produce 20 times stronger biological effects then X [J/kg] deposited by gamma radiation, so the alpha absorbed dose will be X [Gy], while the alpha effective dose will be 20·X [Sv].

distances. Of special concern is the ^{131}I radioisotope that sublimes very easily and therefore is most quickly dispersed by means of atmospheric circulation. Iodine is preferentially absorbed by thyroid gland. If thyroids in the exposed population are not saturated (by means of administering some stable iodine isotope) very soon after the accident, the ^{131}I radioisotope may occupy the gland and in extreme cases cause thyroid cancers (mainly in children).

Radioactive fallout would give rise to soil contamination with such radioisotopes as ^{137}Cs, ^{90}Sr and others. Milk given by cows grazed on contaminated meadows would be contaminated. In effects children who drink plenty of milk would be among the most exposed. For sure one must not disregard such potentially serious effects of potential extreme reactor accidents. However, as the Three Mile Island accident (USA, 1979) has shown, not every serious accident must produce harmful consequences for people and environment. Core of that reactor melted down, but even so nobody of the power plant personnel nor of the Pennsylvania inhabitants suffered.

History shows that consequences of radiophobia (i.e. of irrational, panic fear against radiation) may be much more serious than direct consequences of a radioactive cloud. Such a fear paralysed many people in Europe after the Chernobyl accident and resulted in plenty of unreasonable decisions on abortions (some estimates say about as much as 100 000 cases). Authorities of some countries have set too low thresholds above which radiation was deemed harmful and that way became responsible for killing out herds of reindeers in northern Sweden and Lapland, which deprived inhabitants of those territories of their natural food. Ukrainian authorities commanded unnecessary displacement of about 130 000 inhabitants out of the 30 km radius zone around Chernobyl.

This subject of radiophobia is fascinating by itself and we could give many other examples. One is particularly vivid. Let's start with the following reminder: unit of activity is 1 Bq (**bequerel**) = 1 radioactive decay per second. A bag of chips (400 g) contains about 1 300 Bq activity (for comparison activity of 1 litre of milk is about 45 Bq, of your entire body - 8 000 Bq). If you ate 1 bag of chips per day you would receive a dose (above natural background) higher than the dose (above natural background) which would have received each inhabitant of a larger part of the evacuation zone around the Fukushima failed NPP provided they would not have been evacuated.

Current estimates show that consequences of the Fukushima accident will be at least several times less significant than consequences of the Chernobyl accident, in particular no increase in number of cancer cases is to be expected. Comparing two accidents one must also point out how quickly and openly Japanese authorities informed the nation on the occurred situation. Japans treated (as usual) information published by their authorities as trustworthy since the government-society relations in that country are based on mutual trust. Besides, the Japanese society is constantly taught to rationally react to natural disasters (like earthquakes) frequent in that part of the globe. On the other hand, Soviet authorities were for a relatively long time hiding the news on the Chernobyl accident.

German government decision to abandon nuclear power is an utterly particular case of radiophobia. That decision will cost Germans billions of Euros in higher bills for energy imported from France and Czech Republic, may be in the future also from Poland. Development of solar/wind power becomes sooner or later very expensive for taxpayer. Necessity to increase imports of gas from Russia may additionally make Germany energy-dependent on Russia.

Let's make some analogy. Undoubtedly society should be protected against negative consequences of air/water pollution. However, each action must be reasonable. In pursuit of an unreasonably high purity of tap water we might easily reach so high price of the water, that people would cease to use it for sanitary purposes. That would of course end up in a catastrophe.

Approximately 50 persons lose their lives every week in traffic accidents occurring on Polish roads. That makes about 2 500 casualties per year only in Poland[14]. Even such pretty high numbers do not stop millions of drivers who every day get on their cars. However, should 1% of those people suffer in result of a nuclear disaster, reactions of the public in the whole nation (if not the world) would be incredibly vigorous.

As a matter of fact doses established by some administrations as maximum permissible levels are unreasonably low, about 1/3 of doses from natural background radiation. That would be nothing bad if costs of radiation protection required by such regulations would not be extraordinarily high in relations to debatable benefits. Regulations in many countries require protection against ionizing radiation at the 1 mSv/y level for general population even if background radiation in those countries contributes several or even a few tens of mSv/y. This might be compared to an obligation imposed on inhabitants of a subtropical region to equip wheels of their cars with winter tyres and snow chains.

Inevitably the following question comes in mind: how much are we ready to pay for even illusory safety feeling?

10. Nuclear waste

Nuclear waste is a particular issue if the nuclear power technology is concerned. Nuclear waste is produced during operation of any nuclear reactor mainly as products of fission reactions (fission fragments).

Number of neutrons in an uranium nucleus (143 or 146) is much higher than number of protons (92), therefore uranium isotopes are long-lived ($T_{1/2}$ = 4.5 billion years for ^{238}U, 0.7 billion years for ^{235}U). Fission fragments are much less stable.

Neutrons absorbed by nuclear fuel may also produce trans-uranium (Z>92) radioisotopes, in particular fissionable ^{239}Pu (Z=94). That plutonium may be used as fuel in breeder reactors (see uranium-plutonium fuel cycle in Annex 2, "Fuel cycle"). That same plutonium isotope is produced also in PWR reactors, where its contribution to the final reactor thermal output is moderately high. A particular care must

[14] Word Heath Organization reports that over 1.2 million persons dies each year in traffic accidents, while the number of injured reaches 50 million/year. Age of majority of victims spans the 15-44 years range. By 2020 the number of casualties is going to increase by 60%. Traffic-related mortality rate in Western Europe is 11 deaths per year per 100 000 inhabitants (28.3 in some African countries, for comparison).

be exercised during storage of plutonium since the isotope is useful for military applications (although those applications are not at all as straightforward as someone might expect).

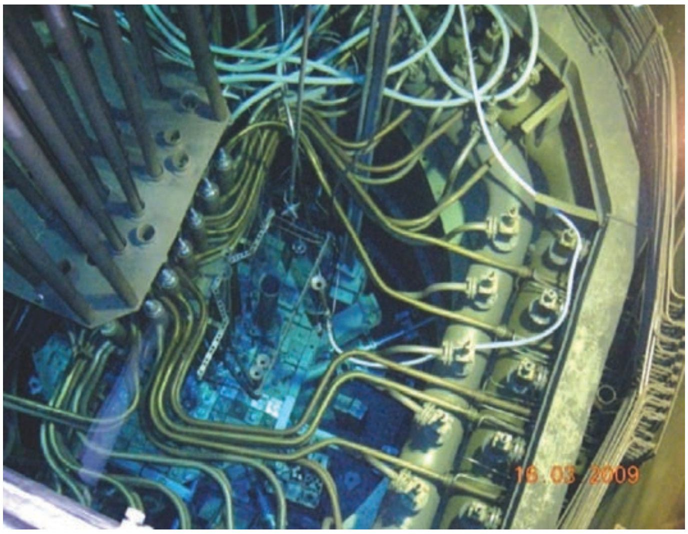
Also constructional materials in the vicinity of a reactor core activate during operation of the reactor[15]. ^{60}Co radioisotope is a typical product of such activation. Constructional materials finally become then some nuclear waste that must be properly managed.

Let us look at typical products of ^{235}U fission, paying particular attention to their $T_{1/2}$ half-life times. Long-lived isotopes found in spent fuel are listed in a separate table shown on next page.

Typical ^{235}U fission fragments
(after T. Jevremovic, Nuclear Principles in Engineering, 2nd Edition, Springer, 2009)

Element	Mass number	$T_{1/2}$	Yield (%)
Strontium	89	51 days	4.8
Strontium	90	28 years	5.8
Yttrium	91	58 days	5.4
Zirconium	95	65 days	6.3
Ruthenium	103	40 days	3.0
Ruthenium	106	1 year	0.4
Antimony	125	2.76 years	0.02
Tellurium	127	109 days	0.04
Tellurium	129	31 days	0.35
Caesium	137	30 years	6.2
Cerium	141	33 days	6.0
Cerium	144	285 days	6.0
Promethium	147	2.6 years	2.4
Samarium	151	90 years	0.44

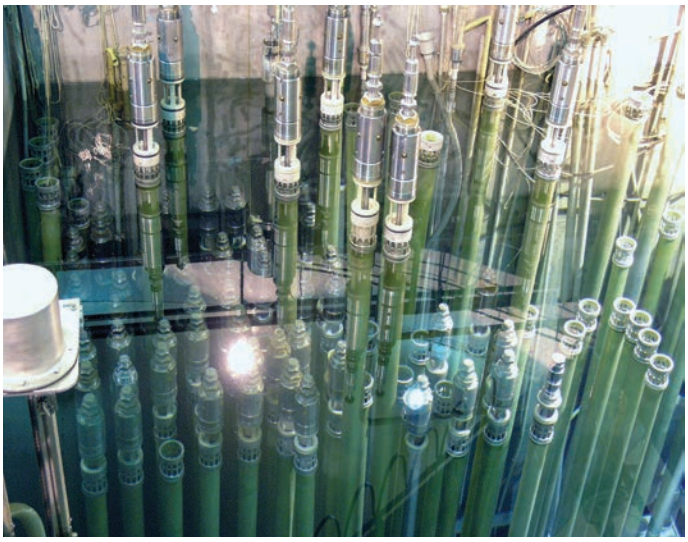
Management of nuclear waste (in particular spent fuel) is an essential technical problem that must be solved if nuclear power technology is to be deemed fully safe and accepted by public.



The MARIA research reactor operated in National Centre for Nuclear Research (NCBJ) in Świerk. Light blue glow seen deep inside the reactor core is the Cherenkov radiation

Contrary to coal/liquid fuel/gas fuel, nuclear fuel never "burns" completely. It's because the fuel gets "poisoned" with time: during operation reactors produce also many different nuclei that strongly absorb neutrons. Typical example is ^{135}Xe. The nuclei accumulate with time in the fuel elements and prevent chain reaction. Such fuel elements may not be used any more as fuel, they become high-activity nuclear waste. Unfortunately life-time of some of the fragments produced in fission reactions is on the order of tens of thousands years, so that the spent fuel remains dangerously active for a really long time. Because of that, management of nuclear waste is an essential social, political and economic issue. Fortunately, a typical 1 000 MW_e NPP produces annually just 3 m^3 (about 27 tonnes) of high-activity waste; that activity drops 1 000 times after just 10 years. Some industrial waste including plastics, eternit (asbestos-cement roofing materials), some chemicals, scrap metals etc. may survive much longer.

Decaying radioactive nuclei in fission fragments produce heat. Therefore freshly spent fuel element are first stored in storage water pools to cool them down. With time their



Spent fuel immersed in water of the MARIA reactor storage tank

Left: cask for shipments of spent fuel. Right: canister for glazed spent fuel (typical height 1.3 m, diameter 40 cm)

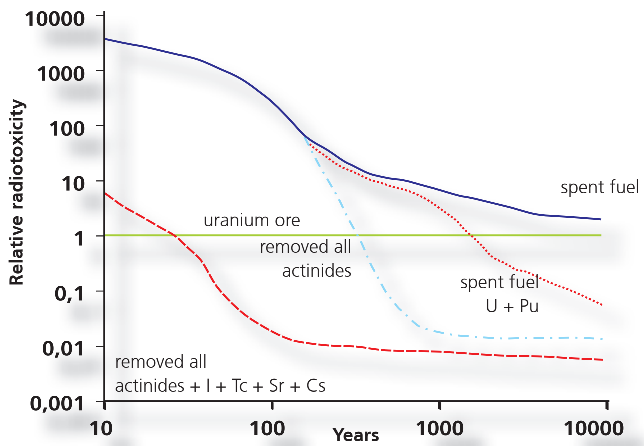
[15] To activate a material means (in our context) to irradiate it with neutrons. Neutrons absorbed by material nuclei give rise to nuclear reactions. After some activation time some radioactive isotopes appear additionally to stable isotopes of which the original material was built.

Casks used to ship spent fuel from EWA and MARIA research reactors in Świerk

activity drops. If no recycling of the waste is planned (see below), it is stored inside of a water pool localized at NPP premises for 20-50 years. For another 30-50 years the waste is next stored in a "dry" bunker in a gaseous atmosphere. Finally the waste may be buried inside a special underground radioactive waste repository (storage yard), which might be arranged for in a former salt mine, loam deposits, or granite rocks.

However, an alternate scenario is also possible: **recycling** of spent fuel. After a few years of cooling down in water (in the reactor storage pool) spent fuel may be shipped to special processing plants where it may be chemically processed to separate fissionable elements (uranium and plutonium that may be used to manufacture fresh fuel elements) and some economically valuable isotopes (e.g. rare earth radioisotopes). About 3% of the starting mass remains, generally in the form of a liquid. The residues are glazed (vitrified), packed into large metal casks (see photos), and shipped to a radioactive waste repository. Vitrified fission products form some oxides of a structure typical for glass. Such glass is very resistant for washing away and sufficiently durable: its properties do not change during the entire time needed for the activity to decay. Unfortunately the glazing procedure is not commonly applied since it requires a very advanced technology and is expensive.

Spent fuel processing plants in France, UK and Belgium produce about 1 000 tonnes of glazed nuclear waste per year (2 500 canisters each of 400 kg). A 1 000 MW_e nuclear reactor produces 5 tonnes (12 canisters) of such glass per year. Such quantities are relatively easy to transport and store behind necessary shields. Long-lived isotopes found in spent fuel are listed in the table below, while influence of spent fuel processing on radiotoxicity of highly active waste produced in nuclear power reactors is charted on the figure below.



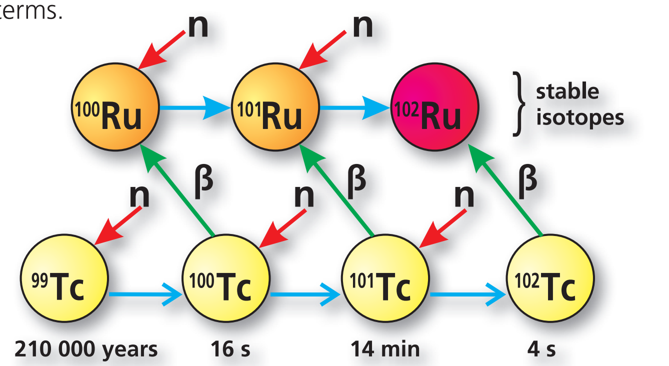
Influence of spent fuel processing on radiotoxicity of highly active waste produced in nuclear power reactors *(after G.J. van Tuyle et al., Nucl. Tech. 101 (1993) 1)*

Long-lived isotopes found in spent fuel		
Isotope	$T_{1/2}$ (years)	Radiotoxicity (Sv/kg) [after GSI-Nachrichten 2/99, p.15]
^{99}Tc	$2.1 \cdot 10^5$	$4.9 \cdot 10^2$
^{129}I	$1.6 \cdot 10^7$	$0.7 \cdot 10^3$
^{135}Cs	$2.3 \cdot 10^6$	$0.8 \cdot 10^2$
^{237}Np	$2.1 \cdot 10^6$	$0.3 \cdot 10^4$
^{238}Pu	88	$1.4 \cdot 10^8$
^{239}Pu	$2.4 \cdot 10^4$	$0.6 \cdot 10^6$
^{240}Pu	$6.6 \cdot 10^3$	$2.1 \cdot 10^6$
^{242}Pu	$3.7 \cdot 10^5$	$0.4 \cdot 10^5$
^{241}Am	432	$0.3 \cdot 10^8$
^{243}Am	$7.4 \cdot 10^3$	$1.5 \cdot 10^6$
^{244}Cm	18	$0.5 \cdot 10^9$

As you can see, spent fuel from which all actinides[16] and basic fission fragments were removed would need to be stored only for a couple tens of years i.e. would present no storage problem. For that reason the so-called P&T (Partitioning and Transmutation) technology capable to extract plutonium, minor actinides[17] (in particular Am and Cm), rare earth, and some other long-lived fission products (see the above table) and to transmute them into other short-lived or stable isotopes is devoted much effort regardless of efforts devoted to arranging for geologic storage yards for nuclear waste. However, it is a technology of the future. It may be difficult to believe that glazed portion of nuclear waste remaining after producing energy sufficient to satisfy lifetime needs of a statistical man fits in a handful.

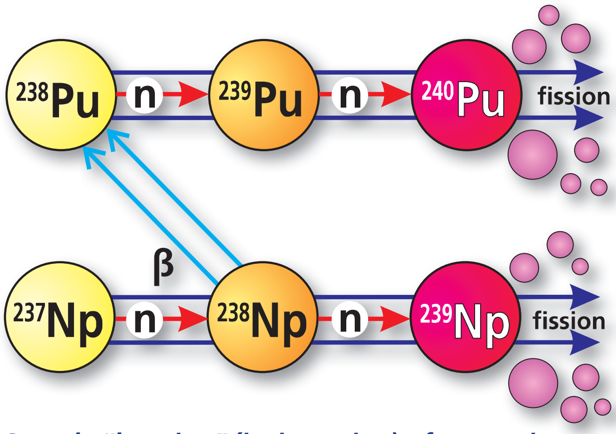
11. Will we be able ever to "burn" radioactive waste?

Let us define first what is the meaning of the "burning radioactive waste" and "transmuting radioactive waste" terms.



Sample transmutations of the long-lived technetium isotope

[16] Actinides are 15 radioactive metals distinguished in the Periodic Table of Elements. Each of them takes the same position in the table as the actinium, metal after which they have been named. Of these metals, only thorium, protactinium, and uranium may be found in Earth crest since their half-life times are comparable to the Earth age.
[17] Minor actinides are actinides excluding U and Pu.

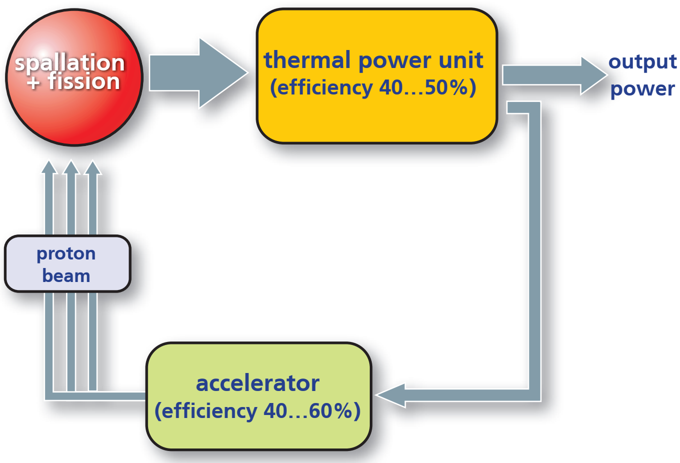


***Sample "burning" (incineration) of neptunium and plutonium After W. Gudowski,** Royal Inst. Techn. Stockholm, Sweden*

Transmutation is conversion of one isotope into another isotope in result of absorbing a neutron. We are interested in transmuting long-lived radioisotopes into short-lived or stable ones. We talk about "incineration" if the resulting isotope undergoes fission into some stable isotopes. Sample processes depicted in the above figures must be initiated by fast neutrons (energies on the order of MeV).

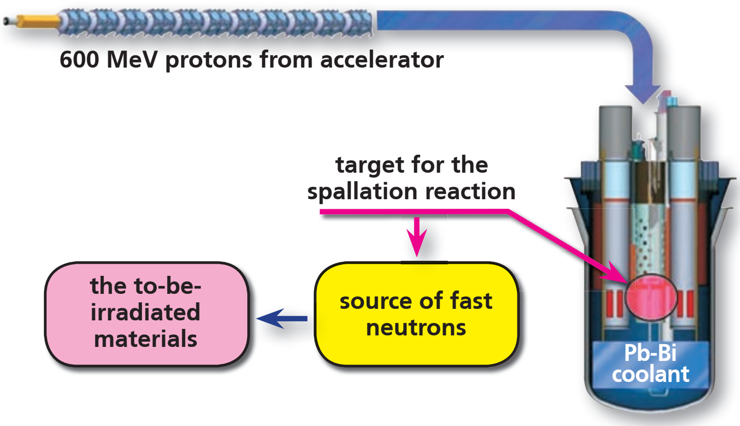
Both mechanisms are currently very intensely researched. Fast neutron reactors and accelerator-driven reactors give some hopes that we will be able to convert both already accumulated and future-produced nuclear waste into some short-lived isotopes that are significantly easier to manage.

"Energy amplifier" (do not take that term too seriously) is another idea proposed at the turn of 20th and 21st century by Professor Carlo Rubbia from CERN (Switzerland). It is based on the so-called spallation reaction induced in heavy nuclei (e.g. lead) by protons accelerated to very high energies on the order of 1 000 MeV. In collisions with protons of such a high energy heavy nuclei are just crumbled into many tiny pieces, including a large number of free neutrons. This high intensity flux of fast neutrons may be used in a subcritical reactor to convert ^{232}Th into fissionable ^{233}U (the **thorium-uranium cycle**) and to "burn" nuclear waste. Ratio of fission-produced energy to the energy necessary to run the accelerator may reach even 15, which explains the "energy amplifier" term coined for marketing purposes.



The "energy amplifier" concept

Sub-criticality of the reactor guarantees safety of that hybrid system: it is enough to turn the accelerator down to stop the chain reaction running within the reactor core. Besides, the thorium-uranium cycle does not produce any military grade plutonium at all, while quantities of trans-uranium isotopes produced in the system might be two or three orders of magnitude lower than quantities produced in the currently operated "ordinary" nuclear power reactors. To demonstrate usability of the concept, a 1-10 mA proton beam and a target capable to generate power above 1 MW are needed, both integrated with a sub-critical reactor core. Research on **accelerator-driven systems (ADS)** is currently conducted in Europe, Japan, Korea, Belgium, Russia and US. Such systems may be demonstrated in a not-far distant future, especially as a result of the Belgian MYRRHA project. Layout of the proposed system is shown in the below figure.

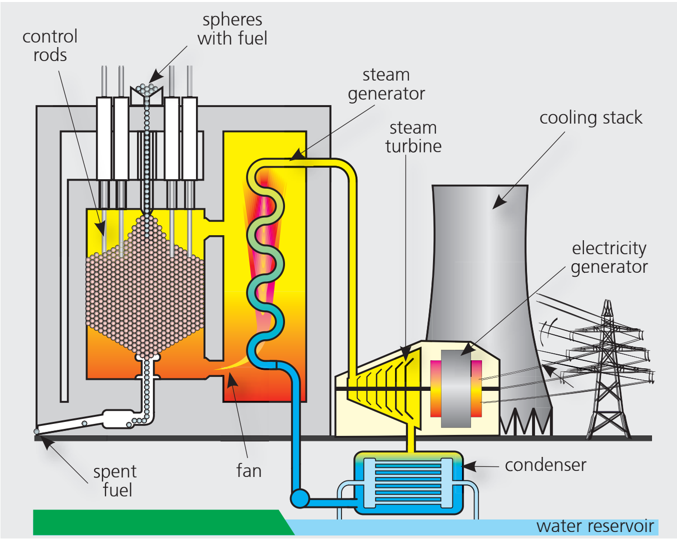


Reactor output 50-100 MWth in subcritical state, around 100 MWth in critical state

Two other innovative approaches include Inert Matrix Fuel and High Temperature Gas Reactors.

New fuel type is tested since plutonium isotopes by-produced during operation of "classical" uranium-"fired" reactors pose a serious problem. **Inert Matrix Fuel** consists of grains of fissionable ^{235}Pu dispersed within a chemically simple inert matrix (e.g. silicon carbide or magnesium oxide). Pay attention that no ^{238}U isotope is present. That latter isotope does not undergo fission in flux of thermal neutrons which is the main source of ^{239}Pu. New fuel type gives hope to gradually get rid of an excessive stock of dangerously poisonous, military-grade plutonium accumulated all over the world. Currently operated NPPs and spent fuel processing plants produce about 100 tonnes of plutonium each year, of which quantity only a small portion is used to manufacture the so-called **MOX fuel** (mixed oxides, a mixture of uranium and plutonium oxides). Stored plutonium must be very reliably protected due to its potential military applications and extremely high toxicity. Inert matrix fuel could also give a chance to "burn" minor actinides (Am, Np, Cm). It is hoped that 4th generation future reactors will be based on such fuel.

The thorium-uranium cycle is employed in the future HTGR *(High Temperature Gas Reactors)*. Thorium is a much more abundant element on Earth than uranium. Flux of fast neutrons may convert thorium into the ^{233}U fissionable isotope. New features in the HTGR reactors in relation to ordinary PWR/BWR reactors include: different fuel in the form of spheres made of carbon ceramics containing fissionable material grains and a gas-cooling system. At outlet gas temperature on the order of several hundred degrees Celsius many chemical reactions become possible. Therefore HTGR reactors might be used to supply high-temperature heat to industrial installations used to desalinate sea water, to produce free hydrogen out of water, to gasify coal. Layout of such a reactor, in which the so-called pebble bed is slowly moving down as the fuel is "burning" is shown in the figure below. Not entirely spent fuel returns to be re-used. In fact reactors of that type belong to breeders, just the employed fuel cycle is not uranium-plutonium and the produced fuel is ^{233}U rather than ^{239}Pu.



Layout of a high-temperature reactor NPP

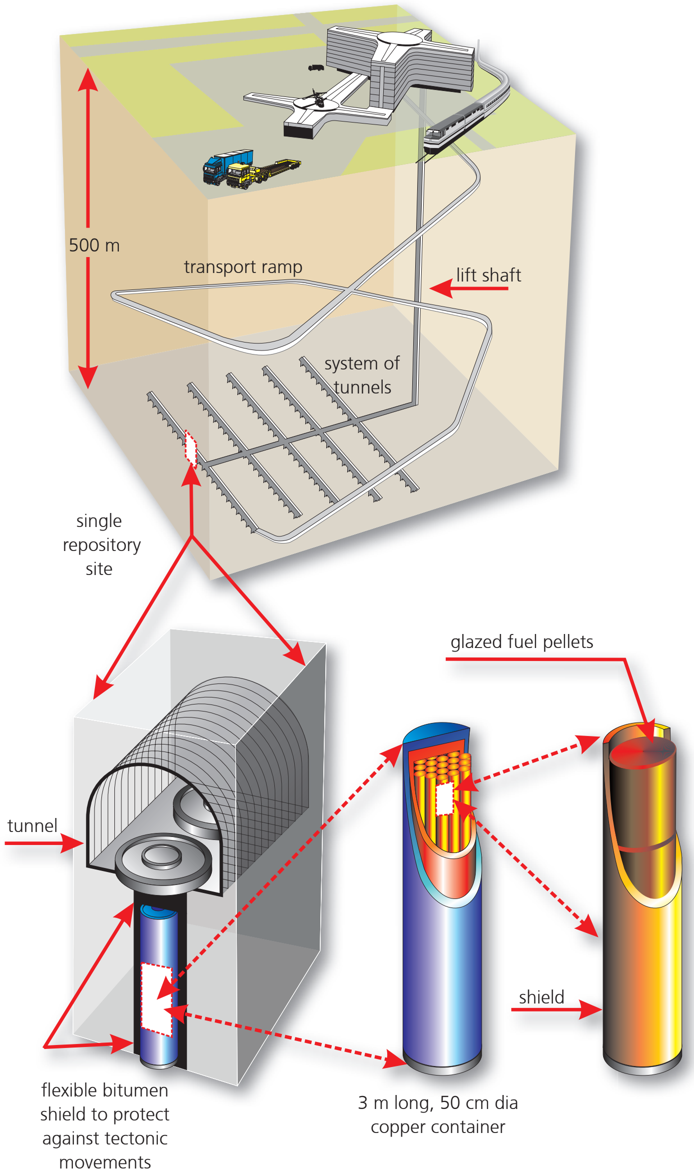
12. Radioactive waste vs. natural background

For increased safety, spent fuel and other long-lived high-activity nuclear waste are stored at the depth 400 - 2 000 m below ground rather than on the surface. Debates on hazards related to storage of nuclear waste produced by nuclear industry often neglect the issue that Earth crust contain pretty much natural radioactive isotopes, of which some are constantly diffusing towards the surface and contribute to background radiation in the environment. It may be shown[18] that all man-made nuclear waste accumulated before 2 000 and cooled down for 500 years will have an activity corresponding to natural activity contained in soil of the 30x30x2 km^3 volume (2 kilometres correspond to the depth of underground nuclear waste storage yards). In other words, the waste will in 500 years cease to be dangerous. Let us recall that much of our "normal" (industrial) waste (plastic containers, some chemical substances etc.) may survive in Earth crust for much longer periods.

Of course the whole nuclear waste issue could be much simpler to tackle provided a waste transmuting/incinerating technique is mastered. However, we can already now say that no nuclear waste buried deeply underground poses any threat to nearby inhabitants (unless someone will start to dig within the nuclear repository area). Nuclear waste repositories are safeguarded against such mistakes. Even if the safeguards were overridden, threat may be only local, but in no case global. Of course awareness of these circumstances does not exempt us from an obligation to take utmost care to keep the waste containers leak proof and that way to protect environment against radioactive substances stored within the containers. The glazing technology was developed to prevent spreading the substances even if they were penetrated by water (water is not able to dissolve glass).

Another approach worked out in Australia is to trap fission products into the **Synroc** ceramic, which is a synthetic rock containing a mixture of titanium dioxide (TiO_2), Ba-hollandite ($BaAl_2Ti_6O_{16}$) and perovskite ($CaTiO_3$). Fission products may be built into the rock crystallite structure. Trapping into such rocks is very efficient, waste content may attain 30% of the rock mass.

Pay attention that a typical 1 000 MW conventional power plant produces each year about 7 million tonnes of carbon dioxide, 200 000 tonnes of sulphur dioxide (both these gases strongly pollute environment), and 200 000 tonnes of ash containing quite large amounts of toxic metals and radioactive elements. Even in France (in which nuclear power programme is particularly well advanced) less that 1 kg of nuclear waste is produced per capita per year, to be compared with 14 tonnes of industrial waste including 140 kg of hazardous waste. Long-lived isotopes account for only 20-30 g in all that nuclear waste, including 10 g of high-activity waste.

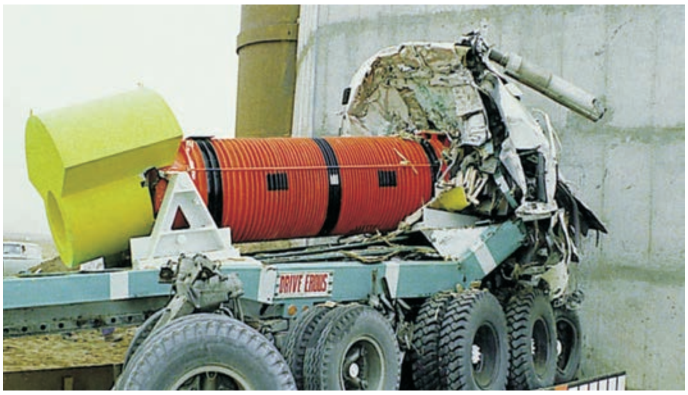


Layout of a typical nuclear waste underground repository
The copper container may also hold glazed recycled nuclear waste. Typical diameters in the Onkalo, Finland repository: vent shaft 5.7 m, tunnel 3.5 m, entrance ramp tunnel 5.5 m. Depth of the lowest level in Onkalo is 520 m. Combined length of tunnels at the 420 m level is 5.5 km, tunnel slope 1:10.

[18] Calculations by Professor Zbigniew Jaworowski †.

13. Transporting spent fuel

Contrary to stereotypes and sometimes alarming media releases, transport of spent fuel is not dangerous at all. About 3000 successful transport operations took place during last 40 years in US alone.



Crash test of shipment cask for spent nuclear fuel
Trailer loaded with a B-type cask of mass 22 tonnes was accelerated to velocity of about 100 km/h and crashed against a concrete wall of mass 690 tonnes http://www.sandia.gov/tp/SAFE_RAM/SEVERIJY.HTM

In US, nuclear fuel was transported by car/rail to a combined distance of 2.5 million kilometres and no single accident ever happened. European data are alike. Safety is provided partly by heavy (120 tonnes) steel transport cask (see photos of casks used to transport spent fuel from EWA and MARIA reactors in Świerk shown in section 10). Cask's walls are 50 cm thick (about 15 times thicker than walls of tanker trucks). Combined mass of the cask and its biological shield is three times as large as mass of the transported spent fuel. Casks are certified to survive (in a leak-proof state) half-an-hour duration fire, fall from 9 m on a concrete ground, piercing test, sinking test, collision with a jet airplane. Not more than 9 spent fuel elements are transported in a single cask. Recently cask design is being improved to guarantee that they might resists also a hypothetical terrorist attack.

14. Impact of nuclear industry on national economy

Impact of nuclear power industry on national economy is hard to overestimate. Not even taking into account increased job opportunities in local communities (about 800 employees per each NPP), jobs for several thousand people are indirectly at stake.

Nuclear industry calls for a higher level of school education all over the country and demands new higher education profiles. It is a source of orders for various R&D works that help to develop potential of universities/research institutes. It helps to improve education of general public.

Industry sectors stimulated by nuclear power industry include:

- civil construction
- heavy industries (high-pressure boilers/valves, turbines)
- precision machinery
- electric/ electronic control & monitoring apparatus
- chemical industry
- local catering, tourism etc.

Polish companies are already participating in construction of the Olkiluoto reactor in Finland.

Production of radiopharmaceuticals in so-called "hot cells" in NCBJ Świerk POLATOM Centre

Nuclear power industry stimulates advancement of medical sciences and services. NPPs may produce radioactive isotopes used in nuclear medicine. Such isotopes are currently produced by the MARIA research reactor operated in NCBJ Świerk.

Every power plant needs some infrastructure (transport means, buildings) and various services (office, finance, insurance etc.). Experience collected in South Korea (Nuclear Technology and Economic Development in the Republic of Korea, IAEA, Vienna 2009) showed that the decision to develop nuclear power in the country resulted in about 500% rise of production volume and revenues in several industry sectors. Besides, quality standards required by nuclear power industry are extremely high, so suppliers must develop a high work culture to comply.

Impact of nuclear power on limitation of consumption of fossil fuels and emissions of harmful greenhouse gases to the atmosphere is an essential issue for any nation. The issue is particularly significant in our country, in which electric power is produced almost entirely from coal.

Environmental costs of running a NPP are insignificant in comparison to operational costs. Reliability of supplies of power and high duty factor of nuclear power plants are also extremely important advantages. Suitably localized plant may supply some metropolitan areas with heat, which is a by-product from the electric power generation point of view. Such layout is referred to as co-generation of electricity and heat. Advantages of that approach have been pointed out by the 2004/8EU Directive issued in February 11, 2004 in the matter of co-generation. The technology was indicated as one of the best possible approaches to save primary energy resources and to limit CO_2 emissions. Heat for municipal CH systems that is co-generated in NPPs may be cheaper than heat produced traditionally, and its use may limit air pollution and greenhouse effects. However, costs to the final user depend of course on the distance, to which the heat would have to be transported.

Local taxes paid by power plants amount to millions of PLN annually. Such source of income usually means for local community (or even for the entire region) noticeably higher living standards, including better medical care, more crèches, nursery schools, schools etc.

The first NPP to be deployed in Poland will have to be purchased abroad. However, with time we can develop our own modern technologies. Development of nuclear power industry may in effect improve general work culture (and consequently improve quality of products) even in industry sectors seemingly distant from the nuclear power industry.

15. Impact of nuclear power plants on tourism

The issue that land value will depreciate and that tourism will decline is often raised by communities, in which some NPP is planned. Both concerns are expressed particularly strongly by communities, in which some amount of money have already been invested in tourism (vacation houses, agro-tourist farms etc.). Are such fears justified? Hardly. A nearby NPP usually increases land value by means of infrastructural benefits brought about by increased streams of revenues supplying budgets of all adjacent communities.

Three arguments against the hypothesis that tourism will decline may be brought forward:

- increased stream of community revenues
- only natural curiosity of people wanting to learn just how such a NPP looks like
- decreased unemployment rate.

A good practice is to run in every NPP an educational/ information centre. For the plant operator such a centre is a platform on which they may cooperate with local community and educate larger groups of visitors. Excursion to a NPP may be attractive for many people. The sole in Poland MARIA research reactor operated in Świerk is visited each year by over 6 000 persons. That number of visitors is limited by capabilities of the reactor staff, much more would-be visitors must wait for an appointment to visit. As exemplified by plants operated in Temelin or Dukovany (Czech Republic), nuclear power plants stir even larger interest of the public than research reactors. Predicted number of visitors to the Hinkley Point (Somerset county at the North Sea coast in UK) NPP under construction is 250 000 annually. And each tourist wants to eat, drink, find an accommodation - don't they?

Another issue is the open question of possible marring the landscape. Plenty depends here on invention of architects and their consultations with local inhabitants. Nevertheless, we should not expect any NPP to increase charm of the landscape (although of course it is a matter of individual aesthetic taste). To hire some artists who are capable to give individual, artistic character to conspicuous building structures as (in case of one of the Cruas NPP cooling stacks) seems to be an interesting initiative[19]. Anyway, potential aesthetic discord must be weighed against the above indicated potential community profits.

[19] See the *http://weburbanist.com/2010/07/18/nuclear-coverup-10-cool-examples-of-cooling-tower-art/* Webpage for more examples of decoration of civil engineering structures in nuclear power plants.

The "Aquarius" painting on one of the cooling stacksof the Cruas (France) NPP
Mural by Jean-Marie Pierret (March 2012)
http://fr.wikipedia.org/wiki/FichierCruasPaintingAquarius.jpg

Decorated cooling stack in the Soweto (South Africa) NPP
By permission of Mr. Duane Braund, author of the painting

The Vandellos (Spain) NPP is located next to a beach *(photo EN DESA)*

Platja de l'Almadrava beach in Vandellos (Spain) is an often cited example of a splendid coexistence of nuclear power industry and tourism. Tourists visiting that beach ignore the nearby nuclear plant (by the way, its architecture is rather pretty, see the photo), as well as stacks of a nearby gas-fired plant. About 1.5 million tourists visiting the Costa Dorada region where the beach is situated leave each year more than 400 million €.

Recently the not operated Bataan NPP located near a beach in Philippines was opened for tourists. The plant is not operated since the Marcos government that made the decision to develop it fell just after the Chernobyl accident. Rising high fear against nuclear power persuaded that time many decision makers to abandon numerous nuclear projects, just like the first Polish nuclear power once planned in Żarnowiec. As a matter of fact some critics of the Philippine project draw public attention to the fact that the Bataan plant was located too close to a tectonic fault line. However, plant operator (the Napocor company) claims that the plant has been designed to survive earthquakes that measure 9.0 on the Richter scale. Anyway, the built but not operated Bataan plant costs Philippine taxpayers about 10 000 USD per day. Napocor hopes that revival of tourist traffic will help not only to partially cover plant upkeep costs, but also to stir up confidence to it, and finally to reverse the decision to put it on hold. By the way, if the plant were operated, nobody would let any tourists to enter plant control room and to shoot there family photos.

There are more positive examples. Polish Senate's Office of Analyses and Documentation published in October 2009 a report clearly stating that development of nuclear power does not hamper tourism, but on the contrary it stimulates it in many cases. Excursions organized by operator of the Tihange NPP in Belgium attract tourists who take an opportunity to visit by the way that small historic town.

Entrance to Visiatome (France) *(source: CEA)*

The Visiatome didactic centre situated next to Flamanville (France) attracts tens of thousands tourists each year.

The Vysoky Hradek renaissance castle situated next to the Temelin NPP (Czech Republic) is surrounded by a landscape park with a collection of fish ponds established in 19th century. The castle is among south Bohemian objects most frequently visited by tourists. It houses NPP information centre featuring attractive exhibitions, interactive exposition devoted to nuclear energy, and a cinema theatre, in which spectators are presented with computer animations revealing all directly inaccessible places of the plant as well as presenting basic information on nuclear physic. An operational Wilson chamber is one of the centre's tourist attractions. The centre offers also Energy Mystic 3D popular movies.

Vysoký Hradek in Czech Republic *(photo. Pavel Kerner)*

NPP in Temelin (Czech Republic) *(source: energetykon.pl)*

For public relation reasons NPP in Olkiluoto (Finland) funded in December 2007 prizes and financially supported Finland's Championship in Figure Skating organized in Rauma, a town close to the NPP development site, as well as paid for renovation of 100 years old historic Finnish fisherman hut belonging to the local Satakunta region museum.

The OL 3 NPP in Olkiluoto (Finland) is built also by some Polish companies *(source: TVO)*

Showy illumination of a NPP in India

The Forsmark NPP Sweden *(photo. Hans Blomberg; http://www.world-nuclear-news.org)*

Conclusions of the above-mentioned report include the following statements: *No example in favour of the thesis that NPPs negatively influence tourism in their neighbourhoods has been found. On the contrary, the report has shown that presence of a NPP can stimulate tourist traffic (examples from Belgium, France, Czech Republic, Sweden). A positive impact of NPPs on development of adjacent communities has been evidenced.*

The Trillo NPP in Spain *(photo Víctor Guisado Muñoz)*

Organized in Visiatome exhibition on various forms of energy (source: CEA)

ANNEX 1:
Energy values of various materials

Nuclear reactions	Released energy (MJ/kg)
D-D (thermonuclear synthesis)	$3 \cdot 10^8$
Pure ^{235}U (fission by thermal neutrons)	$7.0 \cdot 10^7$
D_2O (D-D thermonuclear synthesis)	$3 \cdot 10^6$
UO_2 enriched to 2.5% (fission by thermal neutrons)	$1.5 \cdot 10^6$
Natural uranium (fission by thermal neutrons)	$5 \cdot 10^5$
^{210}Po (α decay $T_{1/2}$ = 138.4 days)	Power 200 W/g
^{238}Pu (α decay $T_{1/2}$ = 87.74 years)	Power 0.5 W/g

Various conventional energy sources	Released energy (MJ/kg)
Hydrogen	120
Methane	50
Fossil fuels	10÷50
Water fall (height 100m)	0.001
Various chemical batteries	0.1÷0.4
Spring	0.00016

Various fossil fuels	Combustion energy (MJ/kg)
Hard coal	20÷37
Brown coal	17
Coke	32
Timber (dry)	10÷15
Crude oil	40÷42
Petrol	41÷44
Heating oil	37÷42

1 MeV = 1 000 000 eV

About 4 eV is released in combustion of 1 carbon atom in oxygen

About 200 MeV is released in fission of a heavy nucleus

Thermonuclear reactions of fusion of light nuclei:

$$D + T \rightarrow \alpha + n + 17.58 \text{ MeV}$$

$$D + D \rightarrow {}^{3}He + n + 3.27 \text{ MeV}$$

$$D + D \rightarrow T + p + 4.04 \text{ MeV}$$

$$D + {}^{3}He \rightarrow \alpha + p + 18.37 \text{ MeV}$$ [20]

[20] Source: Egbert Boeker & Rienkvan Grondelle, Environmental Physics.

ANNEX 2: Uranium fuel cycle

Uranium fuel cycle consists of several distinctive stages. Stage 1 consists in producing uranium oxide U_3O_8 out of mined uranium ore. The diggings are crushed and ground to a fine dust. The dust is chemically processed to separate uranium oxide from the rock. A 1 000 MWe NPP needs about 200 tonnes of U_3O_8 oxide each year.

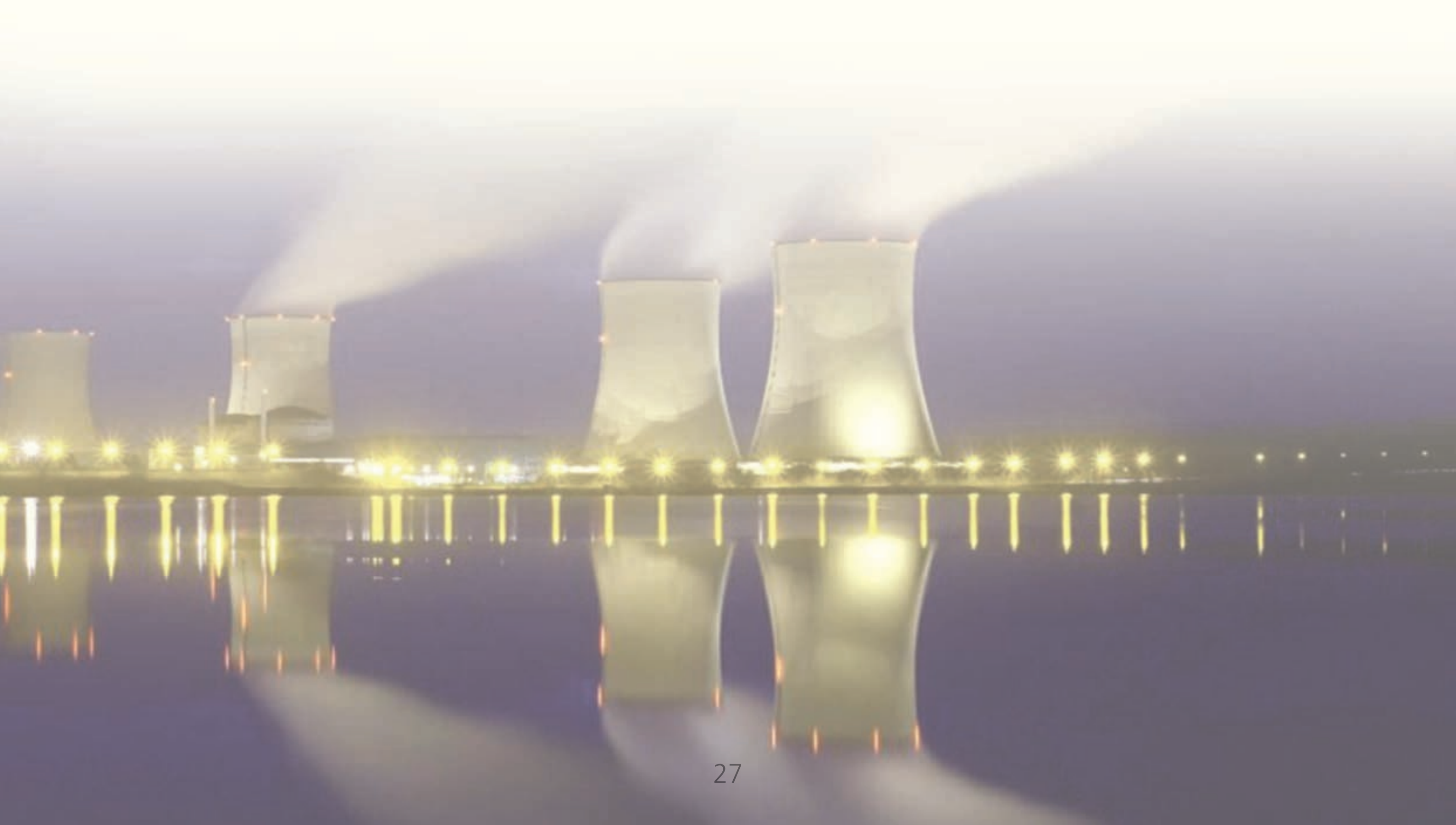
Stage 2 consists in enriching natural uranium to increase content of the ^{235}U isotope. The oxide is chemically converted into the UF_6 gas. The gas is centrifuged in multistage cascades of high-speed centrifuges so that the more heavy ^{238}U isotope is gradually separated from the lighter ^{235}U isotope. The enriched fraction is used to produce nuclear fuel, the depleted fraction (after conversion to a very dense metal) may be used as a very effective shield against gamma radiation. Majority NPPs need uranium enriched to 2 - 4% of ^{235}U. Only the CANDU Canadian reactors may be fuelled by natural uranium. However, the price of the final product (electric energy) is not lower at all, since savings made on skipping the enrichment operation are outweighed by expensive heavy water needed in those reactors as moderator.

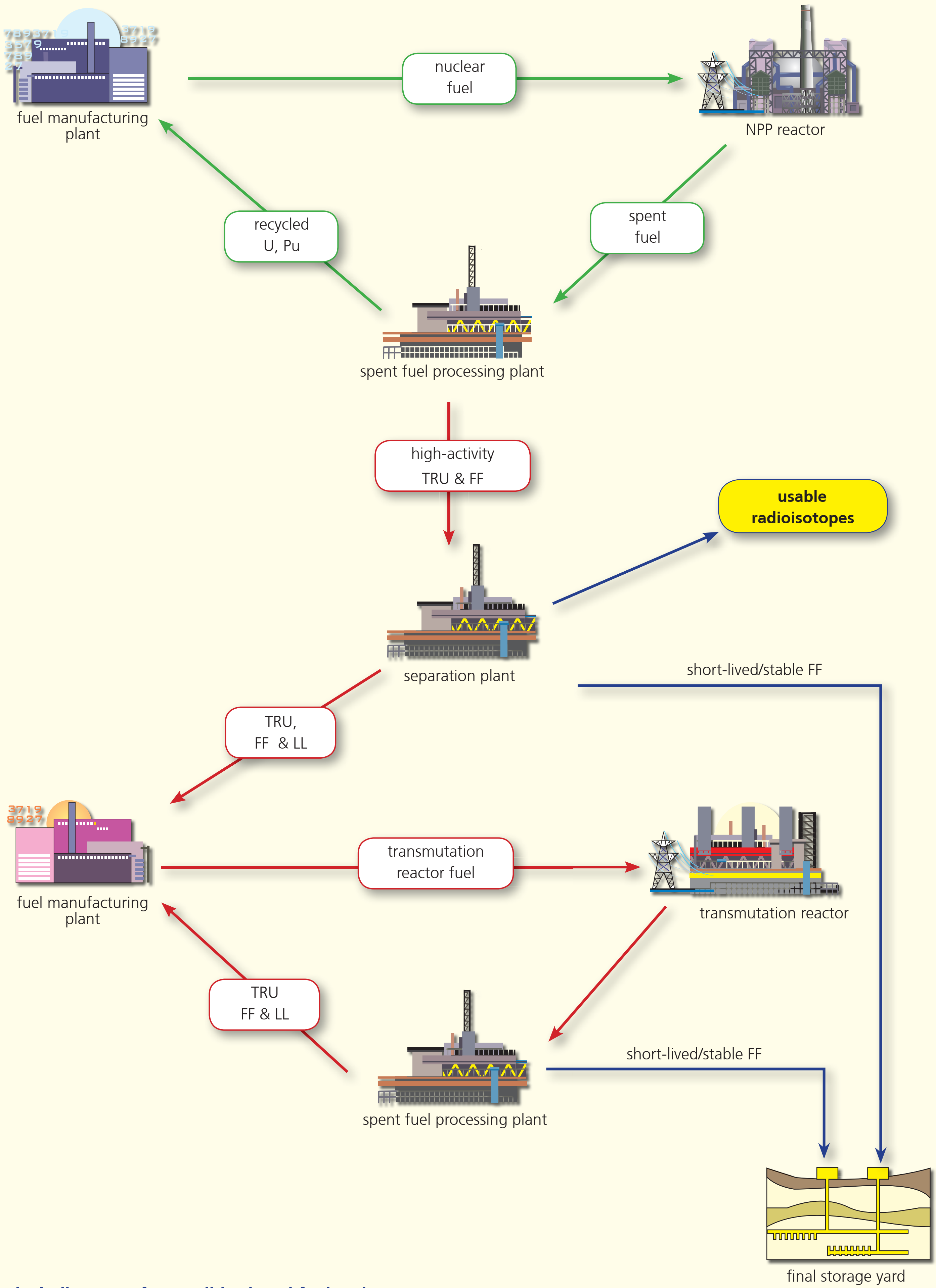
Stage 3 consists in "burning" the fissionable ^{235}U isotope contained within the fuel elements in the core of a reactor. We say the fuel inside reactor core is getting spent. Stage 4 consists in storing the spent fuel nearby the reactor to cool it down. Next it is either shipped to a processing plant to recycle fissionable materials (^{235}U and ^{239}Pu produced within the reactor) or else is prepared to be stored for a long period then shipped to a nuclear waste repository.

Spent fuel unloaded from reactor contains 94 - 95% of uranium and about 1% of plutonium. Plutonium is a reservoir for huge amounts of energy: 1 g of plutonium holds energy equivalent to combustion of 1 tonne of crude oil or to splitting 100 g of uranium. The recycled uranium contains only about 1% of ^{235}U, but that's higher content then in natural uranium, anyway. The "closed fuel cycle" term is presently understood as recycling of fissionable isotopes. The MOX (mixed-oxide fuel) fresh fuel produced in a process referred to as PUREX consists of some suitably processed plutonium mixed with enriched uranium. Stock reserves of accumulated military-class plutonium may be gradually used up to produce the MOX fuel. 7 nuclear fuel processing plants are currently operated in Europe, about 30 reactors may be fuelled by the MOX fuel. Out of about 7 000 tonnes of spent fuel produced each year by all operated light water reactors only about 15% is recycled. After recycling the volume of high-activity nuclear waste is decreased 5 times, while radio-toxicity of the waste is decreased 10 times.

Fission products (fragments, minor actinides) are the remaining 4% of the spent fuel. The actinides are long-lived radio-isotopes. They may be pressed into pellets waiting for future reactors that will transmute them into some short-lived/stable isotopes and/or "burn" them down. Should such transmutation/"burning" operation turn out to be feasible in a single step employing an ADS accelerator-driven sub-critical reactor, a closed fuel cycle of the future would become a reality. A possible block diagram of such a cycle is shown in the figure below.

High-activity solid nuclear waste remaining after fuel recycling is in most cases glazed, loaded into stainless steel containers and shipped to an underground nuclear repository. If spent fuel is not recycled, we are talking about open fuel cycle. Such spent fuel is normally cooled down in order to decrease its activity and radio-toxicity at least 100 times prior to shipment to an underground nuclear repository.





Block diagram of a possible closed fuel cycle

Transuranium elements (TRU), fission fragments (FF) and other long-lived isotopes (LL) are transmuted into some short-lived/ stable isotopes

Because of the oil crisis of the last century's decade of seventies, France decided to increase 3 times share of nuclear power in their national balance of electric power. Bruno Comby (father of the Environmentalists for Nuclear Energy association) claims that cheap electricity produced by French NPPs has reduced CO_2 air pollution by 90%.

"We have no time to experiment with visionary energy sources; civilization is in imminent danger and has to use nuclear - the one safe, available energy source - now or suffer the pain soon to be inflicted by our outraged planet."

James Lovelock
British scientist, ecologist, father of the Gaia concept
("The Independent", May 24, 2004)
http://www.independent.co.uk/voices/commentators/james-lovelock-nuclear-power-is-the-only-green-solution-6169341.html)

Afterword

This brochure is certainly no textbook, it just tries to introduce the reader into some basic nuclear power related topics, including how nuclear power plants are operating, are they safe to operate, and what social issues (in the whole country scale and in the local community scale) are related to development of a NPP at any given site. It is very difficult to convince anyone prejudiced against nuclear power that the technology is definitely competitive in relation to any other technology that may be used to produce electric power. Nevertheless, in all discussions on the subject we should restrain emotions as much as possible. We must remember that any solution aimed to increase energy supplies needs some time to deploy. Besides, the scale in which the energy shortage problem is to be solved must be properly taken into account: it's another thing to power a household, another thing to power heavy industries, and still another thing to power transport.

Time is playing an important role. Determination of all subjects involved is necessary to develop the first NPP in Poland. New power systems must be available before the old ones are decommissioned. Nuclear power have been arising tremendous emotions, fear against it may paralyse objective reasoning. Perhaps having read this brochure the reader will be less emotional if he/she were to speak his/her mind on “atom”. That would greatly facilitate discussions on future of power industry in Poland.

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