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The Future of Nuclear Energy: Facts and Fiction - Part IV: Energy from Breeder Reactors and from Fusion?

Posted by Francois Cellier on November 10, 2009 - 4:51pm in The Oil Drum: Europe
Topic: Alternative energy
Tags: fast breeder reactors, fossil fuel depletion, michael dittmar, nuclear energy, nuclear fission, nuclear fusion, thorium, uranium [list all tags]

This is the fourth part of a four-part guest post by Dr. Michael Dittmar. Dr. Dittmar is a researcher with the Institute of Particle Physics of ETH Zurich, and he also works at CERN in Geneva.

The accumulated knowledge and the prospects for commercial energy production from fission breeder and fusion reactors are analyzed in this report.

The publicly available data from past experimental breeder reactors indicate that a large number of unsolved technological problems exist and that the amount of "created" fissile material, either from the U238 → Pu239 or from the Th232 → U233 cycle, is still far below the breeder requirements and optimistic theoretical expectations. Thus huge efforts, including many basic research questions with an uncertain outcome, are needed before a large commercial breeder prototype can be designed. Even if such efforts are undertaken by the technologically most advanced countries, it will take several decades before such a prototype can be constructed. We conclude therefore, that ideas about near-future commercial fission breeder reactors are nothing but wishful thinking.

We further postulate that, no matter how far into the future we may look, nuclear fusion as an energy source is even less probable than large-scale breeder reactors, for the accumulated knowledge on this subject is already sufficient to say that commercial fusion power will never become a reality.

(Links to 1st, 2nd, and 3rd parts)

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1. Introduction

Over one hundred years ago, physicists began to understand that a huge amount of energy could be obtained from mastering nuclear fusion and fission energies. For example, the production of only 1 kg of helium from hydrogen "liberates" a thermal energy of about 200 million kWh. In the sun, this fusion reaction transforms about 600 million tons of hydrogen into helium every second, thus liberating 4×10^{26} Joules per second.

The understanding of nuclear physics and its technological applications proceeded with breathtaking speed. It took only seven years from the discovery of the neutron in 1931 to the observation of the neutron induced fission of uranium at the end of 1938. This was followed, on the 2nd of December 1942, by a sustained nuclear chain reaction with a power of 0.5 Watt (and up to 200 Watt at a later time) by E. Fermi and his team in a laboratory located below the Chicago University football stadium [1]. The next steps in using nuclear energy were the explosions of the

Hiroshima and Nagasaki fission bombs, on the 6th and 9th of August 1945, resulting in more than 100,000 deaths and the beginning of the nuclear arms race. Only a few years after the first fission bombs exploded, the USA and the Soviet Union had constructed hydrogen fusion bombs. These bombs were up to 1000 times more powerful than the Hiroshima fission bomb.

Also the peaceful application of nuclear fission energy advanced very quickly: by 1954, the thermal energy from a controlled fission chain reaction could be used to produce commercial electric energy [2]. During the next 30-40 years, a large number of commercial nuclear power plants were constructed in most industrialized countries.

The rapid scientific and technical success in bringing this form of power into the production of commercial energy was impressive. Many nuclear pioneers expected that nuclear fission and fusion would provide their grandchildren with cheap, clean, and essentially unlimited energy. In fact, these successes led most of us to a euphoric and blind belief in continuous scientific and technological progress.

In contrast to such dreams, nuclear fission energy nowadays is not cheap, and even the most optimistic nuclear fusion believers do not expect the first commercial fusion reactor prototype until after 2050. One observes further that nuclear fission energy has been stagnating for about ten years and that its relative share in the worldwide electric energy production has decreased from about 18% during the nineties to only 13.8% currently [3].

Furthermore, the average age of the existing nuclear power plants, the limitations of primary and secondary uranium resources as well as the problems related to nuclear proliferation and nuclear waste all lead to doubts about the prospects of the standard water moderated nuclear fission reactors. In fact, it seems clear at this point that as fossil-fuel energy production declines, sufficient energy to ensure the survival of our highly industrialized civilization cannot come from a rapid growth of nuclear fission energy of this sort.

The problem with the limited amount of economically producible uranium resources can theoretically be addressed with the mastering of the technology of nuclear fission breeder reactors. It is claimed that this technology could increase the amount of fissile material from uranium by a factor of 60-100 and much more if the thorium breeder cycle can be realized [4]. It is believed that breeder technology will enable us to bridge the time gap before nuclear fusion energy, which would become the "final solution" to all energy worries, can be mastered [5].

In this fourth and final part of the *Future of Nuclear Energy* report, we discuss the experience with past and current breeder reactors in Section 3. We analyze how the remaining problems will be addressed with the worldwide Generation IV breeder reactor program and with thorium based breeder reactors (Section 4). The remaining obstacles towards a controlled and sustained nuclear fusion reaction chain are presented in Section 5. In order to simplify the discussion, we start in Section 2 with some facts and basic physics principles of nuclear fission and fusion energies.

2. Energy from nuclear fission and fusion, some facts and physics

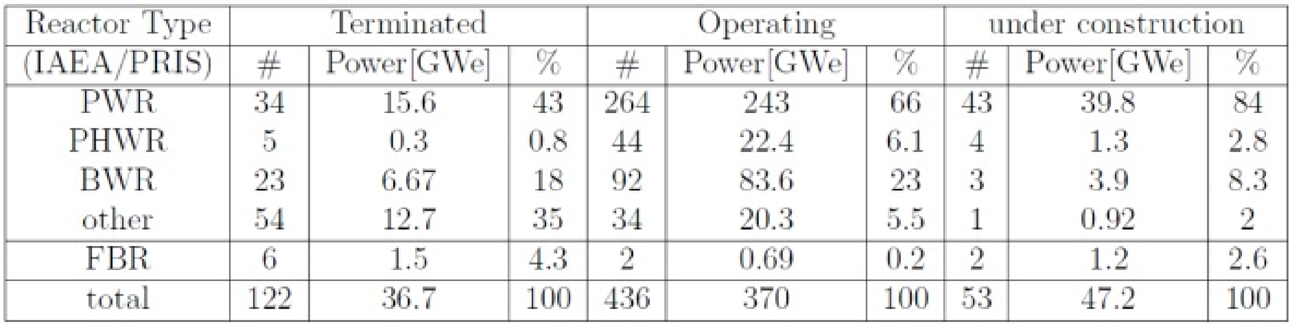
As we have discussed in detail in parts I-III of this report [6], the publicly available data on long term worldwide natural uranium supply are in conflict with even a moderate annual 1% growth rate for conventional water moderated reactors.

Consequently, believers in a bright future of nuclear energy should concentrate their efforts on either (i) the realization of nuclear fuel breeder technology based on the uranium cycle, U238 to PU239, and/or the thorium cycle, TH232 to U233, or (ii) the mastering of commercial nuclear fusion reaction. In this section, an overview of the existing and planned nuclear reactor types and the experience with fast breeder reactors (FBR) is given (2.1). This is followed by a basic summary of the most important principles relevant to the use of nuclear fission and fusion energies (2.2 to 2.4).

2.1. Some facts concerning existing and planned nuclear reactor types

The worldwide nuclear fission reactors produced 2601 TWhe during the year 2008, or roughly 14% of the worldwide electric energy.

For the year 2009, one finds that commercial nuclear energy production will come from 436 nuclear fission reactors with a combined nominal electric power of 370,260 GWe [7].



Reactor Type	Terminated			Operating			under construction		
(IAEA/PRIS)	#	Power[GWe]	%	#	Power[GWe]	%	#	Power[GWe]	%
PWR	34	15.6	43	264	243	66	43	39.8	84
PHWR	5	0.3	0.8	44	22.4	6.1	4	1.3	2.8
BWR	23	6.67	18	92	83.6	23	3	3.9	8.3
other	54	12.7	35	34	20.3	5.5	1	0.92	2
FBR	6	1.5	4.3	2	0.69	0.2	2	1.2	2.6
total	122	36.7	100	436	370	100	53	47.2	100

Table 1: The evolution of different reactor types and their corresponding electric power ratings from the IAEA/PRIS data base (October 2009) [7]. Another five reactors are listed in the "Long Term Shutdown" category, four of which are PHWR's and the fifth is the 0.25 GWe Monju sodium cooled FBR reactor in Japan.

The PRIS data base of the International Atomic Energy Administration (IAEA) shows that the dominant reactor type today including reactors that are currently under construction is the water moderated fission reactor type. The abbreviation PWR (PHWR) stands for pressurized (heavy) water reactor whereas BWR denotes the boiling water reactor. As can be seen from Table 1, these reactors provide over 94% of the nuclear fission power worldwide. The remaining 6% of the nuclear fission power comes from graphite moderated and water or gas cooled older and smaller reactors. It seems that the PWR type has won the competition for the existing reactors and for the next generation of reactors by a large margin.

One observes that only two FBR's are declared operational. A third FBR has been in a "long term shutdown phase" since 1995. The two operational FBR's contribute together 0.2% of the world nuclear power. This tiny contribution from FBR's today is even smaller than it used to be. In the list of 122 decommissioned reactors, one finds 6 FBR's with a combined power of 1.6 GWe, or 4.3%. In the list of 53 reactors (October 2009) currently under construction, one finds only two relatively small FBR's.

These numbers indicate not only that FBR's play a negligible role today and during the next 10 years, but also that their operation experience is far from being an economical and technological success story. Some more details on the worldwide experience with various types of commercial FBR and thorium fuel breeder reactors and their operation are listed below:

- The best operation experience comes from the Russian BN-600 FBR reactor with a rated power of 0.56 GWe. This reactor has been operated commercially for 28 years and is scheduled to close in 2010 [8]. Its average energy availability is given as 73.79%. In a document from the IAEA fast reactor data base [9], one finds that this reactor would be better called a "Fast Reactor," as it was designed to use more fuel than it could produce. A new BN-800 reactor with 0.8 GWe is currently under construction in Russia, and its scheduled start is now given as 2014. Like its smaller "brother," it is designed to consume Pu239 rather than breed surplus fissile material.
- The other "operating" FBR is the Phenix reactor in France. Phenix originally started operation with a power of 0.233 GWe in 1974. Since 1997, it is rated with 0.13 GWe only,

and an energy availability factor of 60.23% is given for 2008. According to the WNA (World Nuclear Association) data base, it ceased power production in March 2009 and will continue being operated as a research reactor until October 2009 [10]. The larger Super Phenix reactor, with a power rating of 1.2 GWe, achieved a maximal energy availability of 32.6% only. This very low performance, in comparison to PWR's, was achieved during the last operational year (1996) after a very short lifetime of only 10 years.

- The Monju reactor in Japan was closed after a serious sodium leak in 1995. For many years now, the reactor is scheduled to "restart the subsequent year." Perhaps this time, it will really restart during the first few months of 2010 [11].
- A next generation FBR reactor is currently under construction in India. According to the current plans, it will start producing electric energy during the year 2011 [12].
- The KNK II reactor in Germany is listed in the IAEA data base [9] with a tiny capacity of 0.017 GWe. During its operational lifetime, 1978 to 1991, it achieved an average energy availability factor of 23.65%. A larger FBR, the SNR-300, with a rated power of 0.3 GWe was completed in 1985, but for various reasons never started. A large 1.5 GWe FBR, the SNR-2, never completed even the design phase.
- A limited experience with a thorium admixture in the nuclear fuel in commercial prototype reactors exists as well. A WNA document mentions two THTR's (Thorium High Temperature Reactors) [13]: one with 0.3 GWe in Germany, which operated commercially between 1986 and 1989; the second was the Fort St. Vrain reactor with a power rating of 0.33 GWe in the USA. It is listed as the only commercial thorium-fuelled nuclear plant, following closely the German design. It was operated between 1976-1989.
- The WNA document mentions further that the experimental Shippingport reactor in the USA, with a power rating of 0.06 GWe, has successfully demonstrated the concept of a Light Water Breeder Reactor (LWBR) using thorium. The Shippingport reactor began commercial electricity production in December 1957. In 1965, the Atomic Energy Commission started designing the uranium-233 / thorium core for the reactor. The reactor was operated as a LWBR between August 1977 and October 1982.

Several countries have so far managed to construct GWe water moderated slow neutron reactors, mostly of the PWR type. These reactors were operated safely and efficiently for many years, using U235 fuel enriched to 3-4%.

In contrast, large breeder reactors, based on a large amount of initial fissile material and the transformation of U238 and Th232 for breeding new reactor fuel, have so far not even successfully passed a prototype phase.

2.2. Energy from nuclear fission and fusion, some basics

Atoms consist of a nucleus, made of protons and neutrons, and electrons. The size and the chemical properties of atoms are defined by the number of electrons surrounding the nucleus. The combined mass of the protons and neutrons, each 2000 times heavier than the electrons, defines roughly the mass of the atoms. As the nucleus is 100,000 times smaller than the atom, it follows that its mass density is huge in comparison with that of the atom. The same chemical characteristics can be expected for atoms with a fixed number of protons and with different numbers of neutrons, and the energy in chemical reactions is of the order of 1 eV (1.6×10^{-19} Joule). As the nuclear properties of an atom depend on the number of neutrons, the name isotope has been introduced to separate the chemically identical atoms according to their numbers of neutrons.

Without going into details, it is known today that the energy source of the sun and other stars is nuclear fusion. This fusion starts from the large number of hydrogen atoms present in the sun. The fusion reaction in stars is possible because of the enormous gravitational pressure that overcomes the electric repulsive force between positively charged protons. Fusion is the source of all heavier elements that were formed in super-novae explosions of super large early stars and shortly after the big bang. For our subsequent discussions on nuclear fusion, it is important to note that a relatively low fusion power density of about 0.3 Watt/m^3, is found in the sun [14]. In contrast, the power density envisaged for a hypothetical fusion reactor must be at least one million times larger.

The nucleus is bound by the very strong nuclear force, which acts against the repulsive electrostatic force of the protons. Measurements have shown that the mass of the various atoms is almost 1% smaller than the mass of the individual protons and neutrons combined. Following Einstein's famous $E = mc^2$ formula, this mass defect corresponds to a huge amount of energy, about 8 MeV (8 million eV) per nucleon. This energy is liberated when one manages to fusion different nucleons together. Starting from the different hydrogen isotopes, e.g. one proton, deuterium (one proton plus one neutron), and tritium (one proton plus two neutrons), a binding energy of up to a few MeV is found. Further fusion of these hydrogen isotopes into the helium nucleus liberates another roughly 20 MeV.

Neutrons and protons in heavy atoms, such as uranium, are less strongly bound than in lighter atoms, such as iron, and energy can be released in the fission of such heavy atoms. For example, 1 MeV per nucleon, or 200 MeV in total, will be liberated in the fission processes of U233, U235, and U238, each containing 92 protons and 141, 143, and 146 neutrons, respectively. The energy liberated per fission reaction is at least 100 million times larger than in a chemical reaction.

It is therefore not surprising that this has created an enormous interest in subatomic physics and its application for ultimate weapons and/or for the commercial use of energy.

2.2.1. Civilian and military use of nuclear energy, some remarks

The focus of this report is the commercial use of nuclear energy. As the evolution of nuclear energy has always been strongly coupled with the military sector, we feel that a few remarks about the dangers of nuclear weapons and the ambiguity of the commercial use of nuclear energy are needed. First of all, governments wishing to have nuclear weapons were not faced with unsolvable problems related to the development of fission bombs based on Pu239 and U235. This is especially true if nuclear physics and engineering knowhow had been built up under the umbrella of peaceful and commercial use of nuclear fission energy.

Furthermore, it is interesting to notice that advocates of nuclear fission energy like to explain why the dangers from nuclear weapons are far less alarming than believed. This is usually followed by the statement that their praised future nuclear energy technology will avoid proliferation problems. A similar appeasement in their argumentation is found with respect to safety and radiation issues. The existing nuclear power plants are claimed to be very safe, and risks are small compared to many other dangers of modern life. Yet, when their favorite future nuclear energy system is being introduced, it is always pointed out that it further reduces the remaining risks by a large factor.

For example it is often argued that U233 produced in a future Th232 breeding cycle will be useless for nuclear weapons. This argument is certainly flawed as countries who want to have nuclear weapon capability will most likely choose the simpler way to make a bomb using Pu239 or U235. Yet, those who know how to breed and separate hundreds of kg's of U233 can easily replace Th232 with U238 and produce a few tens of kg's of Pu239, sufficient to construct a few nuclear bombs.

Those not yet convinced of the mutual support of peaceful and military applications of nuclear energy technology should rethink their positions with respect to the Nuclear Proliferation Treaty, the NPT, and to the so-called "evil" government of Iran.

A careful reading of the treaty [15] reveals that Iran, at least so far, is in agreement with the NPT obligations. However one finds that NPT member countries should not exchange nuclear knowledge with nuclear weapon countries outside the treaty. It is also worth remembering that the official nuclear weapon states, Russia, USA, UK, France, and China, have declared in the treaty their intention to eliminate nuclear weapons as quickly as possible. Almost forty years after these countries signed the NPT, they still have more than 20,000 nuclear warheads.

The nuclear arms race at the end of the second world war and during the subsequent cold war is well documented in many reports, books, and movies, and we refer to the extensive literature largely available now on the internet. Especially for those who are not yet convinced about the dangers of nuclear weapons, we would like to recommend the short you-tube video on the largest explosion ever, the 60 Megaton hydrogen bomb in Siberia in 1961 [16] and to Stanley Kubric's masterpiece movie "Dr. Strangelove, or how I learned to stop worrying and love the bomb" from 1964 [17]. This film, even though almost 50 years old, presents many still relevant ideas related to the 20,000 remaining nuclear warheads.

2.3. Liberating the energy from nuclear fission and fusion

As we have seen in the previous section, a large amount of energy per reaction can be liberated from the fusion of light elements and from the fission of heavy elements like uranium. However at least two additional conditions must be satisfied before such a process can be considered for energy production.

- In order to obtain a useful amount of energy from nuclear reactions, a continuous and controllable fission or fusion must be achieved for a large number of atoms. For example 10^{20} U235 atoms, i.e., 0.05 gr, the amount of U235 found in 6 gr of natural uranium, need to be split every second in a 1 GWe nuclear fission reactor.
- Enough raw material must be continuously available to sustain this chain reaction.

Only three relevant isotopes satisfy these conditions for the nuclear fission process. These are the two uranium isotopes U235 and U233 and the plutonium isotope Pu239. The energy liberated in the fission process is carried dominantly (about 80%) by the two daughter atoms. This energy is relatively easily transferred to a liquid or gas, and the heat can be used to operate a generator.

The chain reaction is possible as each neutron induced fission reaction produces on average between 2-3 neutrons. As one neutron is needed to initiate another fission reaction, 1-2 excess neutrons minus some inevitable losses are in principle available to increase the reactor power or perhaps to start a nuclear fuel breeding process. The introduction of neutron absorbers allows to control the reactivity of the nuclear reaction and thus to increase or decrease the reactor power.

As we have seen in Section 2.1, most of the large scale nuclear power plants of today are of the PWR (pressurized water reactor) type. They use dominantly U235 as primary reactor fuel. In these reactors, the prompt fission neutrons, with kinetic energies of 1 MeV, are slowed down (moderated) by elastic collisions with the hydrogen nuclei in the water molecules to subeV kinetic energies. The nuclear fission probability with such slow neutrons is increased by a factor of up to several hundred. As a consequence, a large reactor can be efficiently operated and controlled with a relatively low initial enrichment of U235, and large scale power production with moderated neutrons has been mastered by many countries. The combined running experience of such large scale reactors, currently more than 13,000 years, has resulted in stable electric energy production combined with small or negligible risks during regular operation up to an electric power output of more than 1 GWe.

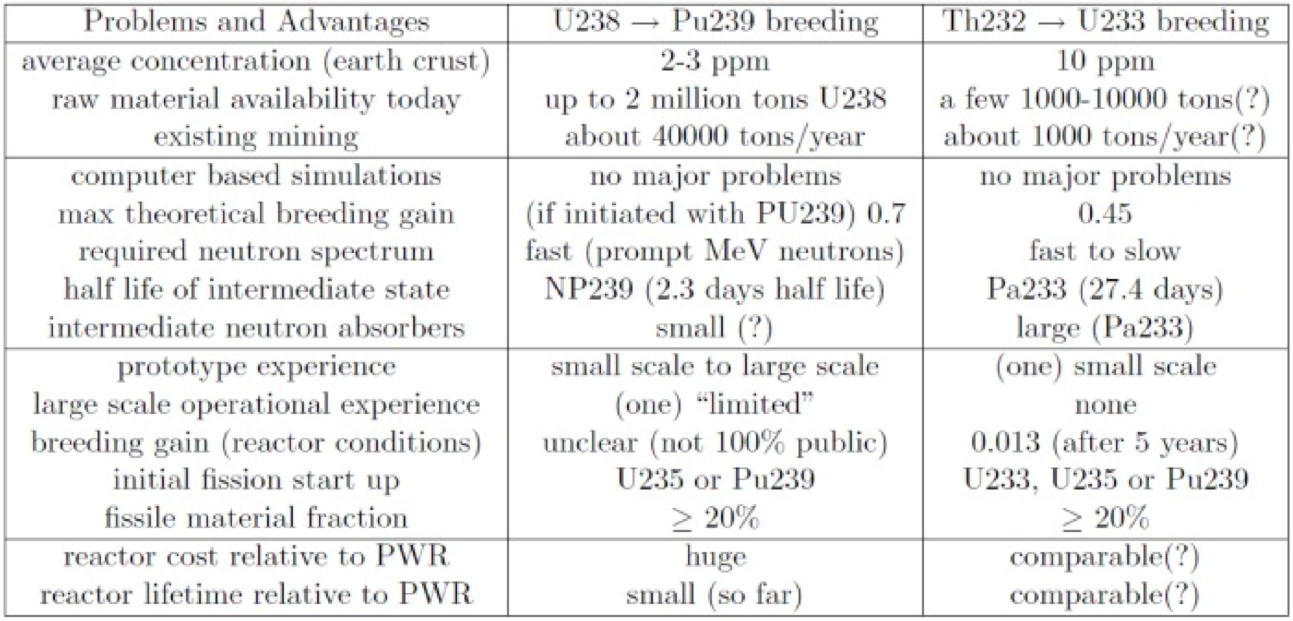
In contrast, the neutron escape rate in smaller reactors and in unmoderated fast reactors is much higher. Therefore, a chain reaction in FBR's with comparable reactor power is more difficult to control, and a larger amount of initial fissile material with a higher density is needed. One consequence is that the required technology to make such highly enriched nuclear fuel will always be faced with the problem of its dual use for bomb making.

The use of the excess neutrons for the transformation of the U238 and Th232 isotopes into fissile Pu239 and U233 looks very promissing, as the amount of fissile material could be increased theoretically by a factor of more than one hundred. The breeding reactions considered would use the excess neutrons according the two reactions:

$$U_{92}^{238} + n \rightarrow U_{92}^{239}(\beta^- \text{ decay}) \rightarrow Np_{93}^{239}(\beta^- \text{ decay}) \rightarrow Pu_{94}^{239} \text{ and}$$

$$Th_{90}^{232} + n \rightarrow Th_{90}^{233}(\beta^- \text{ decay}) \rightarrow Pa_{91}^{233}(\beta^- \text{ decay}) \rightarrow U_{92}^{233}$$

Some advantages and disadvantages for the U238 → Pu239 and the Th232 → U233 breeding cycles and some practical problems are listed in Table 2. Some of these problems and their proposed solutions will be discussed in detail in Sections 3 and 4 of this report. So far only little or no experience exists with large scale GWe breeder prototypes.



Problems and Advantages	U238 → Pu239 breeding	Th232 → U233 breeding
average concentration (earth crust)	2-3 ppm	10 ppm
raw material availability today	up to 2 million tons U238	a few 1000-10000 tons(?)
existing mining	about 40000 tons/year	about 1000 tons/year(?)
computer based simulations	no major problems	no major problems
max theoretical breeding gain	(if initiated with PU239) 0.7	0.45
required neutron spectrum	fast (prompt MeV neutrons)	fast to slow
half life of intermediate state	NP239 (2.3 days half life)	Pa233 (27.4 days)
intermediate neutron absorbers	small (?)	large (Pa233)
prototype experience	small scale to large scale	(one) small scale
large scale operational experience	(one) "limited"	none
breeding gain (reactor conditions)	unclear (not 100% public)	0.013 (after 5 years)
initial fission start up	U235 or Pu239	U233, U235 or Pu239
fissile material fraction	$\geq$ 20%	$\geq$ 20%
reactor cost relative to PWR	huge	comparable(?)
reactor lifetime relative to PWR	small (so far)	comparable(?)

Table 2: A qualitative comparison of the fissile breeding cycles with U238 and Th232. The breeding gain is defined as the ratio of (C-D)/F, where C, D, and F are the numbers of fissile atoms created, destroyed, and fissioned. In order to be called a breeder, more fissile material must be created than fissioned, and the breeding gain must be larger than zero. The "(?)" indicates guestimates, as good information has so far not been found by the author.

We now turn to the fusion process. Nuclear fusion can happen, once the short range nuclear force between nucleons becomes larger than the electrostatic repulsive force between two positively charged nuclei. This can happen if the protons involved either have large kinetic energies or if the protons are compressed by super large gravitational fields as observed in stars. Very high kinetic energies correspond to nucleus temperatures of several tens to hundred million degrees. Such high kinetic energies can be obtained for example in accelerators but only for small numbers. Larger amounts of fusion reactions can be obtained in special magnetic field arrangements.

It follows from first principles that the sometimes discussed "cold fusion" reaction is in contradiction with well established knowledge of subatomic physics. As the repulsive force increases with the number of protons involved, the conditions to achieve fusion with atoms heavier than hydrogen and its isotopes become more and more difficult. It follows that fusion reactions based for example on the "proton-boron" reaction and many others are only possible using accelerators. Ideas to use accelerators for continuous fusion reactions with commercially interesting GW power prove to be wishful thinking once the required amount of 10^{21} fusion reactions per second is considered. The very low efficiency for transforming electric energy into kinetic energy of proton beams poses another fundamental problem for such exotic ideas.

The probability of a fusion reaction depends on the product of the plasma temperature and the fusion reaction cross-section. The deuterium-tritium fusion is a factor of 100 to 1000 easier to achieve than the next two fusion reactions of deuterium and $\mathrm{He}^{3}{}_{2}$ and deuterium-deuterium, respectively. As it is already extremely difficult to achieve even the lowest interesting plasma temperatures on the required large scale, it follows that the only possible fusion reaction under reactor conditions is the deuterium-tritium fusion into helium ($\mathrm{He}^{4}{}_{2}$).

An additional advantage of this reaction is the fact that the produced additional neutron carries 14 MeV of the liberated energy of almost 18 MeV per fusion reaction out of the plasma zone. Thus in theory, it can be imagined that the 4 MeV carried by the helium nucleus are used to keep the plasma temperature high enough, and that the neutron energy is transferred somehow to another cooling medium. This medium is imagined to transfer the heat to a generator.

Unfortunately tritium is unstable; its half life is only 12.3 years; and it does not exist in sizable amounts on our planet. It must therefore be produced in a breeding process. A possible chain reaction could follow the scheme:

$$H_1^2 + H_1^3 \rightarrow He_2^4 + 1 \text{ neutron}$$

$$\text{neutron} + Li_3^6 \rightarrow He_2^4 + H_1^3$$

In comparison to the breeding and energy extraction in fission reactions, at least three additional fundamental problems can be identified for the fusion process:

- A sustained super high temperature, at least 10 million degrees, is required in order to have fusion reactions happening at an interesting rate. Such high temperatures can be achieved in some special magnetic field arrangements or in a tiny volume with very intense laser or particle beams. Unfortunately, no material is known that can survive the intense neutron flux under sustained reactor conditions and the sometimes occurring plasma eruptions.
- It is difficult to transfer the energy from the 14 MeV neutron to a gas or a liquid without neutron losses.
- The considered breeding reaction requires essentially that 100% of the produced neutrons must be used to make tritium. As this is even theoretically impossible, some additional nuclear reactions are proposed where heavier nucleons act as neutron multipliers. However so far, even the most optimistic and idealized theoretical calculations have failed to produce neutrons in sufficient numbers.

In short, the accumulated knowledge today indicates that the proposed fusion reaction is unsus tainable and cannot lead to a sustainable power production. This statement will be corroborated with more details in Section 5.

2.4. Dangers related to radioactive material

We will conclude this section with some issues related to radioactive elements produced and liberated in the use of nuclear energy and the related dangers from ionizing radiation. First of all, there are three types of radioactive decays, producing α, β, and γ radiation. In addition, cosmic rays and various particles produced in high energy physics experiments should also be considered as a potential radiation hazard.

The damage to cells is related to the ionizing potential or the energy deposit per volume originating from a source. The hazard is usually split into high and low radiation dose effects. Very high radiation dose and the corresponding energy deposit result in fast cell death. If large and concentrated enough, the result can be the destruction of vital organs and death. It is important to know that the careless use of radiation during the early days of nuclear physics and its applications have resulted in relatively high cancer rates among the participating scientists and engineers [18].

The more tricky and less well understood damage comes from small dose and long-term effects to the cell DNA. While some self-repair mechanism to broken DNA exists, it is also known that a single unlucky hit by a cosmic ray can transform the normal DNA into a cancer developing DNA, resulting in the death of the host many years later. It follows that the importance of small radiation doses for the development of a particular cancer type and in comparison to many other causes like smoking and asbestos is difficult to quantify. As a result, the associated cancer risks from small radiation doses will continue to fuel the emotional debate about nuclear energy for a long time.

Despite these uncertainties, today the precautionary principle is used in many countries, and very strict rules for people working in a radiation environment are applied. These rules are often summarized under the name ALARA (as low as reasonably achievable). The goal to reduce any radiation exposure to essentially negligible levels is one of the most important occupations of a radiation safety group. As a result of these efforts, assuming that expensive protection measures are taken, the health risks from radioactive contamination under "normal operation conditions" are often much smaller than risks associated with working hazards in many other industrial domains. However, time pressure and profit optimization will always be in competition with ever more strengthened safety regulations.

It is also evident that it is essentially impossible to guarantee "normal operation" of the nuclear industry with its accumulating waste over periods of hundreds of years. A solution to these problems is, as with other similar long-term problems of our industrial growth-based societies, left for future generations.

3. Experience with real breeder reactors

Breeder reactors are based on the idea that only one neutron, out of the 2.5 neutrons on average from the fission of U235 and U233 (and 2.9 neutrons from Pu239), is required to keep the chain reaction going. It can thus be imagined, even if some neutron losses are allowed, that the additional neutrons can be used to make more nuclear fuel from U238 or Th232 than fissioned. Accordingly, a reactor is defined as a *breeder reactor* if more fissile material is produced than consumed.

The number of free neutrons per fission reaction is $\eta = (\sigma_f / \sigma_a) \times \upsilon$, where σ_f is the neutron induced fission cross-section, and σ_a the neutron absorption (the sum of the neutron capture and fission) cross-section, and υ is the average number of prompt fission neutrons [19]. The fission to capture ratio and thus η depend on the neutron energy and the different possible isotopes. As one neutron is required to sustain the chain reaction, breeding is only possible if η is larger than 2. This condition is found for Pu239, U235, and U233 fission, where η for prompt fast fission neutrons is 2.7, 2.3, and 2.45, respectively. For thermal (moderated) neutrons, U233 has the highest η value of 2.3, followed by 2.11 for Pu239, and 2.07 for U235.

Some Pu239 fuel production happens also in standard PWR reactors. Depending on the reactor and fuel design characteristics as well as the amount of remaining fissile fuel in the reactor, up to 30% and more of the produced energy comes from the secondary Pu239 fission.

Two theoretical breeder options exist:

- The use of thermal neutrons and Th232 as input breeding material.
- The use of fast prompt neutrons dominantly from Pu239 fission, thus the name fast reactor, with U238 as the breeding material.

The use of the Th232 → U233 cycle seems, at least on a first glance, more attractive. The reaction can occur in the high fission cross-section domain using moderated neutrons. The fission process with moderated neutrons is well understood, relatively easy to control, and already in use with the standard nuclear water moderated reactors. It seems that in principle one only needs sufficient amounts of U233 mixed with Th232 in order to keep such a reactor operating. Some of the remaining technical obstacles will be discussed in Section 4.4.

For the U238 → Pu239 breeder cycle, one has to operate the fission process, either starting with U235 or Pu239, in the low fission cross-section domain. As a consequence, such reactors have to be operated with highly enriched U235 (HEU) or Pu239 fuels. Thus, one is not only confronted with special safety conditions for a large amount of bomb making material, but also with a huge amount of fissile material that could under certain conditions reach the critical mass resulting in an uncontrolled chain reaction followed by a nuclear meltdown. Furthermore, the cooling of the active reactor zone has to be done with a low neutron absorption cross-section and a high thermal conducting material like liquid sodium. Unfortunately, sodium is chemically very active and can easily burn in contact with oxygen.

3.1. The Shippingport LWBR thorium reactor

The experience with the thorium breeder cycle comes mainly from research at the US Shippingport reactor, rated with a net power of 0.06 GWe. This reactor operated during the 60s, 70s, and 80s. In 1965, the Atomic Energy Commission started designing the uranium-233 / thorium core for the reactor. The reactor was operated as a LWBR between August 1977 and October 1982.

According to the documentation, the reactor was started with a highly enriched 98% U233 inventory of 501 kg and a total of 42,260 kg of Th232 [20]. No details are given about the origin of the 501 kg of U233. However, one can assume that it came from a standard U235 fission reactor, where excess neutrons can be used to transform Th232 (or U238) blankets into U233 (or Pu239).

The reactor had a maximum thermal power of 0.2366 MW (therm) and was operated for 29,047 effective full hours, or about 66% of the time. After five years of operation, a very detailed analysis of the fuel elements was performed. It was found that the total U233 inventory had increased to 507.5 kg, a factor of 1.013. While it is impressive that the reactor could be operated and fueled with Th232 over a period of 5 years, the U233 gain was only about 6 kg of fissile material.

Assuming that such a reactor is supposed to eventually produce the U233 starting fuel for another reactor, it will take a long time before the second package of initial reactor core has been produced. Significant technological breakthroughs are required before this chain can be called feasible on a large scale.

The documents do not say much about the contamination of the 507.5 kg of U233 with fission products and its usefulness for further studies after this five year experiment. The fact that no subsequent reactor experiment has been performed might provide a partial answer to this question.

Furthermore, it is interesting to note that the initial concentration of fissile material in a reactor with only 0.237 GW (therm) energy was very large. It can be estimated that this amount, placed in a standard PWR, could have produced at least 5 times more electric energy than it had during the actual experiment.

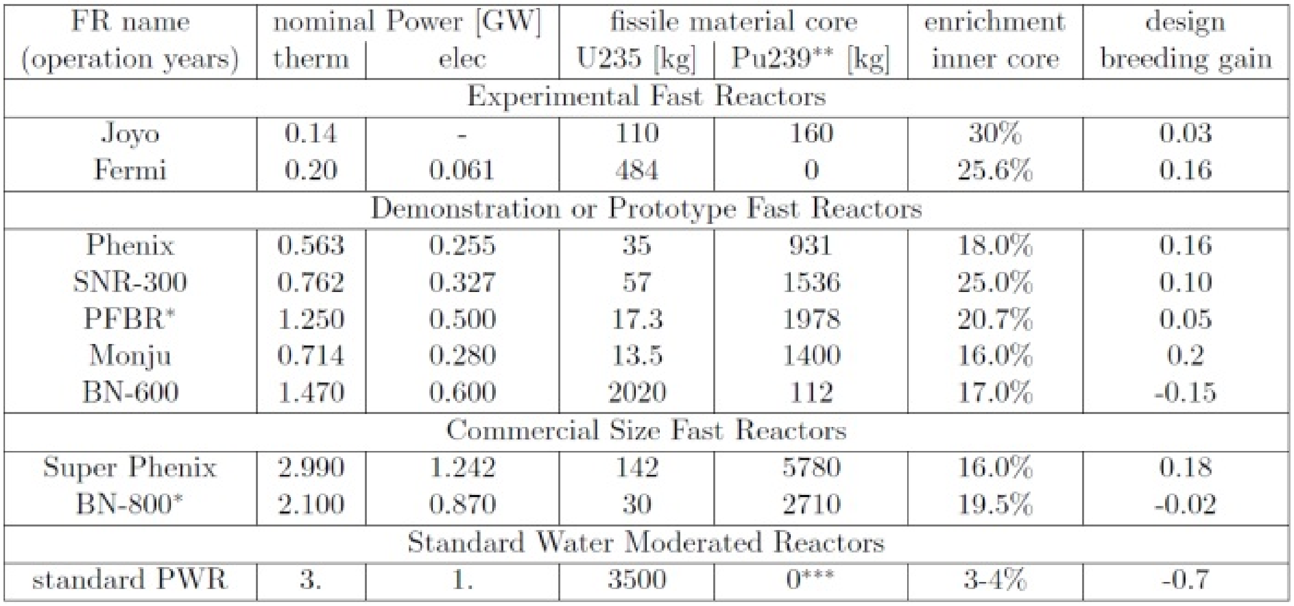
In contrast to the experiments performed at the Shippingport reactor, where the initial core was already U233, a realistic Th232 reactor cycle must be started with an initial U235 or Pu239 core. Consequently, the experience gained with the Shippingport reactor experiment cannot be considered as a proof that the envisaged system can function. It follows that many more tests are needed, before a functioning large-scale prototype Th232 breeder reactor can be constructed.

3.2. Experience with fast reactors

For the purpose of this report, concerning the *future of nuclear energy*, we are mainly interested in the situation with the most important aspect, the question of the fuel breeding option. Unfortunately very little information is provided for the experimental breeding achievements, and most reports present the theoretical design breeding ratios. For example the breeding ratio for the FBR Phenix reactor in France is given in many textbooks as 1.14 [21]. This number corresponds however to the theoretical design, and it seems that a detailed experimental analysis, like the one done for the Th232 to U233 cycle and the Shippingport reactor, is either secret or has not been performed.

Despite the missing experimental data of achieved breeding gains, the IAEA document [22] about the FBR core characteristics provides useful information about the design of such reactors. In this document, a large number of FBR reactors, separated into (1) experimental fast reactors, (2) demonstration of prototype fast reactors, and (3) reactors of commercial size, are presented.

The breeding gain, defined as the ratio of (C-D)/F, where C, D, and F are the number of fissile atoms created, destroyed, and fissioned, and other characteristics of different fast reactors are summarized in Table 3.



FR name (operation years)	nominal Power [GW] therm	elec	fissile material core U235 [kg]	Pu239** [kg]	enrichment inner core	design breeding gain
Experimental Fast Reactors						
Joyo	0.14	-	110	160	30%	0.03
Fermi	0.20	0.061	484	0	25.6%	0.16
Demonstration or Prototype Fast Reactors						
Phenix	0.563	0.255	35	931	18.0%	0.16
SNR-300	0.762	0.327	57	1536	25.0%	0.10
PFBR*	1.250	0.500	17.3	1978	20.7%	0.05
Monju	0.714	0.280	13.5	1400	16.0%	0.2
BN-600	1.470	0.600	2020	112	17.0%	-0.15
Commercial Size Fast Reactors						
Super Phenix	2.990	1.242	142	5780	16.0%	0.18
BN-800*	2.100	0.870	30	2710	19.5%	-0.02
Standard Water Moderated Reactors						
standard PWR	3.	1.	3500	0***	3-4%	-0.7

Table 3: Some design values for the three groups of fast reactors, experimental, demonstration or prototype, and commercial size [22]. Reactors marked with a "" are currently under construction. The design numbers can be compared with the ones of existing large commercial 1 GWe PWR reactors, assuming an average charge of 500 tons of natural equivalent, given in the last line. The "**" and "***" stand for a mixture of different plutonium isotopes dominated by Pu239 and the amount within the initial core, respectively.*

It is very unfortunate that experimental breeding gains are not given in the IAEA fast reactor data base. In absence of any detailed publication, one can assume that the required detailed and very expensive isotope analysis of the reactor fuel has not been performed or published. The theoretical hopes for fuel breeding are thus not backed up with hard experimental data. Nevertheless, already the theoretical breeding gains of the different FBR's are revealing. Ten out of the twelve small experimental reactors were operated in a configuration not for breeding. The other two experimental reactors, listed in Table 3, are the Joyo in Japan and the Fermi in the USA. The Joyo reactor was not designed for the production of electric energy. The Fermi reactor operated for a few years and had a partial core meltdown in 1966. This reactor was the first and only effort in the USA to operate a larger scale breeder reactor and was terminated in 1972.

Another twelve demonstration or prototype reactors are listed in the IAEA report. Among them are the Monju reactor in Japan, the "Russian/Soviet" BN-600, and the Phenix reactor in France.

Only the BN-600 reactor is currently operational and is often considered as the prime example of a successfully operating FBR reactor. However, the IAEA document reveals that this reactor was designed with a negative breeding gain of -0.15.

In comparison, the Phenix and Monju reactors are presented with theoretical breeding gains of 0.16 and 0.2, respectively. It is interesting to note that the potentially better constructed next generation PFBR reactor in India, currently expected to start in 2011, is given with a much smaller theoretical breeding gain of only 0.05.

The third FBR group in the IAEA document describes commercial size reactors. Eleven out of the listed thirteen large FBR projects have been abandoned before any construction plans have been presented, or exist currently only in the design phase. Only one reactor, the Super Phenix reactor in France, has produced some electric energy. During its short operation time, it was operated with a very low efficiency and cannot be considered as a successful breeder prototype. A new commercial size fast reactor is under construction in Russia. The BN-800 is currently scheduled to become operational during the year 2014. It is however quantified with a negative breeding gain of -0.02.

A further confirmation that the BN-800 reactor is not a breeder comes from a WNA document [23], where the reactor is described as:

> "It has improved features including fuel flexibility - U+Pu nitride, MOX, or metal, and with breeding ratio up to 1.3. However, during the plutonium disposition campaign it will be operated with a breeding ratio of less than one."

A possible interpretation of this statement could be that plutonium stocks are already a delicate problem and that Russia wants to get rid of them.

In summary, the IAEA data base for fast reactors does not present any evidence that a positive breeding gain has been obtained with past and present FBR reactors. On the contrary, the presented data indicate at best that a more efficient nuclear fuel use than in standard PWR reactors can be achieved during normal running conditions. However, once the short and inefficient running times of FBR's, in comparison with large scale PWR's, are taken into account, even this better fuel use has not been demonstrated. In fact, the required initial fuel load in FBR's contains at least twice as much natural uranium equivalent and with a fissile material enrichment that is roughly 5 times larger than that in a comparable PWR. A fair comparison of the fuel efficiency should include the efficiency to recycle fissile material from used nuclear fuel in both reactor types.

Three more areas of concern for a future breeder program should be added:

- Fast reactors are known for their *worrying safety record*. For example, it might be true

that serious incidents, like the one that happened with the Chernobyl graphite moderated reactor, cannot happen with modern PWR's. However, only very few nuclear experts would agree to such a statement for sodium cooled FBR's.
- FBR's are known for their huge construction costs relative to PWR's, and it might be tempting to compare some of the past FBR's to a monetary "black hole." An equivalent of 3.5 billion Euros has been invested in the construction of the SNR-300 in Germany. Because of safety concerns related to sodium leaks and other problems, this small FBR has never started operation. This amount of money corresponds to the price tag for a five times more powerful modern PWR reactor.
- A third problem is related to the FBR requirements to have a large inventory of high purity fissile material. The amount of fissile material listed in Table 3 should be compared to the few tens of kgs required for a Pu239 bomb. This problem makes even small experimental FBR reactors highly sensitive to the proliferation problem.

4. Future breeder reactors

As our short overview in Section 2 has already demonstrated, neither sodium cooled FBR reactors based on U238 → Pu239 nor the Th232 → U233 cycle are fashionable commercial reactor types.

As a consequence of the observation that known uranium deposits are limited, scientists from many countries have joined forces and created during the year 2001 the Generation IV reactor forum [24].

In their own words (quote):

> "The Generation IV International Forum, or GIF, was chartered in July 2001 to lead the collaborative efforts of the world's leading nuclear technology nations to develop next generation nuclear energy systems to meet the world's future energy needs."

The work of over 100 experts from ten countries, including Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, Switzerland, the United Kingdom, and the United States, and from the International Atomic Energy Agency and the OECD Nuclear Energy Agency has resulted at the end of the year 2002 in a roadmap document with the title:

A Technology Roadmap for Generation IV Nuclear Energy Systems

After the definition of the goals, identifying promising concepts, their evaluation, and the estimation of the required R&D efforts, six systems have been selected. The selection was based on their estimation that they (quote):

> "feature increased safety, improved economics for electricity production, and new products such as hydrogen for transportation applications, reduced nuclear wastes for disposal, and increased proliferation resistance."

Within the context of this analysis, we are mainly interested to know whether the acknowledged U235 fuel shortages can be solved with future breeder reactors. Therefore, we will only take a closer look at the three FBR's and the one design that has the potential to become a Th232 based thermal breeder. According to a WNA document from August 2009 [25]:

> "At least four of the systems have significant operating experience already in most respects of their design, which provides a good basis for further R&D and is likely to mean that they can be in commercial operation well before 2030."

It is remarkable that the same WNA document contradicts this statement a few lines later:

> "However, it is significant that to address non-proliferation concerns, the fast neutron reactors are not conventional fast breeders, i.e. they do not have a blanket assembly where plutonium-239 is produced. Instead, plutonium production takes place in the core, where burn-up is high and the proportion of plutonium isotopes other than Pu239 remains high. In addition, new reprocessing technologies will enable the fuel to be recycled without separating the plutonium."

4.1. Some details about Generation IV breeder reactors

The Generation IV roadmap document from the year 2002 describes a detailed planning for what needs to be achieved during the next 10-20 years. Depending on the results, one might be able to decide which of the different future reactor concepts can be used to construct real prototype FBR's.

The qualitative proposed research plans for the three FBR's and the Th232 reactor can be sum marized as follows:

- The **Gas-cooled Fast Reactor System (GFR)** is based on a helium-cooled reactor with a small thermal power of roughly 0.5 GW only. A large number of major technological gaps are mentioned in the roadmap leading to a research program of about 20 years and a cost of 940 million US Dollars.
- The **Lead-cooled Fast Reactor System (LFR)** with a possible thermal power between 0.1 GW and 3.6 GW. A relatively long list of "technology gaps" for the LFR is presented, including even some insufficient knowledge of neutron interaction cross-sections. A 15-20 year R&D program with a price tag of 990 million US Dollars is needed before any further statements about the realization of this concept can be made.
- The **Sodium-cooled Fast Reactor System (SFR)** with a thermal power rating between 1 - 5 GW. This concept is closely related to the doubtful success with past sodium-cooled fast reactors in France, Japan, Germany, the UK, Russia, and the United States. It is said that this reactor must be capable of also using the thermal neutron spectrum, because the startup fuel for the fast reactor must come ultimately from spent thermal reactor fuel. The list of technology gaps includes the need to ensure a "passive safe response design base," a "capital cost reduction," and the "proof that a reactor has the ability to accommodate bounding events." A somewhat frightening conclusion of this statement might be that previous sodium prototype FBR's did not satisfy any of these basic reactor safety standards. It is also mentioned that this sodium cooled reactor is the most advanced FBR system. The required R&D program to investigate the remaining problems could be completed over a period of less than 15 years and for 610 million US Dollars.
- The **Molten Salt Reactor system (MSR)** is imagined as 1 GWe reactor with a net thermal efficiency of 44-50%. The design assumes the use of either U238 or Th232 as fertile fuel dissolved as fluorides in the molten salt and that it can operate with thorium as a thermal breeder. The technology gaps mentioned contain a large number of items related to the chemistry of molten salts as well as the need for more accurate basic neutron cross-sections for compositions of molten salt. The time scale of the required R&D program is 15-20 years with an associated price tag of 1000 million US Dollars.

The Generation IV roadmap document can be summarized with the statement that the known technological gaps to construct even prototype breeder reactors were enormous at the time when the document was written. These unknowns are addressed with a detailed planning for the required research projects and the associated cost. Only after these problems shall have been solved, a design and construction of expensive prototype breeder reactors can start.

We are now at the end of the year 2009 and almost half of the originally planned R&D period is over. Essentially no progress results have been presented and the absence of large funding during the past eight years gives little confidence that even the most basic questions for the Generation IV reactors program can be answered during the next few years. Thus, it seems that the Generation IV roadmap is already totally outdated and unrealistic.

This is confirmed by the latest statements at the Global 2009 conference in September 2009 by B. Bigot, the chairman of the French Atomic Energy Commission, which indicate that the plan to have the reactors ready by the year 2030 is now delayed to 2040 and onwards. According to the Website "Supporters of Nuclear Energy," Bigot said "from 2040 onwards, France is planning to use Generation IV FBR's when renewing its fleet" [26].

4.2. The Global Nuclear Energy Partnership (GNEP)

Another initiative, the Global Nuclear Energy Partnership (GNEP) [27] was announced by President Bush in his 2006 State of the Union address. By September 2007, all major nuclear energy countries, except for Germany and a few others, have signed the statement of principles. According to the U.S. Department of Energy, the goals of the initiative are (quote):

> "First, reduce Americas dependence on foreign sources of fossil fuels and encourage economic growth. Second, recycle nuclear fuel using new proliferation-resistant technologies to recover more energy and reduce waste. Third, encourage prosperity growth and clean development around the world. And fourth, utilize the latest technologies to reduce the risk of nuclear proliferation worldwide."

However in June 2009, the U.S. Department of Energy announced that it is no longer pursuing domestic commercial reprocessing, and had largely halted the domestic GNEP program. Research would continue on proliferation-resistant fuel cycles and waste management.

According to a WNA press information [28], the status of this initiative is:

> "Although the future of GNEP looks uncertain, with its budget having been cut to zero, the DoE will continue to study proliferation-resistant fuel cycles and waste management strategies."

It follows that the GNEP initiative will not result in the construction of future breeder reactors.

4.3. Ideas about using thorium as a reactor fuel

During the past years, a large number of articles and books, websites and blogs propose the use of thorium as the breeder material for future nuclear reactors [29]. The promoters advocate many interesting possibilities, indicating that the Th232 cycle might have lots of advantages compared to the U238 breeder cycles in FBR's.

The main problem with these "great" new insights into the use of nuclear fission energy seems to be that nobody from the nuclear energy establishment is interested.

As a result, little or no private and public research money is invested into the question of how to develop a thorium breeder reactor. Ignoring the possibility that past investigations into the thorium fuel cycle have revealed several important problems, one needs to speculate about other reasons.

- that the established nuclear energy experts do not like to see competition from outsiders, or
- that the nuclear fusion community has managed to dominate the entire nuclear energy research domain, and that the available research budgets are already allocated to the ITER plasma research project.

If either of these two possibilities contains some truth, those in favor of developing a thorium breeder reactor should start taking a strong position against the current nuclear energy establishment. They should point out that (i) the current use of nuclear energy has no perspective because of the limited amount of available uranium resources, (ii) the Th232 breeder cycle is by orders of magnitude better than the ideas about U238 breeder cycles with FBR's, and (iii) nuclear fusion is at least 50-100 years away. Leaving these more political issues aside, we would like to repeat some rational statements and the otherwise rarely mentioned problems about the use of the Th232 breeder cycle from the WNA information article [30] entitled:

Developing a thorium-based fuel cycle

where one can read that:

> "In one significant respect U233 is better than uranium-235 and plutonium-239, because of its higher neutron yield per neutron absorbed. Given a start with some other fissile material (U233, U235 or Pu239) as a driver, a breeding cycle similar to but more efficient than that with U238 and plutonium (in normal, slow neutron reactors) can be set up. (The driver fuels provide all the neutrons initially, but are progressively supplemented by U233 as it forms from the thorium.) However, there are also features of the neutron economy which counter this advantage. In particular the intermediate product protactinium-233 (Pa233) is a neutron absorber which diminishes U233 yield."

The statement continues with:

> "Despite the thorium fuel cycle having a number of attractive features, development has always run into difficulties."

The main attractive features are:

- The possibility of utilizing an abundantly available resource that has hitherto been of so little interest that it has never even been properly quantified.
- The production of power with few long-lived transuranic elements in the waste.
- A reduction of radioactive waste, in general.

The problems include:

- The high cost of fuel fabrication due partly to the high radioactivity of U233 chemically separated from the irradiated thorium fuel.
- Separated U233 is always contaminated with traces of U232 (69 year half-life but whose

daughter products such as thallium-208 are strong gamma emitters with very short half-lives). Although this confers proliferation resistance to the fuel cycle, it results in increased costs.
- The similar problems in recycling thorium itself due to highly radioactive Th-228 (an alpha emitter with two-year half life) present.
- Some concern over weapons proliferation risk of U233 (if it could be separated on its own), although many designs such as the Radkowsky Thorium Reactor address this concern. The technical problems in reprocessing solid fuels are not yet satisfactorily solved. However with some designs, in particular the molten salt reactor (MSR), these problems are likely to largely disappear.
- Much development work is still required, before the thorium fuel cycle can be commercialized, and the effort required seems unlikely while (or where) abundant uranium is available. In this respect, recent international moves to bring India into the ambit of international trade might result in the country ceasing to persist with the thorium cycle, as it now has ready access to traded uranium and conventional reactor designs.

The WNA article concludes with the following diplomatic statement:

> "Nevertheless, the thorium fuel cycle, with its potential for breeding fuel without the need for fast neutron reactors, holds considerable potential in the long-term. It is a significant factor in the long-term sustainability of nuclear energy."

A "logic" interpretation of the WNA statement and the list of arguments about thorium and within the context of our review could be:

- The breeding of Pu239 with fast neutrons has huge problems, and it would be great if another nuclear fuel could be found.
- Thorium breeding shows interesting potential if the remaining large number of problems can be mastered in the long term, but right now, we are still far away from this. The contamination with the strong neutron absorber Pa233 and the large radioactivity from U232 and other elements are chief among the currently unsolved problems.
- The well known use of nuclear fission energy in PWR's is unsustainable. The problems related to long-lived transuranic elements, e.g. plutonium and heavier elements, as well as nuclear waste in general, are unsolved. The concern with nuclear weapon proliferation cannot be dismissed either.

5. Fusion Illusions

This section offers a short version of a detailed article by the author in the second edition of *The Final Energy Crisis* [31].

After the second world war, many nuclear pioneers expected that nuclear fusion would provide their grandchildren with cheap, clean, and essentially unlimited energy.

Generations of physicists and physics teachers have been taught at the university and have gone on to teach others that (i) progress made in fusion research is impressive, (ii) controlled fusion is probably only a few decades away, and (iii) given sufficient public funding, no major obstacles stand between us and success in this field.

Here are some quotes from physics textbooks that reflect this sort of optimism:

"The goal seems to be visible now" (Nuclear and Particle Physics; Frauenfelder and Henley 1974)

"It will most likely take until the year 2000 to bring a laboratory reactor to full commercial utilization" (Energy, Resources and Policy; R. Dorf 1978)

"As the construction of a fusion reactor implies a large number of unsolved practical problems, one cannot expect that fusion will become a usable energy resource during some decades! Within a longer time scale however it seems possible!" (Physics, P. A. Tipler 1991)

Obviously this has not happened yet. The fusion optimists have meanwhile become a bit more modest. One can now read: *"If everything goes well, the first commercial fusion reactor prototype might be ready in 50 years from now."*

Such statements only hide the fact that no concept has yet been developed for how to solve the remaining problems. The uncritical media of today reverberated enthusiastically the recent decision by "world's leaders" to provide the ten billion US Dollars needed to start the ITER fusion project [32]. During the past few years, one could read, for example [33]:

- *"If successful, ITER would provide mankind with an unlimited source of energy"* (Novosti, November 15, 2005).
- *"Officials project that 10% to 20% of the world energy could come from fusion by the end of the century"* (BBC News, May 24, 2006).
- *"If successful, it could provide a source of energy that is clean and limitless"* and *"ITER says, within 30 years, the electricity could be available on the grid!"* (BBC News, November 21, 2006).

The public, worried about global warming and oil price explosions, seems to welcome the tacit message that "we -the fusion scientists, the engineers, and the politicians- do everything that needs to be done to bring fusion energy on-line, before fossil fuel supplies become an issue, and before global warming boils us all."

In the following, we challenge the assumption that the ITER project offers any solution to the energy problem, and we quantify the arguments of fusion skeptics.

We start our discussion with an overview of the remaining huge problems facing commercial fusion and offer a detailed description of why the imagined self-sufficient tritium breeding cycle cannot work. In fact, as we are about to see, enough knowledge has been accumulated on this subject to safely conclude that whatever might justify the 10 billion US Dollar ITER project, it is not energy research.

5.1. Remaining barriers to fusion energy

Producing electricity from controlled nuclear fusion would require overcoming at least four major obstacles. The removal of each obstacle would need major scientific breakthroughs before any reasonable expectation might be formed of building a commercial prototype fusion reactor. It should be alarming that at best only the problems concerning the plasma control, described in point one below, might be investigated within the scope of the ITER project. Where and how the others might be dealt with is anyone's guess.

These are the four barriers:

1. Commercial energy production requires steady state fusion conditions for a deuterium-tritium plasma on a scale comparable to that of today's standard nuclear fission reactors with outputs of 1 GW (electric) and about 3 GW (thermal) power. The current ITER proposal foresees a thermal power of only 0.4 GW using a plasma volume of 840 m^3 . Originally it was planned to build ITER with a plasma volume of 2000 m^3 corresponding to a thermal fusion power of 1.5 GW, but the fusion community soon realized that the original ITER version would never receive the required funding. Thus a smaller, much less

ambitious version of the ITER project was proposed and finally accepted in 2005.

The 1 GW (el) fission reactors of today function essentially in a steady state operation at nominal power and with an availability time over an entire year of roughly 90%. The deuterium-tritium fusion experiments have so far achieved short pulses of fusion power of 15 MW (therm) for one second and 4 MW (therm) for 5 seconds, corresponding to a liberated thermal energy of 5 kWh [34]. The Q-value (produced energy over input energy) for these pulses was 0.65 and 0.2, respectively.

If everything works according to the latest plans [35], it will be 2018 when the first plasma experiments can start with ITER. From there, it will take us to 2026, at least another eight years, before the first tritium experiments are tried. The original plans from 2005 are now, even before any serious construction has started, already delayed by four years. In other words, it will take at least 20 years from the agreement by the world's richest countries to construct ITER, before one can find out if the goals of ITER, a power output of 0.5 GW (therm) with a Q-value of up to 10 and for 400 seconds, are realistic. Compare that to the original ITER proposal, which was 1.5 GW (therm), with a Q-value between 10-15 and for about 10,000 seconds. ITER proponents explain that the achievement of this goal would already be an enormous success. But this goal, even if it can be achieved by 2026, pales in comparison with the requirements of steady-state operation, year after year, with only a few minor controlled interruptions.

Previous deuterium-tritium experiments used only minor quantities of tritium, and yet lengthy interruptions between successive experiments were required, because the radiation from the tritium decay was so excessively high. In earlier fusion experiments, such as JET, the energy liberated in the short pulses came from burning (fusing) about 3 micrograms (3 $\times 10^{-6}$ grams) of tritium, starting from a total amount of 20 gr of tritium. This number should be compared with the few kilograms of tritium required to perform the experiments foreseen during the entire ITER lifetime and with the still greater quantities that would be required for a commercial fusion reactor. A 400 sec fusion pulse with a power of 0.5 GW corresponds to the burning of 0.035 gr (3.5×10^{-2} grams) of tritium, a very large number, when compared to 3 micrograms, but a tiny number when compared with the yearly burning of 55.6 kilograms of tritium in a commercial 1 GW (therm) fusion reactor.

The achieved efficiency of the tritium burning (i.e., the amount that is burned divided by the total amount required to achieve the fusion pulse) was roughly 1 part in a million in the JET experiment and is expected to be about the same in the ITER experiments, far below any acceptable value, if one wants to burn 55.6 kg of tritium per year.

Moreover in a steady-state operation, the deuterium-tritium plasma will be "contaminated" with the helium nucleus that is produced, and some instabilities can be expected. Thus a plasma cleaning routine is needed that would not cause noticeable interruptions of production in a commercial fusion plant. ITER proponents know that even their self-defined goal (a 400 second long deuterium-tritium fusion operation within the relatively small volume of 840 m^3) presents a great challenge. One might wonder what they think about the difficulties involved in reaching steady-state operation for a full-scale fusion power plant.

2. The material that surrounds and contains thousands of cubic meters of plasma in a full-scale fusion reactor has to satisfy two requirements. First, it has to survive an extremely high neutron flux with energies of 14 MeV, and second, it has to do this not for a few minutes but for many years. It has been estimated that in a full-scale fusion power plant the neutron flux will be at least 10-20 times larger than in today's state-of-the-art nuclear fission power plants. Since the neutron energy is also higher, it has been estimated that -with such a neutron flux- each atom in the solid surrounding the plasma will be displaced 475 times over a period of 5 years [36]. Second, to further complicate matters, the material in the so

called first wall (FW) around the plasma will need to be very thin in order to minimize inelastic neutron collisions resulting in the loss of neutrons (for more details see next section), yet at the same time thick enough so that it can resist both the normal and the accidental collisions from the 100-million-degree hot plasma for years.

The "erosion" from the neutron bombardment has been estimated to be about 3 mm per "burn" year for carbon-like materials, and it has been estimated to be about 0.1 mm per burn year even for materials like tungsten [36].

In short, no material known today can even come close to meeting the requirements described above. Exactly how a material that meets these requirements could be designed and tested remains a mystery, because tests with such extreme neutron fluxes cannot be performed either at ITER or at any other existing or planned facility.

3. The radioactive decay of even a few grams of tritium creates radiation dangerous to living organisms, such that those who work with it must take sophisticated protective measures. Moreover, tritium is chemically identical to ordinary hydrogen, and as such is very active and difficult to contain. Since tritium is also a necessary ingredient in hydrogen fusion bombs, there is additional risk that it might be stolen. So, handling even the few kg of tritium foreseen for ITER is likely to create major headaches both for the radiation protection group and for those concerned with the proliferation of nuclear weapons.

   Both of these challenges are essentially ignored in the ITER proposal, and the only thing the protection groups have to work with today are design studies based on computer simulations. This may not be of concern to the majority of ITER's promoters today, since they will be retiring before the tritium problem starts in something like 10 to 15 years from now [37], but at some point, it will become a greater challenge also for ITER and especially once one starts to work on a real fusion experiment with many tens of kilograms of tritium.

4. Problems related to tritium supply and self-sufficient tritium breeding will be discussed in detail in Section 5.2, but first, it will be useful to describe qualitatively two problems that seem to require simultaneous miracles, if they are to be solved.
   - The neutrons produced in the fusion reaction will be emitted essentially isotropically in all directions around the fusion zone. These neutrons must somehow be convinced to escape without further interactions through the first wall surrounding the few 1000 m^3 plasma zone. Next, the neutrons have to interact with a "neutron multiplier" material like beryllium in such a manner that the neutron flux is increased without transferring too much energy to the remaining nucleons. The neutrons then must transfer their energy without being absorbed (e.g. by elastic scattering) to some kind of gas or liquid, like high pressure helium gas, within the lithium blanket. This heated gas has to be collected somehow from the gigantic blanket volume and must flow to the outside. This heat can be used as in any existing power plant to power a generator turbine. This liquid should be as hot as possible, in order to achieve reasonable efficiency for electricity production. However, it is known that the lithium blanket temperature cannot be too high. This limits the efficiency to values well below those from today's nuclear fission reactors, which also do not have a very high efficiency.

     Once the heat is extracted and the neutrons are slowed sufficiently, they must make the inelastic interaction with the Li^6 isotope, which makes up about 7.5% of the natural lithium. The minimal thickness of the lithium blanket that surrounds the entire plasma zone has been estimated to be at least 1 meter. Unfortunately, lithium like hydrogen (tritium atoms are chemically identical to hydrogen) in its pure form is chemically highly reactive. If used in a chemical bound state with oxygen, for example, the oxygen itself could interact and absorb neutrons, something that must be avoided. In addition, lithium and the produced tritium will react chemically -which is certainly not included in any present computer modeling- and some tritium atoms will be blocked within the blanket. Unfortunately, additional neutron and tritium losses cannot be allowed, as will be described in more detail in Section 5.2.

  - Next, an efficient way has to be found to extract the tritium quickly, and without loss, from this lithium blanket before it decays. We are talking about a huge blanket here, one that surrounds the few 1000 m^3 plasma volume. Extracting and collecting the tritium from this huge lithium blanket will be very tricky indeed, since tritium penetrates thin walls relatively easily, and since accumulations of tritium are highly explosive. An interesting description of some of these difficulties that have already been encountered in a small-scale experiment can be found in reference [38].

    Finally assuming we get that far, the extracted and collected tritium and deuterium, which both need to be extremely clean, need to be transported, without losses, back to the reactor zone.

Each of the unsolved problems described above is by itself serious enough to raise doubts about the success of commercial fusion reactors. But the self-sufficient tritium breeding is especially problematic, as will be described in the next section.

5.2. The illusions of tritium self-sufficiency

A self-sustained tritium fusion chain appears to be not simply problematic but absolutely impossible. To see why, we shall now look into some details based on what is already known about this problem.

A central quantity for any fission reactor is its criticality, namely that exactly one neutron, out of the two to three neutrons "liberated" per fission reaction, will enable another nuclear fission reaction. More than 99% of the liberated fission energy is taken by the heavy fission products such as barium and krypton, and this energy is relatively easily transferred to a cooling medium. The energy of the produced fission neutrons is about 1 MeV. In order to achieve the criticality condition, the surrounding material must have a very low neutron absorption cross-section, and the neutrons must be slowed down to eV energies. For a self-sustained chain reaction to happen, a large amount of U235, enriched to 3-5%, is usually required. Once the nominal power is obtained, the chain reaction can be regulated using materials with a very high neutron absorption cross-section. A much higher enrichment of 20% is required for fast reactors without moderators and up to 90% for bombs.

In contrast to fission reactions, only one 14 MeV neutron is liberated in the $D + T \rightarrow He + n$ fusion reaction. This neutron energy has to be transferred to a medium using elastic collisions. Once this is done, the neutron is supposed to make an inelastic interaction with a lithium nucleus, splitting it into tritium and helium.

Starting with the above reaction, one can calculate how much tritium burning is required for a continuously operating commercial fusion reactor assuming a power production of 1 GW (thermal). One finds that about 55.6 kg of tritium needs to be burned per year with an average thermal power of 1 GW.

Today, tritium is extracted from Canadian heavy water reactors at extraordinary cost - about 30 million US Dollars per kg. These old heavy water reactors will probably stop operation around the year 2025, and it is expected that a total tritium inventory of 27 kg will have been accumulated by that year [39]. Once these reactors stop operating, this inventory will be depleted by more than 5% per year due to its radioactive decay alone - tritium has a half-life of 12.3 years. As a result, for the prototype "PROTO" fusion reactor, which fusion optimists imagine to start operation not before the year 2050, at best only 7 kg of tritium might remain for the start (Normal fission reactors produce at most 2-3 kg per year, and the extraction costs have been estimated to be 200 million dollars per kg [39].). It is thus obvious that any future fusion reactor experiment beyond ITER must not only achieve tritium self-sufficiency, it must create more tritium than it uses, if there are to be any further fusion projects.

The particularly informative website of Prof. Abdou from UCLA, one of the world's leading experts on tritium breeding, offers relevant numbers both about the basic requirements for tritium breeding and the state of the art today [40]. Yet, let us start with first things first, as understanding such "expert" discussions requires acquaintance with some key terms:

- The *required Tritium Breeding Ratio (rTBR)* stands for the minimal number of tritium nuclei that must be produced per fusion reaction in order to keep the system going. It must be larger than one because of tritium decay and other losses and because of the necessary inventory in the tritium processing system and the stockpile for outages and for the startup of other plants. The rTBR value depends on many system and technology parameters.
- The *achievable Tritium Breeding Ratio (aTBR)* is the value obtained from complicated and extensive computer simulations -so-called 3-dimensional simulations- of the blanket with its lithium and other materials. The aTBR value depends on many parameters like the first wall material and the incomplete coverage of the breeding blanket.
- Other important variables are used to define quantitatively the value of the rTBR. These include: (1) the "tritium doubling time," the time in years required to double the original inventory; (2) the "fractional tritium burn-up" within the plasma, expected to be at best a few %; (3) the "reserve time," the tritium inventory required in days to restart the reactor after some system malfunctioning with a related tritium loss; and (4) the ratio between the calculated and the experimentally obtained TBR.

The handling of neutrons, tritium, and lithium requires particular care, not only because of radiation, but also because tritium and lithium atoms are chemically very reactive elements. Consequently, real-world large-scale experiments are difficult to perform, and our understanding of tritium breeding is based almost entirely on complicated and extensive computer simulations, which can only be done in a few places around the world.

Some of these results are described in a publication by Sawan and Abdou from December 2005 [41]. The authors assume that a commercial fusion power reactor of 1.5 GW (burning about 83 kg of tritium per year) would require a long-term inventory of 9 kg, and they further assume that the required startup tritium is available.

They argue that, according to their calculations, the absolute minimum rTBR is 1.15, assuming a doubling time of more than 4 years, a fractional tritium burn-up larger than 5%, and a reserve time of less than 5 days. Requiring a shorter doubling time of 1 year, their calculations indicate that the rTBR should be around 1.5. More numbers can be read out from their figures. For example, one finds that if the fractional burn-up would be 1%, the rTBR should be 1.4 for a 5 year doubling time and even 2.6 for a 1 year doubling time. The fractional tritium burn-up during the short MW pulses in JET was roughly 0.0001%.

The importance of short tritium doubling times can be understood easily using the following calculation. Assuming these numbers can be achieved and that 27 kg tritium (2025) minus the 9 kg long-term inventory would be available at start-up, then 18 kg could be burned in the first year. A doubling time of 4 years would thus mean that such a commercial 1.5 GW (thermal) reactor can operate at full power only 8 years after the start-up.

Unfortunately, these rTBR estimates are far too optimistic as a number of potential losses related to the tritium extraction, collection, and transport are not considered in today's simulations.

The details become even more troubling when we turn to the tritium breeding numbers that have been obtained with computer simulations.

After many years of detailed studies, current simulations show that the blanket designs of today have, at best, achieved TBR's of 1.15. Using this number, Sawan and Abdou conclude that a small window for tritium self-sufficiency still exists theoretically. This window requires (1) a fractional tritium burn up of more than 5%, (2) a tritium reserve time of less than 5 days, and (3) a doubling time of more than 4 years. Yet even using these numbers, the authors believe it to be difficult to imagine a real operating power plant. In their own words: *"for fusion to be a serious contender for energy production, shorter doubling times than 5 years are needed,"* and the fact is, doubling times much shorter than 5 years appear to be required, which means that TBR's much higher than 1.15 are necessary. To make matters worse, they also acknowledge that current systems of tritium handling need to be explored further. This probably means that the tritium extraction methods from nuclear fission reactors are nowhere near meeting the requirements.

Sawan and Abdou also summarize various effects that reduce the obtained aTBR numbers, once more realistic reactor designs are studied, and structural materials, gaps, and first wall thickness are considered. For example, they find that as the first wall, made of steel, is increased by 4 cm starting from a 0.4 cm wall, the aTBR drops by about 16%. It would be interesting to compare these assumptions about the first wall with the ones used in previous plasma physics experiments like JET and the one proposed for ITER. Unfortunately, we have so far not been able to obtain any corresponding detailed information. However, as it is expected that the first wall in a real fusion reactor will erode by up to a few mm per fusion year, the required thin walls seem to be one additional impossible assumption made by the fusion proponents.

Other effects, as described in detail by Sawan and Abdou [41], are known to reduce the aTBR even further. The most important ones come from the cooling material required to transport the heat away from the breeding zone, from the electric insulator material, from the incomplete angular coverage of the inner plasma zone with a volume of more than 1000 m^3, and from the plasma control requirements.

This list of problems is already very long and shows that the belief in a self-sufficient tritium chain is completely unfounded. However, on top of that, some still very idealized TBR experiments have been performed now. These real experiments show, according to Sawan and Abdou [41], that the measured TBR results are consistently about 15% lower than the modeling predicts. They write in their publication: *"the large overestimate (of the aTBR) from the calculation is alarming and implies that an intense R&D program is needed to validate and update .. our ability to accurately predict the achievable TBR."*

One might conclude that a correct interpretation could have been:

> Today's experiments show consistently that no window for a self-sufficient tritium breeding currently exists and suggest that proposals that speak of future tritium breeding are based on nothing more than hopes, fantasies, misunderstandings, or even intentional misrepresentations.

5.3. Ending the dreams about controlled nuclear fusion

As we have explained above, there is a long list of fundamental problems concerning controlled fusion. Each of them appears to be large enough to raise serious doubts about the viability of the chosen approach to a commercial fusion reactor and thus about the 10 billion US Dollars ITER project.

Those not familiar with the handling of high neutron fluxes or the possible chemical reactions of tritium and lithium atoms might suppose that these problems are well known within the fusion community and are being studied intensively. But the truth is, none of these problems have been studied intensively and, at best, even with the ITER project, the only problems that might be studied relate to some of the plasma stability issues outlined in Section 5.1. All of the other problem areas are essentially ignored in today's discussions among ITER experts.

Confronted with the seemingly impossible tritium self-sufficiency problem that must be solved before a commercial fusion reactor is possible, the ITER experts tell you that this is not a problem that the current ITER project is to address. It won't be until the next generation of experiments - experiments that will not begin for roughly another 30 years according to official plans- that issues related to tritium self-sufficiency will have to be dealt with. They seem to also be comfortable with the fact that neither the problems related to material aging due to the high neutron flux nor the problems related to tritium and lithium handling can be tested with ITER.

However, among those who are not part of ITER and who do not expect miracles, an ever increasing number of scientists is coming to the conclusion that commercial fusion reactors can never become a reality. They are even starting to receive attention from the media as they argue ever more loudly that the ITER project will contribute very little, if anything, to energy research [42].

One scientist who should be listened to more widely is Prof. Abdou. In a presentation in 2003 that was prepared on behalf of the US fusion chamber technology community for the US Department of Energy (DOE) Office of Science on Fusion Chamber Technology, he wrote that *"tritium supply and self-sufficiency are a 'Go-No Go' issue for fusion energy,* [and are therefore] *as critical NOW as demonstrating a burning plasma"* [capitalization in original]. He pointed out that *"there is NOT a single experiment yet in the fusion environment that shows that the DT fusion fuel cycle is viable."* He said that *"proceeding with ITER makes Chamber Research even more critical"* and he asked: *"What should we do to communicate this message to those who influence fusion policy outside DOE?"* [43]. In short, to go ahead with ITER without addressing these chamber technology issues makes very little sense economically.

In the light of everything that has been said in this section, it seems clear that the nuclear fusion scientists should be telling the truth to the tax payers, the policy makers, and the media. They should tell them that, after 50 years of very costly fusion research conducted at various locations around the world, enough knowledge exists to state that:

1. today's achievements in all relevant areas of nuclear fusion are still many orders of magnitude away from the basic requirements of a fusion prototype reactor;
2. no material or structure is known that can withstand the extremely high neutron flux expected under realistic deuterium-tritium fusion conditions; and
3. self-sufficient tritium breeding appears to be impossible to achieve under the conditions required to operate a commercial fusion reactor.

It is late, but perhaps not too late, to acknowledge that the ITER project is at this point nothing more than an expensive experiment to investigate some fundamental aspects of plasma physics. Since this would in effect acknowledge that the current ITER funding process is based on faulty assumptions and that ITER should in all fairness be funded on equal terms with all other basic research projects, acknowledging these truths will not be easy. Yet, it is the only honest thing to do.

It is also the only path that will allow us to transfer from ITER to other more promising research efforts the enormous resources and the highly skilled talents that need now to be brought to bear on our increasingly urgent energy problems. In short, this is the only path that will allow us to stop "throwing good money after bad" and to start dealing with our emerging energy crisis in a realistic way.

6. Summary

In this fourth and final part of our analysis about the *Future of Nuclear Energy*, we have presented status and prospects for nuclear fuel breeder fission reactors and the true situation as it relates to nuclear fusion.

Despite the often repeated claims that the technology for fast reactors is well understood, one finds that no evidence exists to back up such claims. In fact, their huge construction costs, their poor safety records, and their inefficient performance give little reason to believe that they will ever become commercially significant.

Indeed, no evidence has been presented so far that the original goal of nuclear fuel breeding has been achieved. The designs and running plans for the two FBR's, currently under construction in India and in Russia, do not indicate that successful breeding can even in principle be achieved.

Nevertheless, assuming that extensive and costly efforts are being undertaken during the next 20-30 years, a remote possibility of mastering nuclear fission breeder reactor technology can still be imagined. However, it is unclear if (1) enough highly enriched uranium remains to start future commercial breeder reactors on a large scale in 30-40 years from now, and (2) if the people in rich societies will accept risky and costly research efforts during times of economic difficulties. In any case, fast breeder reactors, even under the most optimistic assumptions, will come far too late to compensate for the looming energy decline following the peaking of oil and gas.

In contrast to the remaining open questions relating to fission breeders, we find that the accumulated knowledge about nuclear fusion is already now large enough to conclude that commercial fusion power is not only 50 years away, but that it will always be 50 years away.

The current situation concerning the future of nuclear energy appears in many respects similar to the one described in a famous fairy tale [44], but with a slightly modified ending:

> "In the coming 'autumn and winter' of our industrial civilization brought on by the decline of fossil fuels, it seems clear that the clothes of the Nuclear Fission Energy emperor are far too thin to keep him and others warm, and that the Nuclear Fusion Emperor has no clothes at all!"

Acknowledgments

This report about the *Future of Nuclear Energy: Facts and Fiction*, and especially its fourth part, is a result of many questions that the author asked scientists active within the fission and fusion research communities over the past few years. Essentially, none was answered and no help was provided to get in contact with the corresponding "fission" and "fusion" experts. Thus in some kind of "hobby" research, which included discussions with friends, colleagues, and many believers in never ending technological progress, the different pieces concerning the future of nuclear energy summarized in this report came together.

During early 2007, an attempt was made to discuss the fusion problems in an open and scientific way directly with scientists from the fusion community. After coming as far as fixing the date for a seminar, the author received an email stating that there had been a "misunderstanding," and the envisaged dialog never took place. A similar initiative to discuss open issues about nuclear fission energy was undertaken in 2008. Again, it came as far as a seminar invitation that was canceled when trying to fix a date.

However during the spring of 2007, the author received an invitation to present the *"Status and Prospects of Nuclear Energy"* at the 6th ASPO meeting in Cork, Ireland in September 2007. In preparation for this presentation, the author took the time to study the 2005 edition of the Red

Book in detail. Many questions about the uranium resource numbers, presented in the Red Book, came up, but the inconsistencies were not yet large enough to start doubting the data. This view changed however, when the 2007 edition appeared together with an enthusiastic press declaration in June 2008. As it turned out from comparing the 2007 and 2005 editions, the reported uranium resource data were nothing but a collection of proven and unproven geological data mixed with politically correct wishful thinking about a sustainable and bright future for the peaceful use of nuclear energy. This is how this report with its first three parts concerning the Red Book and the analysis of future nuclear energy technologies started to take shape.

Even though the views expressed in this paper are from the author alone, I would like to thank several colleagues and friends who took the trouble to discuss the content of this report during the past few years with me. They all helped me to bring it into its final form. I would like to thank especially D. Hatzifotiadou, W. Tamblyn, and F. Spano for many valuable suggestions and the careful reading of the paper draft. I would also like to thank S. Newman, who had asked me during the spring of 2007 to prepare a chapter about *"Fusion Illusions"* for the second edition of the book *"The Final Energy Crisis."* Her encouragement was essential to writing the longer report about nuclear fusion energy.

Finally, after several attempts to complete also the report about the Red Book and the status and prospects of nuclear fission energy, it was Prof. F. Cellier who suggested to split this report into four separate parts and submit it to the *Oil Drum* for publication. I am very grateful to him about the many valuable discussions we had, for the encouragement to complete this report, and for his editing work to transform the article into the style needed for the *Oil Drum* publication. I am also grateful to the staff of the *Oil Drum* for having created a place where such articles, often censored in other places, can be published and confronted directly to the comments of a large number of critical readers.

Thus, the author hopes, with the ideas expressed in the quote from Gustave Le Bon below, that this report will function like some kind of "telescope," helping others to observe that some objects are moving around Jupiter.

> *"Science promised us truth, or at least a knowledge of such relations as our intelligence can seize: it never promised us peace or happiness"*
> Gustave Le Bon

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[4] Cf. for example http://en.wikipedia.org/wiki/Fast_breeder_reactor; http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/fasbre.html; and under the subtitle *"Is nuclear energy renewable?"* in http://www.world-nuclear.org/info/inf09.html.

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[9] The IAEA fast reactor data base with many detailed publications can be accessed at http://www.iaea.org/inisnkm/nkm/aws/frdb/index.html. The BN-600 design breeding gain of -0.15 is mentioned in [22], page 46.

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[11] For a list of previously scheduled Monju restarts, cf. http://www.world-nuclear-news.org/stdsearch.aspx?sparam=monju&fid=778.

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