Fusion Illusions: Fundamental questions on the viability of commercial energy production from deuterium-tritium fusion

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1 Introduction

A belief that controlled nuclear fusion will solve all future energy problems is widespread within the scientific community and especially among physicists. Supporting this view are the ideas that the raw materials (hydrogen and deuterium) exist in almost infinite quantities because they can be extracted from ordinary water, the process is "clean" because no long-lived radioactive heavy elements are produced and the process is CO_2 free [1]. The last point was added only a few years ago.

We are told that only one "minor" hurdle remains: How can the raw materials, be kept under high pressure and at a temperature, forming a so called plasma, of about 100 million degrees Celsius for a long period?

Fusion scientists try to achieve fusion conditions, achieved naturally in the center of the sun, using enormous amounts of electric energy to create sophisticated magnetic fields. Enormous and impressive progress on magnetically confined plasmas at high temperatures has been achieved during the last 50 years and the fusion of deuterium and tritium to helium plus "energy" was successfully demonstrated in experiments some 10 years ago [2].

These experiments in question achieved a thermal power production of 4 MW (Million Watt) for 5 seconds and 15 MW for about 1 second. The so called Q-value, the ratio of produced energy to the input energy was still below 1 -i.e., these experiments used more energy than was liberated in the process. Yet these experiments are considered proof that the technological problems of fusion can be resolved in principle, and that a worldwide cooperative effort plus more money will overcome the remaining practical difficulties in the next fusion project. Today's dreams about "infinite cheap and clean energy" will then become reality. This is the story physics students learn at universities and later tell friends, school children, journalists and politicians-left, center, and right.

More advanced courses offer more detail, such as the fact that the deuterium-tritium fusion reaction, $D + T \rightarrow He_2^4 + n + 18$ MeV (million electron volts[1]) has the lowest required temperature combined with the highest fusion reaction rate. For this reason it is the only reaction that is envisaged for a future commercial fusion reactor.

The 18 MeV of liberated energy would be shared between the neutron with a kinetic energy of 14 MeV and the helium nucleus (He_2^4) with 4 MeV. Escaping the reactor core, the neutron would heat up a surrounding medium. The 4 MeV helium nucleus remains in the reactor core and its energy is supposed to keep the plasma temperature high enough for further fusion reactions.

These arguments seem to be sufficient to convince policy makers and the public in general to provide the required funding. Although successfully used to elicit the 10 billion dollars

[1]The energy unit of 1 eV is equivalent to 1.6×10^{-19} Wsec

funding for ITER (according to [1] this stands for *"The way" in Latin. Formerly interpreted to stand for International Thermonuclear Experimental Reactor, although this usage has been discontinued.)* as the next step toward a commercial fusion reactor, the whole story is a great deal more complex as we will demonstrate.

In the following pages, under the sub-title "Energy from nuclear fusion", we describe the well known physics of nuclear fusion, outlining the path to a commercial fusion test reactor as envisaged and explained by the proponents of the ITER project. "Other problems of thermonuclear fusion on planet Earth" chronicles the achievements of the last 50 years of intense and expensive research, evoking the barriers remaining before we can even begin to think about designing a commercial fusion test reactor. In "Illusions of Tritium self-sufficiency", we explain why a real fusion reactor would have to achieve self-sufficient tritium production and why it seems to us that the fulfillment of the necessary breeding parameters would be miraculous.

We conclude that to date not a single experiment has been able to demonstrate that the theoretically imagined process can function in practice. In addition, today's idealized computer-performed "experiments" do not even include a mechanism on how the produced tritium can be extracted. We wonder why this apparently crucial problem related to tritium self-sufficiency does not appear to arouse concern within the fusion program community. Worse, one finds not only that the fusion community generally avoids discussing this problem, but that when they do discuss it, they refuse to do it in a transparent manner. Thus questions about this matter do not seem to meet with the adequate responses and a forum for serious interdisciplinary scientific debate does not exist.

For these reasons, articles like this one may be necessary to draw attention to and stimulate public discussion of scientific concern about the ITER project's approach to solve the energy problem.

2 Energy from nuclear fusion

Over one hundred years ago, physicists began to understand how energy production in stars could last for billions of years. Our own sun, formed about 5 billion years ago, has emitted since that time an energy of about 4×10^{26} Joules per second, corresponding to the fusion of about 600 million tons of hydrogen into helium per second. This process may continue for another five billion years[2], since enough hydrogen exists.

The dominant fusion cycle in the sun starts with the fusion of two hydrogen nuclei (protons). The result is 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 fused into He^4, plus two protons and a large amount of energy. The enormous gravitational pressure in the sun leads to a high enough density and temperature at its center such that continuous fusion occurs.

The production of only 1 kg of helium "liberates" the heat energy of almost 10^9 kWh and scientists quickly saw the energy potential of nuclear processes, especially with the discovery of the neutron in 1931. The neutron-induced nuclear fission of uranium into two lighter elements,

[2]The solar energy production is amazingly stable over 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.

[3]Isotopes of any type of atom contain the same number of protons 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 heavy isotopes are chemically identical to the ordinary hydrogen atom.

plus 2 to 3 neutrons and a large amount of energy, was observed in experiments at the end of 1938. Only 4 years later, on the 2nd of December 1942, a nuclear chain reaction with a power of 0.5 Watt (and up to 200 Watt at a later time) could be sustained by E. Fermi and his team below the Chicago University football stadium [3].

The next steps in using nuclear energy were the explosions of the Hiroshima and Nagasaki fission bombs, on August 6 and 9 of 1945, resulting in more than 100,000 human deaths. This was followed by the nuclear arms race during the Cold War which led only a few years later to hydrogen fusion bombs by the USA and the Soviet Union. These bombs were up to 1000 times more powerful than the Hiroshima fission bomb. The largest fusion bomb to date was exploded in 1961 by the Soviet Union.

It turned out that it was relatively straight forward to operate a controlled fission chain reaction, where the "liberated" heat could be used to operate a generator and produce electricity. For example the first commercial fission reactor was producing electricity in 1954, only 9 years after the first fission bomb was successfully tested. Today, about 440 commercial fission reactors, with a total electric power of about 370,000 MW, operate in 31 countries. They produce about 16% of the worlds electric energy and thus roughly 2.5% of today's world energy use.

Whatever one thinks of the wisdom of nuclear fission power, the quick scientific and technical success in bringing this form of power on line led to euphoric and blind belief in continuous scientific and technological progress. Thus, after the second world war, many nuclear pioneer's expected that nuclear fusion would provide their grandchildren with cheap, clean and essentially unlimited energy. But obviously this has not happened, and today's fusion optimists still do not expect the first commercial fusion reactor prototype for at least another 50 years.

Nevertheless, generations of physicists and physics teachers have been taught at the university, and have gone on to teach others, a) that progress made in fusion research is impressive, b) that controlled fusion is probably only a few decades away and c) that - 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 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)

A similarly uncritically media waxed enthusiastically about the recent decision by the "world's leaders" to provide the ten billion dollars needed to start the ITER fusion project. One can read, for example in the ITER outreach pages, that this funding would permit world-wide collaboration of scientists whose combined effort in nuclear fusion would solve potential future energy problems.

It is evident that all this serves as a relief to the public, which gets more and more concerned about the "global warming" that is related to the burning of fossil fuels, about the dangers of building more fission power plants, about global injustice and poverty as they relate to energy, and of course about the rising energy costs today and possible energy shortages tomorrow.

So the public welcomes 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."

ITER's main justification arguments, summarized by their outreach campaign are:

- Understanding of plasma physics has progressed so impressively that the production of plasma temperatures and density is near to the so called "break-even" point. The "break-even" point means that more energy can be extracted than is needed to heat the plasma to the incredible temperatures required for fusion. Much of ITER's language is more metaphorical than technical, e.g. "bringing the sun to the earth". Sometimes it is acknowledged that we are only talking about the deuterium-tritium fusion reaction and that all other fusion reactions and especially the one in the sun are out of reach.

- The necessary "fusion fuels" are the hydrogen isotopes deuterium (a bound state of one proton and one neutron) and tritium (one proton and two neutrons). The deuterium isotope is found in ordinary water with a concentration of about 0.02% per hydrogen atom. Tritium is an unstable isotope with a half-life of 12.3 years. A real fusion reactor will need initial seeding with tritium from an external source before it can provide its own self-sustained tritium breeding chain with a capacity of at least 55.6 kg per year and a thermal power production of 1000 MW production per year. The tritium breeding should take place within a lithium "carpet" surrounding the plasma zone. The plasma zone has a volume of more than 1000 m^3, and the carpet should have a thickness of at least 1 meter. The self-sufficient fusion chain is then imagined in these steps:

  - The fusion process $D + T \rightarrow He_2^4 + n+$ 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 $n + Li_3^6 \rightarrow He_2^4 + H_1^3$ (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 thick carpet material and collected with negligible losses. The tritium must then be transferred back to the reactor center.

- The fusion optimists claim that if the planned ITER experiments will function as expected today, then the first real electricity production can take place in a later much bigger fusion reactor, called DEMO, perhaps just 30 years from now [4]. If all subsequent DEMO experiments were to function as they predict today, then in roughly 50 years from now, some commercial electricity production can be imagined from a prototype reactor, called PROTO.

This 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 solve, within 50 years or so, all potential energy problems that are feared by the so called energy pessimists. 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 rumors about a looming world energy crisis.

Unfortunately there are reasons to doubt this story.

One problem, which has been noticed by many 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 of the ITER project and 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 the 10 billion dollar ITER project, it is not energy research.

3 Remaining barriers to fusion energy on planet earth

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 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.

These are the four barriers:

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 within the fusion community 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(el) *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(therm) for about one second and 4 MW(therm) for about 5 seconds corresponding to a liberated thermal energy of about 5 kWh. The Q value - produced energy over input energy - for both pulses was 0.65 and 0.2 respectively.

   If everything works as planned, it will be 2022 (or about 6 years after the first plasma experiment has been performed) before ITER tries, for the first time, to achieve a power output of 500 MW(therm) with a Q value of up to 10 and for about 400 seconds. Compare

that to the original ITER proposal which was 1500 MW(therm), 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 2022, 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 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(therm) 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 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 fulfill 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 that surrounds the plasma will be displaced about 475 times over a period of 5 years [5]. *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 and for years.

   The "erosion" for carbon-like materials from the neutron bombardment has been estimated to be about 3mm per "burn" year and even for materials like tungsten it has been estimated to be about 0.1 mm per burn year [5].

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 neutron fluxes can not 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 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 10 to 15 years from now [6]. 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 scattering) to some kind of gas or liquid, like high pressure helium gas, within the lithium carpet. This heated gas has to be collected somehow from the gigantic carpet 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 carpet 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. The minimal thickness of the so called lithium carpet 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 carpet. 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 carpet before it decays. We are talking about a huge carpet here, one that surrounds the few 1000 m^3 plasma volume. Extracting and collecting the tritium from this huge lithium carpet 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 [7].)

  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 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 the next section.

4 The Illusions of tritium self-sufficiency

The fact is, a self-sustained tritium fusion chain 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 $D + T \rightarrow He + n$ 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 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)[4]. 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 around the year 2025 and one expects that a total tritium inventory

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

of 27 kg will be accumulated by that year [8]. 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 "PROTO" 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 [8].). 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 [9].

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 carpet 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 carpet.

- 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 [10]. The authors assume that a commercial fusion power reactor of 1500 MW (burning 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 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. Other numbers can be read from their figures.

For example one finds that if the fractional burn-up would be 1%[5] 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 TBR's 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) a tritium reserve time of less than 5 days and (3) a doubling time of more than 4 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 TBR's 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, we have so far not been able 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 [10], 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 [10], 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 cur-

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

rently 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 Ending the dreams about controlled nuclear fusion

As we have explained in the previous sections, 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 dollar 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 aging 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 [11].

One scientist who should be receiving more attention than he is, is Professor 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 '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?"* [12]. In short, to go ahead with ITER without addressing these chamber technology issues makes no sense at all.

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

"Tell the truth to the tax payers, the policy makers and to the media; 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 will allow us to transfer from ITER to other more promising research 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.

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!" [13].

Acknowledgments

This paper is a result of many questions which the author asked over the past few years directly to physicists within the fusion community. Essentially none was answered and essentially no help was provided to get in contact with the corresponding "fusion" experts. Thus, in some kind of "hobby" research which included many discussions with colleagues the different pieces of the fusion illusion puzzle came together.

During spring 2007, another attempt was made to discuss these unsolved problems in an open and scientific way directly with scientists from the fusion community. Unfortunately, this dialog did not take place. Thus, the author hopes, with the ideas expressed in the quote from Gustave Le Bon below, that this paper might function like some kind of "telescope", helping others to observe that some objects are moving around the Jupiter.

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 read and discuss this paper with me. They all helped me to bring it into its final form. I would like to thank especially W. Tamblyn for his many valuable suggestions and his careful reading of the paper draft.

"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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[13] It seems that "history" sometimes repeats itself. Hans Christian Andersen (1837) fairy tale, "The Emperor's New Suit", can be found here: http://hca.gilead.org.il/emperor.html