# 1. EUSUSTEL WP3 Report
# Nuclear fusion

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## 1.1. Introduction

In the light of major uncertainties in the world long-term energy provision, all long term options, amongst which renewables, fission and fusion, should be further explored and developed so that future generations can choose the composition of an appropriate energy-source basket. It would be irresponsible towards future generations not to pursue a potentially successful energy source such as *nuclear fusion*. Indeed, future fusion power plants have good prospects to qualify as economic and environmentally benign base-load electricity generation plants. The progress of fusion development has been remarkable; all available techno-scientific information shows that steady and significant progress is being made towards a successful reactor. The slow (but steady) pace of progress, however, is linked with the need for large and expensive experimental devices. In the present context of liberalizing energy markets, whereby most actors focus on short time survival and profit making, and the indifference by the public at large towards science and technology development, it is not obvious to convince the decision makers to invest in a long term energy research strategy. Nevertheless, political decisiveness is required to keep the time schedule to establish commercial fusion by the second half of the century.

Although many long-term scenarios tend to ignore nuclear fusion as an energy-conversion technology, the World Energy Council scenarios, performed by the IIASA [1], do not “disregard” nuclear fusion completely, in the sense that a couple of sentences are devoted to it. First it is stated explicitly that nuclear fusion is excluded as an energy option because it is “*not technically feasible today*” (Ref. [1], p 49), whereas, e.g., hydrogen is included as an energy carrier “*because it can be produced with current technologies, although not yet at competitive costs*”. Somewhat further then, this first statement is somewhat mitigated, by saying the following: “*We have not included nuclear fusion explicitly in this study. Had this been done, fusion would have assumed or shared the role played by breeder reactors. However different the two may be from an engineering point of view, there is little to distinguish them in the scenarios. Both are large, centralized, carbon-free producers of electric power that generate radioactive waste and have a practically infinite resource base. Therefore, in our attempt to treat future technologies as generically as possible, breeding and fusion reactors, from today’s viewpoint, look very much alike”* (Ref. [1], p 87).

As just mentioned, and as will be explained below, commercial nuclear fusion is not expected before the second half of this century. Consequently, one could wonder why this technology is dealt with in a project like EU-SUSTEL, in which "only" the electricity provision with a horizon of 2030 is considered. The main reason is to be complete, in the sense that it concerns a potentially interesting technology for which continued R&D support will be necessary to give it a chance to be ready from 2060 or so onwards. Frankly speaking, the recent stalemate with regard to the site location of the International Thermonuclear Experimental Reactor (ITER), only resolved two years after the finalization of the modified final design, and five years after the first final design, is not very encouraging in this regard. Clearly, it is important to keep the awareness high to keep this potentially promising line of research alive.

This document on fusion also aims at providing interesting references where readers can follow fusion developments.

## 1.2. Nuclear Fusion Generalities

Nuclear fusion is based on "combining" or "fusing" hydrogen isotopes, of which the simplest reaction is *Deuterium (D) + Tritium* (T) to produce a *neutron* and a *He-4* nucleus, together with *17.6 MeV*. In the far future, other reactions such as *Deuterium + Deuterium* might be possible.

Two routes for making these fusion reactions happen are pursued, *magnetic fusion* and *inertial fusion*, the first one being the most advanced, and the second to some extent being linked to nuclear weapons research. This report will mainly focus on magnetic fusion research.

This is not the place to detail the fusion principle and the confinement concepts. This information can be found in the web-site published literature ([2], [3], [4]). See also the web-site references at the end of this report on Nuclear Fusion.

The *scientific progress* of fusion research (both in the plasma physics and technology areas) has been quite remarkable. All available techno-scientific information shows that steady and significant progress is being made towards a successful reactor. However, as already mentioned, this slow progress is linked with the need for large and expensive experimental devices. If sufficient financial resources were available, a parallel and thus faster approach could be envisaged; but in a reality of limited resources (and, of actually insufficient financial R&D funding), a sequential route may be the only way to go.

For more than 15 years now, the international magnetic fusion community has focused on developing the design of the *Next Step device ITER*[1] (following the generation of experiments such as TFTR, USA; JET, UK-Europe; JT60-U, Japan). Notwithstanding the sometimes difficult boundary conditions, the ITER activities have been performed with a remarkable drive and dedication. The international ITER Team, the Home Teams and the scientists and engineers in the plasma & fusion laboratories and universities worldwide have operated and collaborated efficiently and successfully. The ITER-design activities with be dealt with in a later section.

Nuclear fusion has some very appealing features: somewhat loosely speaking, one could say that if fusion energy turns out to be feasible, that then the low-term energy issue would be resolved. As far as fuel supply is concerned, it is almost inexhaustible, certainly if one manages to run on D-D in the long run. Also, fusion energy is very environmentally friendly. There are no harmful emissions such as $SO_x$ or $NO_x$ and it is a carbon-dioxide free source. The radioactive inventory is very limited: in the long-term view of D-D fusion, there is little fuel radioactivity involved, and by a careful choice of the structural materials for the reactor, the transmutation due to the 14 MeV neutrons can be strongly limited. As far as safety aspects are concerned, it is important to recognize that the complex nature of a fusion reactor is an advantage. If one element in the orchestrated operation of the reactor fails, then the reaction will come to a halt; there is no possibility for a runaway reaction. Likewise the low energy density nature of a fusion reaction turns out to be a blessing in that the afterheat (if any) of the reactor structure materials can be convected away by natural convection with the air environment.

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[1] ITER = International Thermonuclear Reactor

Having pointed out the nice features of fusion power, it must be said that the finish has not been reached yet. Before being a viable option, fusion development is faced with some non-negligible challenges. In the following subsections, we deal with two important ones: the cost of electricity generation through fusion, and the time schedule for commercial implementation.

## 1.3. The cost of electricity generation through nuclear fusion

Often, detailed cost estimates of fusion power plants are made. We believe that those estimates are of little relevance not least because we are considering here an electricity generation source that will come on line only more than half a century from now! First of all, the future competitiveness of electricity generation through nuclear fusion will depend first and foremost on the prices of the other means of electricity generation with which it will have to compete. E.g., if the prices of the competition are as low as, say, the present-day gas-fired combined cycles with low gas prices as in the nineties, then fusion, as a capital-intensive type of power generation method, may have a hard time to compete. If, on the other hand, gas prices are high and if the constraints put by the greenhouse effect make fossil-fuel use very expensive, and if nuclear fission remains "unpopular" in some or many countries, then fusion might be relatively cost effective compared to other means.

The so-called cost estimates of fusion power have very limited absolute value. The only value of those cost estimates is that they allow to indicate the weak points in the present day fusion reactor design, where then more attention will be needed in the future.

Clearly, two major issues must be concentrated on for a future economic viability of fusion power plants. The capital cost should be as low as possible, and the down time of the reactor should be reduced to the minimum. These items are actually a paraphrasing of the so-called Utility Requirements (in the USA known as “Utilities Requirement Document (URD)”, in Europe adapted as “European Utility Requirements (EUR)”).

Concerning *capital cost*, several elements should be mentioned. First, we believe that time is favorable to fusion. Present day high-tech and expensive technologies (such as remote handling, superconductivity, sophisticated materials) will become more common technologies, half a century from now, with substantial price reductions as a consequence. Second, whereas present-day experiments portray large plants of the order of 1-2 $GW_e$ output, it must be strived for to come up with smaller, more compact and thus cheaper reactors. Next, in order to keep the penalty for borrowing money to a minimum, the construction time of a fusion plant should be limited to the minimum possible. Construction times should certainly not be larger than 6-8 years. In addition, there should exist a watertight licensing procedure, such that an investor who puts a great deal of money into the construction of an expensive plant is given an operation license that permits him to start up the plant immediately after construction, and receives the legal guarantee that his plant will not be shut down prematurely unless compensated for the loss. (The discussion on the premature closure of nuclear fission plants in countries like Sweden, Germany and Belgium will certainly be remembered by future investors.) Finally, time is on the side of fusion with regard to the attitude of investors in liberalized markets. By the middle of this century, the electricity generators will have become used to liberalized markets and it is plausible that high-capital investments will again be possible. Coming back to a previous element just considered, it may also be said that 50 years from now the sociological attitude towards nuclear fission will have been settled one way or another, with the consequent fall out (positive or negative) for nuclear fusion projects.

On the issue of limited down time of a nuclear fusion plant, it is of uttermost importance that the fusion plant has a high *availability*. Regardless of the type of reactor, the electric power output should be roughly continuous. In addition, a high availability factor should be striven for since the machine must "pay back itself" by producing electricity. Availability percentages of 80% over the entire lifetime should be aimed for. An electricity generator who would have to shut down his reactor every month for one week to replace some components, and who may expect several unexpected outages, will never be interested in a fusion plant.

Concerning discussions on the future cost of fusion power, the following considerations are in order. If one asks the question whether utilities would order a fusion plant with a reactor like ITER [5], then the answer is a plain *no.* That machine is much too complex for a utility, which should not come as a surprise. Indeed, ITER is still an *experiment* rather than a routine reactor. The ITER device was optimized towards the goal to demonstrate extended burn with a D-T plasma, thereby integrating all fusion-physics and technological requirements. The fusion community knows that this machine is too complicated for routine electricity generation, but one has to perform the integration exercise at some point in time, and that sour apple must be bitten through. As a consequence of a gradually increasing involvement of the industry's design engineers, those type of reactors will likely be simplified and will become more robust. We are quite confident that, about a half century from now, a future fusion reactor will be much simpler than present-day experiments may lead us to believe.

## 1.4. Time characteristics of fusion development

A typical realistic time frame for commercial fusion power is of the order of 50 years from now. Although some fifty years ago, the same claims (or even more optimistic ones) were made, it is clear that at that time the complications of magnetically confined plasmas (stability, micro-turbulence and anomalous transport, etc.) were grossly underestimated. At the present time, it is justified to say that one has gathered a solid empirical understanding of the plasma behavior, so as to extrapolate towards a reactor. But even with this positive plasma-physics state of affairs, it will still take about half a century before society will have routinely operating commercial fusion plants. One knows how to reach the goal, but the magnitude of the experiments constitutes a long time scale for actual realization.

Suppose that, now that a decision on ITER siting has been taken, it takes another 3 years before groundbreaking for actual ITER construction is commenced, and count then about 8-10 years for construction. Although one could commence with reflections for the design of a (following-step "demonstration") DEMO reactor right after ITER construction, it is clear that that design will be strongly influenced by the ITER experimental results. It is not unrealistic to state that a real (both conceptual and detailed) DEMO design has to wait until the ITER experimental campaign has lasted for about a decade. Let us count 6-10 years for the duration of these real DEMO-design activities (this is not exaggerated keeping in mind the length of the ITER-design process with its

ITER-CDA, ITER-EDA, ITER-CTA, and ITER-Transitional Arrangement phases[2] – and still counting). DEMO construction would again take 8-10 years after which again about 10 years of measurement, testing and experience gathering is needed before final prototype designs may be expected. Add about 10 years for the construction of this first-of-a-kind routine fusion reactor. The above 'guestimate' for a time table leads to 50-60 years from today (given that the *political decisions are taken timely*!).

Even with an unexpected breakthrough in fusion physics or technology, it will be very hard to shorten the time horizon for routine production. The only thing that can drastically speed up this time frame is a massive crash program such as the Manhattan project or the Apollo program. Although in Europe positive attempts have been made by reflecting upon a 'fast-track' program for future development [6], which effectively combines the previously called DEMO and PROTO steps into a 'new' DEMO concept, it is presently doubtful that a crash program will actually be launched in the near future and it is estimated that the middle of this century is the 'logical' delivery date for routine electricity from fusion. Recent experience on decision making with regard to ITER siting is not encouraging, and the envisaged parallel construction of an irradiation device such as IFMIF (International Fusion Material Irradiation Facility) [7] is a necessary step for success, but will be insufficient for a drastic speed up. In our reasoning, fusion is only really commercially available after a "first of a kind" (FOAK) plant has been built. Whether this plant is called a FOAK or a prototype, is not really important.

## 1.5. Concise history of the ITER design

### 1.5.1. ITER Design Activities

The ITER story started already more than 15 years ago. At a summit between the USA and the then Soviet Union in Geneva in 1985, R. Reagan and M. Gorbachev agreed upon a collaboration for fusion research. Soon thereafter, the EU and Japan joined the effort.

From 1988-1990, a first phase, ITER CDA (*Conceptual Design Activities*) took place. The seat of the activity was in Garching, Germany, and there were actually four directors, with one 'primo inter pares' (K. Tomabechi). Recall that, under strong influence of the US delegation, the ITER-CDA device had a major radius of just under 6 m, and that it had a double diverter with two X points.

Then, the partners needed well over a year to agree on the next phase, called ITER EDA (*Engineering Design Activities*), which was supposed to last for 6 years, from 1992 till 1998. This time, it was opted for a single director in charge, but the partners could not even then agree on one site for the design team. It turned out that the team was divided up over three locations, each with a deputy director (Garching, Germany; Naka, Japan; San Diego, USA). The director, together with the so-called Integration Team, was located in San Diego, and the seat of the ITER Council was in Moscow.

As a matter of fact, the ITER-EDA phase turned out to consist of three stages. The first stage, the 'Rebut Stage' (called after its director), was characterized by a radical change in the design concept, with regard to size and configuration. The machine design was now allowed to have a major radius of over 8 m, with only 1 (lower) X point and a 'cold-gas diverter'. The second stage,

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[2] CDA = Conceptual Design Activities; EDA = Engineering Design Activities; CTA = Coordinated Technical Activities. All of these acronyms are clarified in a further Section.

for simplicity called the 'Aymar-1 Stage', was a consolidation phase, whereby the overall Rebut concept was kept, but some moderate changes were introduced. This large ITER-EDA machine had as characteristics: $P_{nom}$ = 1.5 $GW_{th}$, burn time=1000s, $R_{maj}$ = 8.14 m, cost ~ 6 G Euro. [8]. At the end of this stage, the four partners evaluated the design, endorsed it, but when it came to deciding on actual construction, it became clear that the financial tag was too large (although the cost had been known since the end of the nineteen-eighties). The four partners then asked the fusion community to design a smaller machine, with only half the cost and with reduced technical objectives. These activities were carried out during an extended EDA phase of three years, running from 1998-2001. In our logic, this is the third EDA stage, called 'Aymar-2 Stage'. The machine that was conceived was the ITER-FEAT device (*FEAT = Fusion Energy Advanced Tokamak*), with a cost of about 3 G Euro. Other main differences compared to the large ITER, are that the pulse duration will be ~ 300-500 s; with energy amplification factor Q > 10 in inductive regime. In the non-inductive current drive regime Q should be > 5. Further, $P_{nom}$ = 500 $MW_{th}$, $R_{maj}$ = 6.2 m, $I_{plasma}$ = 15 MA (instead of 21 MA for the large ITER), and the construction will be highly modular and evolutive. After approval of the design of this machine, the design was again simply called ITER. ([5], [9], [10], [11])

It must be noted that the USA partner, complying with US Congressional views, did not actively participate in the extended (3-year) EDA phase, or Aymar-2 Stage. It limited itself to an orderly close-out activity that ended in September 1999. During this 3-rd EDA stage, the director moved to Garching and only two design-team sites were kept, the other being Naka.

The third ITER-design phase was called CTA, which stood for *Coordinated Technical Activities*, and ran until the end of 2002. The idea was to assist the Negotiators for site selection, do some preparatory work for site selection and construction, and effectively to keep the ITER-design teams alive during these negotiations. During the CTA, at some point, four site proposals were on the table: a Canadian one, two European ones (Spain and France), and a Japanese one. The Canadian proposal (although perhaps an interesting compromise), was dropped relatively early because the financial commitment of the host country was judged to be too small. It is remarkable that in those early days of the negotiations, it was contemplated to build ITER with only three partners, whereby the Russian Federation would pay a maximum of about 15%, leaving the other two partners, Europe and Japan with the remaining 85%. The host country should then have paid approximately 50%, leaving the 'non-chosen site-candidate partner' with a financial bill of still 35%. It is clear that those were merely ideas floating around, without any real commitments.

At present (having started on January 1, 2003), the so called ITER Transitional Arrangements are taking place, effectively an extension of the ITER CTA (albeit with more emphasis on the negotiations and management-preparation elements), but called differently, because of formal reasons.

### 1.5.2. ITER-site negotiations finally concluded in 2005

By the year 2003, two new partners, China and South Korea had joined the ITER negotiations, and the USA decided to rejoin the ITER club. In 2003, Europe decided to drop the candidacy of Vandellos in Spain, in favor of the Cadarache site in France. That made 6 partners in total. Until the summer of 2005, there were two possible host countries, Japan and Europe, with sites Rokkasho-mura and Cadarache, respectively. The idea was that the host would pay roughly 50% of the total construction cost (including site preparation, amounting in total to 4.5 G Euro), leaving the other five partners with each about 10%. However, for almost two years, there was a stalemate and it was very difficult to come to an agreement. Since December 2003, the negotiations were stalled, because of a tie: three partners support the Cadarache site (the EU, the RF and China), whereas the other three partners prefer the Rokkasho-mura site (Japan, the US and S. Korea).

Early 2004 it was tried to find an opening out of this difficult situation, first through an evaluation analysis of 9 technical criteria of both sites, and subsequently by the so-called 'Broader Approach'. The analysis of the 9 topics brought no relief as both sites drew as conclusion that their site provided the best answers. The Broader Approach amounted to offering the 'non-chosen site-candidate partner' a respectable second-best alternative. Effectively, it was proposed that the agreed-upon ITER-host site would support half of the ITER-construction cost (whereby ITER might comprise a remote data center to give the other partner full access to all data), and would pay half of the construction cost of the materials-radiation experiment IFMIF [7], to be located then in the 'non-chosen ITER site-candidate partner'. The cost of IFMIF is estimated at about 0.9 G Euro, so that half of this cost would amount to about 10% of the cost of ITER. Hence, the ITER host would pay half of ITER and half of IFMIF, or 0.6 / 1.1 or thus 55% of ITER and IFMIF combined. For a long time, it seemed that this "Broader Approach" would not lead to a breakthrough, because both sides were willing to consider that Broader Approach only in the case of ITER at their site. Finally, on June 28 2005, a formal agreement was reached with as outcome that the machine will be built in Cadarache, France. [12] The final deal was largely based on the Broader Approach with some extra compensations for Japan, amongst which, the appointment of the future ITER Director being Japanese.

In the mean time, on December 06 2005, India has been formally welcomed as the seventh full partner of the ITER project. The future ITER planning is that the formal ITER agreement would enter into force near the end of 2006, after which construction can then start as quickly as possible.

## 1.6. Conclusions

Fusion development has so far been very successful. This remarkable scientific progress record together with the appealing features of fusion power, would make it totally irresponsible to stop nuclear fusion development. The major challenge for fusion research is to move decisively forward and take timely decisions for the required future experiments.

The recent stalemate on a site for ITER construction, is perhaps understandable, but is very much to be deplored. Timely decisions are crucial to keep a credible time schedule for fusion development. If partners really do believe so strongly in fusion research as they claim, they should be more decisive. All things considered, for none of the big partners, the financial picture would be outrageous. We hope that ITER will be built quickly, so that fusion research can move forward in the hope that commercial fusion will become a reality at some point in the future.

**Annex**

**pm; not relevant for fusion in the time-frame considered by EU-SUSTEL**

## 1.7. References

[1] N. Nakićenović, et al., Editors, Global Energy Perspectives, Cambridge University Press, Cambridge, 1998.

[2] http://www.jet.efda.org/pages/fusion-basics.html

[3] http://www.pppl.gov/fusion_basics/pages/fusion_basics.html

[4] http://www.llnl.gov/nif/icf/icf.html

[5] IAEA, *Final report of the ITER EDA*, ITER EDA Documentation Series N° 21, International Atomic Energy Agency, Vienna, 2001.

[6] D. King, et al., Conclusions of the fusion fast track experts meeting held on 27 November 2001 on the initiative of Mr. De Donnea, President of the Research Council, to be obtained from the European Commission Services, DS Research & Development, Brussels, Belgium. See also http://www.fusion.org.uk/techdocs/ukaea-fus-521.pdf

[7] IFMIF International Team, *IFMIF Comprehensive Design Report*, IEA, Implementing Agreement for a Program of Research and Development on Fusion Materials, Paris (2003). Available at http://www.iea.org/textbase/techno/technologies/index_fusion.asp

[8] IAEA, *Technical basis for the ITER final design report, cost review and safety analyses (FDR)*, ITER EDA Documentation Series N°16, International Atomic Energy Agency, Vienna (1998).

[9] IAEA, *Summary of the ITER Final Design Report*, ITER EDA Documentation Series N°22, International Atomic Energy Agency, Vienna (2001).

[10] IAEA, *ITER Technical Basis*, ITER EDA Documentation Series N°24, International Atomic Energy Agency, Vienna (2002).

[11] IAEA, *ITER-FEAT Outline Design Report*, ITER EDA Documentation Series N°18, International Atomic Energy Agency, Vienna (2001).

[12] http://fire.pppl.gov/iter_declaration_062805.pdf

**Interesting web sites**:

ITER
http://www.iter.org
JET
http://www.jet.efda.org (see also "links")
EFDA
http://www.efda.org
EU fusion web site
http://europa.eu.int/comm/research/energy/fu/article_1122_en.htm
Princeton Plasma Physiscs Laboratory (USA)
http://www.pppl.gov
http://fire.pppl.gov