EFDA

EUROPEAN FUSION DEVELOPMENT AGREEMENT

A CONCEPTUAL STUDY OF

COMMERCIAL FUSION POWER PLANTS

Final Report of the European Fusion

Power Plant Conceptual Study (PPCS)

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EXECUTIVE SUMMARY

1. Introduction

From 1990 to 2000 a series of studies within the European fusion programme, summarised in References 1 and 2, examined the safety, environmental and economic potential of fusion power. These studies showed that:

- Fusion power has very promising potential to provide inherent safety and favourable environmental features, to address global climate change and gain public acceptance. In particular, fusion energy has the potential of becoming a clean, zero-CO_2 emission and inexhaustible energy source.

- The cost of fusion electricity is likely to be comparable with that from other environmentally responsible sources of electricity generation.

In the period since these earlier studies, there have been substantial advances in the understanding of fusion plasma physics and in the development of more favourable plasma operating regimes, and progress in the development of materials and technology. Accordingly, it was decided to undertake a comprehensive power plant conceptual design study, updated in the light of our current know-how and understanding, 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 3-years study, between mid 2001 and mid 2004, of conceptual designs for commercial fusion power plants. It focussed on four power plant models, named PPCS A to PPCS D, which are illustrative of a wider spectrum of possibilities. These span a range from relatively near-term concepts, based on limited technology and plasma physics extrapolations, to a more advanced conception. All four 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. They also differ substantially from one another in their size, fusion power and materials compositions, and these differences lead to differences in economic performance and in the details of safety and environmental impacts.

This report summarizes the European Power Plant Conceptual Study (PPCS), which continued and expanded earlier European fusion power plant studies [1]. The study was carried out with the help of a large number of experts from both the European fusion research community and its industrial partners.

2. Plant Models

All four of the plant models PPCS A to D are based on the tokamak concept as the main line of fusion development (Fig.1), proceeding through JET and ITER. JET, the world's largest and most advanced operating machine, provides the basis for the plasma physics of ITER, the next step in fusion development.

Two main elements characterise each power plant model: the blanket and the divertor. The blanket is the component where the energetic neutrons produced by the fusion process in the burning plasma are slowed down and deliver their energy in the form of heat and are absorbed by lithium atoms to produce the intermediate fuel, tritium. The divertor is the component

responsible for exhausting from the plasma chamber the fusion reaction products, mainly helium, and the associated heat power.
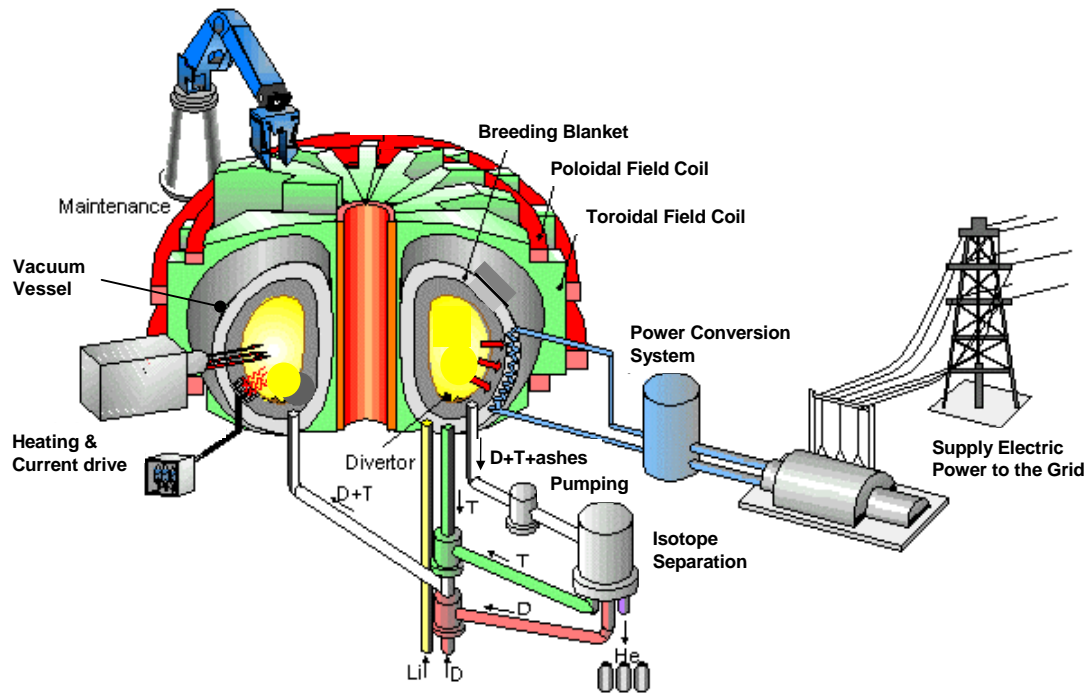

Fig. 1: Schematic diagram of a tokamak fusion power plant.

PPCS A and PPCS B are based on limited extrapolations in plasma physics performance compared to the design basis of ITER. The technology employed in these two models stems from the use of near-term solutions for the blanket. In PPCS A and PPCS B, the blankets are based, respectively, on the "water-cooled lithium-lead" and the "helium-cooled pebble bed" concepts, which have been studied in the European fusion programme. Both of these concepts are based on the use of a low-activation martensitic steel, which is currently being characterised in the European fusion programme, as the main structural material. Associated with these are water-cooled and helium-cooled divertors. The water-cooled divertor is an extrapolation of the ITER design and uses the same materials. The helium-cooled divertor, operating at much higher temperature, requires the development of a tungsten alloy as structural material. This development has been started in the framework of the European programme. For the balance of plant, model A is based on PWR technology, which is fully qualified, whilst model B relies 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 on successively more advanced concepts in plasma configuration and in materials technology. In both cases the objective is to achieve even higher operating temperatures and efficiencies. Their technology stems, respectively, from 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). In PPCS C the divertor is the same concept as for model B. In the most advanced concept, PPCS D, the divertor is cooled with lithium-lead like the blanket. This allows the pumping power for the coolant to be minimised and the balance of plant to be simplified.

A tungsten alloy layer may be assumed on the first wall of the blanket modules facing the plasma since its erosion rate (0.1 mm per full-power-year in ITER-like conditions) is much lower than low Z materials like beryllium (about 3 mm per full-power-year in ITER-like conditions). The use of this tungsten layer does not impact the wastes issue.

For all of the plant models, system analyses were used to integrate the plasma physics and technology constraints, together with other considerations such as unit size and availability, to produce self-consistent plant parameter sets with approximately optimal economic characteristics. The variations in assigned plasma physics and technology constraints drove variations in the fusion power and plant core dimensions, mainly associated with variation in the overall efficiency of the plant, as the electric power output delivered to the network was kept approximately the same for all the models (1500 MWe), with PPCS A having the largest, and PPCS D the smallest, fusion power and plant core dimensions (Fig. 2). The main parameters of the PPCS models are shown in table 1. Following the systems analysis, the conceptual designs of the four Models were developed, and analyses were made of their economic, safety and environmental performance.
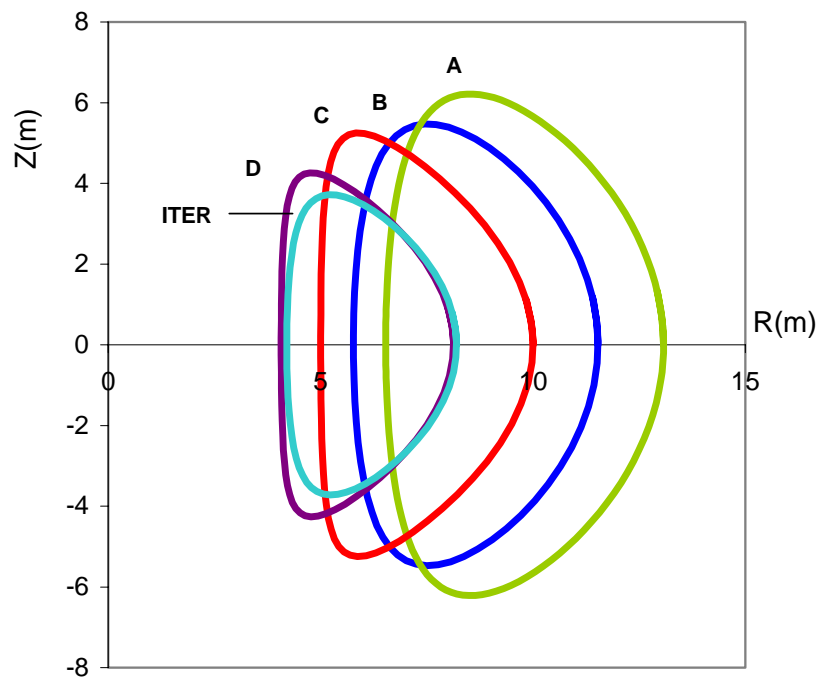

Fig. 2: Illustration of the sizes and shapes of the plasmas in the PPCS Models.

Two key innovative concepts, developed within the study, are worthy of a special note:
- One is a scheme for the scheduled replacement of the blanket and divertor, which shows the potential for good overall plant availability (at least 75%).
- The other is a conceptual design for a helium-cooled divertor, which permits heat loads (10 MW/m^2) twice as high as those previously foreseen for helium-cooled concepts.

	Model A	Model B	Model C	Model D
Parameter (plasma physics)				
Unit Size (GW$_e$)	1.55	1.33	1.45	1.53
Fusion Power (GW)	5.00	3.60	3.41	2.53
Aspect Ratio	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.25	0.47	0.47
Major Radius (m)	9.55	8.6	7.5	6.1
TF on axis (T)	7.0	6.9	6.0	5.6
Plasma Current (MA)	30.5	28.0	20.1	14.1
β_N(thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Bootstrap Fraction	0.45	0.43	0.63	0.76
P_{add} (MW)	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Parameter (engineering)				
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor Peak load (MWm^{-2})	15	10	10	5
H&CD Efficiency	0.6	0.6	0.7	0.7
Plant Efficiency[*]	0.31	0.37	0.42	0.6
Coolant blanket	Water	Helium	LiPb/He	LiPb
T_{in}/T_{out} (°C)	285/325	300/500	480/700 300/480	700/1100
Coolant divertor	Water	Helium	Helium	LiPb
T_{in}/T_{out} (°C)	140/167	540/720	540/720	600/990
Power conversion	Rankine	Rankine	Brayton	Brayton

[*] the plant efficiency is the ratio between the unit size and the fusion power

Table 1: Main parameters of the PPCS models.

3.   Safety and Environmental Impacts

Fusion power stations will have extremely low levels of fuel inventory in the burning chamber, therefore their power production stops a few seconds after fuelling is stopped. They have low levels of residual power density (arising from the decay of activated materials) in their structure after the termination of burn and they will not emit any of the greenhouse gases. In the PPCS models these favourable inherent features have been exploited, by appropriate design and choice of materials, to provide major safety and environmental advantages.

- If a total loss of active cooling were to occur during the burn, the plasma would switch off passively due to impurity influx deriving from temperature rises in the walls of the reaction chamber. Any further temperature increase in the structures, due to residual decay heat, cannot lead to 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 (bounding accident) would not exceed 18 mSv, below the level at which evacuation would be considered in many national regulations (50 mSv,

the value which is also recommended by the International Commission on Radiological Protection).

- The power plant will be designed to withstand an earthquake with an intensity equal to that of the most severe historical earthquake increased by a safety margin, in accordance with the safety design rules in force (for example, in France this margin approximately corresponds to an increase of 1 degree on the Richter scale). It would also be possible to provide any features that might be needed to meet the non-evacuation criterion in case of impact of a large aircraft.

- In case of fire, a maximum of a few grams of tritium could be released, by appropriate partitioning of the tritium inventory, which is consistent with the non-evacuation criterion.

- If there is substantial use of beryllium as an in-vessel component (approximately 560 tons are foreseen within the blanket of model B), it may be necessary to recycle it to satisfy the EU legislation on beryllium chemical toxicity.

- The radiotoxicity of the materials (namely, the biological hazard potential associated with their activation) decays by a factor ten thousand over a hundred years. All of this material, after being kept in situ for some decades, will be regarded as non-radioactive (contact dose rate lower than 0.001 mSv/h, decay heat lower than 1 W/m^3) or recyclable (contact dose rate lower than 20 mSv/h, decay heat lower than 10 W/m^3). The recycling of some material could require remote handling procedures. 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.

- None of the materials required are subject to the provisions of non-proliferation treaties.

4.   Economics

 "Internal cost" is the contribution to the cost of electricity from constructing, fuelling, operating, maintaining and disposing of power stations. The internal cost of electricity from the four PPCS fusion power plants was calculated by applying the codes also used in the Socio-economics Research in Fusion [2] programme. The PROCESS code, adopted in the study, uses well-attested methodologies validated against industry's cost estimates of ITER. The PPCS plant models differ in physical size, fusion power, the re-circulating power used to drive the electrical current in the burning plasma, the energy multiplication that occurs in the blankets, the efficiency of converting thermal to electrical power, and other respects. Accordingly, the total internal cost of electricity varies between the models, ranging from 5-9 €cents/kWh for model A down to 3-5 €cents/kWh for model D, depending on the assumed level of maturity of the technology considered. The calculated internal cost of electricity from all the models is in the range of estimates for the future costs from other sources (e.g. gas combined cycle, wind), obtained from the literature.

The internal costs of electricity generation do not include costs such as those associated with environmental damage or adverse impacts upon health. The "external costs" of electricity from the four PPCS plant models were estimated by scaling from the results from the Socio-economics Research in Fusion [2] programme using the well-established code ExternE. Because of fusion's safety and environmental advantages, these external costs are low. In summary, all four PPCS models have low external costs: much lower than fossil fuels, and comparable to, or lower than, wind power.

## 5.	Developments needs

It is clear from the PPCS results that the main thrusts of the European fusion development programme are on the right lines. These are:

- ITER;

- optimisation of existing low activation martensitic steels, together with development of tungsten alloys, and their testing in fission Material Test Reactors and then in the fusion-specific irradiation facility IFMIF, as soon as it becomes available. Parallel development of the more advanced materials envisaged in the PPCS; and

- development of blanket models, to be tested in ITER, based on the use of low activation martensitic steels as the main structural material.

It is also clear from the PPCS results that more work has to be undertaken on the development of divertor systems, ultimately capable of combining high heat flux tolerance and high temperature operation with sufficient lifetime in power plant conditions, and on the development and qualification of maintenance procedures by remote handling to satisfy the availability requirements of power plants. The first of these will require more emphasis on the development of tungsten alloys as structural materials and confirms the need to pursue the development of tungsten alloys as armour material. The effort already made to design and develop an efficient Remote Handling System, successful on JET, and now under way for ITER, will have to be further pursued with a view to power plant operation.

A focussed and fast development along the above lines would result in an early demonstration commercial power plant with substantial safety and environmental advantages and, during operation when reliability issues had been ironed out, acceptable economics.

Reflection on the PPCS results and the trends in the results, in the light of the understanding that they have brought in their train, also suggests that the following detailed steps should be undertaken:

- Performance of a DEMO power plant study. The time is now ripe for such a study to give guidance to the programme.

- Development and testing of helium-cooled divertor concepts capable of tolerating peak heat fluxes greater than 10 MW/m^2.

- Establishment of a Remote Handling Test Facility, to be used for the development of maintenance concepts capable of delivering high availability.

## 6.	Conclusions

The PPCS results for the near-term Models A and B suggest that a first commercial fusion power plant - one that would be accessible by a "fast track" route of fusion development, going through ITER and the successful qualification of the materials currently being considered - will be economically acceptable, with major safety and environmental advantages. These models rely on plasma performances marginally better than the design basis of ITER. The results for models C and D illustrate the potential for more advanced power plants.

Acknowledgments

References

1. I. Cook, G. Marbach, L. Di Pace, C. Girard and N. Taylor, "Safety and environmental impact of fusion", EFDA-S-RE-1, April 2001.
2. "Socio-economic aspects of fusion power", EUR (01) CCE-FU 10/6.2.2, April 2001.

CONTENTS

EUROPEAN POWER PLANT CONCEPTUAL STUDY

1. INTRODUCTION

1.1 Background and objectives

From 1990 to 2000 a series of studies within the European fusion programme, summarised in References 1 and 2, examined the safety, environmental and economic potential of fusion power. These studies showed that:

- Fusion power has very promising potential to provide inherent safety and favourable environmental features, to address global climate change and gain public acceptance. In particular, fusion energy has the potential of becoming a clean, zero-CO_2 emission and inexhaustible energy source.

- The cost of fusion electricity is likely to be comparable with that from other environmentally responsible sources of electricity generation.

In these earlier studies, conceptual design of the commercial fusion power plant "models" was pursued only to the extent needed to establish with confidence the primary features of their safety, environmental impacts and economic performance. Moreover, in the period since these earlier studies, there have been substantial advances in the understanding of fusion plasma physics and in the development of more favourable plasma operating regimes, and progress in the development of materials and technology. Accordingly, it was decided to undertake a comprehensive power plant conceptual design study, updated in the light of our current know-how and understanding, 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 3-years study, between mid 2001 and mid 2004, of conceptual designs for commercial fusion power plants. It focussed on four power plant models, named PPCS A to PPCS D, which are illustrative of a wider spectrum of possibilities. These span a range from relatively near-term concepts, based on limited technology and plasma physics extrapolations, to a more advanced conception. All four 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. They also differ substantially from one another in their size, fusion power and materials compositions, and these differences lead to differences in economic performance and in the details of safety and environmental impacts.

This report summarizes the European Power Plant Conceptual Study (PPCS), which continued and expanded earlier European fusion power plant studies. The terms of reference of the PPCS are given in Annex 1. The study was carried out with the help of a large number of experts from both the European fusion research community and its industrial partners.

1.2   Scope of this report

The body of this report is written so as to be accessible by scientific readers who are not fusion experts: further details are provided in Annexes. Extensive accounts of the origin of the safety and environmental advantages of fusion power, and of the methods used to demonstrate these, were given in the report on earlier studies [1]. These details are not repeated in this report, but the main points of the calculations and results are described.

2.   BASIC FEATURES OF FUSION POWER PLANTS

2.1   D-T fusion reaction

All four of the plant models PPCS A to D are based on the tokamak concept as the main line of fusion development, proceeding through JET and ITER. A schematic diagram showing the basic principles of a fusion power station, based on the "tokamak" magnetic configuration, is given in Fig. 1.
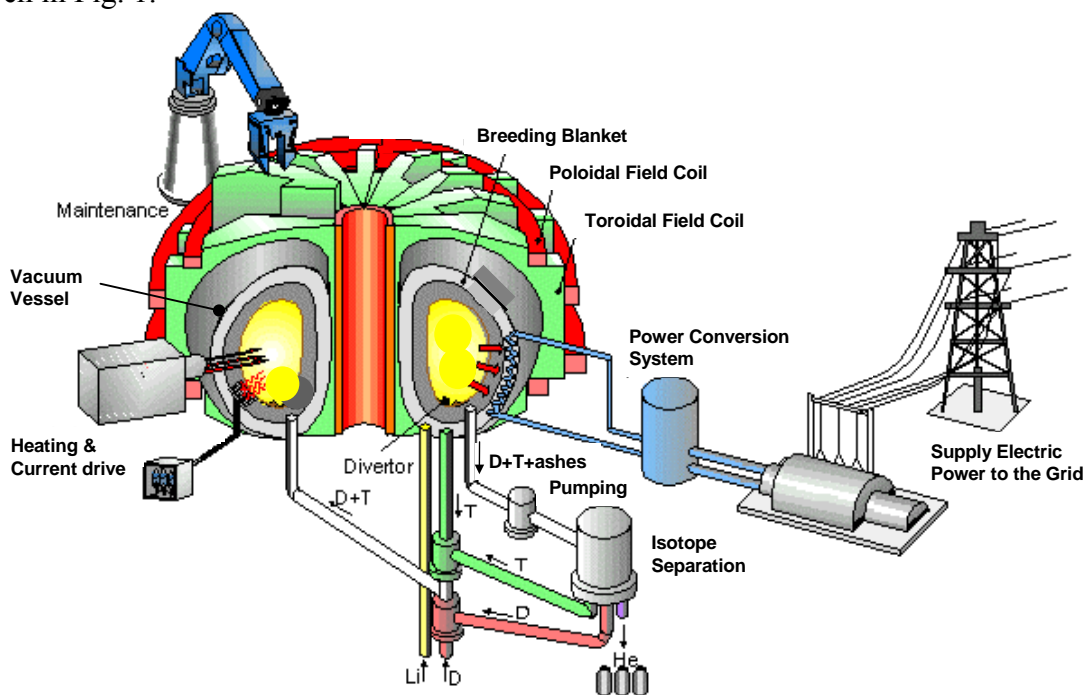
Fig. 1: Schematic diagram of a tokamak fusion power station.

In such a power station, energy is released when nuclei of deuterium and tritium fuse to form helium nuclei. Each such fusion event sets free an energy of 17.6 MeV, of which 14.1MeV appears as the kinetic energy of a neutron and 3.5 MeV appears as the kinetic energy of a helium nucleus. These events occur in a very high temperature (around a hundred million degrees) ionised gas, known as a plasma, of deuterium and tritium. The hot plasma is held thermally insulated from the material surroundings by magnetic fields. It is heated, in part by the kinetic energy of the helium nuclei released from the reactions, in part by an electric current carried by the plasma, and in part by auxiliary heating systems such as radio frequency sources or beams of particles.

The fuels for fusion are deuterium and lithium. Compounds of lithium (not lithium itself) are in the blanket. They interact with the neutrons from the plasma to generate tritium, which is extracted from the blanket and injected, together with deuterium, into the plasma to sustain the fusion process. The fuels burning in the plasma are continually replenished during operation.

2.2   Tokamak configuration

There are several basic concepts for the practical implementation of fusion power. Of these, the "tokamak" concept has been developed furthest, and has produced 16 MW of fusion power for a short time in a validating experiment using deuterium and tritium in the European JET tokamak. The PPCS power plants are based on the tokamak concept. In such a power plant, the plasma is held by the magnetic fields in a torus-shaped vacuum chamber. Thus the blanket surrounding the plasma is also toroidal. The blanket is the component where the energetic neutrons produced by the fusion process in the burning plasma are slowed down and deliver their energy in the form of heat and are absorbed by lithium atoms to produce the intermediate fuel, tritium. The heat is removed from the blanket by a flow of coolant fluid to steam generators and used to produce electricity in the conventional way. Between the blanket and the vacuum vessel is another toroidal structure, the shield. This serves to reduce the neutron flux to the vacuum vessel and the ex-vessel structures. The magnetic fields are created in part by electric currents in the plasma, and in part by currents in coils surrounding the vacuum vessel. To minimise dissipation of energy, these coils are superconducting. An additional component is the divertor. The divertor is located in the vacuum vessel below the plasma: its function is to evacuate the flow of hot gases (helium, and unburned deuterium and tritium) exhausting from the plasma.

These key components are shown in Fig. 2, a cut-away illustration of the fusion power core of the PPCS C power plant. The other plant models are broadly similar, their designs differing from one another in the following respects: the assumptions on achievable physics parameters; the blanket and divertor concepts; material specifications; and consequential changes. Key points are summarised in the appropriate sections below, with further details in the Annexes.
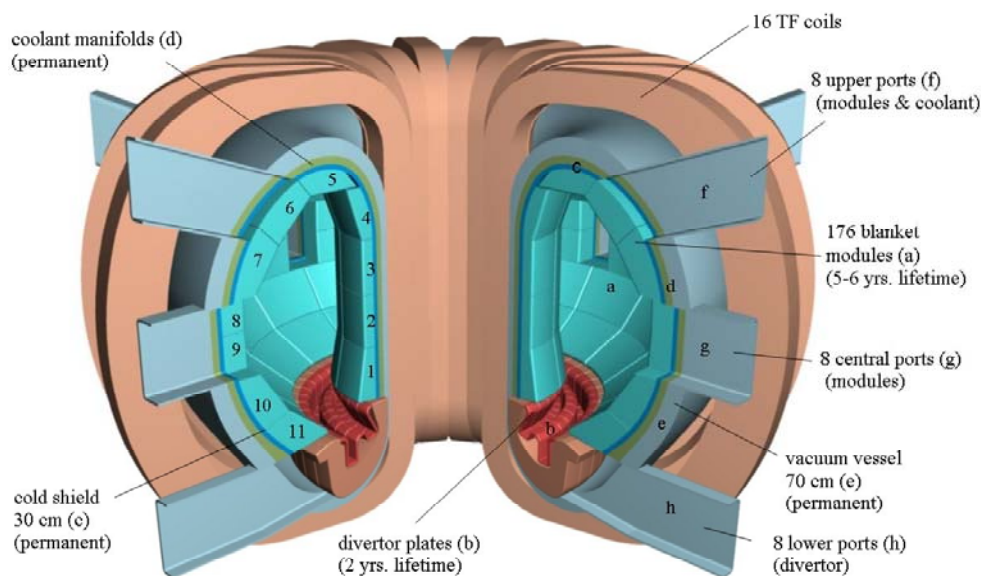

Fig. 2: Cut-away view of the fusion power core of the PPCS model C;
the other models are broadly similar.

2.3   Safety and environmental characteristics

Fusion power stations will have extremely low levels of fuel inventory in the burning chamber, therefore their power production stops a few seconds after fuelling is stopped. They have low levels of residual power density (arising from the decay of activated materials) in their structure after the termination of burn and they will not emit any of the greenhouse gases. In the PPCS models these favourable inherent features have been exploited, by appropriate design and choice of materials, to provide major safety and environmental advantages. Notwithstanding the often substantial changes in fusion power, plant dimensions, and design details compared to earlier studies, the broad features of all the safety and environmental conclusions of the earlier studies have been confirmed and demonstrated with increased confidence and understanding.

3.   FUSION POWER PLANT MODEL SELECTION AND DESIGN

3.1   Design methodology

All four of the plant models, PPCS A to D, are based on the tokamak concept. On the basis of the requirements expressed by the European industry and utilities, all models are assumed to work in steady state [3].

PPCS A and PPCS B are based on limited extrapolations in plasma physics performance compared to the design basis of ITER. The technology employed in these two models stems from the use of near-term solutions for the blanket. In PPCS A and PPCS B the blankets are based, respectively, on the "water-cooled lithium-lead" and the "helium-cooled pebble bed" concepts, which have been studied in the European fusion programme. Both of these concepts are based on the use of a low-activation martensitic steel, which is currently being characterised in the European fusion programme, as the main structural material. Associated with these are water-cooled and helium-cooled divertors. The water-cooled divertor is an extrapolation of the ITER design and uses the same materials. The helium-cooled divertor requires, instead, the development of a tungsten alloy as structural material due to the high operating temperature of the coolant, which is incompatible with the maximum operating temperature of Eurofer. This development has been started in the framework of the European fusion programme. For the balance of plant, model A is based on PWR technology, which is fully qualified, whilst model B relies 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 on successively more advanced concepts in plasma configuration and in materials technology. In both cases the objective is to achieve even higher operating temperatures and efficiencies. Their technology stems, respectively, from 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). In PPCS C the divertor is the same concept as for model B. In the most advanced concept, PPCS D, the divertor is cooled with lithium-lead like the blanket. This allows the pumping power for the coolant to be minimised and the balance of plant to be simplified.

Two key innovative developments made within the Study are worthy of special note. One is the development of a scheme for the scheduled replacement of the internal components that would have a limited lifetime, the blanket and divertor in particular. The envisaged

maintenance scheme is based on a segmentation of the blanket in large modules, which is an evolution from the ITER replacement scheme, and shows the potential for good overall plant availability (at least 75%). The blanket segmentation in vertical, "banana-shaped" segments considered during the ITER CDA has not been reconsidered in the PPCS. The other key innovative development is a new conceptual design for a helium-cooled divertor, which permits the toleration of heat loads (10 MW/m^2) twice as high as those previously foreseen for helium-cooled concepts.

There are no significant constraints on materials availability for the PPCS plant models, even for an extensive use of fusion power over centuries, and none of the materials required are subject to the provisions of the non-proliferation treaties.

For all of the plant models, systems analyses were used to integrate the plasma physics and technology constraints, together with other considerations such as unit size and availability, to produce self-consistent plant parameter sets with approximately optimal economic characteristics. The use of economic requirements to select the design parameters was one way in which the PPCS differed from earlier European studies. The variations in assigned plasma physics and technology constraints drove variations in the fusion power and plant core dimensions, with PPCS A having the largest, and PPCS D the smallest fusion power and plant core dimensions. The conceptual designs of the four Models were then developed in detail, and analyses were made of their economic, safety and environmental performance.

To begin the process of plant model design, systems code and analytical studies explored the interrelationships of plasma performance, materials performance, engineering, economics and other factors. The systems code studies employed a self-consistent model, PROCESS [4], described and used in earlier studies, but updated and extended, incorporating plasma physics and engineering relationships and limits, improved costing models validated against the ITER cost estimates and by comparison with similar US studies, and availability. PROCESS varies the free parameters of the design, subject to assigned plasma physics modelling and constraints, and engineering relationships and constraints, so as to minimise the cost of electricity. Supplementary analytical studies were used to gain further understanding.

The parameters arising from the PROCESS calculations were used as the basis for the conceptual design of four plant models, which are effectively illustrative of a wider spectrum of possibilities. In the course of the design process, feedback of engineering results from the designers and of reviewed plasma physics assessments was input to re-iterated PROCESS calculations, and led to further iterations of the designs.

3.2   Plasma physics basis

At the heart of the PROCESS code is a physics module, which was originally 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 [5]. The use of this simplified level of physics in a systems study of a conceptual power plant mirrors the earlier use in the conceptual studies of ITER. As with ITER, further studies will be needed to explore in more detail the important physics aspects of the power plant concepts, if we are to refine them towards more comprehensive power plant designs.

The most important aspects of the physics are the use of IPB98y2 scaling law for the energy confinement, a divertor module based on a simplified divertor model benchmarked to 2D

code runs, a synchrotron reflection coefficient based on experimental measurements (this can play an important role in divertor protection by core plasma radiation) and a current drive efficiency calculated using NBI efficiency based on a modified Mikkelson-Singer calculation.

The numerical limits used in PROCESS were based upon an assessment made for this purpose by an expert panel within the European fusion programme, and subsequent minor updating. These issues are described further in Annexes 2 and 3 to this report. For the two near-term Models, A and B, 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 current. Models C and D are based on progressive improvements in the level of assumed development in plasma physics, especially in relation to plasma shaping and stability, limiting density, and in minimisation of the divertor loads without penalising the core plasma conditions. A brief discussion of the main issues involving plasma physics is given in sub-section 3.4, and the main parameters are presented in Table 1.

3.3   Maintenance scheme

A key development of the PPCS was a concept for the maintenance scheme, evolved from the ITER scheme, which is capable of supporting high availability. The frequency and the duration of in-vessel maintenance operations are the prime determinants of the availability of a fusion power plant. The divertor is expected to be replaced every two full-power-years because of erosion, the blanket every five full-power-years, corresponding to not more than 150 dpa of neutron damage in steel.

ITER uses a segmentation of the internals, especially the blanket, in several hundred modules. In a power plant, such a large number of modules would result in an availability barely above 50%, which is unacceptable. To overcome this difficulty, a completely different segmentation of the reactor internals has been considered in a number of earlier power plant conceptual studies, the ARIES studies in particular. Under this scheme, complete radial sectors of the tokamak are handled as individual units, the number of sectors being driven by the number of toroidal field coils. As this scheme was the only alternative available at the start of the PPCS, it was assessed in great detail. The engineering challenges related to its implementation are considerable. Assuming the resolution of these challenges, it was assessed that the resulting availability would range between 76 and 81%. This range is acceptable for a fusion power plant, though below the availability anticipated by the proponents of this concept.

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.

Maintenance issues are presented in detail in Annex 9.

3.4   Systems analyses and overall plant parameters

The economics of fusion power improves markedly with increase in the net electrical output of the plant. As a compromise between this factor and the disadvantages for grid integration of large unit size, the net electrical output of all the Models was chosen to be around 1,500

MWe, substantially larger than in earlier European studies. The fusion power is then determined, primarily, by the thermodynamic efficiency and power amplification of the blanket concept, and the amount of gross electrical power recirculated for purposes including current drive: this in turn is determined by the plasma physics basis. The result of these factors is a progressive fall in the fusion power, from PPCS A to PPCS D. Also, from PPCS A to PPCS D, there is a progressive increase in blanket operating temperature, and thus in thermodynamic efficiency, and an increase in the "bootstrap" contribution to the plasma current, which reduces the recirculating electric power. Given the fusion power, the plasma size and power density are primarily determined by the assigned constraints on plasma core physics relating to restricting heat loads to the divertor. Taken together, these considerations lead to a fall in the size of the plasma, from Model A to Model D, shown in Fig. 3.

Studies were also performed, using the systems analysis model, to investigate the extent to which load-following (adjusting the electrical output of the plant to match fluctuating demand) will be possible. Both from the plasma physics and technology viewpoints, it would be feasible to reduce the electrical output by about fifty percent.

The possible benefits of using high temperature superconducting coils (HTS) were not investigated in details, in particular the consequences of working with a higher magnetic field than that considered in the PPCS models (between 13 and 13.5 T at the conductor). However, even at this field, the use of HTS could have significant benefits both in terms of cost and in design simplifications.
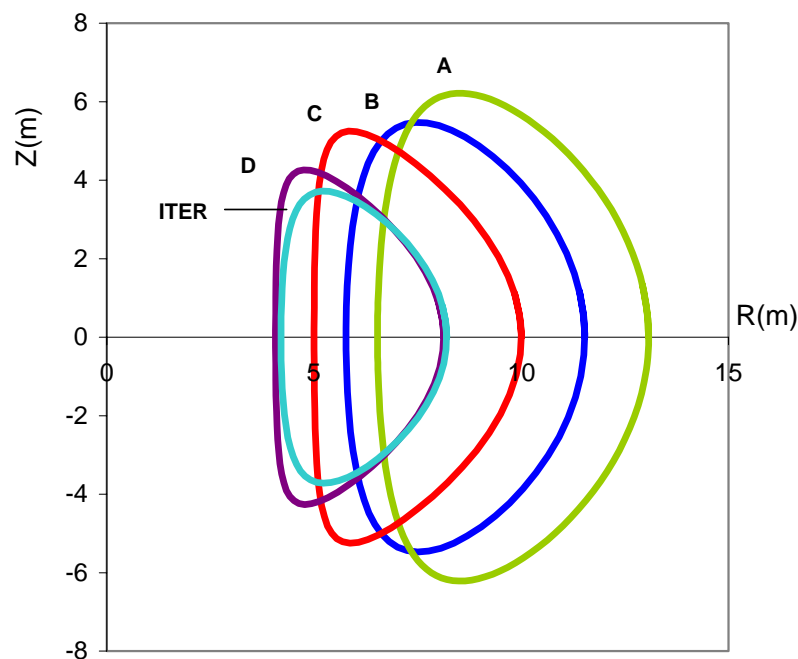

Fig. 3: *Illustration of the sizes and shapes of the plasmas in the PPCS Models.*
For comparison, ITER is also shown: this is very similar to Model D.
The axis labels denote major radius (R) and height (Z).

The main parameters of the four Models are shown in Table 1.

Parameter	Model A	Model B	Model C	Model D
Unit Size (GW$_e$)	1.55	1.33	1.45	1.53
Blanket Gain	1.18	1.39	1.17	1.17
Fusion Power (GW)	5.00	3.60	3.41	2.53
Plant efficiency *	0.31	0.36	0.42	0.60
Aspect Ratio	3.0	3.0	3.0	3.0
Elongation (95% flux)	1.7	1.7	1.9	1.9
Triangularity (95% flux)	0.25	0.25	0.47	0.47
Major Radius (m)	9.55	8.6	7.5	6.1
TF on axis (T)	7.0	6.9	6.0	5.6
TF on the TF coil conductor (T)	13.1	13.2	13.6	13.4
Plasma Current (MA)	30.5	28.0	20.1	14.1
β_N(thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
Average Temperature (keV)	22	20	16	12
Temperature peaking factor	1.5	1.5	1.5	1.5
Average Density (10^{20}m^{-3})	1.1	1.2	1.2	1.4
Density peaking factor	0.3	0.3	0.5	0.5
H_H (IPB98y2)	1.2	1.2	1.3	1.2
Bootstrap Fraction	0.45	0.43	0.63	0.76
P_{add} (MW)	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Q	20	13.5	30	35
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor Peak load (MWm^{-2})	15	10	10	5
Z_{eff}	2.5	2.7	2.2	1.6

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

Table 1: Main parameters of the PPCS models.

4.   KEY FEATURES OF THE FOUR MODELS STUDIED

4.1   Model A

Model A is based on a liquid lithium-lead blanket with water cooling (Fig. 4). The lithium serves as a tritium-generating material and the lead as a neutron multiplier in order to improve the conversion efficiency. The structural material is the reduced-activation ferritic-martensitic steel Eurofer, under characterisation in the European fusion programme. The in-vessel shield is water-cooled steel, as is the vacuum vessel.

In the blanket modules, the cooling water average pressure and temperature are respectively 15 MPa and 300 ºC, which is similar to the operating conditions of PWR fission plants. The power conversion system of this Model is based on the fully qualified PWR technology and its overall thermodynamic efficiency is similar to that of a PWR fission plant. For good maintenance characteristics, a segmentation of the blanket into large modules has been adopted.

Two alternative divertor concepts have been considered, which are shown in Fig. 5. The first one is an "ITER-like" divertor. It consists in a water-cooled copper alloy (CuCrZr) structure (tubes) with tungsten plasma-facing armour, with a tolerable divertor heat flux of 15 MW/m^2. The use of copper alloy limits the temperature of the coolant to 150 ºC; for that reason, this concept is named "low temperature" divertor. To maximize the electricity production of the plant, the water cooling the divertor should be, as in the blanket, at PWR conditions. This could be achieved by using EUROFER tubes protected by a thermal barrier made of pyrolitic graphite in order to provide a more uniform repartition of the incident heat flux. The resulting concept is named "high temperature" divertor.

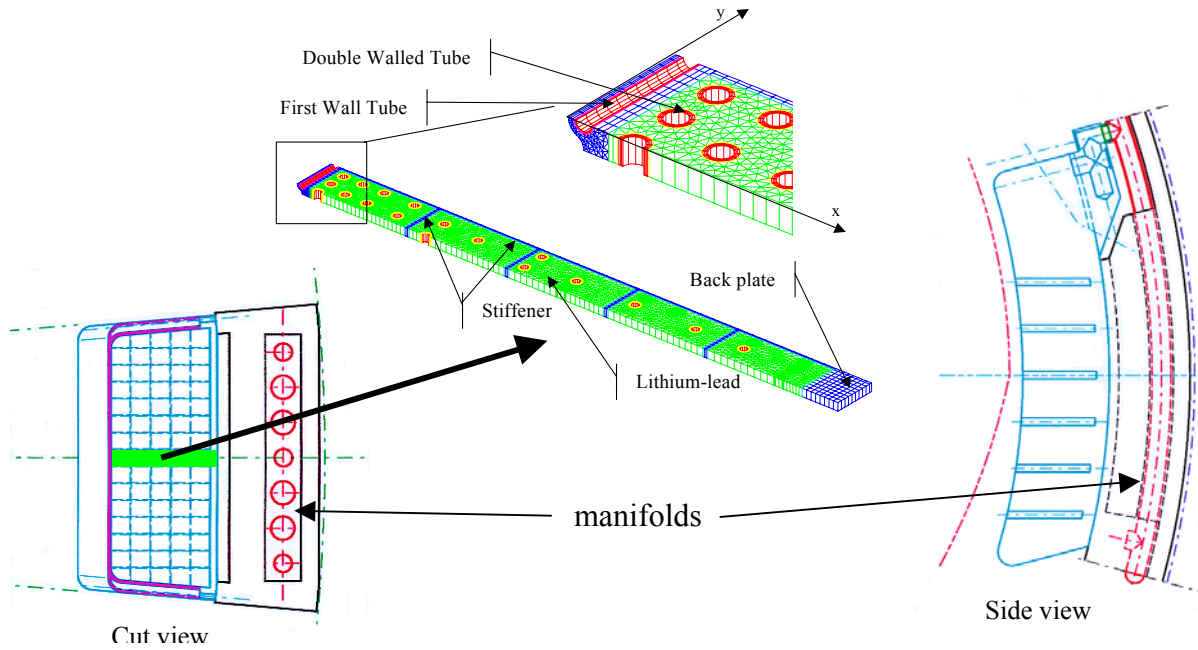Model A is described in detail in Annex 4.

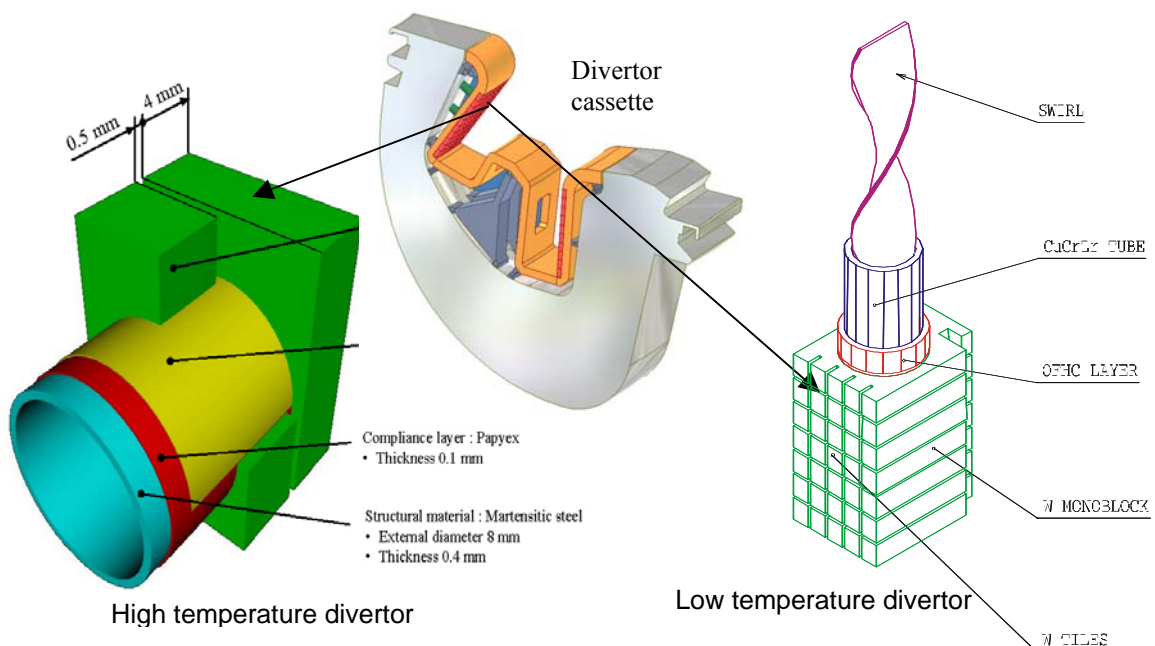*Fig. 4: Blanket concept of PPCS Model A (WCLL).*

Fig. 5: The water-cooled divertor concepts of PPCS Model A.

4.2   Model B

Model B is based on a blanket made by alternate layers of lithium ortho-silicate, which serves as a tritium-generating material, and pebbles of beryllium, which serves as a neutron multiplier. Helium is used as coolant, allowing a higher operating temperature than in Model A. In the blanket modules the helium average pressure is 8 MPa and the helium temperature is in the range 300ºC – 500ºC. The in-vessel neutron shield is in two sections: a "high-temperature" shield directly behind the blanket, of helium-cooled Eurofer, and a "low-temperature" shield behind that, which is helium-cooled zirconium hydride. The low-temperature shield receives a neutron dose low enough to make it a lifetime component of the plant. Fig. 6 shows a view of the radial module segregation of the tritium-generating zone (BZ), the high temperature shield (HTS), the low temperature shield (LTS), and a sketch of the coolant manifolding. For good maintenance characteristics, a segmentation of the blanket into large modules has been adopted.
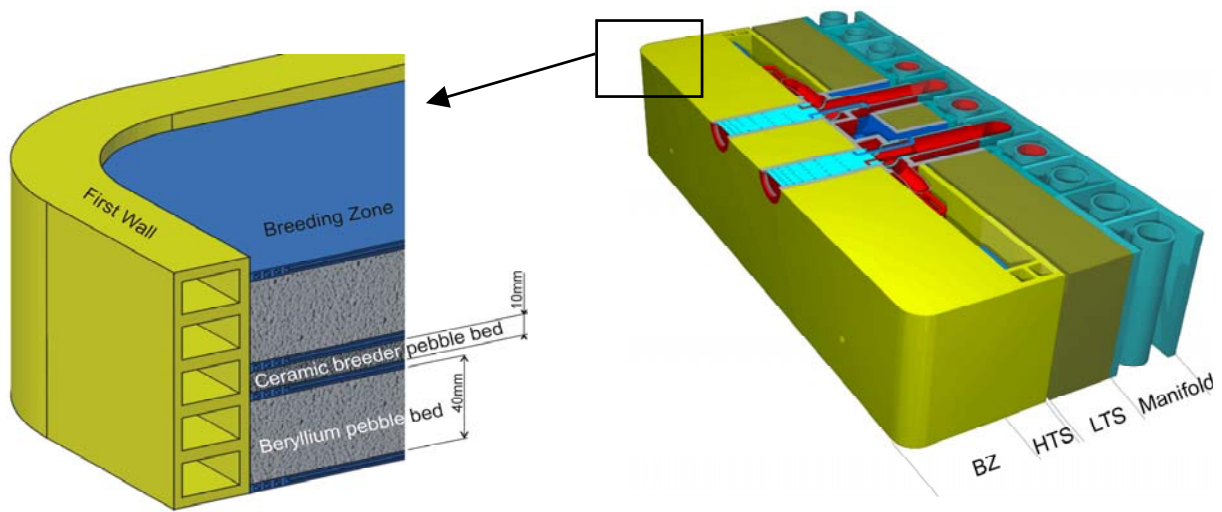
Fig. 6: Blanket concept of model B (HCPB).

Helium coolant is also assumed for the divertor, which is made of tungsten alloy (armour material) and EUROFER and tungsten alloy (structural material). It is noteworthy that the innovative divertor design permits a tolerable divertor heat flux of 10 MW/m^2: a high value for a helium-cooled divertor. Two He-cooled divertor concepts have been devised, as shown in Fig. 7, using two different techniques to enhance heat transfer:

- In the HETS concept by the impingement effects on the hemispherical surface and by the effects of centripetal acceleration (increase of turbulence) when the fluid moves on the inner side of the sphere.
- In the HEMP/HEMS concept by the implementation of pins or slots arrays (increase of turbulence and of surface of heat exchange).

A modular design is considered for both concepts in order to limit the thermal stresses. Model B is described in detail in Annex 5. The conceptual designs of the He-cooled divertor are described in detail in Annex 8.
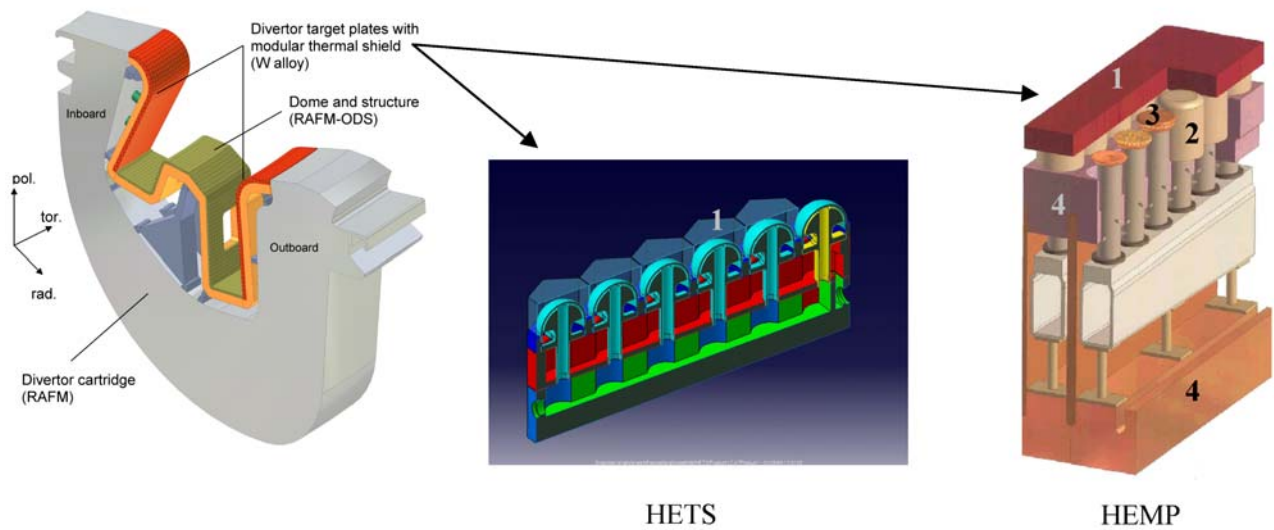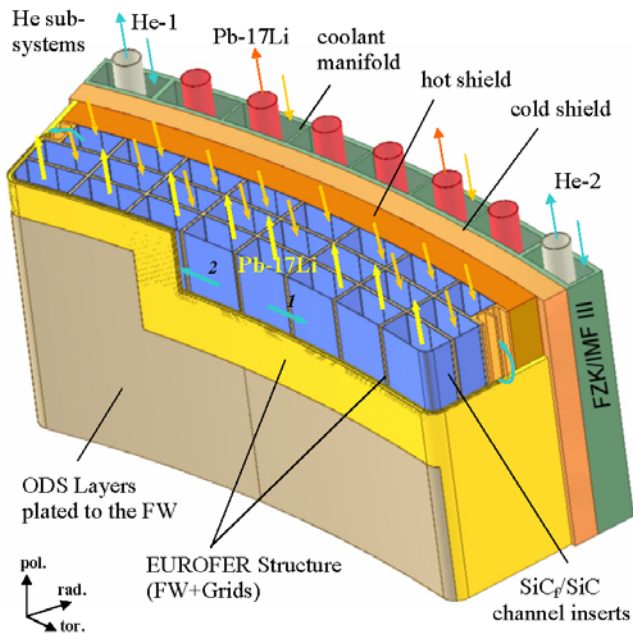
Fig. 7: He-cooled divertor concepts.

4.3   Model C

Model C has a lithium-lead blanket in which heat is removed by circulation of the lithium-lead itself and helium coolant passing through channels in the structure. This structure is mainly Eurofer, with oxide-dispersion-strengthened RAFM steel in the highest temperature zone (facing the plasma). This design is an evolution of a concept developed for the ARIES-ST power plant. Fig. 8 shows the principle construction of the blanket. The modules are large, stiff boxes with a grid structure inside, which are used as flow channels for the Pb-17Li and helium. High-pressure (8 MPa) helium gas is used to cool the first wall and the entire steel structure. For good maintenance characteristics, a segmentation of the blanket into large modules has been adopted.

The liquid-metal Pb-17Li serves as a coolant as well as the tritium-generating material. Its outlet temperature is maximised for efficiency reasons. It enters the modules at 460 °C and exits at 700 °C, which is above the maximum permissible temperature for steel. Therefore, the LiPb flow channels are lined by silicon carbide composite inserts, providing thermal and electrical insulation but no structural function. The thermal insulation allows higher temperature operation of the LiPb for improved thermodynamic efficiency, whilst the electrical insulation avoids MHD effects when pumping the LiPb at high velocity.

The PPCS C divertor is a helium-cooled design as in model B (see section 4.2). Model C is described in detail in Annex 6.

Fig. 8: Dual-coolant blanket (model C), equatorial outboard blanket module (1.5 x 3.0 x 1.6 m³ rad x tor x pol).

The table within the figure:

Main features:

- helium-cooled RAFM steel structures (EUROFER)
- ODS plated FW to use the high-temperature strength of ODS
- self-cooled breeding zone with Pb17Li as breeder and coolant
- SiC$_f$/SiC flow channel inserts as electrical (MHD) and thermal insulators leading to high exit temperature and high thermal efficiency

Dual Coolants	T_{Inlet} (°C)	T_{Outlet} (°C)	ΔT (K)
Helium (8 MPa)			
Overall blanket	300	480	180
FW	300	450	150
Grids	450	480	30
Pb-17Li	480	700	220

4.4 Model D

The most advanced of the PPCS Plant Models, Model D, uses a lithium-lead blanket in which the LiPb itself is circulated as primary coolant. The structure is made by silicon carbide composite. The divertor structure is also in silicon carbide composite, with tungsten armour, cooled by liquid lithium-lead. The objective for PPCS D is to reach very high blanket operating temperatures, and thus a very high thermodynamic efficiency, as well as very low decay heat densities and low coolant pressures, accepting a higher development risk. The temperature of the coolant in the blanket modules is in the range 700 ºC – 1100 ºC. In order to simplify the lithium-lead flow path and to maximize the blanket coverage, a segmentation of the blanket in vertical, "banana-shaped" segments has been assumed for this model.

Model D is described in detail in Annex 7.

4.5 Engineering parameters of the plant models

Table 2 indicates the power repartition and the overall efficiencies of the plants. The net electric power is obtained by subtracting the electric power required for H&CD and for pumping from the gross electric power. The accurate assessment of the power consumptions by other sub systems, mainly cryogenic, is quite difficult in the frame of a conceptual study. The expected values being relatively low (a few tens of MW), it has been decided not to take them into account in the calculation of the net electric power. This can be refined in further studies considering, in addition, possible improvements in either physics or technology for a tenth-of-a-kind reactor. In any case, the methodology being the same for all reactors models, it allows a pertinent comparison between them.

	Model A	Model B	Model C	Model D
Fusion Power (MW)	5000	3600	3410	2530
Blanket Power (MW)	4845	4252	3408	2164
Divertor Power (MW)	894	685	583	607
LT Shield Power (MW)	-	67	-	-
Pumping Power (MW)	110	375	87	12
Heating Power (MW)	246	270	112	71
H&CD Efficiency	0.6	0.6	0.7	0.7
Gross Electric Power (MW)	2066	2157	1696	1640
Net Electric Power (MW)	1546	1332	1449	1527
Plant Efficiency *	0.31	0.36	0.42	0.6

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

Table 2: Thermodynamic parameters.

4.6 Divertor armour and plasma facing materials

A tungsten alloy armour has been chosen for the divertor for all models. This choice allows to maximise the divertor lifetime, assumed to be at least 2 FPY for a thickness of the armour of about 5 mm, because of the low sputter yield. The only possible alternative is molybdenum, which is less interesting from the waste management standpoint.

As a conservative design choice, a tungsten alloy layer can be assumed on the first wall of the blanket modules to limit its erosion. The erosion rate of tungsten (0.1 mm/FPY in ITER-like conditions) is much lower than low Z materials like beryllium (about 3 mm/FPY in ITER-like conditions). The use of this tungsten layer does not impact the waste categorisation discussed in sub-section 6.3. An issue could be the transmutation of tungsten to osmium via rhenium under prolonged irradiation by 14 MeV neutrons, which could induce embrittlement; however, this is not a killing issue for an armour material.

Such layer has not been taken into account in the neutronic analyses of models A and B because of its limited influence on the results. Under more optimistic assumptions, such as those made for model C, a bare stainless steel first wall has been considered as possible.

5. ECONOMICS

5.1 Types of cost

There are two classes of contributions to the cost of electricity from any power source: internal costs and external costs. The term "internal costs" refers to the contributions to the cost of electricity from constructing, fuelling, operating, maintaining and disposing of, power stations. The PPCS internal costs are discussed in sub-section 5.2 below. The internal costs of electricity do not include costs such as those associated with environmental damage or adverse impacts upon health. The PPCS "external costs" are discussed in sub-section 5.3 below. There are also significant economic factors associated with constraints on power production within the energy system as a whole: as discussed in an earlier report [2], these factors favour fusion power as a base load electricity source in the future energy mix.

The PPCS plant models differ in physical size, fusion power, the re-circulating power used to drive the electrical current in the burning plasma, the energy multiplication that occurs in the blankets, the efficiency of converting thermal to electrical power, and other respects. Accordingly, the total internal cost of electricity varies between the models.

5.2   Internal costs

The internal costs of electricity from the four PPCS Models were calculated using the code PROCESS briefly described in sub-section 3.1 above and used in earlier studies. This uses well-attested methodologies validated against industry's cost estimates of ITER. The total capital cost, including interest during construction, is combined with replacement costs, other operating costs, payments into a decommissioning fund, and the availability, to obtain the internal cost of electricity. This is done in a standard manner, the "levelised cost" methodology, which is used for example in OECD and IAEA studies [6].

Earlier work with PROCESS [4], confirmed and elucidated by analytical studies, showed that the dependence of cost of electricity on the key parameters of the plasma, of the heat conversion cycle and of the reactor availability is well represented by the following expression:

$$\text{coe} \propto \left(\frac{1}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{0.4} N^{0.3}} \qquad (1)$$

Here coe is cost of electricity, A is the availability, η_{th} is the thermodynamic efficiency, P_e is the net electric power, β_N is the normalised plasma pressure, and $N = n/n_G$ is the Greenwald normalised plasma density. It is interesting to note that there is no dependence on the cost of fuel (lithium and deuterium). Fig. 9 shows the cost of electricity for each of the PPCS Models, as calculated in detail by PROCESS, together with the above scaling expression.
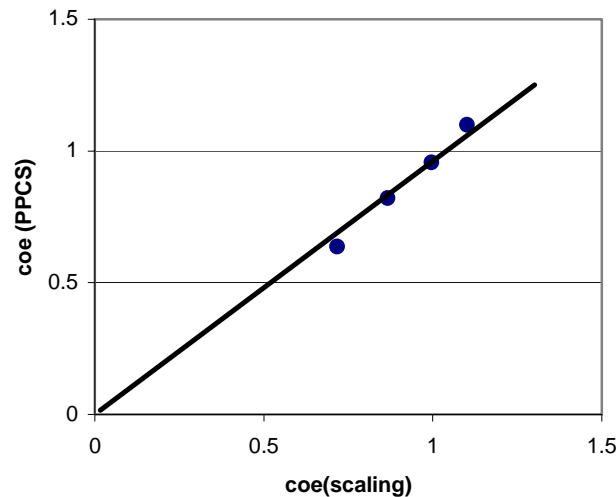

Fig. 9: Relative internal cost of electricity, calculated by PROCESS, for the four PPCS Models, plotted against the scaling shown in equation (1). The cost falls from Model A to Model B to Model C to Model D, reflecting the assumed levels of plasma physics and technology development.

As with all systems, the absolute value of the internal cost of electricity depends on the level of maturity of the technology. For an early implementation of these power plant models, characteristic of a tenth of a kind plant, the cost range of the PPCS plant models is calculated

to be 5 to 9 Eurocents/kWh. In a mature technology in which technological learning has progressed, the costs are expected to fall in the range 3 to 5 Eurocents/kWh. For all the Models, the internal cost of electricity is in the range of estimates, in the literature, for future costs from other sources. Both the near-term Models have acceptable competitive internal costs.

Fig. 9 also illustrates an important general point: the four PPCS Models are good representatives of a wide class of possible conceptual designs. Internal costs in the region of those of Model C, and the corresponding broad level of development, though not the precise plasma physics and technology of Model C itself, are considered to be the most likely outcome of the fusion development programme.

The PPCS economics modelling has been validated against other codes and against the ITER98 cost estimates. The agreement is generally very good, illustrating the robustness of the PPCS analyses. As usual, the most important capital cost issue is the cost of the large magnets. These are assumed to be based around conventional superconducting technology; Nb_3Sn for the toroidal field and NbTi for the poloidal field. However, advances in superconductors, to lower cost materials and to higher temperature superconductors, could reduce these costs.

5.3   External costs

A methodology for evaluating the external costs of electricity generation was developed for the European Union: it is known as "ExternE". In earlier studies [3], this system was used to evaluate the external costs of fusion electricity and compare these with the external costs of other sources. The PPCS external costs were estimated by scaling from these earlier results. The main external-cost-relevant differences between the PPCS Models and the most closely corresponding models forming the basis of the earlier studies are the masses of material and their activation: these form the basis of reliable scaling. The estimated external costs vary between 0.09 Eurocent/kWh for model A and 0.06 Eurocent/kWh for model D. For comparison, according to the same "ExternE" study, the estimated external cost would be 0.05 Eurocent/kWh for wind power, 1 to 2 Eurocent/kWh for methane and 5 to 8 Eurocent/kWh for oil power stations.

Because of fusion's safety and environmental advantages, its external costs are low. All four PPCS Models have external costs much lower than those of fossil fuels and comparable to wind power. Model C and Model D, which make use of silicon carbide, have the lowest external costs. Indeed, the external costs are dominated by the costs of conventional items, particularly conventional accidents during construction.

5.4   Summary

The details of the economic assessment of the four PPCS plant Models are reported in annex 11. The main points in the results are as follows.

- The calculated internal cost of electricity from all the models was in the range of estimates for the future costs from other sources, obtained from the literature.

- Within this range, PPCS A has the highest internal cost, followed by PPCS B, then PPCS C, with the very advanced model PPCS D having the lowest internal cost.

- Both of the near-term plant models, PPCS A and PPCS B, have acceptable competitive internal costs.

- All four PPCS models have low external costs: much lower than fossil fuels and comparable to wind power.

6. SAFETY AND ENVIRONMENTAL IMPACTS

6.1 Prime features

Fusion power stations will have extremely low levels of fuel inventory in the burning chamber, therefore their power production stops a few seconds after fuelling is stopped. They have low levels of residual power density (arising from the decay of activated materials) in their structure after the termination of burn and they will not emit any of the greenhouse gases. These favourable generic features lead to substantial safety and environmental advantages, but the full expression of these advantages depends upon the details of design and materials selection. The PPCS Models generally differ substantially in their gross power, major radii, aspect ratio and power density from the Models that formed the basis of earlier studies, so full safety and environmental analyses have been performed.

The foundations of all the analyses of safety and environmental impacts were comprehensive calculations of neutronics, activation and derived quantities. These were performed in 3 dimensions, using the codes MCNP and FISPACT, and they are presented in detail in Annex 10.

6.2 Accident analyses

To establish the worst consequences of an accident driven by in-plant energies, bounding accident analyses were performed for Plant Models A and B, in which a hypothetical event sequence is postulated. This was assumed to be a total loss of cooling from all loops in the plant, with no active cooling, no active safety system operating, and no intervention whatever for a prolonged period. The only assumed rejection of decay heat is by passive conduction and radiation through the layers and across the gaps of the model, towards the outer regions where eventually a heat sink is provided by convective circulation of the building atmosphere. The temperature rise is assumed to mobilise tritium and activation products, both erosion dust loose in the vessel and solid activation products in structure mobilised by volatilisation at the surfaces. This inventory, together with the entire contents of one cooling loop, is the source term assumed to be available for leakage from the plant through successive confinement barriers, using conservative assumptions. The fraction of this source that escapes into the environment is then transported, under worst weather assumptions, to an individual at the site boundary.

To assess this bounding sequence for Models A and B, temperature transients were computed in a finite-element thermal model, mobilisation and transport through the confinement layers were modelled, and dispersion and dose calculations completed. Fig. 10 shows the calculated poloidal temperature profile in Model A, ten days after the onset of the hypothetical accident.
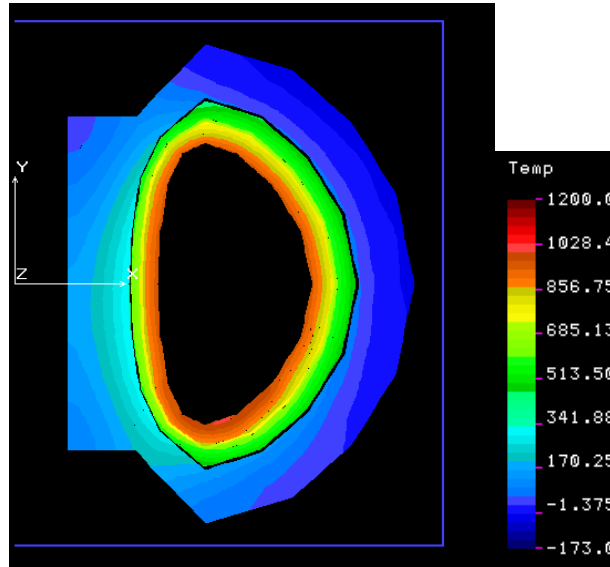
Fig. 10: Temperature profile in a poloidal cross-section of PPCS Model A, 10 days after the onset of a hypothetical bounding accident in which a total loss of all coolant is postulated, together with the failure of all active safety systems. The temperatures are in degree Celsius and Y denotes the vertical direction.

The histories of temperatures throughout the structures were obtained for times up to 100 days. These are illustrated in Fig. 11. Fig. 11, and the detailed calculations, show that at no time does any component reach a temperature close to melting. The decay heat densities in PPCS D are so low that there are essentially no temperature rises in even the worst case accidents, and even when conservatively calculated.

Given the temperature histories, the mobilisation of material by volatilisation from surfaces was modelled conservatively by the code APMOB used in earlier studies. Aerosol processes that occur during the movement of mobilised material within the nested containment structures, and the leakages of material from one containment volume to another, were modelled with the code FUSCON. Uncertainties were bridged by conservative assumptions. The dispersion of released material, and resulting doses to a hypothetical most exposed individual at the site boundary were calculated by using the results for worst case weather. This whole procedure gives the conservative estimates of the consequences of worst case accidents to Models A and B shown in Table 3. The differences between the two values come from the fact that a pressure suppression system (condensation pool) is used for model A, in which radioactive material, released in the vacuum vessel, can be trapped. In model B, instead, the radioactive materials mobilised during the accident is confined in an expansion volume with an assumed leak rate of 3% of the volume per day at 1 mbar overpressure.

Model	Dose
A	1.2 mSv
B	18.1 mSv

Table 3: Conservatively calculated doses to the public arising from the most severe conceivable hypothetical accident driven by in-plant energies.
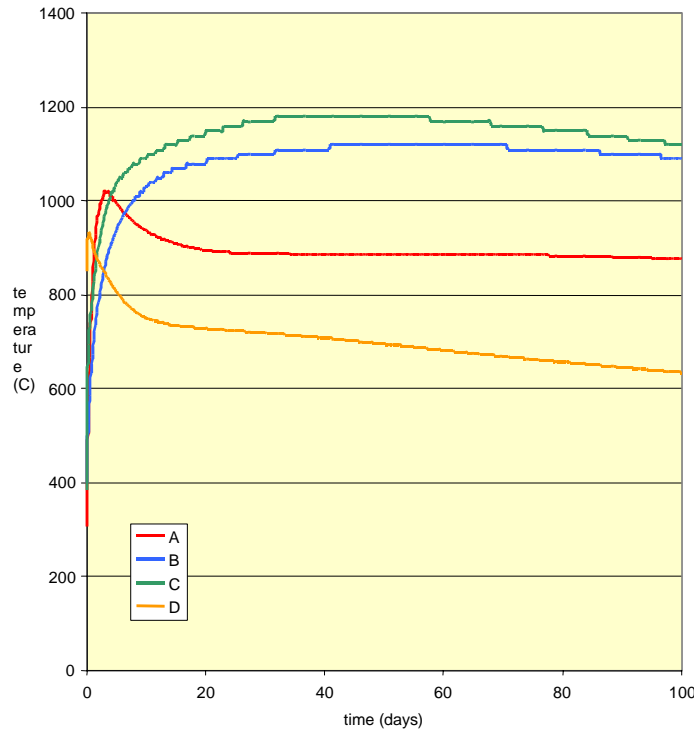
Fig. 11: Conservatively calculated temperature histories, for hypothetical bounding accidents in the outboard first wall of the four PPCS Plant Models.

It must be emphasized that these doses have been calculated in order to show the safety potential of the fusion power plants considered in this study: these conservatively calculated doses are below the level at which evacuation would be considered in many national regulations (50 mSv), level which is also recommended by the International Commission on Radiological Protection (ICRP 63). A different approach would be followed prior to construction of a power plant, including the application of the ALARA principle (As Low As Reasonably Achievable), which would lead to a minimisation of the doses to the public.-

The above sequence of calculations has also been performed for Models C and D, as far as the calculation of bounding temperature transients. Based on these calculations and our general understanding, it is assessed that the bounding doses in PPCS C would be similar to PPCS B and the bounding doses for PPCS D would be significantly lower.

The fundamentals of fusion safety, namely that low consequences of worst case accidents are guaranteed by inherent characteristics and passive features of design, entail that a fusion power station would be very resistant to adverse human factors. The conservative analysis of worst case accidents presented above was independent of the details of accident initiation and progression, such as might be caused by human factors.

This report has focussed on reporting the analyses of hypothesised worst case accidents, since the very low consequences of such accidents are among the most attractive features of fusion power plants and provide one of the main motivations for pursuing fusion development. However, this does not exhaust the safety issues: fusion power plants must be designed to lower the consequences and frequencies of lesser accidents. These issues were addressed in earlier studies and, with great thoroughness, in the ITER safety studies, with favourable outcomes. Within PPCS, studies were performed to verify that the new designs and plant

parameters did not lead to outcomes that would invalidate the earlier conclusions. Systematic accident identification and ranking studies were performed. Based on these, four accident scenarios were selected for detailed analysis. The results of these calculations confirmed the conclusions of the earlier studies and the doses arising were much lower than the doses from the hypothetical bounding accidents summarised above (e.g. by 2 orders of magnitude for model B).

6.3   Categorisation of activated material

The waste categorisation of the four plant models is based on the contact dose rate, the heat production and the clearance index. The clearance index $I_c(D)$ can be calculated for each material and irradiation condition, taking into account the contribution of all the contained nuclides:

$$ I_c(D) = \sum_{i=1}^{z} \frac{A_i}{L_i} $$

where A_i is the specific activity after storage, L_i is the clearance level and i represents the different nuclides contained in the material.

If a material cannot be cleared, it must be either recycled or disposed of. Accordingly, four categories of materials are defined: Non Active Waste (NAW), Simple Recycle Material (SRM), Complex Recycle Material (CRM) and Permanent Disposal Waste (PDW). The definitions of these are equivalent to those adopted in earlier studies, and use the limits shown in table 4. The recycling conditions and the clearance levels are in line with the recommendations of ICRP [7] and IAEA [8].

Activated material classifications	*Contact dose rate after 50 y (mSvh⁻¹)*	*Decay heat per unit volume after 50 y (Wm⁻³)*	*Clearance index after 50 y*
PDW, Permanent Disposal Waste (Not recyclable)	*> 20*	*>10*	*> 1*
CRM, Complex Recycle Material (Recyclable with complex RH procedures)	*2 - 20*	*1 - 10*	*> 1*
SRM, Simple Recycle Material (Recyclable with simple RH procedures), Hands On Recycling for D < 10 μSvh⁻¹	*< 2*	*< 1*	*> 1*
NAW, Non Active Waste (to be cleared)	*< 0.001*	*< 1*	*< 1*

Table 4: Definitions of categories of active material.

The non-active waste can be processed as normal scrap metal, while simple and complex recycle material can be recycled for further use – employing straightforward processes in the case of SRM. The activation of the materials in all four Models decays relatively rapidly – very rapidly at first and broadly by a factor ten thousand over a hundred years. For much of this material, after an adequate decay time, the activity falls to levels so low that it would no longer be regarded as radioactive, but could be "cleared" from regulatory control. Other material could be recycled or reused in further fusion power plant construction. Only a small amount, if any, would require long-term disposal in a waste repository. As an example, the outcome for Model B, which is constructed of near-term materials, approximately one hundred years after shutdown of the plant, is presented in Fig. 12. It may be seen that there is

no permanent disposal waste if (complex) recycling is implemented. Alternatively, should recycling not be considered, the wastes would have to be buried in a repository, the type of which depends on the nuclides (a limitation on the activity is defined for each nuclide) contained in the materials and the local regulations. As an illustration, the German repository of Konrad only foresees deep disposal whilst shallow land disposal is foreseen in El Cabril (Spain), CSA (France) and SFR (Sweden), with different limitations on the specific activities of the nuclides. For example, the limit concerning tritium is 10^9 Bq/kg in El Cabril, 2×10^8 Bq/kg in CSA and 10^8 Bq/kg in SFR.

The decision on whether or not to actually recycle the recyclable material is a matter for future generations to determine, possibly on economic criteria, but the fact that it could be recycled if desired is an indication of the relatively low hazard potential of the material.
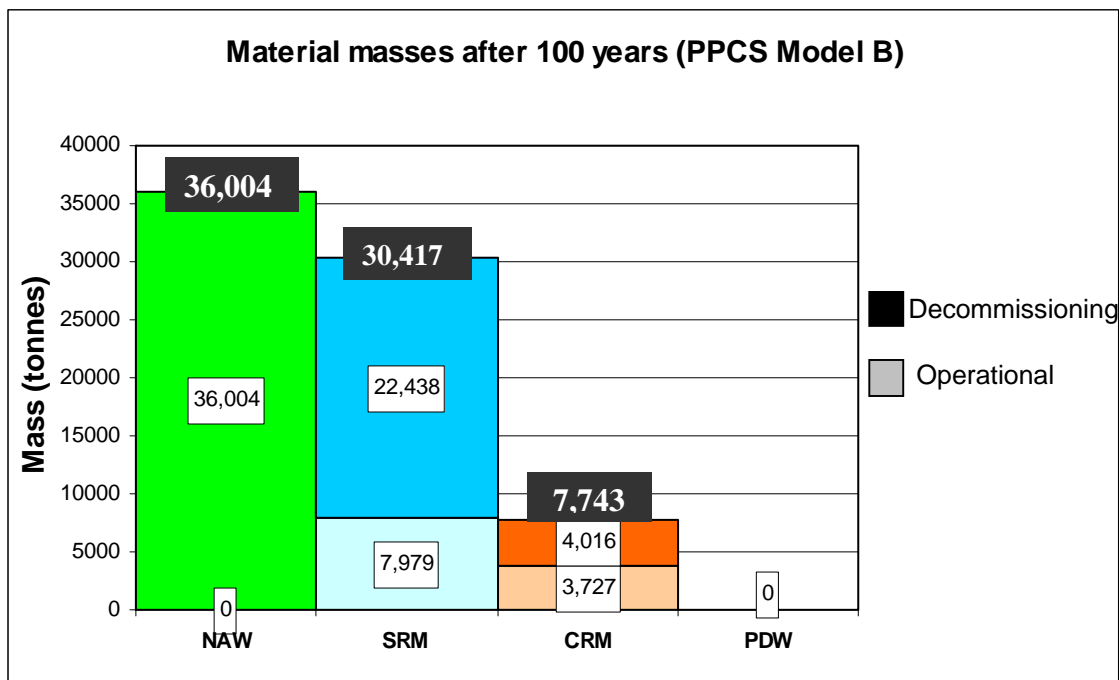

Fig. 12: Categorisation of all material arising from the operation and decommissioning of PPCS Model B.

6.4 Other factors

Detailed assessments of effluent releases, and of resulting doses via both atmospheric and aqueous pathways, were performed in earlier studies [1]. The doses were calculated to be very small: even on a conservative basis of calculation they were significantly below internationally accepted limits. Those effluent releases, scaled to the PPCS plant models with some refinements, have also been used as inputs to the calculations of the external costs, reported in sub-section 5.3 above. As reported there, the external costs are low.

Occupational radiation exposure is very dependent on the fine details of plant design and operating practices: this is very apparent from the detailed studies that have been made for ITER. However, such details are not available from a conceptual study such as PPCS. Broad and conservative assessment were made in earlier studies [1], and in PPCS these were extended with the intention of indicating the areas where detailed attention to design and

operating practices might be worthwhile. The results suggest that the blanket tritium removal system and the vacuum pumping system may be the areas most warranting detailed attention in any further detailed studies. Assessments were also performed in earlier studies of hazards (if any) that might arise from exposure to electromagnetic fields. It was concluded that there are no hazards to the public (apart from those that are inherent in all methods of electric power generation, handling and transmission), and that control of occupational exposures should be reasonably straightforward to achieve.

6.5   Summary

If a total loss of active cooling were to occur during the burn, the plasma would switch off passively due to impurity influx deriving from temperature rises in the walls of the reaction chamber. Any further temperature increase in the structures, due to residual decay heat, cannot lead to 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 (bounding accident) would be below the level at which evacuation would be considered in many national regulations (50 mSv, the value which is also recommended by the International Commission on Radiological Protection).

The power plant will be designed to withstand an earthquake with an intensity equal to that of the most severe historical earthquake increased by a safety margin, in accordance with the safety design rules in force (for example, in France this margin approximately corresponds to an increase of 1 degree on the Richter scale). It would also be possible to provide any features that might be needed to meet the non-evacuation criterion in case of impact of a large aircraft. In case of fire, a maximum of a few grams of tritium could be released, by appropriate partitioning of the tritium inventory, which is consistent with the non-evacuation criterion.

If there is substantial use of beryllium as an in-vessel component (approximately 560 tons are foreseen within the blanket of model B), it may be necessary to recycle it to satisfy the EU legislation on beryllium chemical toxicity.

The radiotoxicity of the materials (namely, the biological hazard potential associated with their activation) decays by a factor ten thousand over a hundred years. All of this material, after being kept in situ for some decades, will be regarded as non-radioactive (contact dose rate lower than 0.001 mSv/h, decay heat lower than 1 W/m^3) or recyclable (contact dose rate lower than 20 mSv/h, decay heat lower than 10 W/m^3). The 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. There will be no need for geological repositories. Thus the activated material from fusion power stations would not constitute a waste management burden for future generations.

None of the materials required are subject to the provisions of non-proliferation treaties.

7.   DEVELOPMENT NEEDS

It is clear from the PPCS results that the main thrusts of the European fusion development programme are on the right lines. These are:

- ITER;
- the optimisation of existing low activation martensitic steels, together with the development of tungsten alloys, and their testing in IFMIF, and the parallel development of the more advanced materials envisaged in the PPCS; and
- the development of blanket modules, to be tested in ITER, based on the use of low activation martensitic steels as the main structural material.

It is also clear from the PPCS results that more work has to be undertaken on the development of divertor systems, ultimately capable of combining high heat flux tolerance and high temperature operation with sufficient lifetime in power plant conditions, and on the development and qualification of maintenance procedures by remote handling to satisfy the availability requirements of power plants. The first of these will require more emphasis on the development of tungsten alloys as structural materials and confirms the need to pursue the development of tungsten alloys as armour material. The effort already made to design and develop an efficient Remote Handling System, successful on JET, and now under way for ITER, will have to be further pursued with a view to power plant operation.

A focussed and fast development along the above lines would result in an early demonstration commercial power plant with substantial safety and environmental advantages and, during operation when reliability issues had been ironed out, acceptable economics.

Reflection on the PPCS results and the trends in the results, in the light of the understanding that they have brought in their train, also suggests that the following detailed steps should be undertaken.

- Development of a fifth reactor model based on the helium-cooled lithium-lead concept (HCLL), which appears to have considerable safety, environmental and economic potential, considering that this is one of the two blanket lines (HCLL and HCPB) selected in EU since 2002 for testing in ITER. In fact, a power plant study for the HCLL model has already been launched in 2004.
- Performance of a DEMO power plant study. The time is now ripe for such a study to give guidance to the ITER-accompanying programme in plasma physics and technology.
- Development and testing of helium-cooled divertor concepts capable of tolerating peak heat fluxes greater than 10 MW/m^2.
- Establishment of a Remote Handling Test Facility, to be used for the development of maintenance concepts capable of delivering high availability.
- Studies aiming at optimising the shielding efficiency of helium-cooled blankets with minimal thickness on the inboard side of the torus.

8. OVERALL CONCLUSIONS

The PPCS results for the near-term Models A and B suggest that a first commercial fusion power plant - one that would be accessible by a "fast track" route of fusion development, going through ITER and the successful qualification of the materials currently being considered - will be economically acceptable, with major safety and environmental advantages. These models rely on plasma performances marginally better than the design basis of ITER. The results for models C and D illustrate the potential for more advanced power plants.

In the PPCS plant models, the favourable inherent safety features of fusion have been exploited, by appropriate design and materials choice, to provide substantial safety and environmental advantages. In particular:

- If a total loss of active cooling were to occur during the burn, the plasma would switch off passively due to impurity influx deriving from temperature rises in the walls of the reaction chamber. Any further temperature increase in the structures, due to residual decay heat, cannot lead to 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 (50 mSv, the value which is also recommended by the International Commission on Radiological Protection).

- The radiotoxicity of the materials (namely, the biological hazard potential associated with their activation) decays by a factor ten thousand over a hundred years. All of this material, after being kept in situ for some decades, will be regarded as non-radioactive or recyclable (contact dose rate lower than 20 mSv/h, decay heat lower than 10 W/m^3).

The two classes of contributions to the cost of electricity from any power source - internal cost and external cost – were both studied in PPCS:

- The calculated internal cost of electricity from all the models was in the range of estimates for the future costs from other sources, obtained from the literature.

- All four PPCS models have low external costs: much lower than fossil fuels and comparable to wind power.

The most notable of the technical advances achieved during the PPCS are: the conclusions that plasma performance broadly thirty percent better than the design basis of ITER is sufficient for economic viability; the evolution from the ITER maintenance scheme of a maintenance concept capable of delivering high availability; and the development of a helium-cooled divertor concept capable of tolerating a peak heat load of ten MW/m^2.

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ANNEXES