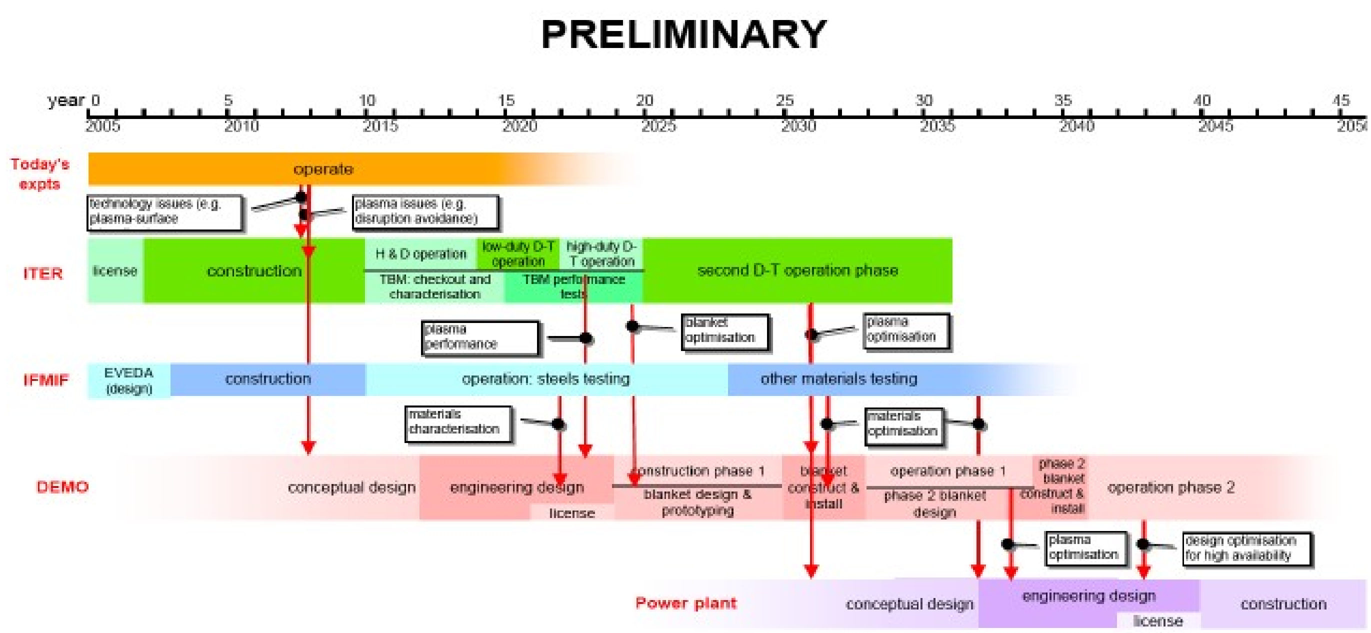
Beyond ITER

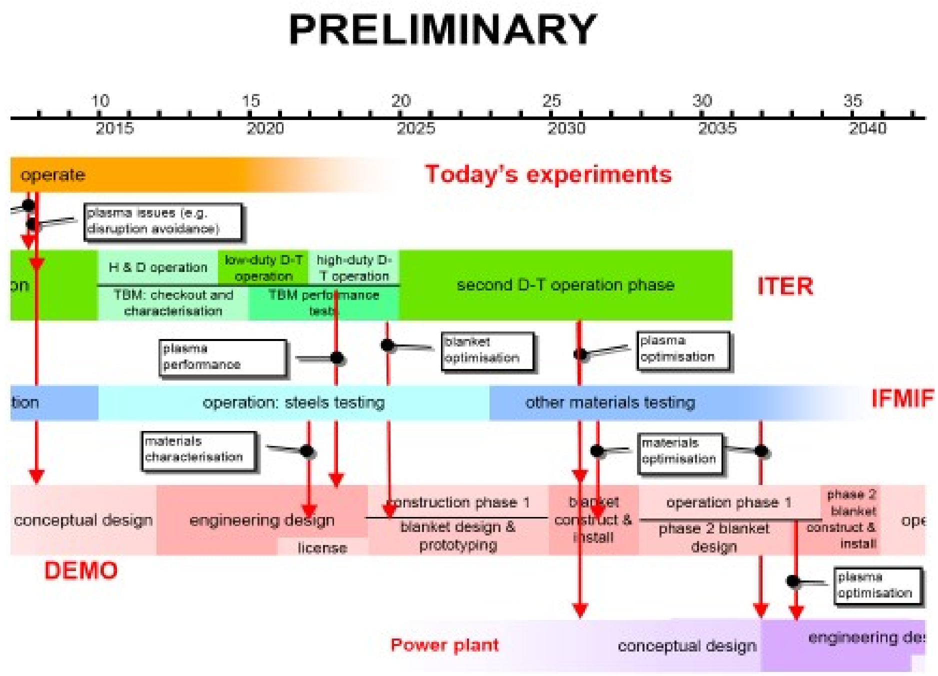
The steps beyond ITER are open at this stage. During the ITER construction and operation period, other magnetic confinement schemes or inertial fusion may show more promise than ITER, so the door is open for these schemes to supersede the tokamak in subsequent steps. Certainly, the technologies developed for and tested on ITER: remote maintenance, tritium breeding high temperature blankets, and high heat flux components, will provide essential information whatever the confinement scheme used.

The concept of the "fast track" to fusion power, should ITER continue to demonstrate that the tokamak line of magnetic confinement is the most promising for power generation, has recently been further elaborated in studies at EFDA and at Culham Laboratory. This approach is designed to speed up the development to the extent possible. It is designed around "pillars" of the programme - ITER, IFMIF, and existing large tokamaks - considered essential to further progress, as well as "buttresses" - e.g. a components test facility, and a new "satellite" non-nuclear tokamak to more rapidly study the implications of ITER physics - that can speed progress and reduce risks.

The programme that is evolving, in this ongoing work, is shown below (graphics by permission Prof. Sir Chris Llewellyn Smith, from his presentation at IAEA Fusion Energy Conference, Vilamoura, 2004):



The key part of this figure is shown below:



Such a plan shows why it will be very difficult to commission the first commercial-sized tokamak before 2050. However it could be that sufficient information is gained on the step beyond ITER (DEMO), through its staged operation, and it is sufficiently prototypical of the series production of power plants, that it will be possible to be more confident at an earlier stage concerning the economic viability of the first series of power plants produced.

Updated 9 September, 2005

Beyond ITER

ITER is planned to operate at a nominal fusion power of 500 MW_t. If DEMO (the next device after ITER, and the first to generate electricity) is to be a device of approximately similar physical size (and hence cost), its fusion power level has to be increased by about a factor of 4, so that the electrical power potentially delivered to the network will be in the range of 500 MW_e, typical of one of today's power stations (albeit rather a small one). The general level of heat fluxes through the walls will be about 4 times higher than in ITER, and plasma performance needs to be improved to gain this 4-fold increase. Calculations show that this performance could be achieved with an ~15% increase in ITER linear dimensions, and an ~30% increase in the plasma density above the nominal expected to be confined by the basic magnetic fields on ITER (this capability can be checked on ITER). It then remains for enough to be learnt on the ITER blanket test beds to allow the DEMO blanket to be designed to withstand 4 times the ITER steady heat loads on those components.

If these systems work successfully on DEMO, DEMO itself can be used as a prototype commercial reactor creating a "fast track" to fusion. This would accelerate the availability of fusion as an energy option by about 20 years. A further step would no doubt subsequently be made for the first-of-a-series commercial-sized fusion power reactor (PROTO), doubling the electrical power by increasing linear machine dimensions by less than 10%, without assuming any improvement in physical behaviour.

Fusion Power Reactor Economics

Challenge 7 - economic viability - incorporates the solutions adopted to resolve all the other challenges. Assuming plant capital cost scales with the tokamak volume, one can expect DEMO capital costs in the region of 14 €/W_e based on the cost estimates for ITER. Those of PROTO will then be typically 8 €/W_e and, with economies of series production of fusion plants subsequently, capital costs could reduce to ~ 4 €/W_e. This should be compared to today's fission and coal plants at ~ 3 €/W_e and 1.5 €/W_e respectively. However, the capital costs of today's coal plants do not include costs to mitigate environmental damage, nor do any of the above costs include the fuel, operating and decommissioning costs, which for coal are typically comparable to the capital costs and should be lowest for fusion. A more rigorous treatment of potential fusion electricity prices in relation to those of coal and nuclear is given by this model.

Fusion therefore currently looks like it can reach a position of economic competitiveness with other energy sources, that will be available at that time, if things work out well. It is evident that there are a number of challenges to be met and overcome before one can really guarantee that economic viability, and the table shows the overlapping nature in which it is planned to solve the challenges of fusion on the coming devices. Although it is not possible to know if ITER and steps beyond it will throw up further challenges, the timescale predicted from today's perspective seems achievable provided the development programme continues at today's level during the period.

Conclusion

The last 50 years of fusion research and development have continually thrown up new challenges to test the ingenuity and skills of at least two generations of scientists and engineers. So far they have been up to the job and no "show-stoppers" are in view. Nevertheless there are many challenges still to be faced, and there may be some which are unseen from today's perspective, so it is impossible to guarantee the delivery schedule completely. The next step, ITER, which is essential to realising the key technologies of a viable energy source, has to be built and operated first. Only then will it be possible to check with confidence the accuracy of the prediction of Lev Artsimovitch, grandfather of the tokamak, who said in 1972 - "Fusion will be there when society needs it".

Fusion development has many unique aspects:

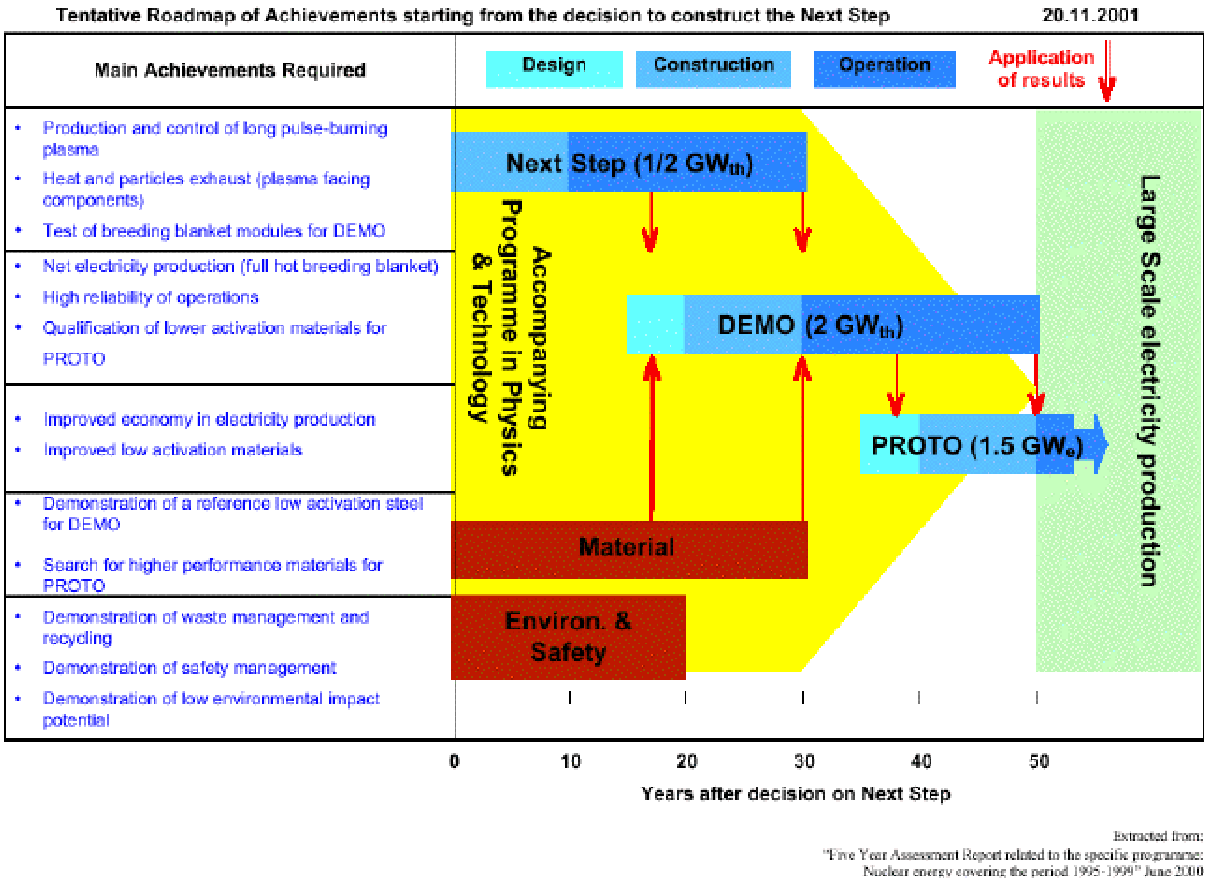
- it has a very specific goal which will take a long time to reach and which satisfies such a basic human need that it can only be developed by governments as an option they would like to posess - normal rules of commercial development within the world's short-term economic perspective do not apply in a situation where resources are reaching their limits;
- it requires continuity of investigation and passing on of know-how across generations of physicists and engineers, requiring not only continuous levels of funding for the main research line, but also funding to attract and train newcomers to the field on supporting experiments;
- it requires multidisciplinary approaches to the solutions of problems;
- it is the classic example of open research conducted on a world stage and used to bring scientists and engineers together from different backgrounds and political allegiances to share their knowledge openly.

Because of these aspects, many of the challenges originally posed have since been met, and certainly with them the plan and timing for reaching the ultimate goal is as secure as it can be.

Updated 15 February, 2005

The Fast Track to Fusion

The progress on fusion power development in Europe was last independently assessed by the "Airaghi Panel" in 2000. They drew up the following roadmap for fusion development.



Extracted from: "Five Year Assessment Report related to the specific programme: Nuclear energy covering the period 1995-1999" June 2000

Since then a similarly independent panel chaired by Prof. D. King (Chief Scientific Advisor to UK PM Blair), concluded, at the end of 2001, as follows:

1. *"The ITER project is the essential step towards energy production on a fast track. The engineering design has been finalised, and a modest upgrading could readily be achieved over the life of ITER, by fully exploiting the inherent flexibility of the present ITER design in demonstrating the technical feasibility of fusion power on a 20-30 year timescale. The tests of breeding and energy extraction blanket modules prototyping the full size blanket for DEMO should receive particular attention.*
2. *Future commercial systems are likely to be energy-injected, and not self-sustained. Since the DEMO generation is energy-injected, current thinking is that in a fast track approach, the DEMO and PROTO generations could be combined into a single step that should be designed as a credible prototype for a power-producing fusion reactor, although in itself not fully technically and economically optimised. This would depend strongly on the development of adequate materials, as discussed in 4 below.*
3. *The emphasis in the research work on ITER should be on demonstration of sustained fusion power production and extraction; ITER will serve as an enabling research machine regardless of the design of later commercial reactors. Within the EU fusion programme the fusion Associations should concentrate on accompanying R&D for ITER and plasma physics. Other Europeanfacilities such as stellerators and spherical tokamaks should address possible improvements of concepts and of designs for future reactors.*
4. *The mission of fusion materials science is to provide solutions for a sustainable, environmentally benign and economically attractive energy technology. In addition to the essential information provided by ITER on plasma facing materials an appropriate high-energy, high intensity neutron source such as the International Fusion Material Irradiation Facility (IFMIF) is required to test and verify material performance when subjected to extensive neutron irradiation of the type*

encountered in a fusion reactor. In a fast track approach, the detailed engineering design of IFMIF should be completed during FP6 [2006-2010]*. Before that the irradiation test requirements should be examined to identify to which extent relevant studies could be done on Neutron Spallation Sources available now and in the foreseeable future in Europe or elsewhere. In combination with such irradiation experiments, the theoretical modelling of radiation damage and of the structural evolution of materials is instrumental in the understanding and the control of underlying processes. Such material studies could also contribute to progress and innovation in other areas such as aeronautics and space, energy systems and advanced processing. Proper co-ordination with other EU programmes in materials research should be explored.*

5. *From the above results that the following elements are of key importance to achieve a faster track towards fusion energy production:*
   - *Construction of ITER should start as soon as reasonably achievable. As a first step,the present mandate of negotiations with the EU international partners regarding the ways of establishing an ITER Legal Entity should be soon extended in order to address ITER cost sharing and site dependent issues.*
   - *The two major international ventures on fusion energy development, i.e. ITER and IFMIF should proceed in a co-ordinated way, with the realization of ITER starting in parallel with the detailed engineering design of IFMIF.*
   - *Regarding the use of existing fusion devices, mostly devoted to plasma physics, in particular the use of the JET facilities, it is important not to interrupt abruptly their programmes as long as they can efficiently continue to contribute to improve the knowledge base needed for the next steps and develop the necessary experience in operating fusion machines. JET should be phased out progressively according to the schedule of the ITER realization and to the availability of financial resources.*

   These elements of a faster track towards fusion energy production will require additional resources in the first leg of the track, in particular during FP6 and FP7, as more activities need to be done in parallel. Eventually the total amount of public funding to reach the long-term objective could be reduced substantially if it proves possible to save one generation of fusion devices. These additional resources for the first leg of the track should be sought also by expanding the international collaboration. A clear lead from Europe could be expected to generate a positive response from both existing and potential ITER partners.
6. *At the present stage of fusion energy research, industry is mostly involved through the construction of fusion devices and through its participation in the ITER design. From this point of view most of the financial resources required for the construction of ITER should go to industry. The role of industry in the engineering of fusion devices should grow significantly during the realization of ITER, and later of DEMO/PROTO. The direct involvement of the electricity producers, the utilities, should increase progressively along the route to energy production. However, in order to drive the programme most efficiently towards power production it is important to harness the energies of individuals within the industrial communities including engineering companies, component manufacturers and electricity producers to assist in managing all phases of the programme. The existing fora where utilities and industry can bring in their views on fusion energy research should extend further their activities in order to ensure that fusion developments meet industrial requirements for energy production."*

Updated 21 October, 2004

Reactor Model

The design of a fusion power reactor based on magnetic fusion has still to be worked out. However, irrespective of the design, something can be said about the economics of fusion reactors by making some basic assumptions:

- the reactors will use D+T reactions and the water or helium coolants will drive steam or gas turbines;
- fusion power plants will preferably be a similar generating capacity to today's coal and nuclear plants - this means that power delivered to the network per plant should be in the range 500 - 1500 MW(electric);
- the economic rules that apply in today's environment to coal and nuclear plants will apply to fusion - the cost of raising money for the investment must be considered, and future benefits and costs must be discounted to estimate an appropriate cost (and subsequently, price) of electricity;
- lifetime costs (i.e including decommissioning and waste disposal) must be included;
- although ITER is not a full power plant it incorporates most of the same equipment at roughly the right scale - some additional power generation equipment will be needed and higher heat tolerance and longer endurance nuclear components must be used, and the physical size may be a little larger, but there will be economies of scale due to series production of identical plants, so the cost of ITER is to some extent representative of a fusion power plant.

Using these assumptions, a reactor cost model has been developed around the following equations:

- $P_{gen} = P_{fus} (0.2 + 0.8 M) \eta_{th} - P_{internal} - P_{fus}/Q/\eta_{hcd}$
  - where P_{gen} is the power delivered to the network;
  - P_{fus} is the fusion power;
  - M is the blanket neutron power amplification;
  - η_{th} is the thermal conversion efficiency;
  - $P_{internal}$ is the in-house electrical power consumption (except heating and current drive);
  - Q is the plasma power amplification (of heating and current drive power);
  - η_{hcd} is the efficiency of conversion of electricity to heating and current drive power to the plasma.
- Cost of electricity (COE)= Discounted project cost/Discounted electricity to the network
- Discounted project cost = Direct + Indirect + Construction Interest + Maintenance
- Direct costs are taken as some factor times ITER costs.
- Indirect costs, interest during construction and maintenance (including decommissioning) are calcualted as a factor of direct costs.
- Discounted electricity to the network = Sum over operating life $[P_{gen} A_n/(1+d)^{(n-0.5)}]$
  - where A_n is plant availability in year n;
  - d is the discount rate.
- Domestic electricity price = 2.5 times COE.
- Industrial electricity price = 0.462 times domestic prices (these values are currently appropriate in Europe).

Most of the above terms are explained more fully in the online help feature of the model. The model allows the effect of varying any parameter to be shown graphically.

The results show that, provided a power reactor cost can be maintained near the cost of ITER, there are good chances that the price of electricity produced in future by fusion will be comparable to that achieved today from coal and fission, especially when environmental costs not currently factored into those energy sources are included.

The model also shows the importance of the various parameters (both technical and economic) to achieving that goal.

Updated 15 February, 2005

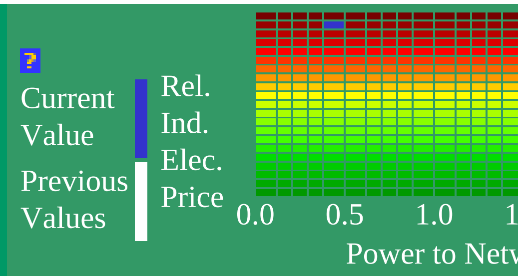
Fusion Power Reactor Performance

Start

Reset

Settings

The graph shows the price of industrial electricity. The green zone is most desirable - prices are similar to those industry pays today. All future electricity prices may be more than today.
Click "Reset" to return to defaults, and clear results.



Major Inputs

Fusion Power (MW)	In-house Power (MW)	Plasma Amplification	Plasma Power Input Efficiency	Blanket Neutron Power Multiplier	Turbine Efficiency	Direct Costs x ITER	Plant Life (Y)
3200 ?	200 ?	10.0 ?	0.5 ?	1.2 ?	0.35 ?	1.33 ?	25.0 ?

Result (all values calculated)

Power to Network (MW)	Plant Efficiency	Cost of Electricity (cents/ kWh)	Relative electricity price (domestic)	Relative electricity price (industrial)
459.2 ?	0.14 ?	22.43 ?	2.33 ?	3.87 ?

Other Assumptions

Operation, Maintenance, Decommissioning (frac. Direct)

1.12 ?

Discount rate after construction (%)	Project Personnel	Unit cost - M$/yr	Total Personnel	Support unit cost/Project personnel - M$/yr	Total Support
5.00 ?	600 ?	0.1 ?	866.5 ?	0.06 ?	519.9 ?

Availability (%): Year 1	Year 2	Beyond	Power load on standby (% normal)	Unit electricity cost	Electricity
45 ?	60 ?	85 ?	20 ?	0.065 ?	63.5 ?

Gen. Spares, Consum- ables, Services ?

% direct cost/y	Total
0.8 ?	461 ?

	Cost (% Direct)	Replaced/y	Replacement Cost
First Wall	3 ?	0.2 ?	345.7 ?
Blanket	4 ?	0.1 ?	230.5 ?
Divertor	5 ?	0.3 ?	864.4 ?

Waste disposal (% direct cost/y of first wall, blanket, and divertor)	Total	Insurance, Taxes, Fees (% Direct/yr)	Total	Decommisioning (% direct, total)	Discounted Decommissioning Costs
20 ?	288.1 ?	1.0 ?	576.2 ?	0.2 ?	235.7 ?

Indirect Construction Cost (frac. Direct)	Project Management Personnel	Materials & Expenses	Design & Engineering Services	Licensing	Taxes, Fees, Insurance	Energy & Services	Personnel Training	Launching Costs
0.29	5.0	3.0	0.8	0.4	2.0	1.0	1.8	15.0

Construction Interest (frac. Direct+Indirect)	Construction Interest Rate (%)	Fraction of construction time when half spent.	Construction Time (Y)
0.178	5.00	0.6	8.0