Go-No-Go Problems for controlled Nuclear Fusion on Planet Earth; do we already know enough to terminate public research funding for nuclear fusion? Part II

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Abstract

In part I of this report, the experience gained during the past 20 years of the design and construction process of the ITER Tokamak research project has been analysed. It was found that the accumulated knowledge during those decades provides already enough scientific evidence to conclude that: (1) Tokamaks are not the technology which leads to commercially competitive energy production; and (2) there is no reason to continue the funding of the ITER project with additional several billions of Euros from the taxpayer public research budget.

The physics of nuclear fusion reactions and the fundamental problems of using such reactions for commercial energy production are presented in Part II of this report. It is demonstrated that, in addition to the requirements of containing hydrogen isotopes at temperatures of about 150 million degrees Celsius within a large volume magnetic "bottle", several other essentially unsolvable, fundamental problems for controlled nuclear fusion on our planet exist.

Those additional problems are: (1) the tritium self-sufficiency; (2) the unknown first wall material shield, which has to protect the lithium blanket, the superconducting magnet and the entire fusion apparatus from splashes of the tens of millions of degrees Celsius plasma instabilities in the plasma fusion zone, with a volume of a thousand m^3, and which at the same time is essentially transparent to the heavy neutron bombardment; and (3) the unknown practical mechanism which transfers the "liberated" fusion energy from the energetic neutrons to a "gas" or a "liquid" at a few hundred degree Celsius, required to operate a steam generator.

Accordingly, it can be concluded that the achievement of a stable plasma of hydrogen isotopes at a temperature of hundreds of millions of degrees Celsius, contrary to frequent claims by scientists lobbying for the ITER and similar projects, is absolutely not sufficient to construct a fusion power plant. The situation is even worse, as those problems can neither be investigated with the 20 billion Euro ITER nor any other similar project around the planet like, for instance, Germany's Stellerator project Wendelstein 7-X.

Once those problems are acknowledged within the scientific community, the interested public and by those responsible for the public funding of basic research, and perhaps after some serious discussions, it might become obvious that commercial electric energy production from nuclear fusion processes can not be realised on our planet.

If it is true that the public funding of science and technology has the purpose to learn and understand fundamental facts, and what is accordingly possible and impossible, then one can conclude that todays knowledge about the obstacles for controlled nuclear fusion on our planet is already sufficient to terminate research funding for nuclear fusion power plants.

1 Introduction

In part I of this report, [1], official documents from the ITER community published during the last 30 years of planning and construction of the ITER project, were analysed, and compared to the original claims of those lobbying for the public research funding for controlled nuclear fusion. It was concluded that the information obtained during the past decades, and for a budget of about 20 billion Euros of taxpayers' money, shows that:

> *"Sufficient information about the design and construction of large Tokamaks has been obtained during the last 20 years, and those data allow to conclude that this technology will not lead to electricity producing fusion power during the first half of the 21s century."*

However, instead of looking for an acceptable phase out of the ITER project, the public is regularly bombarded by pseudo scientific success newspaper stories claiming yet another breakthrough, such that fusion energy will soon become reality. Three recent (2019) articles from some popular science media, usually written or supported by scientists and politicians lobbying for further public funding, can be found in the following references [2]. The headlines of those articles are speaking for themselves:

(1) *"Artificial intelligence speeds efforts to develop clean, virtually limitless fusion energy"*;
(2) *"A commercial path to fusion"*; and
(3) *"Improving the magnetic bottle that controls fusion power on Earth"*.

When analysing such articles, one almost always reads that reaching a stable plasma at temperatures of more than hundred million degrees is the main problem for the realisation of nuclear fusion power plants. Even though this idea is widely shared and distributed by most scientists from all around the planet, it is far from the well known facts.

As will be detailed in the following, in addition to the already overwhelming difficulties related to reaching stable plasma conditions of hydrogen isotopes, which is supposed to be studied and solved with the ITER experiment or other plasma physics experiments, several other fundamental go-no-go problems for controlled nuclear fusion exist, and those other problems can neither be investigated with the ITER project, nor with any other existing hypothetical plasma physics apparatus.

Among those fundamental problems, known since decades [3], and likely even more important than the creation of a stable 150 million degrees Celsius plasma, one finds:

- No significant tritium sources exist beyond the needs from the relatively small scale DT fusion experiments at ITER. This is different for a future energy producing fusion reactor, which has to be tritium self-sufficient and thus has to breed significantly more tritium isotopes than fusioned in the DT fusion process. Qualitatively, the breeding reaction has to be initiated from interactions of the 14 MeV neutrons, produced in the DT fusion process, with a lithium blanket with a thickness of at least 50-100 cm, surrounding the few 1000 m^3 plasma area. So far, even the most optimistic simulations failed to find such a suitable material composition. In addition, there is no chemical and mechanical process which achieves an almost 100% tritium extraction efficiency from the several hundred tons of lithium in the breeding zone and at the same time avoids chemical reactions of the hydrogen atoms (chemical identical with a tritium nucleus) and the lithium and other surrounding materials.

- There is no known material which can survive simultaneously (1) some chaotic plasma eruptions and (2) at the same time can stand the damage from the extremely damaging intense 14 MeV neutrons flux. There is also no significant intense neutron source, where such materials can be tested for Tokamak fusion like conditions.

- No physical mechanism which shows how the energy from the 14 MeV neutrons can be transferred in the few thousand m^3 material surrounding the plasma zone to some liquid has so far been presented.

As those problems need to become known and understood by a broader audience, a more detailed discussion of those problems and their current scientific understanding will be presented in the following sections.

The basics of nuclear physics, required to understand the potential and problems of nuclear fusion and nuclear fission energy, is presented in section 2. In particular it should become clear from this section that claims about the potential energy production, either from mysterious cold fusion reactions, or from fusion reactions involving heavier elements than deuterium and tritium hydrogen isotopes are in contradiction to basic nuclear physics, sufficiently well understood since several decades. Accordingly, such claims belong to pseudo science and do not need to be discussed any further in this report.

A more quantitative analysis of the problems, which exist for a practical deuterium-tritium nuclear fusion power plant, is presented in the subsequent sections 3 and 4. In section 3 the physics questions related to the energy transfer and nuclear interactions of the 14 MeV neutrons, emitted essentially isotropically outside of the 1000 m^3 plasma fusion zone, with the material surrounding the fusion are discussed. In particular the problems related to destructive interactions of neutrons with the material, which protects the apparatus from plasma instabilities, are discussed. Furthermore, it is shown that no practical physics process is known which allows an efficient energy transfer from the neutrons to some gas or liquid, like in any power plant.

The, essentially unsolvable, problem of the tritium self-sufficiency, required for a hypothetical future fusion power plant, is presented in section 4.

The known and essentially unsolvable technical problems for a practical nuclear fusion power plant are summarised in section 5. As those problems are far larger than the ones which are addressed by Stellerator projects like Wendelstein 7-X and the ones which might eventually be studied with the ITER project, it can be understood why nuclear fusion power plants will always remain hypothetical energy source of the far away future.

Consequently it can be concluded that the accumulated knowledge is already sufficient to terminate publicly funded research for nuclear fusion power plants as quickly as possible, such that those human resources and the billions of taxpayers' Euros from the research budget could be used to address the accumulated environmental and social problems, created by the existing destructive globalised economy.

2 Energy from nuclear fusion

Over one hundred years ago, physicists began to understand the atomic structure. Atoms have a rather dense positively charged center, the nucleus, where essentially all the atomic mass is concentrated, which is surrounded by a cloud of negatively charged electrons. The size of the Atom, roughly 10^{-10} m, is defined by this electron cloud. In comparison, the size of the nucleus, formed by different numbers of positively charged and neutral nucleons, the protons and neutrons, is about 100000 times smaller than the size of the atom. While the electromagnetic force was understood several decades earlier, the understanding of the atomic structure required several scientific breakthroughs: (1) the development and understanding of relativistic quantum mechanics and (2) the postulation of a new strong force, much stronger than the electromagnetic force, which however acts only on distances comparable to the size of the atomic nucleus.

It took a few generations of physicists and another hundred years to understand the fine details of this force and this type of research has led to what is studied today under the names of subnuclear physics, high energy physics and particle physics. This ongoing research about the physics at scales thousands of times smaller than the atomic nucleus, still fascinates millions of people interested in science all around the planet.

However, the basic knowledge about the structure of the atomic nucleus, accumulated during the first half of the 20th century, is sufficient to understand the basics about the enormous energy release from nuclear fission of heavy atoms like uranium and especially the functioning of the sun and billions of stars, due to the fusion of protons and neutrons.

After the discovery of the neutron in 1932, and the precise measurements of the mass of the different atoms it was quickly realised that bound states of a few nucleons had a mass about 0.8% smaller than the mass of isolated protons and neutrons. It was found that only relatively few combinations with roughly equal or slightly more neutrons than protons can form stable bound states under the nuclear force. While the proton is known as a stable particle, unbound (free) neutrons have a lifetime of about 15 minutes. Neutrons can thus only be found in bound states in the nucleus from where they might be liberated in energetic nuclear reactions.

Due to the increasing electrostatic repulsion of the protons, it was understood that the nucleons for elements beyond iron become less strongly bound and that atoms with more than around 90 protons become unstable. For example uranium with 92 protons and 143 (or 147) neutrons, is unstable[1] and disintegrates under what is called radioactive decay into lighter elements. The uranium decays into energetic α particles, the helium nucleus made of 2 protons and 2 neutrons and the thorium nucleus with 90 protons and 141 (or 145) neutrons. It was found that heavy atoms, like uranium, when hit by energetic neutrons can also be fissioned into 2 lighter nuclei, between 2 to 3 neutrons and an enormous amount of energy. This energy release per fission reaction is about 100 million times larger than the energy released in chemical atomic reactions, e.g. when burning fossile fuels. It is the discovery of fission energy which led to the developments of the nuclear fission bomb and to nuclear fission power plants.

It was quickly realised that the nuclear fusion of protons and neutrons will release about up to 7 times more energy per nucleon (and thus per mass unit), than observed in fission reactions and per nucleon[2], and around 1938 it was understood that it is nuclear fusion of hydrogen isotopes which powers the sun and billions of stars in the universe. For example the nuclear fusion of about 1.01 kg of protons into 1 kg of helium “liberates” an energy of almost 10^9 kWh, about 10 times larger than the energy obtained from the fission of 1 kg of the uranium (U235 isotope).

The dominant nuclear fusion cycle in the sun starts with the fusion of two hydrogen nuclei (protons), where one proton is transformed (via the weak interaction) into a neutron, a positron and a neutrino. The result of this first fusion reaction is the nucleus of the heavy hydrogen isotope called deuterium, a proton-neutron bound state[3]. Next, another proton is added to make He^3, the helium nucleus made of 2 protons and one neutron. Finally two He^3 nuclei are fusioned into He^4, two protons and a large amount of energy is liberated.

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[1] The Uranium isotopes with 143 neutrons and 147 neutrons have a half lifetime of about of 0.7 billion years and 4.5 billion years.

[2] However, the energy release in one fusion reaction of deuterium-tritium isotopes is roughly 10 smaller than the one released in one fission reaction of heavy elements like uranium.

[3] Isotopes of any type of atom contain the same number of protons (and electrons), but differ in the number of neutrons. Three types of hydrogen isotopes are known, ordinary hydrogen (just one proton), deuterium (one proton and one neutron) and tritium (one proton and two neutrons). These heavier hydrogen atoms are chemically identical to the lightest (only one proton) hydrogen atom.

The nuclear fusion in the center of the sun, formed about 5 billion years ago, heats the center of the sun to several millions degrees and still about 5500 degree at its surface. The energy from this solar fusion power generator is sent isotropically, and with an almost perfect blackbody light spectrum, into space. The energy released per second has been measured to be about about 4×10^{26} Joule, corresponding to the fusion of about 600 million tons of hydrogen into helium per second. Calculations show that enough hydrogen fuel remains in the sun, so that this process may continue for another five billion years[4].

The hydrogen fusion cycle in stars, massive like our sun, is possible thanks to the enormous gravitational pressure, which brings nucleons close enough together to initiate the process in the center and keep it under control. An introduction about many more interesting details about the nuclear fusion processes in stars, their evolution over their lifetime, and the synthesis of heavier elements in Super Novae explosions, can be found for example at Wikipedia or in astrophysics text books.

However, for the purpose of managing controlled nuclear fusion processes on our planet the gravitational pressure is not available and other methods are required. As has been pointed out already, the kinetic energy of the positively charge nucleons needs to be large enough to bring them close enough, such that the nuclear force becomes stronger than the electrostatic repulsion. For a small number of particles such energies can be achieved with accelerators, and essentially all nuclear fusion and fission reactions have been studied in detail during the last hundred years.

In particular it was found that the largest energy release per nucleon with up to about 7 MeV/nucleon (1 MeV = 1.6×10^{-13} Joule) was found in fusion processes where the helium nuclei is formed. This energy release should be compared to the nuclear fission process of uranium for example where about 200 MeV of energy is liberated in every fission reaction, corresponding to slightly less than 1 MeV per nucleon. Fusion reactions of heavier elements, with additional charged nucleons require higher kinetic collision energies and less and less energy per nucleon is liberated.

In particular only a few nuclear fusion reactions need to be considered for practical purposes on our planet, these are:

$$\begin{array}{l} (1)\ H^2 + H^2 \rightarrow H^3 + H^1 + \ 4.03 \text{ MeV} \\ (2)\ H^2 + H^2 \rightarrow He^3 + n + \ 3.27 \text{ MeV} \\ (3)\ H^2 + H^3 \rightarrow He^4 + n + 17.59 \text{ MeV} \\ (4)\ H^2 + He^3 \rightarrow He^4 + H^1 + 18.35 \text{ MeV} \end{array}$$

In contrast to the sun, unavailability of He^3 combined with the required roughly 10 times higher kinetic energy (temperature) and roughly 5-10 times lower fusion reaction probability in collisions, leaves only one fusion reaction accessible on our planet. This is reaction 3, the nuclear fusion of the heavy hydrogen isotopes deuterium and tritium. The released kinetic energy of 17.59 MeV is roughly shared between the neutron (of about 14 MeV) and the helium nucleus. This process has been managed in the nuclear fission-fusion bomb, where the fusion conditions, a combination of high enough kinetic energy (the equivalent of a plasma at hundreds of millions degrees Celsius) combined with high density of the heavy hydrogen isotopes are initiated by an uranium or plutonium nuclear fission explosion. Obviously this option is impossible for commercial energy production. Consequently the accessibility of nuclear fusion as an energy source on our planet requires the technical solution to at least four fundamental problems:

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[4] The solar energy production is amazingly stable within about ±0.1%, and since millions of years, and just right to enable a vast amount of different life forms on our planet. It is generally believed that other (cosmic?) disasters might end life on earth much earlier than the 5 billion years permitted by the solar fusion fuel reserves.

- How to heat and keep the plasma, made of a mixture of deuterium and tritium nuclei, and with a growing amount of the helium nucleus (produced in the nuclear fusion process), stable for days and under fusion conditions at hundreds of millions degrees Celsius and for a volume of at least 1000 m^3.

- Tritium, with a half lifetime of 12.3 years, does not exist in sizeable quantities on our planet. Any realistic proposal for a commercial nuclear fusion energy power plant must thus explain how the required tritium is obtained.

- A realistic proposal for a commercial nuclear fusion energy power plant must also explain how the energy carried by the neutron outside of the plasma can be used to heat a gas or a liquid to several hundred degree Celsius.

- The magnet configuration, and the surrounding heat protection shield as well as the lithium blanket material, where tritium might be produced in neutron lithium reactions, must be sufficiently thick to resist plasma eruptions and at the same time thin enough to not absorb even a few % of neutrons emitted from the plasma zone. At the same time, this material must be resistant to the intense neutron radiation and the hot plasma eruptions.

At best, only the first problem is investigated with ITER like plasma physics projects. But, as has been explained in Part I of this report, it seems that enough has been learned already during the past 20 years from the ITER construction, to conclude that Tokamaks are not the technology which leads to the a commercial nuclear power plant.

In the following the accumulated knowledge about the other three problems is presented and it is demonstrated that those problems are essentially technically unsolvable. Consequently it follows that commercial energy production from nuclear fusion is not an answer to the growing energy and environmental problems.

2.1 Technological challenges for nuclear fusion power plants

Whatever one thinks of the wisdom of nuclear fission power, the quick scientific and technical success in bringing this form of power online, led to an euphoric and rather un-scientific belief in continuous never ending scientific and technological progress. Thus, after the second world war, many nuclear pioneers expected that the technology to use nuclear fusion on our planet could be developed within a few decades and that this form of energy would provide their grandchildren with cheap, clean and essentially unlimited energy[4]. While such promises were obviously wrong, they did not result in a serious investigation about the real problems. Consequently today's fusion scientists, in all industrialised countries, still claim that commercial nuclear fusion reactors should be ready within the next few decades, but only if further billions of Euros from public research funds are invested accordingly in this type of research.

Before going into the details of the technical problems, it is interesting to see how the scientists and science politicians from ITER and similar projects are presenting the remaining challenges.

2.1.1 The views of the scientifically minded nuclear fusion lobbyists

Despite a growing number of scientists, questioning the possibility of a technological realisation of nuclear fusion power plants[5], the university bachelor education for physicists and physics teachers still mostly follows a story told since decades:

- that progress made in fusion research is impressive;

- that controlled fusion is probably only a few decades away; and
- that - given sufficient public funding - no major obstacles stand between us and success in this field.

Here are some quotes from physics textbooks that reflected this sort of optimism some decades ago and some of them are still used today:

"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 utilisation" (Energy, Resources and Policy; R. Dorf 1978)

"As the construction of a fusion reactor implies a large number of unsolved practical problems, one can not 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)

Today's "teaching", which relies mostly on what can be found for example in the quotes from the ITER outreach pages, [6], is summarised accordingly (Quotes):

"Three conditions must be fulfilled to achieve fusion in a laboratory: very high temperature (to provoke high-energy collisions); sufficient plasma particle density (to increase the likelihood that collisions do occur); and sufficient confinement time (to hold the plasma, which has a propensity to expand, within a defined volume)."

"In ITER, fusion will be achieved in a tokamak device that uses magnetic fields to contain and control the hot plasma. The plasma particles are heated – that is, sped up – by different types of auxiliary heating methods. The fusion between deuterium and tritium (DT) nuclei produces one helium nucleus, one neutron, and great amounts of energy."

"The helium nucleus carries an electric charge which will be subject to the magnetic fields of the tokamak and remain confined within the plasma, contributing to its continued heating. However, approximately 80 percent of the energy produced is carried away from the plasma by the neutron which has no electrical charge and is therefore unaffected by magnetic fields. The neutrons will be absorbed by the surrounding walls of the tokamak, where their kinetic energy will be transferred to the walls as heat."

"In ITER, this heat will be captured by cooling water circulating in the vessel walls and eventually dispersed through cooling towers. In the type of fusion power plant envisaged for the second half of this century, the heat will be used to produce steam and –by way of turbines and alternators– electricity."

"In terms of sheer scale, the energy potential of the fusion reaction is superior to all other energy sources that we know on Earth. Fusing atoms together in a controlled way releases nearly four million times more energy than a chemical reaction such as the burning of coal, oil or gas and four times more than nuclear fission."

"Fusion research has increased key fusion plasma performance parameters by a factor of 10,000 over 50 years; research is now less than a factor of 10 away from producing the core of

a fusion power plant."

Some qualitative ideas about the necessary "fusion fuels", the hydrogen isotopes deuterium (a bound state of one proton and one neutron) and tritium (one proton and two neutrons) are also presented on those outreach pages, [7]

In the deuterium-tritium (DT) fusion reaction, high energy neutrons are released along with helium atoms. These electrically-neutral particles escape the magnetic fields that confine the plasma and are absorbed by the blanket covering the surrounding walls.

If the blanket modules contain lithium, a reaction occurs: the incoming neutron is absorbed by the lithium atom, which recombines into an atom of tritium and an atom of helium. The tritium can then be removed from the blanket and recycled into the plasma as fuel.

Blankets containing lithium are referred to as breeding blankets. Through them, tritium can be bred indefinitely. Once the fusion reaction is established in a Tokamak, deuterium and lithium are the external fuels required to sustain it. Both of these fuels are readily available.

A future fusion plant producing large amounts of power will be required to "breed" all of its own tritium. Through its Test Blanket Module (TBM) program, ITER will be the first fusion device to test this essential concept of tritium self-sustainment."

In short, the self-sufficient fusion chain is imagined in these steps:

- The fusion process $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He}_2^4 + \mathrm{n}+$ plus energy. About 80% of the liberated fusion energy is taken up by the neutron which leaves the plasma zone. The energy carried by the helium nucleus will be used to keep the plasma hot enough for subsequent fusion reactions. After the neutron has been slowed down, similar to the neutron moderation in a fission reactor, the breeding reaction $\mathrm{n} + \mathrm{Li}_3^6 \rightarrow \mathrm{He}_2^4 + \mathrm{H}_1^3$ (tritium) should take place. Both, deuterium and lithium are relatively cheap and exist, for all practical purposes, in essentially unlimited quantities on our planet.

- The tritium produced in this process must then be extracted from the blanket material and collected with negligible losses. The tritium must then be transferred back to the reactor center.

This story looks like being too good to be true. It shows that our human institutions are capable of planning over much longer time scales than the 4-year lifetimes of governments. And it seems that, if scientists get sufficient funding, they can always solve all potential energy and environmental problems.

After all, who can doubt that the world's best scientists and engineers will be able to build upon and dramatically extend the impressive technological progress that we have witnessed during the last 50-to-100 years. It seems, in short, that everything necessary is being done today in planning for our energy future and that one would be foolish to listen to any of the rumours about a looming world energy crisis.

Unfortunately there are reasons to doubt this story.

2.1.2 The views of nuclear fusion lobbyists are flawed!

One problem, which has been noticed already by many observers, is the fact that essentially the same story has been told for some 30-to-50 years now. The most significant difference in today's version is that controlled fusion is now seen to be about 50 years away instead of the originally imagined 20-to-30 years. Yet, the ITER scientists never seem to challenge any of the above assumptions and work enthusiastically on their specific assigned problems.

In what follows, we will challenge the assumptions used to justify the funding of the ITER project and other smaller but similar projects around the planet like for instance the Stellerator project in Germany and the we will quantify the arguments of fusion skeptics. We start with a comparison on what fusion scientists have achieved so far, what they expect to achieve with a successful ITER program and what would actually be required for a hypothetical commercial fusion reactor. This overview of the remaining problems facing commercial fusion, many of them will not even be studied within the ITER project, will demonstrate that a large number of "divine interventions" will be required if the belief in controlled fusion is to be kept alive.

Chief among the problems to be discussed here is the imagined self-sufficient tritium breeding cycle. One might compare it to the plan to operate a fission reactor with heavy non-radioactive elements like lead. In fact, as we are about to see, it seems that enough knowledge has been accumulated on this subject to safely conclude that whatever might justify several tens of billions of Euros (Dollars) for ITER like projects, it is not energy research.

3 Remaining barriers to commercial fusion energy on planet earth

Producing electricity from controlled nuclear fusion requires a technology to remove 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 about 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.

The current quantitative challenge about those technological barriers can be summarised as follows:

1. Commercial energy production requires that one achieves steady state fusion conditions for a deuterium-tritium plasma on a scale which is comparable to that of today's standard nuclear fission reactors with outputs of 1000 MW(electric) and about 3000 MW(thermal) power. The current ITER proposal foresees a thermal power of only 400 MW 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 1500 MW, but it was realized quickly 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.

   Today's 1000 MW(electric) *fission* reactors 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(thermal) for about one second and 4 MW(thermal) for about 5 seconds corresponding to a liberated thermal energy of about 5 kWh. The Q value - produced thermal energy over input electric energy - for both pulses was 0.65 and 0.2 respectively[5].

   If everything works according to the 2018 provisional ITER operation plan, it will be at earliest around 2036-2038 (a delay of about 15 years compared to the original design plan) before ITER experiments might achieve a power output of 500 MW(thermal) with

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[5] A more honest Q value estimation would include some estimate of the thermal to electric energy loss factor from the neutron energy to thermal energy and then to electric energy. However, as this would reduce the claimed Q values significantly it seems that ITER lobbyists do not want this problem to be considered further.

a Q value of up to 10 and for about 10-50 seconds. Compare that to the original ITER proposal which was 1500 MW(thermal), with a Q value between 10-15 and for about 10000 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 in 2038, pales in comparison with the requirements of steady state operation, year after year, with only a few minor controlled interruptions.

Previous deuterium-tritium experiments in the 1990s used only minor quantities of tritium and yet lengthy interruptions between successive experiments were required. The likely reasons for those interruptions were repairs and perhaps of the already excessively high radioactivity from the tritium decays inside the apparatus. In earlier fusion experiments, such as JET, the energy liberated in the short pulses came from burning (fusing) about 3 micro-grams (3×10^{-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 still greater quantities that would be required for a commercial fusion reactor. A 400 sec fusion pulse with a power of 500 MW corresponds to the burning of about 0.035 gr (3.5×10^{-2} grams) of tritium. A very large number when compared to 3 micro-grams, but a tiny number when compared with the yearly burning of 55.6 kilograms of tritium in a commercial 1000 MW(thermal) fusion reactor.

The achieved *efficiency* of the tritium burning (i.e., the amount that is burned divided by the total amount that was 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 that would not cause noticeable interruptions of production in a commercial fusion plant is needed. ITER proponents know that even their self-defined goal (a 400 second long deuterium-tritium fusion operation at a Q value of 10, and within the relatively small volume of 840 m^3) presents a great challenge. For example, even in the latest plans from 2018, [8], it will take at least 10 years from the first plasma operation to achieve this goal. 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 fulfil 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. 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 and with similar thermal power. Since the neutron energy is also higher, it has been estimated that -with such a neutron flux- each atom in the solid that surrounds the plasma will be displaced about 475 times over a period of 5 years [9]. *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 instabilities and eruptions from the 100-million-degree hot plasma and for years.

   The “erosion” for carbon-like materials from the neutron bombardment in a commercial fusion reactor has been estimated to be about 3 mm per “burn” year and even for materials like tungsten it has been estimated to be about 0.1 mm per burn year [9].

In short, no material known today can even come close to meeting the requirements just described. And exactly how a material that meets these requirements could be designed and tested remains a mystery, because tests with such extreme and energetic neutron fluxes[6] are neither foreseen at ITER nor at any other existing or planned plasma physics 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 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 of the few kg of tritium that are foreseen for ITER is likely to create major headaches both for the radiation protection group and for the people 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 15-20 years from now [10]. 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 the following section. 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 nuclear scattering) to some kind of gas or liquid, like high pressure helium gas, within the lithium blanket of some few 100 m^3. 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, one knows already that the lithium blanket temperature can't be too hot, thus limiting possible efficiencies well below the ones 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 about 7.5% of natural occuring lithium[7]

     The minimal thickness of a so called lithium blanket that surrounds the entire plasma zone has been estimated to be at least 1 meter. Unfortunately, lithium like hydrogen

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[6] Intense 14 MeV neutron fluxes require significant amounts of DT fusion reactions, as neutrons produced in nuclear fission have energies of at most around 1 MeV.

[7] The 93.5% the natural lithium can not be used for the tritium breeding reaction.

(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 modelling - and some tritium atoms will be blocked within the blanket. Unfortunately, additional neutron and tritium losses can not be allowed as will be described in more detail in section 4.

- Next, the engineers need to find an efficient way to extract the tritium quickly, and without loss, from this lithium blanket before it decays. While the word blanket implies a relatively thin lithium containing cover surrounding the few 1000 m^3 plasma zone, the hidden but well known fact is that this "blanket" needs to be at least between 50-100 cm thick, such that the imagined energetic neutrons can indeed be slowed down to transfer their energy to some "liquid or gas" and next perform a nuclear interaction with lithium producing tritium and a helium nucleus. In reality one is thus not talking about a blanket but an enormous amount of the Li^6 isotope of perhaps at least 100-300 m^3.

  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 [11].)

  And 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 plasma fusion reactor zone.

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

4 Illusions of tritium self-sufficieny

The fact is, a self-sustained tritium fusion chain needed for Tokamaks, Stellerators or any other plasma creating fusion machines, appears to be not simply problematic but absolutely impossible. To see why, we will 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 transfered 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. In order that a self-sustained chain reaction can happen, a large amount of uranium 235, enriched to 3-5%, is usually required. Once the nominal power is obtained, the chain reaction can be regulated using materials which have a very high neutron absorption cross section. A much higher enrichment of up to 90% is required for bombs and for fast reactors such that they can function even without moderators.

In contrast to fission reactions, only one 14 MeV neutron is liberated in the $\mathrm{D} + \mathrm{T} \rightarrow \mathrm{He} + \mathrm{n}$ fusion reaction. This neutron energy has to be transferred to a medium using elastic nuclear 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 might easily calculate how much tritium burning is required to operate a continuous operating commercial fusion reactor assuming a power production of 1000 MW(thermal)[8]. One finds that about 55.6 kg of tritium needs to be burned per year with an average thermal power of 1000 MW.

Today's tritium is extracted from nuclear reactors at extraordinary cost - about 30 million US dollar per kg from Canadian heavy water reactors. These old heavy water reactors will probably stop operation between 2025 to 2040 and one expects that a total tritium inventory of 27 kg will be accumulated by the year 2025 [12]. But 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 "DEMO" fusion reactor, which fusion optimists imagine to start operation not before the year 2050, at best only about 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 about 200 million dollars per kg [12].). 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 professor Abdou from UCLA, one of the world's leading experts on tritium breeding, allows us to get some relevant numbers both about the basic requirements for tritium breeding and the state of the art today [13].

But first things first: Understanding such "expert" discussions requires an acquaintance with some key terms:

- The "required tritium breeding ratio", rTBR, stands for the minimal number of tritium nuclei which 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 the quantitative 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 also lithium requires particular care, not only because of radiation protection, but also because tritium and lithium atoms are chemically very reactive elements. Consequently, real-world, large-scale experiments are not easily performed and today's understanding about the tritium breeding is based almost entirely on complicated and extensive computer simulations, 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 [14]. The authors assume that a commercial fusion power reactor of 1500 MW (burning

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[8] This is relatively small compared to today's standard 3000 MW(thermal) fission reactors which achieve up to 95% steady state operation.

about 83 kg of tritium per year) would require a long-term inventory of 9 kg and they further assume that the required start-up tritium is available.

They argue that according to their calculations, the absolute minimum rTBR is 1.15, assuming a doubling time of at least 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. Other numbers can be read from their figures. For example one finds that if the fractional burn-up would be 1%[9] the rTBR should be 1.4 for a 5 year doubling time and even 2.6 for a 1 year doubling time.

The importance of short tritium doubling times can be understood easily using the following calculation. Assuming these numbers can be achieved and that the 27 kg tritium (2025) less 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 1500 MW(thermal) reactor can operate at full power only about 8 years after the start-up.

And if anything these rTBR estimates are far too optimistic since 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 today's computer simulations.

After many years of detailed studies, current simulations show that today's blanket designs have, at best, achieved TBRs of 1.15. Using this number, Sawan and Abdou conclude that theoretically a small window for tritium self-sufficiency still exists. This window requires (1) a fractional tritium burn up of more than 5%, (2) the tritium operation reserve inventory of less than 5 days and (3) a doubling time of less than 5 years. But using these numbers, the authors believe it is difficult even to imagine a real operating power plant. In their 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 TBRs much higher than 1.15 are required. 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 which reduce the obtained aTBR numbers once more realistic reactor designs are studied and one considers structural materials, gaps, and first wall thickness. 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, so far, it was not possible to obtain any corresponding detailed information. However, as one expects 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 [14], 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. All these real experiments show, according to Sawan and Abdou [14], 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)

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[9] The fractional tritium burn-up during the short MW pulses in JET was roughly 0.0001%.

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 Summary: Ending the dreams about controlled nuclear fusion

As explained in the previous sections, there is a long list of fundamental problems concerning controlled nuclear 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 tens of billions Euros (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 3. *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" change the subject and tell you that this is not a problem for their ITER project. In their view it will not 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. Perhaps they are also comfortable with the fact that neither the problems related to material erosion due to the high neutron flux nor the problems related to tritium and lithium handling can be tested with ITER. Perhaps they are expecting miracles from the next generation of experiments.

However among those who are not part of ITER and those who are not expecting miracles it seems that times are changing. More and more scientists are coming to the conclusion that commercial fusion reactors can never become reality. Some are even receiving a little attention from the media as they argue louder and louder that the entire ITER project has nothing to do with energy research [15].

One scientist who should be receiving more attention than he is, is Professor Abdou. In a presentation in 2003[10] , 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 'Go-No-Go' issues 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?"* [16]. In short, to go ahead with ITER without addressing these chamber technology issues makes no sense at all.

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[10] Even though his presentation was made already in 2003, essentially nothing has changed during the last 15 years.

In light of everything that has been said in this article, it seems clear that this is what should be done:

"Tell tax payers, policy makers and the media the truth. Tell them that, after 50 years of very costly fusion research conducted at various locations around the world, enough knowledge exists to state":

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

It is late, but perhaps not too late, for the fusion community to acknowledge that everything that has been done to date tells us that commercial energy production from nuclear fusion is never going to be a reality.

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 research projects, acknowledging these truths will not be easy. But it is the only honest thing to do.

It is also the only path that would allow to transfer the enormous monetary resources and the highly skilled human talents from ITER to other more promising research projects, that need now to be brought to bear on our increasingly urgent energy and environmental 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.

If we do not take this path, the entire scientific community might before too long be embarrassed and devastated when the truth is discovered even by uneducated "children":

"The Fusion Emperor has no clothes!" [17].

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6 conflict of interests

The author states that there is no conflict of interest.

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[10] The latest construction and operation time line details can be found here http://www.iter.org/faq#When_will_ITER_be_operational. This schedule should be compared to the original promised timeline at https://www-pub.iaea.org/MTCD/Publications/PDF/ITER-EDA-DS-24.pdf one which led to the agreement to construct the ITER Tokamak. More details about the continuous delays of the ITER project were presented in Part I of this report [1].

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