Science or Fiction


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Is there a Future for Nuclear?

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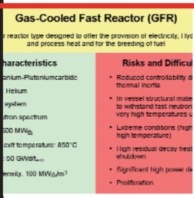
Content



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This booklet served as preparation for both participants and speakers at the conference »Science or Fiction – Is there a Future for Nuclear?«. This international conference on fusion energy and new nuclear reactor models was organized by Global 2000/Friends of the Earth Austria and took place 8 November 2007 in Vienna.

This booklet contains our contribution to the ongoing discussion about future energy security and what paths we should take. We focus on the possible future scenarios for nuclear power. The nuclear industry is trying to secure its own future by reintroducing old concepts like nuclear fusion and updating old fission reactors in so-called Generation IV systems. While there is enough information available on both fission and fusion energy from project financiers, research institutions and the European Commission, who gave the lion share of energy research funds into fusion research, we attempt here to provide a broader perspective and examine how much is Fiction and what these concepts could mean in some future Reality, which is upon us to decide on Now.

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Do we need nuclear power to meet the challenge of climate change?

The principal challenges today are sustainable development and climate change and how society can decide on a fair distribution of resources and energy as well as a radical reduction of CO_2 emissions.

It is important to understand that the decay of CO_2 in the atmosphere is a slow process. Therefore the impact of today's CO_2 emission reduction will be visible only in coming decades. If we want to prevent severe climate change, there is no time to waste: **CO_2 reduction needs to be cheap, effective and implemented without delay. Can nuclear power be part of such measures?**

Experience with nuclear power does not suggest it could fulfil these requirements: Enormous sums of money have been invested in the development and continuous improvement of nuclear energy technology since the 1950's. However, with a share of hardly 7%, nuclear energy is not substantially contributing to world energy demand. Reasons for this have been continuous technical and safety-related problems: The first generation of mostly small prototype nuclear reactors were characterised by many teething problems. Only the second generation – these are most of today's operating NPPs – could gain a short construction boom in the 1980's. Nuclear was cut off basically for good by the accident in Three Mile Island, USA, in 1979, which resulted in a total construction stop for nuclear power plants (NPPs) in the United States. The severe reactor accident in Chernobyl, Ukraine, in 1986 caused a large part of the European population to become more sensitive to the dangers of nuclear power. The trust of EU citizens into »peaceful« nuclear technology is low, a fact that is confirmed by polls every year: »Europeans perceive nuclear power to be more of a risk than an advantage« and further: »Most Europeans would either reduce or keep the current share of nuclear energy....« [EUROPEAN COMMISSION 2007].

Foratom, the European trade agency for the nuclear industry, is heavily promoting a nuclear renaissance as a powerful tool to minimize CO_2 emissions. Foratom might be facing a tough job: at present, 439 NPPs worldwide generate 372 GW electrical energy and 31 NPPs are under construction, most of which are in Asia and only one in Europe. During 2006, two new NPPs were connected to the grid and six were permanently shutdown [IAEA PRIS 2007]. Forecasts by IAEA, IEA and OECD indicate no dramatic change, but only a slow growth of nuclear power by 2030 – with a net growth rate of only 600 MW annually. **With such a slow growth rate nuclear power cannot play an important role in future world energy production.**

The nuclear industry is now improving its image and presence in the public discussion and increasing its marketing activities, but its actual capacity for construction of new power plants is very limited. Due to decreased economic activity, financial losses and a process of consolidation, only a handful of companies are still on the market. Currently, this industry has to tackle the lack of skilled personnel and production capacities for its very specialized products. A substantial come-back in the shape of newly constructed plants before 2030 can be excluded.

Nuclear power: CO_2 free?

- Nuclear is not CO_2 free if the whole uranium fuel cycle is taken into consideration. Using current uranium ore grades (~ 2% concentration) results in 32g of CO_2 equivalent (CO_{2eq}) per kWh of nuclear electricity (kWh_{el}) in Germany. In France, it is only 8g/kWh_{el}, while it is higher in Russia and in the USA, 65g and 62g respectively. One reason for this is the quality of uranium: the lower the grade, the more CO_2. A substantial increase of nuclear electricity generation would require the exploitation also of lower grade uranium ores and thus would increase the CO_2-emissions up to 120g CO_{2eq}/kWh_{el}, which is much more than other energy technologies: natural gas co-generation 50-140g CO_{2eq}/kWh_{el}); wind power 24g, hydropower 40g; energy conservation 5g CO_{2eq}/kWh_{el}) [OEKO 2007].

- Not to be forgotten is that uranium mining destroys the landscape and contaminates soil, air and the water in the mining regions and each ton of uranium creates several tons of tailings.

- A very dangerous legacy is the so-called back end of the nuclear fuel cycle, the nuclear waste: spent nuclear fuel which is dangerous for the environment and to humans and cannot be neglected for millions (!) of years. Potential sites chosen for the repositories for highly active waste are usually rejected by the local population – provided public debate is not oppressed by the state.

- The plans for Generation IV reactor systems intend to achieve the reuse of spent fuel. However, final repositories will still be needed, as chapter 2 describes. Another popular misconception is that fusion technology does not generate radioactive waste. Fusion is addressed in chapter 3.

- These chapters point out that any reactor can be used for the production of fissile material for nuclear bombs and therefore Generation IV reactor systems cannot claim to be proliferation resistant; the same applies for the fusion reactor.

The Programme »Generation IV«

New challenges, old tricks

➲ »Generation IV« Background

We are currently witnessing the discussion whether and under which conditions to allow the large commercial reactors from the 1970's, 1980's and 1990's (Generation II) to operate longer than the customary life time span of 30 years. At the same time, new reactors (Generation III) are being introduced – evolutionary designs developed from Generation II, without drastic changes. Generation III NPPs are already in operation in Japan, and in construction in the European Union. According to many scientists, the utilization of these reactors is limited in time because in their opinion uranium reserves (uranium being the source material for nuclear fuel for most Generation III reactors) will dry up within the next three decades.

Due to these dismal prospects, the Generation IV International Forum (GIF) was founded in 2000. Until recently, it was composed of 10 countries (Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, Switzerland, the United Kingdom, and the United States) as well as the European Union via Euratom. At the end of 2006, China and Russia also joined the initiative. Membership in this international forum commits participating countries to support long-term research efforts. This includes – via EURATOM – also countries which actually are opposed to nuclear power.

In 2001, the IAEA initiated the similar »International Projects on Innovative Nuclear Reactors and Fuel Cycles« (INPRO). It is funded through the IAEA budget. GIF and INPRO have agreed to formalize cooperation at the technical level [HIRSCH et al 2005]. As of February 2007, 28 countries or entities are members of INPRO.

The message of GIF and INPRO to media, politicians and the population is as follows: Generation IV means a safe, economically competitive, and a proliferation-resistant power source without the problem of increasing greenhouse gas emissions. Generation IV is even presented as sustainable, a label which is usually – and with good reason – reserved for renewable energy sources and conservation. The fact that none of the six reactor concepts selected for development fulfils all Generation IV aims is usually not mentioned [HIRSCH et al 2005].


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Generation IV and what the nuclear industry tells us about it

Generation IV does not only stand for the development of new reactor types. It is a comprehensive framework programme for an international research cooperation effort to develop new nuclear energy systems – from resource extraction to final nuclear waste disposal. GIF has laid down its research needs and formulated eight development goals, which should fulfil four political goals: sustainability, economic viability, safety and protection against acts of terrorism [SCHULENBERG 2004].

➲ »Generation IV« Goals

1. Sustainable energy production with long-term available systems based on an effective usage of fissile material with the lowest possible contamination of the air.

2. Improvement of the protection of humans and the environment by minimising nuclear waste and the decay heat of the waste, as well as reducing long-term radiotoxicity.

3. Clear economic competitiveness with other energy sources.

4. Financial risk comparable to the financial risk of other energy projects.

5. Improved safety and reliability.

6. Lower probability of occurrence and minor consequences of nuclear core damage.

7. No need for emergency measures outside the nuclear installation.

8. The theft of weapon grade fissile material should be made more difficult or impossible, plus best protection against terror attacks.

➲ »Generation IV« Reactor Concepts

The Generation IV R&D programmes promote the following reactor systems [SCHULENBERG 2004] (also see Technical Specifications p. 28-31):

I. Gas-Cooled Fast Reactor (GFR)
The GFR system is a helium-cooled reactor with fast-neutron spectrum and a »closed fuel cycle«, which is primarily envisioned for electricity production and actinoide (= actinide) management. Using the breeder concept shall improve the use of the nuclear fuel by two orders of magnitude compared to current thermal reactors.

II. Lead-Cooled Fast Reactor (LFR)
The LFR systems are reactors cooled by liquid metal (lead or lead/bismuth) with a fast-neutron spectrum and a »closed fuel cycle« and a wide range of unit sizes from small »batteries« up to large single plants. The LFR battery option is a small factory-built turnkey plant with a very long core life (10 to 30 years). With fast neutrons and the »closed fuel cycle«, an efficient conversion of fertile uranium and the use of actinoides shall be achieved.

III. Molten Salt Reactor (MSR)
The MSR system, primarily envisioned for electricity production and waste burn-down, is based on a thermal neutron spectrum and a »closed fuel cycle«, where the uranium fuel is dissolved in the sodium fluoride salt coolant that circulates through graphite core channels. Fuel loading, reprocessing and separation of fission products during operation shall enable a high availability. The reactor also will serve to eliminate actinoides by simply adding them to the molten salt.

IV. Sodium-Cooled Fast Reactor (SFR)
The SFR system consists of a fast-neutron reactor and a »closed fuel cycle«. This reactor type should mainly serve to eliminate highly radioactive waste, plutonium and other actinoides.

V. Supercritical-Water-Cooled Reactor (SCWR)
The SCWRs are high-temperature, high-pressure water-cooled reactors that operate at pressures and temperatures at which there is no difference between liquid and vapour phases (permitting to save expenses for components like heat exchangers). This reactor type was designed mainly to generate cheap electricity.

VI. Very-High-Temperature Reactor (VHTR)
The VHTR system uses a thermal neutron spectrum and a once-through uranium fuel concept. The main purpose of this gas-cooled reactor type is the generation of power, hydrogen and process heat.

In 2002, the Technology Roadmap for Generation IV Nuclear Energy Systems was published. All member states used it as basis to prepare and conduct their R&D programmes [NERAC 2002]. While research into the individual systems is being performed independently of each other, other problem areas are to be solved together for all six systems (e.g. »closed fuel cycle«, development of fissile material und material features, hydrogen production, safety and reliability, economic efficiency, physical protection and proliferation barriers).

Generation IV and what the nuclear industry would rather not tell us

By all appearances, the main goal is to save the »sinking ship« by trying to win back trust into nuclear power with the population. Obviously, the facelift uses climate change as one of the most important arguments to demonstrate the need for nuclear power. The nuclear industry wants to give the new generation of reactors the image of being sustainable, economically viable, safe, reliable and terror resistant. Many respected institutions (e.g. the Massachusetts Institute of Technology MIT) consider GIF's goals as unrealistic [MIT 2003]. The following chapter examines how realistic these ambitious GIF Technology Roadmap 2002 goals are.

Eight claims and eight nuclear daydreams

Sustainability is a concept that not only takes into account a comprehensive human-ecological context, but also a broader time horizon. According to the Brundtland Commission 1987, »sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs«. Sustainability could be defined as making use of the natural system in such a way that its primary features are maintained in the long-term and can be handed over to future generations as unchanged as possible.

➲ »Generation IV« and Sustainability

Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization [NERAC 2002] is the first goal GIF is pursuing. But the Uranium extraction itself generates 80% of today's radioactive waste (by mass; not by radioactivity). To produce one ton of nuclear fuel, which is used in light-water reactors, several thousands or tens of thousands of tons – depending on the uranium content – of uranium ore must be extracted. The amount of radioactive tailings left behind in the uranium mine area is of corresponding volume. For example, the affected regions of New Mexico (USA) and Wismut (former GDR) must cope with more than 100 million tons of radioactive waste from uranium extraction on the surface [HIRSCH et WEISH 2007]. Even if all other problems were solved, energy generation with nuclear energy systems could only be advantageous in the short term, and not in the longer term, because of the waste issue. Radioactive waste, which is created by the »peaceful« use of nuclear power, represents an extraordinarily high long-term threat potential. It cannot be neglected for millions of years, which is unique in the industrialized society [HIRSCH 2007]. Many geologists warn against the waste management option highly regarded mainly in Europe: the deep underground repository, which will be made inaccessible with barriers of concrete. The main problem is that it is simply impossible to conduct a safety case for the necessary long time periods of millions of years. At this point, science reaches its limit to make predictions [HIRSCH 2007]. The disposal site would have to be protected continuously against a variety of threats including water ingress, overheating, sabotage, and theft of the waste for abuse, which is clearly impossible. Not only earthquakes, distortions and volcanism, but also future ice ages might pose a threat because glaciers can dig up and remove enormous amounts of rock.

Gradually, however, a shift away from nuclear power is taking place. The Generation IV initiative attempts to reverse this shift by making nuclear energy attractive and presenting it as sustainable and CO_2-free, labels usually – and with justification – reserved for renewables. This strategy will help the nuclear industry and nuclear research institutions to survive [HIRSCH et al 2005].

➲ »Generation IV« and Nuclear Waste

The second goal, *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment* [NERAC 2002], is a high strung promise and would of course require a large amount of research funds. The announced reduction of nuclear waste has to be properly examined. According to GIF, the »closed fuel cycle« is celebrated as a major advantage of Generation IV concepts. A system with a »closed fuel cycle« is regarded as more effective and sustainable [HIRSCH et al 2005]. A 2003 study by the U.S. Massachusetts Institute of Technology found that the fuel cost with a »closed fuel cycle« – including waste storage and disposal charges – to be about 4.5 times the cost of a once-through fuel concept. Therefore it is obviously not realistic to expect that there ever will be new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safe waste disposal and proliferation. The long-term waste management benefits of advanced »closed fuel cycles«, involving reprocessing of spent fuel, are indeed not outweighed by the short term risks and costs, including proliferation risks [MIT 2003].

To put reprocessing in a positive light, the nuclear industry has started to call it recycling. Reprocessing is not new, it has been practised for quite a long time. The wording might give the impression of a closed cycle which – in the name sustainability – does not use up resources or generate nuclear waste. However, this is a misperception. The fuel chain (a more appropriate wording than »fuel cycle«) always requires fresh uranium, which is not renewable and can be produced merely at the high price of enormous environmental damage. And that is not the only inconvenient truth: during operation of the reactor, atomic nuclei with a high mass number (e.g. ^{235}U) are continuously split in the nuclear fuel into nuclei with low mass numbers with a high neutron surplus. The conversion of fissile material into fission products releases energy. The fission products are often instable and therefore radioactive. The gaseous fission products, like the radioactive isotopes of the noble gases argon, krypton and xenon (mainly the radiologically important isotopes ^{133}Xe and ^{85}Kr), and the volatile radioactive iodine isotope (^{131}I) can partially escape – depending on the tightness of the fuel rod claddings – into the atmosphere and can be traced in the surrounding of nuclear installations. Solid fission products (e.g. radioactive isotopes of strontium and caesium) have to be stored as radioactive waste. However, even here a small share escapes in the form of radioactive aerosols (^{134}Cs, ^{137}Cs, ^{90}Sr).

Not all fissile material in a fuel rod can be split during irradiation. To make use of the still usable share of the original fissile material – instead of storing it unused in the final repository – it has to be separated by reprocessing. At first, this complex and hazardous process appears to reduce the radioactivity of the waste. However, by making use of this additional fissile material from reprocessing in fission reactors, still more fission products are generated that have to be stored as waste in final repositories. Moreover, the end of the nuclear age is going to be deferred, since more nuclear facilities have to be built and finally have to be decommissioned (leading to the production of »decommissioning waste»). The »recycling« of spent fuel rods results in a dangerous concentration of radioactive fission products. This results in a larger volume of total waste, partly with a higher activity concentration, in the long-term.

In addition to the already discussed fission products, actinoides are also produced during reactor operation, among them plutonium, which can be used for nuclear weapons and nuclear fuel. The actinoides can be degraded by neutron bombardment, a fact that the systems of Generation IV are destined to make use of for the reduction of the amount of waste already inside the reactor.

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Today around 10 000 tons of spent nuclear fuel is generated per year [HIRSCH 2007]. Each ton not only contains fission products that have to be stored in some final repository, but also several kilograms of plutonium and other actinoides (= actinides). In a reprocessing plant these materials are separated. The plutonium is either mixed with non-enriched uranium to produce mixed oxide fuel (MOX fuel) and used again to fuel reactors (whereby the plutonium share is around 5%) or for building nuclear weapons. The separated uranium is enriched in the isotope ^{235}U in enrichment plants to reach enrichment up to 3-5%. This uranium can then also be re-used in nuclear reactors as LEU (low enriched uranium) reactor fuel, while enrichment to 20% and more provides HEU (highly enriched uranium) applicable for building nuclear weapons (for an advanced fission explosive device, uranium is usually enriched to 90% or more). The depleted uranium, unusable for reactors, is mainly used for the construction of airplanes and penetrating ammunition. The unusable radioactive fission products are »for the time being« put in interim storage since the question of final disposal has not yet been solved. What would be needed is practically the complete separation of all long-lived nuclides, so that the remaining waste needs to be stored safely for only a shorter time. A separation efficiency of 99% as achieved so far is not really sufficient, when taking into account the amount of waste that is actually generated! Reprocessing also leads to high emissions in gaseous and liquid form, which still contain radioactive substances in spite of off-gas and waste water treatment procedures.

It would be necessary to develop some »super-reprocessing« technology (separation efficiency of 99,99%), which would, contrary to current methods, not damage the environment and not pose a catastrophic danger [HIRSCH 2007]. As a measure to improve their image, the nuclear industry is now announcing the complete degradation of long-term toxic actinoides during reactor operation. For this purpose, fast neutrons are used in the reactor core. The Sodium-Cooled Fast Reactor should be able to reach the required 99,99% conditioning and reprocessing of the actinoides with the help of an adjusted reactor geometry and a »closed fuel cycle« approach [SCHULENBERG 2004]. What is omitted here: the »unrecyclable« fission products are still left over. Generation IV reactors are far away from the goal to successfully minimize and manage their nuclear waste [HIRSCH et al 2005]. This is where the story ends: the operation of nuclear installations is probably never possible without the creation of radioactive waste. It is our opinion that nuclear technology can not contribute to environmental protection.

➲ »Generation IV« and Competitiveness

The third goal is that *Generation IV nuclear energy systems will have clear life-cycle cost advantage over other energy sources* [NERAC 2002]. Nuclear energy can hardly be economically competitive in the long-term, since renewable energy resources will never dry up, as long as the sun shines. Fossil resources, however, are limited. The reserves of the currently most important primary energy sources (oil, gas and natural uranium) are scarce. A switch to sustainable (thus renewable!) energy sources is inevitable and has to take place sooner or later. It seems that any delay can only mean a benefit for those with a direct economic interest in nuclear energy, or for those interested in nuclear proliferation.

The Greenpeace report of 2005 says that the estimated costs for the development of the six Generation IV concepts are about 6 billion US$. It is more than likely that overruns will occur both for costs and for the time required. According to one of the strongest supporters of the GIF programme, the French government, Generation IV »will at best be ready for commercial deployment around 2045«, and not 2030 as officially envisaged by GIF. This is to be seen against the background that nuclear energy is currently not cost competitive in a deregulated market; not with coal and natural gas, and also not with wind energy [HIRSCH et al 2005]. There seems to be efforts made in France currently to speed up the development on Generation IV, with the first prototype in operation by 2020. It remains to be seen whether those plans will be implemented.

➲ »Generation IV« and Financial Risks

The fourth goal says that *Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects* [NERAC 2002]. It seems that the nuclear industry or rather large energy utilities are currently trying to win over banks and investors to invest into nuclear energy projects. They are trying to give the impression that nuclear power plants are heading towards a comeback as a viable energy form, and therefore construction of several nuclear power plants should be in the pipeline. However, it is quite risky to conclude that an increased demand for electricity would lead to higher construction activity within the nuclear industry, especially since the technical feasibility of future systems has yet to be solved. The demand for electricity alone is not yet enough to build a new nuclear power plant; the acceptance of the population, the chosen site, safety etc. are key. Actually there is a growing need for electricity. However, there are only a few realistic plans for new nuclear power plants [WENISCH 2006].

➲ »Generation IV« and Safety

The fifth goal, *Generation IV... will excel in safety and reliability* [NERAC 2002], is probably where nuclear technology has mostly failed up until now. The negative image of the nuclear industry as unsafe and unreliable is to become a thing of the past. However, it is an error to think that any risk can be limited by one or the other measure. A certain risk will always prevail: earthquake, terror, sabotage, human or technical failure, usage of equipment exceeding the original life time design, adverse coincidence, unexpected physical and chemical phenomena, and war. In the near future, some important energy sources will be depleted: in July 2007 the IEA (International Energy Agency) warned that a new oil crisis will occur in the next five years and that Peak Oil will be reached within this decade [IEA 2007]. A response to scarcer fossil resources and a forecasted worldwide demand increase has to be found. However, nuclear power is not an adequate answer. Many more nuclear plants would have to be constructed than is currently possible. Also, the more plants, the higher is the accident risk. And finally, uranium resources would not last long enough to support reliable and long-term operations [WENISCH 2006]. It will in the foreseeable future – again due to shortage – be necessary to switch to currently available renewable technologies. Even though investments can increase the safety of nuclear installations, this is definitely not an argument to continue pursuing this technology. In our opinion, an immediate phase–out and a switch to alternative energy forms would be safer and more reliable.

Similar arguments are applicable for goals six and seven, a *very low likelihood and degree of reactor core damage* and the *elimination of need for offsite emergency response* [NERAC 2002]. Due to the extreme operational conditions (higher temperatures, higher pressure, higher burn-up) Generation IV systems could even turn out to be more dangerous than currently operated installations, and therefore their design must be more sophisticated. These problems can be avoided altogether by switching to sustainable technologies, which do not pose these risks in the first place.

➲ »Generation IV« and Proliferation

Focus has been put on research into goal eight, to *increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism* [NERAC 2002].

»Regarding proliferation, it is generally recognized that it is a practical impossibility to render civilian nuclear energy systems proliferation-proof. Thus, it cannot be expected that Generation IV will achieve a great leap forward in this respect.« [HIRSCH et al 2005]

To build a nuclear weapon, highly enriched uranium (HEU, consisting mostly of ^{235}U or ^{233}U) is needed, or the neptunium isotope ^{237}Np or »weapon-grade« plutonium [SHOLLY 2007]. In reactors operated with uranium fuel, several plutonium by-products are generated through neutron bombardment of the uranium isotope ^{238}U. The plutonium isotope ^{239}Pu is very well suited for building nuclear weapons because of its low critical mass. Only some 5 kg is considered sufficient in a well configured bomb geometry to initiate a nuclear explosion (with advanced technology, the amount could be smaller still). Whether plutonium is »weapon-grade« or only »reactor-grade« depends mainly on the content of the plutonium isotope ^{240}Pu, which is also generated during the fission process. This isotope emits neutrons because of spontaneous fission and hence can lead to premature detonation of a nuclear device, with lower yield. Weapon-grade plutonium therefore has to have much lower share of ^{240}Pu than reactor–grade plutonium. To prevent the development of weapon-grade plutonium, plutonium has to be kept inside the reactor as long as possible. The plutonium then has to be separated from the fission products in a reprocessing plant. The separation methods were originally developed for military reasons and can be used for the separation of weapon-grade as well as of reactor-grade plutonium. The complete control over the usage of all reprocessing plants concerning the production of weapon-grade plutonium is almost impossible. To win fissile material for reactor fuel purposes therefore poses a substantial proliferation risk. In order to exclude the abuse for military purposes, plutonium should not be produced in the first place.

➲ »Generation IV« and Thorium

In the search for alternative fissile material, Generation IV research programs are also examining the potential of using thorium instead of uranium as fuel. The first experiences with thorium were made with High-Temperature Reactor types (HTR). This technology is now to serve as a basis for the Very-High-Temperature Reactor types (VHTR) of Generation IV. India, a country hosting only poor uranium deposits but large thorium sand deposits, and possibly other countries, are considering establishing a thorium-based fuel chain [KREUSCH et al 2006]. The argumentation used by the nuclear industry that using thorium reactors would reduce the production of plutonium and the stock piles of existing weapon grade plutonium [KAKODKAR et al 2006] has to be taken with a grain of salt: We believe that a thorium economy is not less dangerous than a plutonium economy. Neutron bombardment of the thorium isotope ^{232}Th leads over detours to the development of the dangerous uranium isotope ^{233}U. The ^{233}U has similar features like ^{239}Pu – low critical mass – and is usable both for nuclear reactors and nuclear weapons. Another by-product is ^{232}U, whose short lived daughter products (e.g. ^{208}Tl) are hard gamma emitters and make problems in the handling, reprocessing and recycling of bred ^{233}U. However, it is this feature that is now used as argument to make the thorium fuel chain more immune to proliferation risks [KAKODKAR et al 2006]. What a strange argumentation! The generation of a highly radioactive by-product is being sold as an advantage, which should justify using thorium instead of uranium.

The discussion about proliferation barriers puts a second problem on the backburner: the radiotoxicity of plutonium and uranium is not to be underestimated, be it weapon-grade or reactor-grade. The inhalation of a 40 billionth (!) gram ^{239}Pu is enough to reach the limit for the annual dose of workers. A few kilograms of ^{239}Pu (about the size of a tennis ball) is enough to kill – theoretically – all of human kind should everybody inhale a fraction. Due to its half-life of 24000 years it has a high long-term toxicity. ^{233}U also is highly toxic and has a half life of 159000 years.

Another difficulty with using thorium is the delayed decay of the intermediate product ^{233}Pa. After a longer shutdown of a thorium-fuelled plant, an unwanted excess of fissile ^{233}U (and therefore an unwanted increase of the reactivity of the fuel) is produced due to the delayed activity of protactinium [KAKODKAR et al 2006]. In general, we consider the thorium fuel chain to be dangerous and difficult to control, it only causes new problems.

➲ »Generation IV« and Fast Breeder

There are many strong indications that the eight goals of GIF cannot be reached. However, the question is why Generation IV systems have been researched for so many years. Only little is really new about Generation IV reactor systems. Half of the six »new« reactor concepts are based on the old concept of the Fast Breeder. However, hardly a dozen of them were ever built as commercial reactors. All but one, Belojarsk/Russia, were shut down by the operators, some after a very short time of operation, usually due to problems with reactor control, accidents and civil protests. The Fast Breeder concept as such is extremely dangerous. »Breeding« stands for the generation of a fissile material (e.g. ^{239}Pu) while using up other fissile material at the same time (e.g. ^{238}U). The term »fast« refers to the usage of fast neutrons, which are used to split the fissile uranium isotopes ^{238}U, which cannot be split with the slowed-down (so called thermal) neutrons. The »bred« fissile material, ^{239}Pu or ^{233}U, can after extraction be reused as fresh reactor fuel. This reactor has to work without a moderator (which slows down neutrons). Fast neutrons initiate a fission reaction with a much lower probability compared to thermal neutrons. For this reason, it is necessary to increase the concentration of fissile material in comparison to moderated reactor types. This high concentration of fissile material results in high thermal density. In this type of reactor, an adequate cooling medium has to be found, one that does not serve as a moderator, and therefore water is excluded.

Breeder reactor cooled with liquid sodium have had continuous problems. Most of the reactors had to be shut down: sodium-caused corrosions and leakages, the creation of sodium hydroxide, the release of hydrogen and violent exothermal reactions due to the contact of sodium with air or water. These are only a few of the problems that have caused accidents in the past.

The Japanese Fast Breeder in Monju was closed down after a severe accident (sodium fire) in 1995; a restart failed mainly due to resistance of the population. The French Fast Breeder Superphénix was closed down as the last Breeder in Europe used for electricity generation

after numerous events such as sodium leaks, destroyed heat exchangers and dangerous power fluctuations. The French Breeder Phénix is still operating as a research reactor, mainly for irradiation purposes, and will be shut down in 2009.

Research institutions and R&D departments of nuclear companies hope to receive research funding for concepts they had developed, but which have not been applied successfully in the last 30 years [WENISCH et PRAUHART 2006]. There is reason to believe that there are efforts to revive the old concepts of breeder reactors. Recent events and insecurities in energy supply are used to back up the research need: the 1990 oil crisis (Gulf war), the 2005 rapid oil price increase (Hurrican Catrina), the 2006 gas crisis (conflict between Ukraine and Russia), the 2006 adjustment of coal reserve (Germany revised the data downwards), the 2007 current peak-oil-warning within this decade by the IEA and the threat of climate change. However, Generation IV Breeder systems are a new edition of the Fast Breeder concept. A switch to Fast Breeders is likely to be a continuation of the plutonium economy and thorium economy on a scale yet unseen. Vast quantities of highly toxic materials like plutonium and uranium isotopes would be transported around the world like oil or coal. This has to be prevented at all costs.

Fusion

Fusion Basics

Nuclear fusion is the process which powers the sun and the other stars. For nuclei with low mass it is energy wise more convenient to form heavier nuclei. This process is by far the largest and most important energy source known in the universe. In principal, nuclear fusion is the reversed process of nuclear fission which is the process of breaking apart nuclei of atoms.

Two major natural powers are important for fusion, the electromagnetic force and the strong (nuclear) force. Nuclei under normal conditions are quite distant objects with much space between them because of the repellent electrostatic force which acts on the protons. Only when two nuclei are brought together to a distance of approximately 10^{-15} m or less, fusion can be initiated. Under these conditions, the repellent force of the positive charged protons is overpowered – by the approximately 100 times stronger nuclear force – as it is in any nucleus. For nuclei lighter than iron or nickel this process releases more energy than was needed to initiate the action.

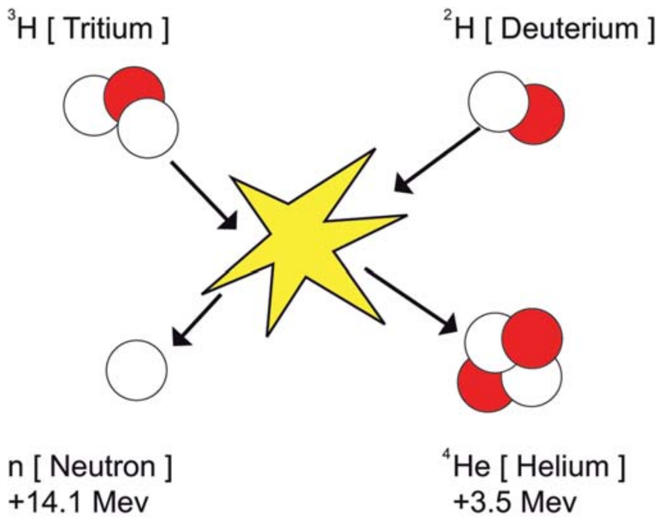


Figure 1: Illustration of the fusion of deuterium and tritium

➲ The necessary conditions

To start the process of nuclear fusion it is necessary to bring two nuclei close enough to each other to enable the nuclear power to pull them together and form the heavier nucleus of a new element. How can this be achieved?

In the case of the sun it is the enormous amount of mass which exerts (through force of gravity which is 28 times the earth's gravity) enough pressure to fulfil the requirements for nuclear fusion. Due to the high pressure the resulting temperature and the heat from the fusion reactions, the core of the sun heats up to 15 million Kelvin.

On earth it is not possible to create such pressure by any imaginable technology. The problem can only be solved by using high temperature. At high temperature there is a point where particles move so fast that there is a sufficient probability for them to collide and overcome the electrostatic barrier which keeps nuclei apart under »normal« conditions. The temperature needed to make the process work on earth is above 100 million Kelvin. That is about ten times the temperature of the sun core.

➲ Technical processes for fusion

At temperatures needed for fusion reactors with positive energy output, matter is not in one of the three well known states solid, liquid, gaseous but in the fourth state known to science as plasma. Matter in the plasma state has special properties. Atoms in the plasma state are partly or totally ionised, which means that the nuclei and the electrons of the core of the atoms are completely separated. The atoms in a plasma with high temperature – like in the sun – are totally ionised. A whole branch of science – plasma physics – deals with the properties of matter in the plasma state.

It is obvious that there is no material on earth which is able to contain matter at 100 million Kelvin. Any wall would transit to an evaporated state within the blink of an eye and furthermore the plasma would instantaneously loose the necessary energy to keep the process of fusion going through heat transfer. Fortunately it is not necessary to build walls to confine the plasma. Due to the fact that matter in the plasma state does not contain neutral atoms but only ionised nuclei it is in principal possible to confine the plasma with the help of magnetic fields.

In a fusion reactor the magnetic field has to fulfil several functions. First of all it has to confine the plasma somewhere in mid-air within the fusion reactor. Secondly the magnetic field has to have such properties that the plasma zone can be provided with fresh matter for the fusion process without interfering with the fusion and without destabilising the plasma. Last but not least it should be able to remove the fusion products while the reactor is running. Further properties would be advantageous for a future power generating fusion reactor, like the possibility to breed the fusion-fuel within the same process.

The fuel for the fusion process might be in principal any element lighter than iron. For the ITER (International Thermonuclear Experimental Reactor) device the fuel is planned to be deuterium and tritium. ITER will according to the fusion community be the last step prior to a prototype nuclear fusion power plant, the so called DEMO. Deuterium can be extracted from water since it exists as a contingent of 0,015% of all present hydrogen while tritium can be derived from lithium. Furthermore, the heavy isotopes of hydrogen only contain one proton in the nuclei. So the repelling force is relatively low.

Some fusion processes and their energy-output, contain the lightest elements hydrogenium and helium:

$$^{2}H + ^{3}H \dashrightarrow ^{4}He + n + 17.6\ MeV$$
$$^{2}H + ^{3}He \dashrightarrow ^{4}He + p + 18.3\ MeV$$
$$^{2}H + ^{2}H \dashrightarrow ^{3}He + n + 3.3\ MeV$$
$$^{2}H + ^{2}H \dashrightarrow ^{3}He + p + 4.0\ MeV$$

The reaction of tritium and deuterium produces one neutron which carries most of the energy of the reaction. Neutrons are uncharged particles, and as such they are able to escape the fields confining the plasma. As a consequence, the neutrons are suitable to carry the energy out of the plasma to the wall of the reactor where the kinetic energy of the neutrons can be transformed to heat and used for energy production through a turbine. Furthermore, the neutrons can be indirectly used for the breeding of tritium from lithium. The energy which remains with the helium nucleus can not escape the magnetic confinement and so it contributes to the necessary – as the plasma continuously looses energy through radiation – heating of the plasma.

➲ The differences between nuclear fusion and fission

Nuclear fusion and nuclear fission are based more or less on the same physical principals. In both cases changes of the composition of atomic nuclei are initiated artificially to gain energy out of this process. The energy emerges from the different bond energy of the nucleons (protons and neutrons) of the initial nuclei and the fission/fusion products according to Albert Einstein's famous formula $E=m \cdot c^2$ for the equivalence of mass and energy. If energy can be gained by fusion or fission depends on the bond energy of the nuclei contained in the reaction.

In fission, heavy elements like uranium or thorium are used. Energy is gained due to the physical properties of these elements. Certain limiting conditions for the nuclear fission have to be maintained to prevent an uncontrolled fission process.

For light particles you gain energy by the fusion process into heavier particles. The fusion of two nuclei always leads to a well determined fusion nucleus. If the limiting conditions for the fusion process are not obtained – for example due to a breakdown of the magnetic field caused by a short – the fusion comes to a halt, however, the technical structure of the reactor can be severely damaged due to the contact of the wall with hot plasma. The neutron radiation of the fusion process activates the wall materials of a fusion reactor and leads to embrittlement. In case of an accident tritium (and activated dust) can be released to the environment. Most of these materials are transformed into their radioactive isotopes by the capture of this neutron. The huge mass of radioactive waste of a fusion reactor stems mainly from this process.

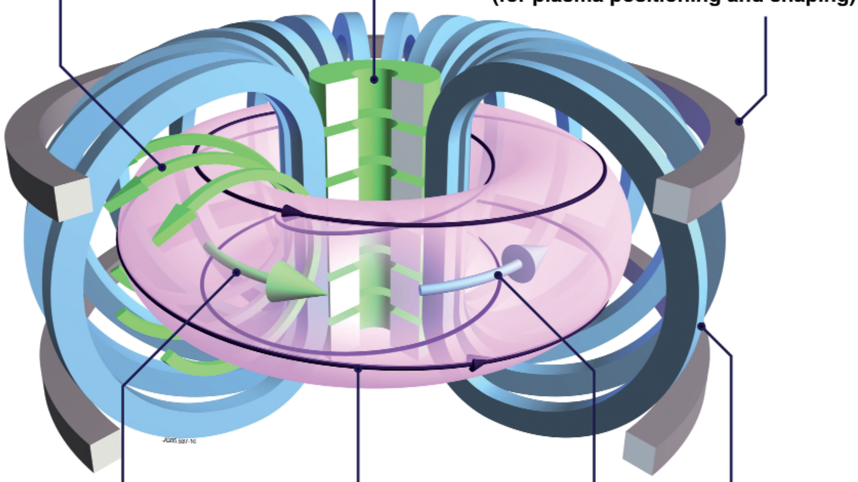
➲ History and current development

Research into fusion began soon after World War II, but only following the 1955 UN conference on so-called »peaceful use« of nuclear energy were national programs on fusion declassified. The conference also triggered international scientific cooperation into fusion. Until the start of the international scientific exchange, two different solutions for the magnetic confinement of the plasma had been developed: the Tokamak in the Soviet Union and the Stellarator in the USA.

Tokamak (Russian abbreviation for toroidal chamber in magnetic coils) is the most developed concept at the moment. The major advantage of this concept is the relatively simple construction of the magnetic coils. The Tokamak is a rotational symmetric »torus« whose slice plan is not a circle but D-shaped. The induction of plasma currents are used to generate the helical component of the magnetic field. This is necessary because the magnetic field depends at any point inside the torus on the radius. Inducing the current in the plasma enforces a pulsed operation of the reactor. The plasma in a Tokamak can move freely parallel to the surface of the torus and is restricted perpendicular to the surface.

The largest existing Tokamak is the JET (Joint European Torus) in Culham UK. But still the energy output/input ratio is not sufficient for a self-sustaining fusion reaction . JET holds the »record« with 0.7 output / input ratio. In other words, currently the fusion process consumes 30% more energy than it produces.

Initially, the United States, the Soviet Union, the European Union and Japan joined forces. In 1988 efforts on the conceptual design started and was followed by the engineering design in 1998. Work was finished by mid-2001. Funding of 650 million US$ was necessary to prove the practical feasibility of the design for this single device. In mid-2005, the future site for the ITER device was chosen. As a part of the deal for ITER to be built in Europe, it was agreed that the EU will conduct one fifth of its procurement in Japan and that Japan will provide one fifth of the staff for ITER. In June 2007, the Russian Federation started as the last party the ratification of the contract for the ITER organisation.



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Further steps after the planned formation of ITER organisation as a legal international entity include obtaining the licence for construction in 2008, to start with the assembly of the Tokamak in 2012 and to have the first plasma – which means to start the reactor for the first time – by the end of 2016.

Postulating the success of ITER – which shall have a power output of 500 MW (thermal) – the next step on the road to »commercial« use of fusion energy would be the building of DEMO, the first fusion reactor for energy production. Its power output would need to be approximately four times higher than the output of ITER for economic reasons. The fusion community hopes that the knowledge gained from ITER will allow to forecast with sufficient accuracy the behaviour of DEMO to implement the necessary concepts of design and construction.

➲ Money, fundraising, plans

Until the end of the 1990's, approximately 10 billion euro were spent for research and development of plasma science and fusion. When estimating the costs for the European Union for the time until fusion is likely to be an available energy source one has to add between 20 and 30 billion euro [TAB 2002]. Currently, the following investments are planned for the ITER project:

National Parties of ITER

Procurment	Total	CN	EU	JA	KO	RF	US	IN	JF
Total (1000) IUA	3021	239	1064	496	241	223	236	241	341
Share (%)	100	8	35	16	8	7	7	8	11

Figure 2: Investment share of the ITER participants. (http://www.iter.org/a/index_nav_4.htm)

[CN = People's Republic of China, EU = European Union together with the Swiss Federation, JA = Japan, KO = Republic of Korea, RF = Russian Federation, US = United States of America, IN = Republic of India, JF = Joint funding. 1 IUA (ITER Units of Account) = 1000 US$ at January 1989 values , 1 IUA is approximately 1400 euro in 2005 money]

The total value of the capital investment for ITER amounts to 2.755 kIUA. In addition, the cost of spare pares and items needed after only a few years of operation (for full DT operation) amounts to the rest of the costs indicated above.

EU funding for the ITER organisation was recently provided via the 7th framework programme 2007-2011 under the title Fusion Energy Research. For this period, programme funding will be 1.947 billion euro (funds from EURATOM).

The aim of the fusion energy research programme is focused on the ITER activities which shall provide the necessary knowledge base for the prototype of a technically and economically feasible fusion reactor with respect to safety and the responsibility for the environment. The most important points listed by the European Union are the following:

- Realisation of ITER site preparation, management, technical and administrative support, construction of equipment and installations and support to the project during construction.
- R&D in preparation of ITER operation-physics and technology research; assessing specific key technologies, consolidating ITER project choices, and preparing for operation.
- Technology activities in preparation of DEMO – a »demonstration« fusion power station
- long-term R&D activities – further development of improved concepts for magnetic confinement schemes, theory and modelling for understanding the behaviour of fusion plasmas and coordination of Member States' research on inertial confinement.
- Human resources, education and training in view of the immediate and medium term needs of ITER, and for the further development of fusion.
- Infrastructures – construction of the international fusion energy research project ITER will be an element of the new research infrastructures with a strong European dimension.
- Technology transfer process.

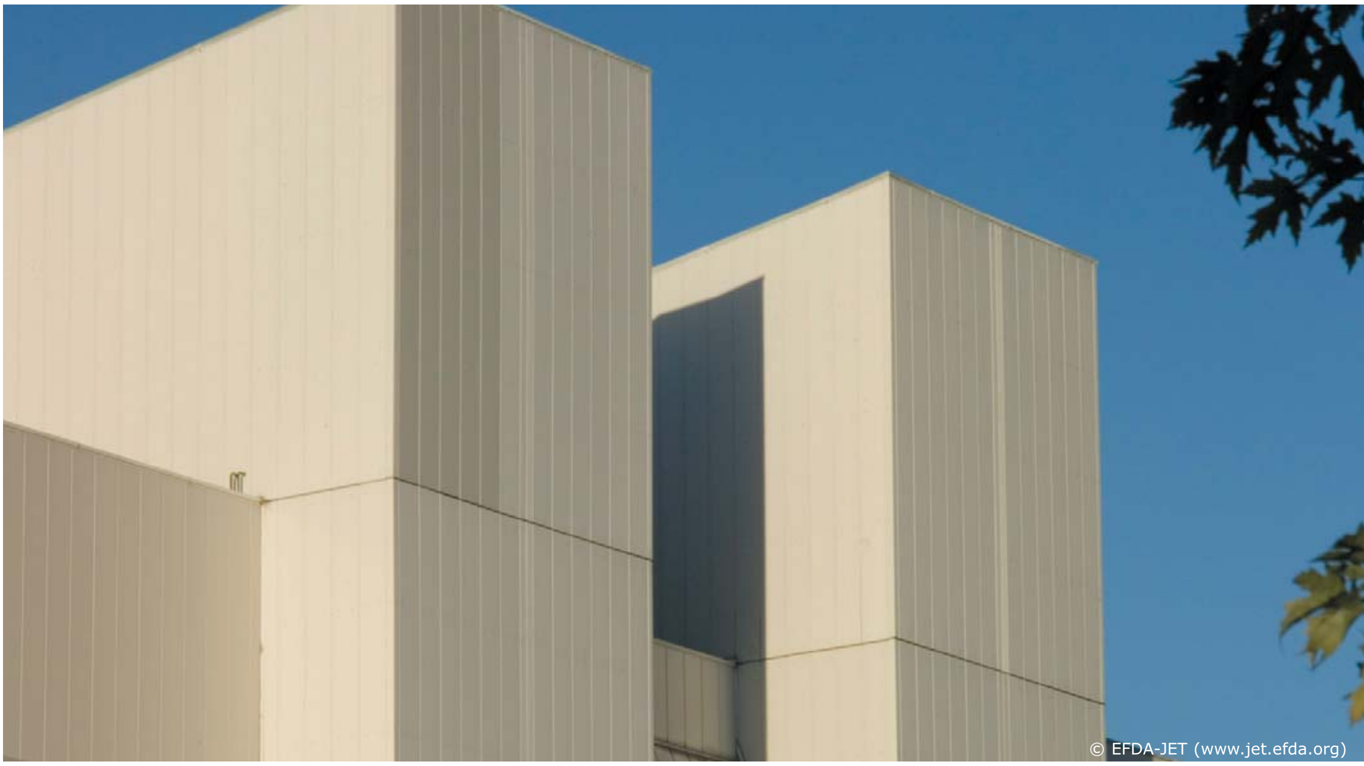
The question whether fusion will be an economically reasonable option for energy supply is quite difficult to answer. Several considerations have to be taken into account.
Initial costs are very high. Estimates for fusion reactors with an output of 1000 MW electrical power (which is comparable to nowadays nuclear power plants) are estimated to be around 5000 €/kW installed capacity [WARD 2002]. Further liberalisation of the energy sector makes it more and more unlikely that companies will take the risk of such enormous investments.

The operational costs are characterised by the necessary exchange of components like the plasma facing structures which suffer from degeneration because of the neutron radiation. The estimated costs are of the order of 10% of the overall costs and the exchanged components add to the radioactive waste.

The costs for the fuel are difficult to estimate but seem, as is the case for nuclear power plants, to be only a small share of the overall costs.

Decommissioning is apart from reactor construction one of the major cost factors. Activated materials are going to be handled and radioactive substances need to be stored over many decades up to several hundreds of years. As for nuclear power plants, the waste problem is currently – and is likely to remain – unsolved for ever.

If fusion should really be an available source for energy production in the second half of the century, it is hard to predict in which surrounding it will find itself. Different imaginable fusion reactors have been assessed. The range of the predicted costs is from slightly above 3.7 to 8 ct/kWh euro [WARD 2002], which indicates that fusion energy will not be more competitive in the future than renewable energy source are already today.



➲ The global players of nuclear fusion

Seven countries including the People's Republic of China, the Republic of India, Japan, the United States of America, the Republic of Korea, the Russian Federation and the European Union (including the Swiss Confederation) agreed formally in November 2006 to contribute to the financing of the ITER project. ITER itself will be located in the south of France on an existing nuclear site near Cadarache.

The participating countries are representing the major contributing countries to the scientific work on nuclear fusion throughout the last 70 years. The knowledge derived from experiments will be shared among these seven contributing countries.

A list of companies which have been working on the ITER project can be found on the homepage of the ITER organisation (http://www.iter.org/industry.htm) and on the webpage of the European Participant Team of ITER, the European Fusion Development Agreement which provides (https://www.efda.org/eidi/) a list of potentially interested companies for the further activities at the ITER site. Naturally a project like ITER is economically interesting for a wide range of companies coming from different fields as construction business, heavy industry or nuclear (fission) suppliers.

Uncertainties & Risks

➲ Nuclear weapons proliferation

Fusion reactors are not proliferation resistant, since they can be used to generate fissile material. The use of a fusion reactor to produce weapon-grade fissile material is easy to detect, but only with the establishment of an appropriate monitoring system [LIEBERT 2001]. »Fusion reactors pose less of a proliferation threat than fission reactors, in particular it would be of limited use to »rogue« states or sub-state terrorist groups.« However, within the framework of an advanced nuclear weapons programme, tritium from fusion reactors could be used to make advanced nuclear weapons [POSTNOTE 2003]. Tritium is used as a booster to increase the strength of the nuclear weapon.

➲ Nuclear Waste

Because of the neutron radiation of the fusion process, the walls of the reactor are activated. The type of resulting isotopes depends on the wall materials. For the technical boundary conditions of ITER, a total radiotoxic potential of 10 billion Sievert (Sv) at the start of decommissioning is predicted. Analysis shows a decrease to 10 million Sv after 100 years [ITER-WASTE]. Nonetheless, a certain amount of structural material will constitute high-level waste and has to be stored for a long time. The radioactive elements with the longest half-life regarding the activated materials – up to dozens of years – are found among the transition metals. The plasma-facing components are planned to be made mainly of beryllium, carbon and tungsten.

The amount and toxicity of nuclear waste from fusion reactors depends on the type and amount of structural material which is exposed to extreme conditions (heat, neutron flux, activation). These materials would constitute nuclear waste when removed from the reactor at the end of the lifetime of the component or the plant. The total volume could be twice that of a fission reactor.

➲ Radiation hazards

Tritium: Tritium is a radioactive isotope of hydrogen, with a half-life of 12.32 years. Tritium decays by emission of low-energy beta radiation. The amount of tritium in a hypothetical fusion power plant will reach the mass of some kilograms. The major part of the tritium will only be stored at the site. For ITER, the predicted amount of mobilisable tritium within the reactor systems is less than 500 grams. The resulting activity is in the order of 10^{17} Bq. During normal operation of the fusion reactor, a small amount of tritium is released. But in case of an accident it is likely that a greater amount of tritium will be released into the environment.

Tritium is especially dangerous due to its great mobility and the many possibilities of incorporation as it replaces hydrogen in water molecules and biological matter. Tritium constitutes a minor external radiation hazard and is not likely to be absorbed in the lungs trough inhalation.

The biological half-life of ingested tritium is approximately 10 days [DOE 1991]. But there is evidence that when the tritium atom is part of an organic molecule this time span may exceed 500 days [FAIRLIE 1992]. According to Rosalie Bertell, the relative biological effectiveness values for tritium beta rays are higher than the quality factor of unit generally used in radiation protection. Tritium increases the risk for cancer and other health problems in particular stillbirth and birth defects. The teratogenic risk of tritium is six-fold the risk of mortal cancer. [BERTELL 2005] This is ignored by the International Commission on Radiation Protection (ICRP).

➲ Accidents

The EU working group on Safety and Environmental Aspects of Fusion Power concluded that an accident due to an internal event (e.g. loss of coolant) could result in a maximum dose to a human below the EU intervention level for evacuation.
However, consequences of a worst case scenario e.g. due to an external event as earthquake or sabotage could cause a maximum dose to a human of 400 mSv, resulting in the need of evacuating people from the vicinity of the plant [COOK et al. 2001]. Because of lack of experience with fusion reactors, the prediction what would really happen is very uncertain.

The vast majority of the activated products is bound in the solid metallic structures. Nevertheless, a certain amount of these materials is mobilized by corrosion and erosion during normal operation and to a greater extent in case of incidents and accidents. For a fusion reactor, especially tungsten is hazardous due to the possible production of hydrogen under off-normal hot conditions. Fore safety reasons – to prevent hydrogen explosions – it will be necessary to set a rigorous limit for these substances inside the reactor vessel.

➲ Fusion Fuel

Assuming that the ITER fuel will be tritium and deuterium, it is necessary to make sure both will be available: Deuterium is produced from seawater through electrolysis. Lithium is required for the breeding of tritium. Lithium can also be extracted from seawater. It has a share of 0,002% of the earth core, from where it can be extracted by mining activities, with all the well-known environmental damages usually connected with such activities.

➲ Commercial realisation of fusion

The practicability of any future fusion plants will depend on their safety, environmental impact and economic viability. However, there are considerable uncertainties in the predictions as they rely on a range of assumptions about future power plant designs and future structural materials [POSTNOTE 2003].

It is impossible to foresee the resources necessary for the development of the fusion reactor from research to technical and later to commercial realisation of a fusion power plant.
The goal of the fusion community is to prepare the construction of a commercial fusion reactor in 2050 by the realisation of ITER and DEMO (Demonstration fusion power plant). [TAB 2002]

A big challenge for the realisation of a commercial fusion power reactor is the development of suitable structural materials. This will require a dedicated testing facility, although some material testing can be carried out at ITER. Construction of an International Fusion Materials Irradiation Facility for testing materials will probably become necessary.

Commercial realisation in 2050 is a very optimistic prognosis. During the 50 year history of fusion research, the difficulties of developing a fusion power plant have been underestimated and the time line for realisation had to be constantly postponed [TAB 2002].

For a contribution to the reduction of CO^2 within a climate change context, fusion power plants will be far too late. Last but not least, nuclear fusion prolongs or even increases the centralised production of energy with the known problems of distribution grids (security of supply) and a significant lack of a democratic decision process concerning questions of energy sources and energy availability.

In any case fusion power would be of limited use to developing countries because it would involve high capital costs as well as an advanced infrastructure and skills base [POSTNOTE 2003].

The costs as far as it can be predicted today will be around 5000 €/kW installed capacity. Such investments can only be cost effective under stable and relatively high energy price conditions or with state guarantees. Assuming that the competitiveness of renewable energy will advance through technical progress like it did in the recent years fusion energy will be an expensive form of energy even without taking into account the cost for research and development since the 1950’s.

Conclusions & Outlook

The nuclear industry tries to make the best out of every energy crisis and use it as their marketing strategy. Shortages and insecurities in energy supply are used to back up the research need for nuclear power: from the 1990 oil crisis (Gulf war) to Hurricane Catrina, and the 2006 gas crisis (conflict between Ukraine and Russia), to the steady peak-oil-warning by the IEA and the threat of climate change. Nuclear power is presented as the answer and claims at the same time that the well-known problems of nuclear energy are overcome. The solution is the development of new nuclear reactor systems based on nuclear fission plus reprocessing called Generation IV and – completely new – nuclear fusion reactors.

Generation IV

Research institutions and R&D departments of nuclear companies hope to receive research funding for concepts they have developed, but which have not been applied successfully in the last 30 years [WENISCH et PRAUHART 2006]. Generation IV breeder systems are a new edition of the Fast Breeder concept, which would mean a continuation of the plutonium economy on a scale unseen until now. Another track being investigated is the thorium fuel route. This would be the continuation of the High Temperature Reactor development: a prototype was operated in the 1970's for the first time in Germany, but never reached stable working conditions before the reactor was finally shut down twenty years later. Only one very small reactor of this type is in operation today – in China.

The nuclear industry promotes it's potential to be part of the solution of all energy problems of our planet: With new reactors, new fuel cycle systems and last but not least by providing the world with a practically infinite energy source: nuclear fusion.

During more than 50 years of research, construction and operation of nuclear facilities, the nuclear industry has created a lot of problems without a solution (safety of nuclear installations, nuclear waste, radioactive emissions etc.). However, they are still trying to receive more public funding and support, claiming that future nuclear energy will be better than previous systems.

The claim

Under the title Generation IV reactor concepts, the nuclear industry promises new systems as a response to the upcoming scarcity of fissile material (uranium), the issue of proliferation and the requirement of safe repositories for high level nuclear waste.

➲ Reality

Generation IV reactor systems consist of reactors for energy production plus reprocessing facilities. Part of the systems are also plutonium breeders, which are designed to produce electricity and at the same time »breed« new plutonium. The reprocessing facilities separate fissile material from spent fuel to manufacture MOX fuel. This »recycling« of course generates new nuclear waste.

Vast quantities of highly toxic materials like plutonium and uranium isotopes would be transported around the world like oil or coal, and pose a considerable accident risk as well as become a target for sabotage and terror.

Moreover, Generation IV reactor systems will probably enhance the possibilities to stash away fissile material, since the amount needed for a nuclear explosion is small: between 10 kg – 50 kg Uranium (^{235}U) or 5 kg Plutonium (^{239}Pu), depending on the construction. The efforts of the nuclear industry to construct more and more nuclear facilities and provide fissile material for civil purposes will probably outweigh the non-proliferation efforts of the

IAEA.
New reactors are expected to have simpler and cheaper designs. However, due to the extreme conditions under which those reactors are operating (extremely high temperatures, pressures etc.), Generation IV reactors need even more sophisticated safety systems.

It is widely assumed that Generation IV systems will not be commercially available before 2030 and there is no indication that these reactors will make nuclear power leave the league of the most expensive sources for electricity generation.

Fusion

Fusion is the other nuclear technology which is to provide the world with sustainable energy supply. Nuclear fusion is a relatively young field of science. Development started in the 1950's and had to deal predominately with questions concerning the properties of the plasma state. Much scientific progress has been made in this field. Today the major obstacles on the way to nuclear fusion power plants are no longer related to principal scientific questions but rather to questions of design and suitable technical solutions. European fusion research is focused on the ITER project. This is financed by the 7th framework programme 2007-2011 with 1.947 billion euro from EURATOM research funding. The next step in the ITER program, after finishing the construction of the ITER facility, is to prove that a self-sustaining fusion process can be achieved by 2017. Another step to commercial realization of a fusion reactor is the construction of DEMO – a Demonstration fusion power plant, which should produce electricity.

The claim

Preparation for the construction of a commercial fusion reactor is planned to be finished in 2050.

➲ Reality

Even though this sounds far ahead in the future, it is actually a very optimistic time schedule. During the past 50 years of fusion research the difficulties of developing a fusion power plant have been underestimated and timelines for realization have been postponed again and again.

Fusion technology may have some advantages compared to a fission reactor, however, it is not true that it would be proliferation resistant: Even a fusion reactor can be used for breeding weapon-grade plutonium. Decommissioning of the fusion facility creates nuclear waste, which has to be stored for a long time – at least for thousands of years.

The feasibility of constructing and operating fusion plants will depend on their safety level, environmental impact and economic viability. These factors are hard to predict because the outcome depends on a range of assumptions regarding future power plant designs and future structural materials. Surprising developments cannot be excluded during the research process. In particular the technical realization of a material which provides a shield against neutron radiation and is not quickly degrading due to activation at the same time is a big challenge. This could even require new test facilities before an applicable solution is found.
Fusion power plants will not be ready in time to contribute timely to the CO^2 reductions. Even when finished, they will be of limited use because of the very high investment costs.

RECOMMENDATIONS

When deciding on the next steps in energy policy, time and money are key. When looking at long-term planning and construction time of nuclear power plants, and the high investments costs, public funding for R&D and the actual construction and operation are not justified.

On average the price per installed kW of constructing a nuclear power plant is around two times that of coal and four times that of a gas plant. Furthermore, the time it takes to build a nuclear power plant is between 5-10 years, while a gas plant is built in 3 years and a wind farm in around 6 months. After 60 years of development with support of public funds in several large countries, the overall costs of nuclear power have not been reduced significantly. Still, any new nuclear power plant built today would need support on several levels from the state (e.g. US federal financial incentives for the first new nuclear power plants).

The costs of renewable energy are forecasted to decrease due to improved technologies and economies of scale. As a rule of thumb it is said that for a doubling in production, the price of renewables falls by 20%. [FROGATT-2 2006]

To invest into the costlier option also means that per euro spent less carbon is displaced. This opportunity cost is an unavoidable consequence of not following the least-cost investment option: the order of economic priority is also the order of environmental priority. [LOVINS 2006]

Energy policy is now at a crossroad where it has to decide whether nuclear energy could be part of a sustainable energy future. Since there is not much time to develop new technical solutions it is much more efficient in terms of abatement of global warming to deploy existing and refine **safe & cheap solutions: improving efficiency and renewable energy resources.**

The growth of our economies has been associated with an important reduction of their energy intensities. Without that increase in energy efficiency, about twice as much additional fossil energy would have been consumed. That is, the contribution of nuclear and renewable energy has been outweighed by far by the increase of efficiency and structural changes in energy conversion and use. [FROGATT-1 2006]

Realization of »negajouls« (conservation of energy and increase of energy efficiency) is the biggest energy source worldwide and the one with the smallest CO_{2eq}/kWh. Minimizing the energy demand is the condition for a sustainable energy supply by renewables. Instead of importing oil, gas or biomass, a sustainable energy system has to rely on regional energy resources.

Big players in the electricity business (like Vattenfall, ENEL, RWE or E.ON) obstruct the deployment of regional energy production in various small power plants. They prefer to build big plants (even using dirty lignite) and dictate this policy to the governments. Big players are not interested in modernizing and improving power grids and allowing regional electricity producers to feed energy into the power grids. They are also not interested in giving municipalities control over regional grids. They love big nuclear power plants like Fast Breeders and the new EPR, or fusion reactors with capacities well over 1000 MW, to keep their monopoly in the electricity market. Since electricity is traded at the stock exchange, they can sustain high prices by shutting down plants to create shortages.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Many small grids with regional input from renewable sources could regain control to consumers and could also be part of a bigger national grid where surplus could be exchanged if needed. More independence could be reached by options to deliver electricity also in isolated operation in the regional network.

A dramatic reduction of energy demand is the prerequisite for a sustainable energy supply in the future: e.g. thermal insulation of buildings and an efficient use of energy for heating, lightning and of course transport.

However, this presupposes a clear political decision for efficiency. In order to prevent the worst effects of climate change, policy must act independently from the short-term interests of companies selling energy or energy consuming goods. A reliable basis for a sustainable energy system that satisfies energy needs based on renewables has to be established.

Gas-Cooled Fast Reactor (GFR)

Breeder reactor type designed to offer the provision of electricity, Hydrogen and process heat and for the breeding of fuel

Characteristics

- Fuel: Uranium-Plutoniumcarbide
- Coolant: Helium
- Breeder system
- Fast neutron spectrum
- Power: 600 MW_{th}
- Coolant exit temperature: 850°C
- Burn-up: 50 GWd/t_{HM}
- Power density: 100 MW_{th}/m^3

Risks and Difficulties

- Reduced controllability due to low thermal inertia
- In-vessel structural materials will have to withstand fast-neutron damage and very high temperatures up to 1600°C
- Extreme conditions (high pressure, high temperature)
- High residual decay heat after shutdown
- Significant high power density
- Proliferation

Lead-Cooled Fast Reactor (LFR)

Breeder reactor type designed for the management of high-level wastes and for the breeding of fuel

Characteristics

- Fuel: Matrix-confined mixture of Uranium, Plutonium and other actinoides
- Coolant: Lead or Lead-Bismuth
- Breeder system
- Fast neutron spectrum
- Power: up to 3600 MW_{th}
- Coolant exit temperature: 800°C
- Burn-up: up to 150 GWd/t_{HM}
- Fuel charging cycle: 30 years

Risks and Difficulties

- Incompatibility of Nitride matrix with cladding tube material
- In-vessel structural materials will have to withstand fast-neutron damage
- Extreme conditions (high pressure, high temperature)
- Additional environmental risks due to the use of Lead coolant
- Less charging cycles also means less maintenance
- Proliferation

Sodium-Cooled Fast Reactor (SFR)

Breeder reactor type designed for the management of high-level wastes and for the breeding of fuel

Characteristics

- Fuel: Matrix-confined mixture of Uranium, Plutonium and other actinoides
- Coolant: Sodium
- Breeder system
- Fast neutron spectrum
- Power: up to 5000 MW_{th}
- Coolant exit temperature: 550°C
- Burn-up: up to 200 GWd/t_{HM}
- Power density: 350 MW_{th}/m^3

Risks and Difficulties

- Sodium causes heavy reactions in contact with air (fire) and with water
- Corrosion behaviour
- Maintenance process for cooling systems filled with liquid Sodium
- In-vessel structural materials will have to withstand fast-neutron damage
- Extreme conditions (pressure, temperature, high power density)
- Pyrometallurgical reprocessing in plant

Molten Salt Reactor (MSR)

Reactor type designed to offer the possibility of ongoing fissile charge, reprocessing and separation of nuclear waste

Characteristics

- Fuel: Uranium- or Plutoniumfluoride
- Coolant: same as fuel
- Thermal (slow) neutron spectrum
- Power: 1000 MW_{th}
- Coolant exit temperature: 850°C
- Ongoing addition of actinoides for degradation and destruction of nuclear waste
- No charging cycles for fissile charge

Risks and Difficulties

- Incompatibility of Nitride matrix with cladding tube material
- In-vessel structural materials will have to withstand fast-neutron damage
- Extreme conditions (high pressure, high temperature)
- Additional environmental risks due to the use of Lead coolant
- Less charging cycles also means less maintenance
- Proliferation

Supercritical-Water-Cooled Reactor (SCWR)

Simplified reactor type designed for the generation of low-cost electricity

Characteristics

- Fuel: Uranium Dioxide
- Coolant: supercritical water
- Thermal (slow) neutron spectrum
- Power: 1700 MW_{th}
- Coolant exit temperature: 510°C
- Burn-up: 45 GWd/t_{HM}
- Power density: 100 MW_{th}/m^3

Risks and Difficulties

- Single-phase coolant at supercritical conditions (water above 374°C and 22,1 MPa)
- „Low cost target»: Simplification of the reactor at the expense of safety (reduction of size of the cooling system shall reduce costs, but also minimizes the coolant inventar and therefore provides additional risks in case of an accident)
- Direct cycle for compact containment
- Proliferation

Very-High-Temperature Reactor (VHTR)

Advancement of the THTR reactor type, with extreme coolant exit temperatures up to 1000°C applicable for applications such as process-heat or Hydrogen production

Characteristics

- Fuel:Zirconium Carbide coated rods or pebbles (fissile material e.g. Thorium)
- Coolant: Helium
- Thermal (slow) neutron spectrum
- Power: 600 MW_{th}
- Coolant exit temperature: 1000°C
- Burn-up: up to 200 GWd/t_{HM}
- Power density: up to 10 MW_{th}/m^3

Risks and Difficulties

- Fuel and material behaviour at extrem conditions (very high temperature!)
- Direct-cycle for electricity supply only; indirect-cycle for additional process-heat supply
- Involuntary power and temperature peaks
- Development of a high temperature Helium turbine
- Proliferation

Stellerator

Fusion reactor designed for continuous operation

Characteristics

- Fusion reactor
- Fuel: Deuterium, Tritium
- Inherent confining magnetic field
- Continuous operation
- Power: 2000 MWth

Risks and Difficulties

- General technical feasibility
- High investment costs and long development time (~50 years)
- Very small manufacture and assembly tolerance for all components
- Embrittlement of structural material due to high neutron flux
- Possible neutron source for the breeding of weapon grade materials
- Proliferation of Tritium

Tokamak

Most advanced fusion reactor design, which nevertheless will not be available before 2050

Characteristics

- Fusion reactor
- Fuel: Deuterium, Tritium
- Parts of the magnetic field through induction into the plasma
- Pulsated operation
- Power: 2000 MWth

Risks and Difficulties

- General technical feasibility
- High investment costs and long development time (~50 years)
- Embrittlement of structural material due to high neutron flux
- Possible neutron source for the breeding of weapon grade materials
- Proliferation of Tritium

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Burnup
In the field of nuclear energy conversion the burnup is the amount of thermal energy that has been produced per mass unit of a fuel element. Usually it is expressed in gigawatt-days per ton of heavy-metal. In contrast to fossil fuel the fuel in nuclear reactors cannot be converted »in one go« since the fuel undergoes changes during its use in the reactor which require the fuel elements to be exchanged.

Becquerel
The becquerel (symbol Bq) is the SI derived unit of radioactivity, defined as the activity of a quantity of radioactive material in which one nucleus decays per second. It is therefore equivalent to s^{-1}. The older unit of radioactivity was the curie (Ci), defined as 3.7×1010 becquerels or 37 Gbq. In a fixed mass of radioactive material, the number of becquerels changes with time. Sometimes, amounts of radioactive material are given after adjustment for some period of time. For example, one might quote a ten-day adjusted figure, that is, the amount of radioactivity that will still be present after ten days. This de-emphasizes short-lived isotopes. SI uses the becquerel rather than its equivalent, the reciprocal second, for the unit of activity measure to eliminate any possible source of confusion regarding the meaning of the units, because errors in specifying the amount of radioactivity, no matter how far-fetched, could have such serious consequences.

Decommissioning
The decommissioning of nuclear facilities is sometimes referred to as nuclear decommissioning, to mark the difference between »conventional« decommissioning and dismantling projects. In fact, the main difference to the dismantling of a »conventional» facility is the possible presence of radioactive or fissile material in a nuclear facility, which requires special precautions. Decommissioning involves many administrative and technical actions, whose purpose, after a facility has been taken out of service, is to allow its release from regulatory control and relieve the licensee of his responsibility for its nuclear safety.

Fast Breeder Reactor
The fast breeder or fast breeder reactor (FBR) is a fast neutron reactor designed to breed fuel by producing more fissile material than it consumes. The FBR is one possible type of breeder reactor.

Fissile Material
Any material capable of undergoing fission.

Fission Products
Result of the fission process; some fission products decay rapidly, others exist as nuclear waste for centuries.

Light Water Reactor
A light water reactor or LWR is a thermal nuclear reactor that uses ordinary water, also called light water, as its neutron moderator. This differentiates it from a heavy water reactor, which uses heavy water as a neutron moderator. In practice all LWRs are also water cooled.

MOX
Mixed oxide, or MOX fuel, is a blend of plutonium and natural uranium, reprocessed uranium, or depleted uranium which behaves similarly (though not identically) to the low enriched uranium feed for which most nuclear reactors were designed. MOX fuel is an alternative to low enriched uranium (LEU) fuel used in the light water reactors that predominate nuclear power generation. An attraction of MOX fuel is that it is a way of disposing of surplus weapons-grade plutonium, which otherwise would have to be handled as a difficult-to-store nuclear waste product, and a nuclear proliferation risk.

Nuclear Reprocessing
Nuclear reprocessing separates any usable elements (e.g., uranium and plutonium) from fission products and other materials in spent nuclear reactor fuels. Usually the goal is to recycle the reprocessed uranium or place these elements in new mixed oxide fuel (MOX), but some reprocessing is done to obtain plutonium for weapons. It is the process that partially closes the loop in the nuclear fuel cycle.

Proliferation
Nuclear proliferation is the spread of nuclear weapons production technology and knowledge to nations that do not already have such capabilities.

Radiotoxicity
Measure of how nocuous a radio nuclide is to health. The type and energy of rays, absorption in the organism, residence time in the body, etc. influence the degree of radiotoxicity of a radio nuclide.

Bq	Becquerel (SI unit of radioactivity)
°C	degree Celsius (SI unit of temperature)
CGS	Centimeter-Gram-Second (CGS unit system)
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent (measure of global warming potential of greenhouse gases)
Cs	Cesium
DEMO	Demonstration Fusion Power Plant
DOE	US Department of Energy
EFDA	European Fusion Development Agreement
ENEL	Ente Nazionale per l'Energia Elettrica
EPR	European Power Reactor
EU	European Union
EURATOM	European Atomic Energy Community
eV	Elektronvolt (natural unit of energy = 1.6 x 10-19 Joule in SI)
FZKA	Forschungszentrum Karlsruhe
g	gram (CGS – unit of mass)
GDR	German Democratic Republic
Generation II	second generation
Generation III	third generation
Generation IV	fourth generation
GFR	Gascooled Fast Reactor
GIF	Generation IV International Forum
GWd/t_{HM}	Gigawatt-day per ton of heavy metal (derived unit of burn-up)
HEU	Highly Enriched Uranium
HTR	High-Temperature Reactor
I	Iodine
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
ITER	International Thermonuclear Experimental Reactor
J	Joule (SI unit of energy, work and heat)
kg	Kilogram (SI unit of mass, 103 g in CGS)
Kr	Krypton
LEU	Lowly Enriched Uranium
LFR	Lead cooled Fast Reactor
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide Fuel
MSR	Molten Salt Reactor
MTOMR	Medium Term Oil Marked Report
NERAC	Nuclear Energy Research Advisory Committee
Np	Neptunium
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
Pa	Pascal (SI unit of pressure)
Pa	Protactinium
PPCS	Power Plant Conceptual Study
PRIS	Power Reactor Information System
Pu	Plutonium
PuO_2	Plutonium dioxide
R&D	Research and Development
RWE	Rheinisch-Westfälisches Elektrizitätswerk
s	Second (SI unit of time, CGS unit of time)
SCWR	Supercritical Watercooled Reactor
SFR	Sodium cooled Fast Reactor
SI	Système international d'unités (SI unit system)
Sr	Strontium
Sv	Sievert (= unit of dose equivalent, describes the biological effects of radiation)
Th	Thorium
THTR	Thorium-High-Temperature Reactor
Tl	Thallium
U	Uranium
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
UO_2	Uranium dioxide
US$	United States Dollar
USA	United States of America
VHTR	Very-High-Temperature Reactor
W	Watt (SI unit of power)
Wh	Watthour (SI unit of work, energy and heat)
Wh_{el}	Watthour electric
W_{th}	Watt thermic
Xe	Xenon

Metric Prefixes:

μ	mikro (= 10^{-6}, therefore one part in a million)
m	milli (= 10^{-3}, therefore one part in thousand)
k	kilo (= 10^{3}, therefore 1 000 or thousand)
M	Mega (= 10^{6}, therefore 1 000 000 or million)
G	Giga (= 10^{9}, therefore 1 000 000 000 or billion)

Radioactive Nuclides:

Description of radioactive nuclides: e.g. ^{137}Cs: the mass number (137) indicates the number of nucleons