Power Plant Conceptual Studies in Europe

D. Maisonnier 1), D. Campbell 1), I. Cook 2), L. Di Pace 3), L. Giancarli 4), J. Hayward 1), A. Li Puma 5), M. Medrano 6), P. Norajitra 7), M. Roccella 8), P. Sardain 1), M. Q. Tran 9), D. Ward 2)

1) EFDA CSU Garching, Boltzmannstr. 2, D-85748 Garching, Germany
2) UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK
3) ENEA Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy
4) CEA Saclay, 91191 Gif-sur-Yvette, France
5) EFDA CSU JET, Culham Science Centre, Abingdon OX14 3DB, UK
6) CIEMAT, Av. Complutense 22, 28040 Madrid, Spain
7) FZK, Postfach 3640, 76021 Karlsruhe, Germany
8) LT Calcoli, Piazza Prinetti 26/3, 23807 Merate, Italy
9) CRPP, 1015 Lausanne, Switzerland

e-mail contact of the main author: david.maisonnier@tech.efda.org

Abstract. The European Power Plant Conceptual Study (PPCS) has been a study of the conceptual designs of five commercial fusion power plants, with the main emphasis on system integration. The study focused on five power plant models, named PPCS A, B, AB, C and D, which are illustrative of a wider spectrum of possibilities. The models are all based on the tokamak concept and they have approximately the same net electrical power output, 1500 MWe.

The PPCS allows the clarification of the concept of DEMO, the device that will bridge the gap between ITER and the first-of-a-kind fusion power plant. An assessment of the PPCS models with limited extrapolations highlighted the physics issues that must be addressed to establish the DEMO physics basis. Similarly, a review of the DEMO technical objectives brings to the fore the issues that must be addressed to establish the engineering and technological basis for DEMO.

1. Rationale for the Power plant Studies in Europe

The aim of the European fusion programme is the exploitation of fusion as a commercial energy source. The programme is “reactor oriented” and it is aimed at the successive demonstration of the scientific, the technological and the economic feasibility of fusion power. A series of large tokamak devices, namely JET (Joint European Torus), ITER and DEMO, constitutes the backbone of the European programme. ITER, the “next step” machine, shall demonstrate the scientific feasibility of fusion and should strongly contribute to demonstrate its technological feasibility. DEMO shall confirm the technological feasibility of fusion power and demonstrate its commercial viability.

For a reactor-oriented fusion development programme, it is essential to have a clear idea of the ultimate goal of the programme, namely a series of models of fusion power plants, in order to define the correct strategy and to assess the pertinence of the on-going activities. Also, a model of DEMO is essential to assess the pertinence of the ITER objectives.

2. The European Power Plant Conceptual Study

From 1990 to 2000 a series of studies within the European fusion programme [1, 2, 3] examined the safety, environmental and economic potential of fusion power. In the period since the establishment of the plant models developed for these earlier studies, there have been substantial advances in the understanding of fusion plasma physics and of plasma operating regimes, and progress in the development of materials and technology. Accordingly, it was decided to undertake a more comprehensive and integrated study to serve as a better guide for the further evolution of the fusion development programme.

The European Power Plant Conceptual Study (PPCS) has been a 4-years study, between mid 2001 and mid 2005, of conceptual designs for commercial fusion power plants [4]. The PPCS plant models differ substantially in their plasma physics, electrical output, blanket and divertor technology from the models that formed the basis of the earlier European studies.

3. Requirements for a fusion power plant

European utilities and industry developed the requirements that a fusion power plant should satisfy to become an attractive source of energy [5]. They concentrated their attention on safety, waste disposal, operation and criteria for an economic assessment. The most important recommendations are summarised as follows:

- There should be no need for an emergency evacuation plan, under any accident driven by in-plant energies or due to the conceivable impact of ex-plant energies.
- No active systems should be required to achieve a safe shut-down state.
- No structure should approach its melting temperature under any accidental conditions.
- "Defence in depth" and, in general, ALARA principles should be applied as widely as possible.
- The fraction of waste which does not qualify for "clearance" or for recycling should be minimised after an intermediate storage of less than 100 years.
- Operation should be steady state with power of about 1 GWe for base load and have a friendly man-machine interface. However, as the economics of fusion power improves substantially with increase in the net electrical output of the plant, the net electrical output of all the PPCS models was chosen around 1.5 GWe.
- Maintenance procedures and reliability should be compatible with an availability of 75 - 80 %. Only a few short unplanned shut-downs should occur in a year.
- Since public acceptance is becoming more important than economics, economic comparison should be made with energy sources with comparable acceptability but including the economic impact of "externalities".

4. The PPCS plant models

The interrelationships of plasma performance, materials performance, engineering, economics and other factors were explored using a systems code, supplemented by the understanding gained from earlier analytical studies. The systems code studies employed the self-consistent mathematical model PROCESS [6]. This code incorporates plasma physics and engineering relationships and limits, together with improved costing models validated against the ITER costs and by comparison with similar US studies.

PROCESS varies the free parameters of the design so as to minimize the cost of electricity. The parameters arising from the PROCESS calculations were used as the basis for the conceptual design of the five models. The analyses also show which plasma, materials and engineering parameters are key to further improving the economics.

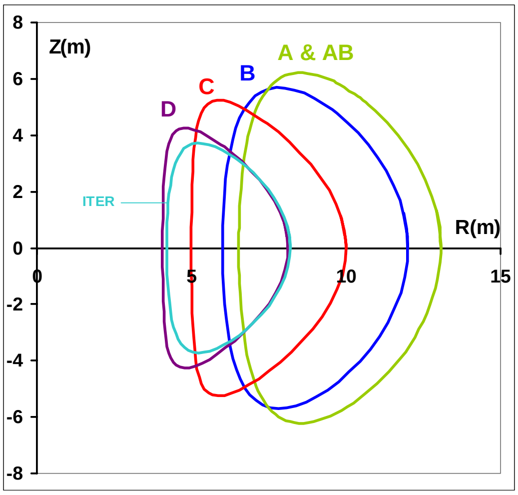


FIG. 1: Illustration of the sizes and shapes of the plasmas in the PPCS Models. To ease the comparison, model B has been renormalised to 1.5 GWe (size scaled with plasma volume). The original size of model B, as shown in tables 1 and 2, is 1.33 GWe.

For comparison, ITER is also shown: this is very similar to Model D.

The axis labels denote major radius (R) and height (Z).

4.1. Plasma Physics Basis

The PROCESS code employs a plasma physics module that, in its original form, was developed for the Conceptual Design Activity phase of ITER and used to explore the early ITER design. This was modified to reflect further developments and has been updated to incorporate modern scaling laws. For the three near-term models, PPCS A, PPCS B and PPCS AB, the plasma physics scenario represents, broadly, parameters about thirty percent better than the design basis of ITER: first stability and high current-drive power, exacerbated by divertor heat load constraints, which drive these devices to larger size and higher plasma currents. PPCS-C and PPCS-D are based on progressive improvements in the level of assumed development in plasma physics. The main parameters of the PPCS models are given in Table 1.

4.2. Plant Models

Models A, B and AB are based, respectively, on the “water-cooled lithium-lead”, the “helium-cooled pebble bed” [7] and the “helium-cooled lithium-lead” [8] blanket concepts. Associated with these are water-cooled and helium-cooled divertors. The water-cooled divertor is an extrapolation of the ITER design. The helium-cooled divertor, operating at much higher temperature, is discussed in section 4.5 of this paper. For the balance of plant, model A is based on PWR technology, which is fully qualified. Models B and AB rely on the technology of helium cooling, the industrial development of which is starting now, in order to achieve a higher coolant temperature and a higher thermodynamic efficiency of the power conversion system.

PPCS C and D are based, respectively, on a “dual-coolant” blanket concept (helium and lithium-lead coolants with steel structures and silicon carbide insulators) and a “self-cooled” blanket concept (lithium-lead coolant with a silicon carbide structure).

4.3. Thermodynamic Parameters and Power Conversion Cycles

The fusion power is determined primarily by the thermodynamic efficiency and power amplification of the blankets and by the amount of gross electrical power re-circulated, in particular for current drive and coolant pumping. The net efficiency calculated during the PPCS for models AB and B, using a standard Rankine cycle was only 2 or 3 percentage points

Parameter	**Model A**	**Model AB**	**Model B**	**Model C**	**Model D**
Unit Size (GW_e)	1.55	1.50	1.33	1.45	1.53
Fusion Power (GW)	5.00	4.30	3.60	3.41	2.53
Plant net efficiency[1]	0.31/0.3[2]	0.35	0.36	0.42	0.60
Aspect Ratio	3.0	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.27	0.25	0.47	0.47
Major Radius (m)	9.55	9.56	8.6	7.5	6.1
TF on the TF coil cond. (T)	13.1	13.4	13.2	13.6	13.4
Plasma Current (MA)	30.5	30.0	28.0	20.1	14.1
β_N(thermal, total)	2.8, 3.5	2.7, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Average Temperature (keV)	22	21.5	20	16	12
Temperature peaking factor	1.5	1.5	1.5	1.5	1.5
Average Density ($10^{20}m^{-3}$)	1.1	1.05	1.2	1.2	1.4
Density peaking factor	0.3	0.3	0.3	0.5	0.5
H_H (IPB98y2)	1.2	1.2	1.2	1.3	1.2
Bootstrap Fraction	0.45	0.43	0.43	0.63	0.76
P_{add} (MW)	246	257	270	112	71
n/n_G	1.2	1.2	1.2	1.5	1.5
Q	20	16.5	13.5	30	35
Av. neutron wall load (MWm^{-2})	2.2	1.8	2.0	2.2	2.4
Divertor Peak load (MWm^{-2})	15	10	10	10	5
Z_{eff}	2.5	2.6	2.7	2.2	1.6

[1] The plant efficiency is defined as the ratio between the net electric power output and the fusion power.

[2] Depending on the divertor concept used, either an ITER-like conception with water outlet temperature of 150°C or a more advanced conception with water outlet temperature of 300°C.

TABLE 1: Main parameters of the PPCS Models

higher than the one calculated for model A. Moreover, such a modest gain is dependent on the successful development of a helium cooled divertor able to support a maximum heat load of $10MW/m^2$ and on the development and qualification of the technology for a balance of plant using helium.

Advanced power conversion cycles have been studied taking PPCS model AB as a basis, aiming at an increase in gross efficiency [9]. Among them, the so called “improved supercritical Rankine cycle” seems the most promising. A revised configuration of the primary heat transport system leads to closer heat transfer curves between the primary and secondary, maximizing the thermal exchange effectiveness. It results in higher steam temperatures (increase of gross efficiency) and less steam mass flow (increase of net efficiency) compared to the other supercritical cycles. The improvement of the gross efficiency, with respect to the PPCS reference, is about 4 percentage points. As an alternative, independent supercritical CO_2 Brayton cycles were considered for the blanket and divertor cooling circuits, in order to benefit from the relatively high operating temperature of the latter. In this case, it is possible to obtain a gross efficiency similar to the one achieved with the supercritical, improved Rankine cycle.

4.4. Maintenance Scheme and Blanket Segmentation

In a fusion power plant the divertor is expected to be replaced every two full-power-years because of erosion, and the blanket every five full-power-years, corresponding to not more than 150 dpa of neutron damage in the steel of the first wall.

ITER uses a segmentation of the blanket into 440 modules. In a power plant, such a large number of modules would result in an availability barely above 50%, which is unacceptable. As an alternative, a segmentation of the blanket into the smallest possible number of “large modules” has been assessed. The maximum size of a module is determined by the size of the quasi-equatorial ports through which the modules must pass, which is limited by the magnet arrangements. The total number of modules is between 150 and 200. The feasibility of suitable blanket handling devices was investigated, and it was assessed that a plant availability of at least 75% could be achieved [10].

The larger the individual blanket element to be removed, the larger the electro-magnetic (EM) loads that will act upon that element. Already in ITER, the blanket modules are “slit” in order to reduce the loads in case of plasma disruption. Very rough evaluations indicated that, with a blanket segmentation in “large modules”, it might not be possible to develop a mechanical attachment system able to support the loads.

To accommodate these two conflicting requirements, the “multi-module” concept has been proposed and will be further assessed. The basic principle is to consider a “strong-back” structure onto which are attached a number of smaller blanket “modules”. The large size of the strong-back would allow a limited number of pieces to be handled remotely, whilst the small size of the “modules” would reduce the EM loads to acceptable values.

4.5 Helium-cooled divertor

A helium cooled divertor has been chosen for models AB, B and C to simplify the balance of plant by using the same coolant for all internal components.
Two main concepts are currently considered [11].

- The HETS (High Efficiency Thermal Shield), in which heat transfer is enhanced through the impingement effects of a helium jet on the hemispherical surface at the rear side of the plasma facing structure and the effect of the centripetal acceleration as turbulence promoter when the fluid moves on the side of the sphere.
- The HEMJ (HElium cooled Modular divertor concept with multiple Jets), in which heat transfer is enhanced through the impingement of several jets on the plasma-facing structures (Fig. 2). The HEMS (HElium cooled Modular divertor concept with Slot array) concept is an alternative in which slots arrays are used as turbulence promoters.

CFD simulations and stress analyses have shown the potential of all three concepts to meet the design requirements.

Mock-ups of “single finger units” of both HEMJ and HEMS have been manufactured (Fig. 3) and tested within a heat flux range of 5-13 $\mathrm{MWm^{-2}}$. The mock-ups were then subjected to destructive post-examinations, which revealed damages presumably due to micro cracks initiated during the fabrication processes. Neither brittle failure nor re-crystallisation of the thimble was detected in any mock-up. Altogether, it can be said that the ability of the HEMJ and HEMS He-cooled divertor concepts to resist heat loads of 10 $\mathrm{MW/m^2}$ was confirmed.

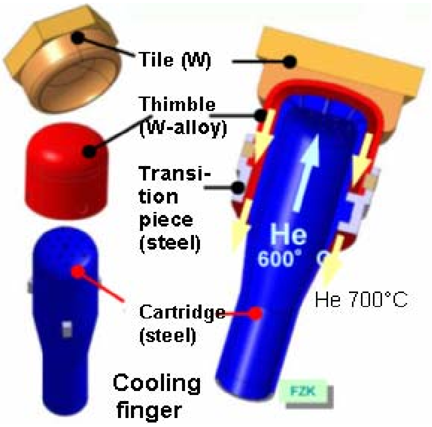
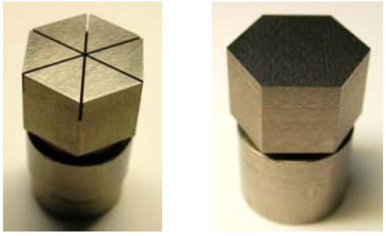


FIG. 2: HEMJ concept for a He-cooled divertor



HEMJ HEMS

FIG. 3: Examples of mock-ups of "single finger units" prior to testing

Significant efforts are still required to prove the feasibility of this concept, in particular the mechanical properties of the W-alloy before and after irradiation.

5. Assessment of the PPCS models

In the PPCS models, the favourable inherent features of fusion have been exploited, by appropriate design and material choices, to provide safety and environmental advantages. The following are particularly noteworthy.

- A total loss of active cooling cannot lead to structures melting. This result is achieved without any reliance on active safety systems or operator actions.
- The maximum radiological doses to the public arising from the most severe conceivable accident driven by in-plant energies would be below the level at which evacuation would be considered in many national regulations.
- Material arising from operation and decommissioning will be regarded as non-radioactive or recyclable after one hundred years (recycling of some material could require remote handling procedures, which are still to be validated). An alternative could be a shallow land burial, after a time (approximately 100 years) depending on the nuclides contained in the materials and the local regulations.

The cost of electricity from the five PPCS fusion power plants was calculated by applying the codes developed in the Socio-economics Research in Fusion [3] programme. The calculated cost of electricity for all the models was in the range of estimates for the future costs from other environmentally friendly sources [12].

6. DEMO

6.1. General

One important outcome of the conceptual study of a fusion power plant (FPP) is to identify the key issues and the schedule for the resolution of these issues prior to the construction of the first-of-a-kind plant. Europe has elected to follow a "fast track" in the development of fusion power [13], with 2 main devices prior to the first commercial FPP, namely ITER and DEMO. These devices will be accompanied by extensive R&D and by specialised machines and facilities to investigate specific aspects of plasma physics, plasma engineering, materials and fusion technology, eg the International Fusion Material Irradiation Facility (IFMIF). If the

ITER objectives and machine design are now well established, this is not the case for DEMO. It is therefore worthwhile to reflect on the difficulties encountered during the development of the PPCS “near-term” models, namely models A, B and AB, prior to the selection of the main parameters and technical choices for DEMO.

The following sections present some preliminary considerations following a European review of its “fast track” fusion development strategy. The implications suggested for ITER are therefore not yet necessarily agreed among the international ITER partners. The emphasis in this paper is on engineering and technological aspects since physics issues were presented separately at this conference [14].

6.2 Fusion Milestones

To start construction of a FPP a number of milestones have to be achieved in a timely fashion, in particular:

- qualification of materials (120/150dpa – steel in FW – for blanket materials, 40/60dpa for divertor materials[1]) and of in-vessel components;
- validation of the overall power plant architecture – in particular the segmentation of the internal components, and demonstration of remote handling procedures;
- qualification of H&CD systems;
- qualification of ex-vessel components and systems if and when required.

Within the European fusion development scenario, DEMO will be the key device for meeting the milestones listed above. To start construction of DEMO assumes that ITER, IFMIF and other tests facilities will have given satisfactory results on plasma physics, materials, internal components, tritium technology and H&CD systems.

In addition to meeting the above milestones, both DEMO and the FPP will have to satisfy a number of requirements in the areas of safety, public acceptance and economics which are not discussed in this paper.

6.3. Critical Issues

Previous analyses [15] have highlighted the internal components (blanket and divertor) as critical and the European technology R&D programme has been amended accordingly.

After an extended commissioning phase, DEMO will have to operate with a high level of availability. This availability, together with the neutron wall loading, will determine the length of the DEMO operational phase required for the qualification of the internal components. A reasonable scenario can be developed by assuming an average availability in excess of 30% and an average neutron wall load of 2MW/m^2.

The PPCS concluded that the ITER maintenance scenario is not reactor relevant. The validation of the power plant architecture and the qualification of the remote handling

---

[1] It is assumed that the structural material selected for the first FPP will be the ferritic steel Eurofer and that this material will maintain acceptable properties up to a fluence corresponding to 120/150dpa.

procedures by the complete replacement of the internal components should therefore be demonstrated in DEMO.

Preliminary considerations indicate that the following issues should be resolved in ITER prior to the start of DEMO operations.

- The validation of the bulk of the “DEMO Physics issues” should be completed during the phase 1 of ITER operations (it is currently foreseen in phase 2). In the phase 2 of ITER operations, the DEMO relevant plasma scenario should be validated with a full tungsten first wall (the replacement of the complete first wall is currently not foreseen in ITER).
- A validated breeding blanket concept able to ensure the tritium self-sufficiency of DEMO and to operate with high reliability and availability.
- A validated divertor concept able to operate in DEMO-like conditions with high reliability and availability.
- The validation of the H&CD technology for steady-state operation.

7. Conclusions

The PPCS results for the near-term models suggest that a first commercial fusion power plant will be economically acceptable, with major safety and environmental advantages. These results also point out some of the key issues that should be resolved in DEMO and, more generally, help to identify the physics, engineering and technological challenges of fusion.

Acknowledgment

PPCS was a collaborative effort between seven European Fusion Associations and the European industrial consortium EFET. It was jointly funded by the European Communities and by government agencies of Belgium, France, Germany, Italy, Spain, Sweden and the United Kingdom. Work on DEMO presented here was a collaborative effort of the EFDA Working Group. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] J. Raeder et al., Safety and environmental assessment of fusion power (SEAFP), European Commission DGXII, Fusion Programme, report EUR-FUBRU XII-217/95, June 1995.
[2] I. Cook et al., Results, conclusions and implications of the SEAFP-2 programme, Fusion Engineering and Design 51-52 (2000) 409-417.
[3] Socio-economic aspects of fusion power, EUR (01) CCE-FU 10/6.2.2, European Fusion Development Agreement Report, April 2001.
[4] D. Maisonnier et al., The European Power Plant Conceptual Study, Fusion Engineering and Design 75-79 (2005) 1173-1179.
[5] R. Toschi et al., How far is a Fusion Power Reactor from an Experimental Reactor, Fusion Engineering and Design 56-57 (2001) 163-172.
[6] I. Cook, R.L. Miller and D.J. Ward, Prospects for economic fusion electricity, Fusion Engineering and Design 63-64 (2002) 25-34.
[7] M. Gasparotto et al., DEMO Blanket Technology R&D Results in the EU, Fusion Engineering and Design 61-62 (2002) 263-271.

[8] A. Li Puma, et al., Breeding Blanket Design and Systems Integration for a Helium-Cooled Lithium-Lead Fusion Power Plant, Fusion Engineering and Design 81 (2006) 469-476.
[9] M. Medrano et al., Study of Power Conversion Cycles for He-cooled Reactor Concepts for DEMO, Proceedings of the 24th SOFT, Warsaw, Poland, (2006), to be published.
[10] E. Bogusch et al., Blanket Handling Concepts for Future Fusion Power Plant, Fusion Engineering and Design 69 (2003) 135-139.
[11] P. Norajitra et al., European Development of He-cooled Divertors for Fusion Power Plants, Nuclear Fusion 45 (2005) 1271-1276.
[12] D J Ward et al., The economic viability of fusion power, Fusion Engineering and Design 75-79 (2005) 1221-1227.
[13] European Council of Ministers, 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 (commonly called the King Report).
[14] D. Campbell et al., Critical Physics Issues for Tokamak Power Plants, Proceedings of this conference.
[15] K. Lackner et al., Long-Term Fusion Strategy in Europe, Journal of Nuclear Materials (2002) 307-311.