EUROPEAN FUSION POWER PLANT STUDIES

I Cook[1], D Maisonnier[2], N P Taylor[1], D J Ward[1], P Sardain[2],
L Di Pace[3], L Giancarli[4], S Hermsmeyer[5], P Norajitra[5], R Forrest[1], for the PPCS Team.

[1]*Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
ian.cook@ukaea.org.uk
[2]*EFDA CSU, Garching, Germany*
[3]*Euratom/ENEA Fusion Association, Frascati, Italy*
[4]*Euratom/CEA Fusion Association, Saclay, France*
[5]*Euratom/FZK Fusion Association, Karlsruhe, Germany*

ABSTRACT. The European Power Plant Conceptual Study (PPCS) reported in the summer of 2004. Several conceptual designs ("Models") for commercial fusion power plants were developed, spanning a range from relatively near term to more substantial extrapolations. The parameters of the Models were chosen by systems analysis to be economically optimal, given the assigned constraints on plasma and technology performance. The conceptual designs were developed in some detail and analyses were made of their safety, environmental impacts and economic performance. The calculated cost of generating electricity from the Models is in the range of published estimates for the future costs from other sources. Even the near-term Models are economically viable. External costs are very low, for all the Models: similar to wind power and much less than for fossil fuels. Economic optimization of the designs did not jeopardize their safety and environmental performance. All the Models proved to have the attractive and substantial safety and environmental advantages found in earlier studies, now established with greater confidence.

I. INTRODUCTION

From 1990 to 2000 studies within the European fusion program examined the safety and environmental impacts[1,2,3] and economic potential[4,5] of commercial fusion power. The results strongly suggested that fusion power could be a key contributor to reconciling global economic development with safety and protection of the environment. However, during the years since the establishment of the main features of the conceptual designs upon which those studies were based, there have been substantial advances in the understanding of fusion plasma physics and plasma operating regimes in tokamaks, and progress in the development of fusion materials and technology. Moreover, those safety and environmental studies were based on designs that were not economically optimized, and the various studies were not intended to be fully consistent with one another in detail. Accordingly, a more comprehensive and integrated study, updated in the light of our current know-how and understanding, was launched to serve as a better guide for the future evolution of the fusion development program.[6] This was the Power Plant Conceptual Study (PPCS), which reported in the summer of 2004.[7]

The parameters of the Models were chosen by systems analysis to minimize the calculated cost of generating electricity, given the specifically assigned constraints on plasma and technology performance. The use of economic requirements to select the Model parameters was one of the ways in which the PPCS differed from earlier European studies. The conceptual designs were developed in some detail, including innovative aspects. Analyses were made of their safety, environmental impacts and economic performance.

II. SELECTION OF THE MODEL PARAMETERS

Four Models (PPCS-A, PPCS-B, PPCS-C and PPCS-D) for commercial fusion power plants were developed. These span a range from relatively near term, based on limited plasma physics and technology extrapolations, to an advanced conception. These specific conceptual designs are illustrative of a wider spectrum of possibilities. All are based on the concepts of the main line of tokamak fusion development, proceeding through ITER. The parameters of the Models were chosen by systems analysis, using multi-parameter optimisation, to minimize the calculated "internal" (see section VI) cost of electricity, given the specifically assigned constraints on plasma and technology performance. Those analyses also show which plasma, materials and engineering parameters are keys to further improving the economics.

The interrelationships of plasma performance, materials performance, engineering, economics and other factors were explored using a systems code, supplemented by the understanding gained from analytical studies such as those reported earlier.[8] The systems code studies employed a very extensive self-consistent mathematical model, PROCESS, as described and used in earlier studies[5,9,10] but updated and extended. This code incorporates plasma physics and engineering relationships and limits, and availability, together with improved costing models validated against the well-assessed ITER costs and by comparison with similar US studies (ARIES-1, ARIES-RS and ARIES-ST).[11,12,13,14]

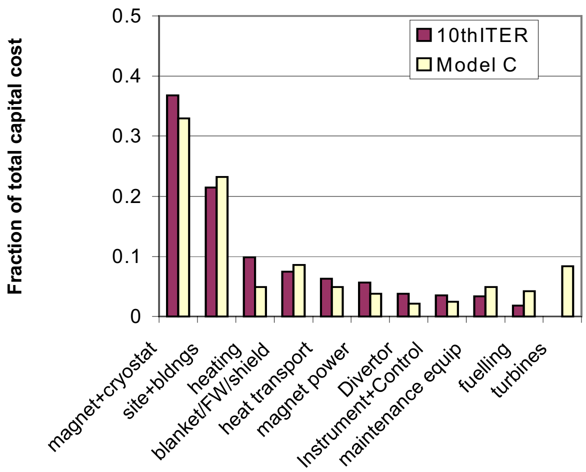

Fig. 1 Comparison between the fractional capital cost contributions for PPCS Model C and ITER98 (adjusted to bring them to a common basis).

To illustrate the validation of the costing models, Fig. 1 shows a comparison between the breakdown of the contributions to the Model C capital costs and those for the ITER98 design.[15] To make a like-for-like comparison, the ITER98 costs have been adjusted to reflect the learning effects appropriate to a "tenth of a kind" ITER. The high degree to which the PROCESS calculations agree with the very well validated and detailed ITER capital costs gives confidence in the robustness of the economic modelling in PROCESS.

PROCESS varies the free parameters of the design, subject to assigned plasma physics modelling and constraints, and engineering relationships and constraints, so as to minimize the "internal" (see section VI) cost of electricity. The parameters thus arising from the PROCESS calculations were used as the basis for the conceptual design of the four Models. In the course of the design process, feedback of engineering results and of reviewed plasma physics assessments was input to re-iterated PROCESS calculations, and led to further iterations of the designs.

II.A. 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.[16] The most important aspects of the plasma physics are: the use of the 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 as constraints in PROCESS were based upon an assessment made for this purpose by an expert panel within the European fusion programme,[17] and subsequent minor updating. For the two near-term Models, PPCS-A and PPCS-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 currents. PPCS-C and PPCS-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 divertor loads without penalisation of the core plasma conditions. The main constraining parameters are included within Table I.

II.B. Materials Technology Basis

The broad features of the materials technology of the four Models are as outlined in section III below. On this basis, key parameters needed for the systems analysis, such as the blanket energy gain, thermodynamic efficiency, maximum tolerable wall load, and maximum tolerable divertor heat flux, were calculated and used in PROCESS.

II.C. 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, at the times of the statutory outages, because of erosion. The blanket is expected to be replaced every five full-power-years: since the average wall load is of order 2 MW/m^{-2} (see sub-section II.D below) with a peak of about 3 MW/m^{-2} on the mid-plane, this lifetime corresponds to not more than 150 dpa of neutron damage to a steel structure.

Two families of maintenance schemes were studied and evaluated, using the expertise of European industry. The first was based on a scheme similar to that of ITER, but with segmentation of the blanket into the smallest possible number of “large modules”. The maximum size of a module is determined by the size of the quasi-equatorial ports through which the modules must pass. The size of these ports is limited by the magnet arrangements, in particular by the need to minimise the size of the toroidal field coils. 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% can be achieved. An alternative scheme, based on a completely different segmentation of the internals, as exemplified in the ARIES studies,[18] was also assessed in detail. In this scheme, complete radial sectors of the tokamak are handled as individual units. The engineering challenges are considerable: assuming resolution of these, it was assessed that the plant availability would range between 76% and 81%.

The first of the above schemes was adopted for PPCS. Details can be found in the PPCS Final Report.[7]

II.D. Systems Analyses and Overall Plant Parameters

The economics of fusion power improves substantially with increase in the net electrical output of the plant (see equation 1, below). As a compromise between this factor, and the disadvantages for grid integration of large unit size, the target net electrical output of all the Models was chosen to be 1,500 MWe, substantially larger than in earlier European studies. The fusion power is then determined by the thermodynamic efficiency and power amplification of the blankets and by 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 Model A to Model D. 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. As a result of these factors, in no Model does the first wall neutron load attain the limits that would have been set by the design. Taken together, these considerations lead to a fall in the size of the plasma, from Model A to Model D, shown in figure 2.

Studies were also performed, using the systems analysis code, 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 main parameters of the four Models are shown in Table I.

Note that the plant efficiency is here defined as the ratio of the net electric power output to the fusion power. Thus it embraces the effects of the thermodynamic efficiency and energy multiplication of the blanket, pumping power, current drive power, and so on. Detailed analyses of the power flows are given in the PPCS overall final report.[7]

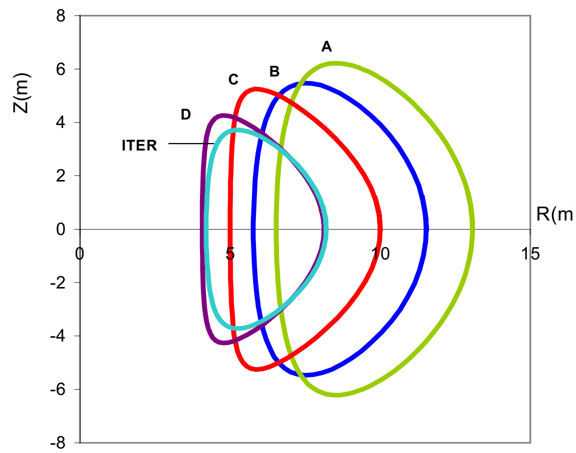

Fig. 2. Illustration of the sizes and shapes of the plasmas in the PPCS Models. For comparison, ITER is also shown: this is similar in size and shape to Model D. The axis labels denote major radius (R) and height (Z).

TABLE I. Main parameters of the PPCS Models.

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)	5.0	3.6	3.4	2.5
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 cond. (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
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
Current drive power fraction	0.20	0.21	0.11	0.06
Average neutron wall load	2.2	2.0	2.2	2.4
Divertor Peak load (MW/m^{-2})	15	10	10	5
Zeff	2.5	2.7	2.2	1.6

III. KEY TECHNOLOGY FEATURES OF THE PLANT MODELS

The broad features and materials basis of the blankets and divertors are briefly summarised below. Full details are given in the PPCS Final Report.[7] Note that lithium is isotopically enriched, to varying degrees, in the blankets.

III.A. Model A

Model A is based on a liquid lithium-lead blanket with water cooling, as studied in the European blanket programme. The structural material is the reduced-activation ferritic-martensitic steel Eurofer, under optimisation and characterisation in the European fusion programme. The in-vessel shield and vacuum vessel are water-cooled. In the blanket modules, the cooling water average pressure and temperature are respectively 15 MPa and 300 ^{o}C, which is similar to the operating conditions of PWR fission plants. The power conversion system is based on fully qualified PWR technology with overall thermodynamic efficiency similar to a PWR fission plant.

Two alternative divertor concepts have been considered, both water cooled. The first one (which was the reference concept for the economic analysis) uses copper alloy (CuCrZr) 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 ^{o}C. To maximise the electricity production of the plant, the water cooling should be, as in the blankets, at PWR conditions. This could be achieved by using Eurofer tubes protected by a thermal barrier made of pyrolytic graphite. This is the basis for the second divertor concept.

III.B. Model B

Model B is based on a blanket made by alternate layers of lithium ortho-silicate and pebbles of beryllium, also extensively studied in the European blanket programme. Helium is used as coolant, allowing a higher operating temperature. In the blanket modules the average helium pressure is 8 MPa and the helium temperature is in the range 300 ^{o}C – 500 ^{o}C. 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 (which is a permanent component) behind that, comprising helium-cooled zirconium hydride.

Helium cooling is also used for the divertor, made of tungsten alloy (armour material) and Eurofer and tungsten alloy (structural material). The innovative divertor designs permit a tolerable divertor heat flux of 10 MW/m2: a high value for a helium-cooled divertor. Two helium-cooled divertor concepts have been devised: the heat transfer at the thermal shield being enhanced by two different techniques. One technique uses the impingement effects of the coolant on a hemispherical surface, the other technique uses pin or slot arrays.

III.C. 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 reduced activation ferritic-martensitic steel in the highest temperature zone facing the plasma. The lithium-lead 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 lithium-lead for improved thermodynamic efficiency, while the electrical insulation avoids MHD effects in pumping. This design is an evolution of a concept developed for the ARIES-ST power plant.

The liquid lithium-lead serves as a coolant as well as a tritium-generating material. Its outlet temperature is maximised for efficiency reasons. It enters the modules at 460 ^{o}C and exits at 700 ^{o}C, which is above the maximum permissible temperature for steel. Therefore for this reason also the lithium-lead channels are thermally insulated with a layer of silicon carbide composite.

The divertor is a helium-cooled design as in Model B.

III.D. Model D

The most advanced of the PPCS Models, Model D uses a lithium-lead blanket in which the lithium-lead itself is circulated as the primary coolant. The blanket structure is made by silicon carbide composite, with tungsten armour. The divertor structure is also silicon carbide composite, with tungsten armour, cooled by liquid lithium-lead. The objective for Model D was to reach very high blanket operating temperatures, and thus very high thermodynamic efficiency, as well as very low decay heat densities and low coolant pressures, while accepting a high development risk. The temperature of the coolant in the blanket modules is in the range 700 – 1100 ^{o}C.

IV. SAFETY

Fusion power plants will have extremely low levels of fuel inventory in the burning chamber, their power production stops with no fuelling, they make no use of any fissile material, and they have relatively low levels of after-burn power density and long-term activation. 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.[2,3] Because the PPCS Models were developed to satisfy economic objectives, they generally differ substantially in their gross power, major radius, aspect ratio and power density from the Models that formed the basis of earlier studies,[2,3] so full safety and environmental analyses were performed. Details can be found in the PPCS Final report.[7] This section summarises the analyses of accidents, focussing upon hypothetical bounding accidents, while section V summarises the analyses performed for environmental impacts.

Comprehensive calculations of neutronics, activation and derived quantities formed the foundations of all the analyses of safety and environmental impacts. These were performed in 3 dimensions, using the codes MCNP and FISPACT.

IV.A. Bounding accidents

To establish the bounding consequences of an accident driven by in-plant energies, bounding accident analyses were performed, in which a hypothetical event sequence is postulated. For Models A and B, 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. (For Models C and D, the lithium-lead was retained in the model, but not circulated, so as to retain the decay heat generation by the lithium-lead itself.) 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, 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.

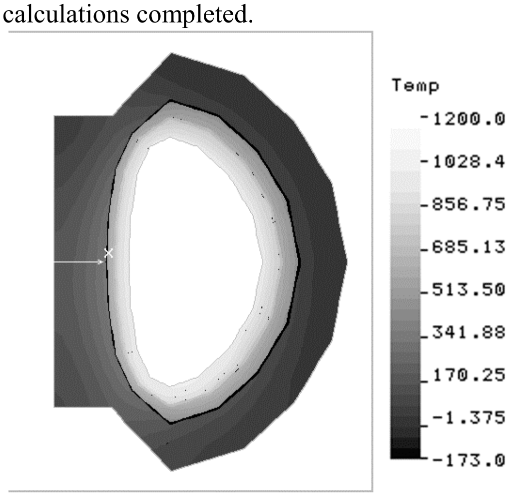

Fig. 3 Temperature profile in a poloidal cross-section of PPCS Model A, 10 days after the onset of a hypothetical bounding accident in which a total loss of all coolant is postulated, together with the failure of all active safety systems. The temperatures are in degrees Celsius and Y denotes the vertical direction.

The histories of temperatures throughout the Models were obtained for times up to 100 days. Fig. 3 shows the calculated poloidal temperature profile in one of the near-term Models, Model A, ten days after the onset of the hypothetical accident.

Figure 4 shows the calculated temperature histories for the bounding accident sequences in the outboard first walls of all the Models.

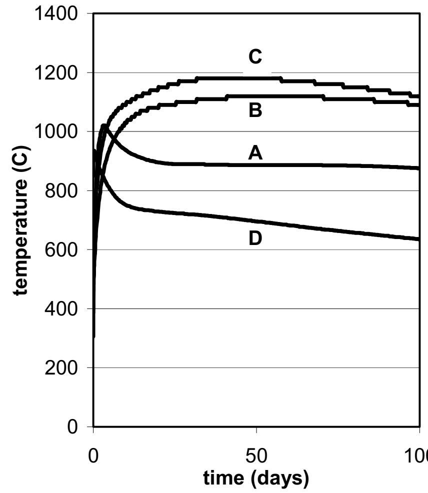

Fig. 4. Conservatively calculated temperature histories, for hypothetical bounding accidents in the outboard first wall of the four PPCS Models.

The maximum temperatures attained in the near-term Models, A and B, are shown in Table II. At no time does any component reach a temperature close to melting. Because of its very low level of decay heat power, the temperatures in Model D actually fall in the bounding accident.

TABLE II Maximum temperatures reached in the four Plant Models in the bounding accident scenario, assuming prolonged absence of any active cooling

	Model A	Model B	Model C	Model D
FW	1030 ºC	1130 ºC	1180 ºC	935 ºC
blanket	1000 ºC	1130 ºC	1190 ºC	934 ºC
shield	918 ºC	1140 ºC	1190 ºC	881 ºC
VV	836 ºC	1040 ºC	1150 ºC	716 ºC
TF coil	772 ºC	990 ºC	1120 ºC	692 ºC
cryostat	165 ºC	216 ºC	230 ºC	123 ºC
divertor	1240 ºC	1140 ºC	1210 ºC	908 ºC

Details of the analyses of the later phases of the bounding accident sequences is given in the PPCS Final Report.[7] These were performed only for Models A and B.

Given the temperature histories, the mobilisation of material by volatilisation from surfaces was modelled conservatively by the code APMOB used in earlier studies.[3,4] The mobilised source terms assessed for input to the release modelling also included the maximum 1 kg in-vessel tritium inventory, 10 kg of dust and (for Model A) 0.5 kg of activated corrosion products. Aerosol processes that occur during the movement of mobilised material within the containment structures, and leakages of material from one containment volume to another, were modelled with the code FUSCON. Uncertainties were bridged by conservative assumptions. Dispersion of released material, and doses to a hypothetical most exposed individual at the (1km) site boundary were calculated for worst case weather. This whole procedure gives conservative estimates of the consequences of worst case accidents to Models A and B shown in Table III.

Table III. Conservatively calculated worst case doses from worst case accidents.

Model	Dose
PPCS-A	1.2 mSv
PPCS-B	18.1 mSv

These conservatively calculated doses are not much greater than – or similar to – typical annual doses from natural background.

For Models C and D, only a qualitative assessment of the worst case doses was performed. Mainly because of the smaller inventories of mobilisable material in these Models, and the much smaller enthalpies of the primary coolants (essentially zero for Model D), it was assessed that bounding doses from Model C will be similar to or less than the (already small) bounding doses from Model B and the bounding doses from Model D will be much smaller still.

IV.B. Other issues

The above sub-section focussed on reporting the analyses of hypothesized 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, of course, exhaust the safety issues: in addition, fusion power plants must be designed to lower the consequences and frequencies of lesser accidents. These issues were addressed in earlier European power plant studies[1-3] and, with great thoroughness, in the ITER safety studies, with favourable outcomes. Within PPCS,[7] detailed 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, seven accident scenarios were selected for detailed analysis. The results of these calculations confirmed the conclusions of the earlier studies[1-3]: the doses arising were, of course, much lower than the doses from the hypothetical bounding accidents summarised above, which were themselves very low.

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.

The role of external events in accidents is very dependent on the fine details of design. Accordingly, in earlier studies,[1-3] external hazard accidents were assessed through consideration of hypothetical bounding cases. For example, in the event of confinement damage by a very rare or hypothetical ultra-energetic ex-plant event, such as an earthquake of hitherto never experienced magnitude, an upper bound to the release of tritium is set by the vulnerable inventory, which is about one kilogram. Even if calculated on very conservative assumptions, the release of one kilogram would result in a maximum dose to a member of the public that would give rise to health effects smaller than the typical consequences of the external hazard itself. On realistic assumptions the maximum dose would be lower, and this very hypothetical scenario could be removed by design provision. Essentially, such external hazards are an economic issue.

V. ENVIRONMENTAL IMPACTS

To begin with a very generic, and very significant, feature: fusion power plants will not emit any of the greenhouse gases: a major environmental advantage in itself.

The remainder of this section summarises the analyses performed concerning the categorisation of activated materials, and emissions. Details may be found in the PPCS Final Report.[7]

V.A. Categorisation of activated material

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 or in the nuclear industry. Only a small amount, if any, would require long-term disposal in a waste repository. Using the same criteria as in the earlier studies[1-3] – which have been assessed to be conservative for recycling - the categorisation of the materials accumulated from the operation and decommissioning of the PPCS Models has been performed, using the full three-dimensional activation data. As an example, the outcome for Model B, which is constructed of near-term materials, one hundred years after shutdown of the plant, is presented in Fig. 5.

It may be seen that there is no permanent disposal waste. This is true for all the Models. There would be no long-term waste burden on future generations.

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.

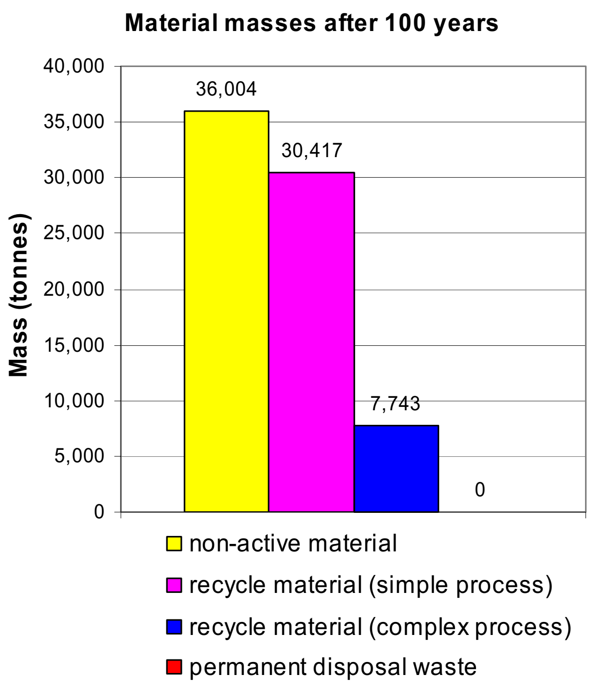

Fig. 5 Categorisation of all material arising from the operation and decommissioning of PPCS Model B. The non-active waste can be processed as normal scrap metal, while simple and complex recycle material can be recycled for further use – employing straightforward processes in the case of simple recycle material. There is no material in the permanent disposal waste category.

V.B. Effluents

Detailed assessments of effluent releases, and of resulting doses via both atmospheric and aqueous pathways, were performed in earlier studies.[1-3] The doses were found to be very small: even on a conservative basis of calculation, they were significantly below internationally accepted limits. Those effluent releases were scaled to the PPCS Models, with some refinements. The doses were still, of course very small. They were one of the inputs to the calculation of external costs, reported in subsection VI.B below. As reported there, the external costs are low for all the Models.

VI. ECONOMICS

There are two classes of contributions to the cost of electricity from any power source: internal costs and external costs.[5] "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 VI.A. Internal costs do not include costs such as those associated with environmental damage or adverse impacts upon health. In the case of some present sources of electricity, these "external" costs are substantial. The PPCS external costs are discussed in sub-section VI.B.

VI.A. Internal costs

The internal costs of electricity from the four PPCS Models were calculated using the code PROCESS briefly described in sub-section IIA above and used in earlier studies.[4,5] 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.[10]

The PPCS Models differ in physical size, fusion power, the re-circulating power used to drive the current in the plasma, the energy multiplication that occurs in the blanket, the efficiency of converting thermal to electrical power, and in other respects. Accordingly, the internal cost of electricity varies between the Models. All these differences originate in differences in the assigned constraints on plasma, materials and engineering performance: earlier work with PROCESS,[8] confirmed and elucidated by analytical studies, showed that the dependence of internal cost of electricity on the key parameters is well represented by the following expression.

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

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.

Fig. 6 shows the internal cost of electricity for each of the PPCS Models, as calculated in detail by PROCESS, plotted against the above scaling expression.

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 €cents/kWh. In a mature technology in which technological learning has progressed, the costs are expected to fall in the range 3 to 5 €cents/kWh. In more detail, the ranges of calculated internal cost of electricity from the four Models are shown in Table IV.

Table IV. Calculated ranges of internal cost of electricity from the PPCS Models.

PPCS Model	Internal cost of electricity (€cents/kWh)
A	5 –9
B	4 – 8
C	4 – 7
D	3 - 5

For all the Models, the internal cost of electricity is within the range of estimates, in the literature, for future costs from other sources.[17] Both the near term Models have acceptable competitive internal costs.

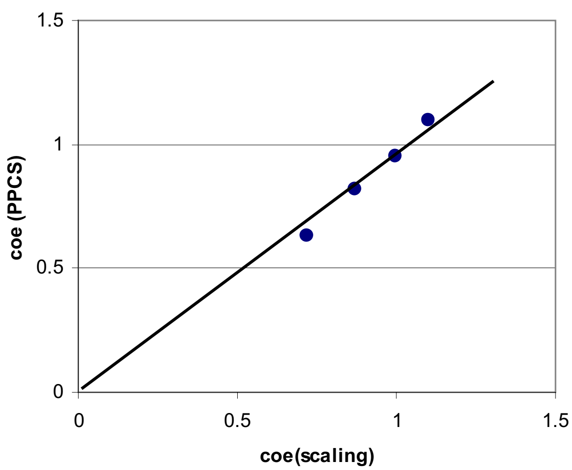

Fig. 6 Relative internal cost of electricity, calculated by PROCESS, for the four PPCS Models, plotted against the scaling shown in equation (1). The cost falls from Model A to Model B to Model C to Model D, reflecting the assumed levels of plasma physics and technology development. Absolute costs are described in the text.

The good agreement shown in figure 6, between the detailed validated PROCESS calculations and the simplified transparent expression (1), points to an important general point: the four PPCS Models are good representatives of a wide class of possible economically optimized conceptual designs of commercial fusion power plants. Internal costs in the region of those of Model C, though not the precise plasma physics and technology of Model C itself, are considered to be the most likely outcome of the fusion development program.

VI.B. 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,[5,19] 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 the well-established 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 are shown in Table V below.

Table V. Estimated external costs of electricity generation by the PPCS Models.

Plant Model	External cost (€cents/kWh)
A	0.09
B	0.07
C	0.06
D	0.06

VII. OVERALL SUMMARY AND CONCLUSIONS

The costs of generating electricity from the PPCS Models were calculated using well-established methodology benchmarked against the well-established ITER costs. These calculated costs are in the range of published estimates for the future costs of electricity from other sources. Even the near-term Models are economically viable.

The "external" costs were also calculated. External costs are those associated with any environmental damage or adverse effects upon health. These costs were very low, for all the Models: similar to wind power and much less than fossil fuels.

Economic optimization of the designs did not jeopardize their safety and environmental performance. All the Models proved to have the attractive and substantial safety and environmental advantages shown in earlier studies, now established with greater confidence. These advantages include:

- If a total loss of all cooling were to occur, temperature increases in the structures would not approach melting. This result is achieved without reliance on active safety systems or operator actions. The maximum radiological doses to the public – assessed with deliberate pessimism – would be not much more than, or similar to, typical annual doses from background radiation.

- The radiotoxicity of the materials decays very rapidly at first, and broadly by a factor ten thousand over a hundred years. All of this material, after remaining in situ for several decades, may be regarded as non-radioactive or recycled, with no need for repository disposal. There would be no waste management burden on future generations.

Consideration of the results suggests that an additional near-term Model, based on a helium cooled lithium-lead blanket with Eurofer structure, would have considerable merits. Such a concept is being developed as one of the European Test Blanket Modules for ITER.

The PPCS results for the near-term Models suggest that a first generation of fusion power plants – those that would be accessible by a fast track route of fusion development,[20] going through ITER and the successful qualification of materials currently being investigated in the European fusion programme – will be economically acceptable with major safety and environmental advantages. The remaining PPCS results illustrate the potential for more advanced power plants.

Accordingly, it is concluded from the PPCS results that the main thrusts of the European fusion development program are on the right lines.

ACKNOWLEDGMENTS

PPCS was performed as a collaborative effort by six European Fusion Associations and by European industry (EFET-EWIV). It was jointly funded by Euratom and by government agencies of Belgium, France, Italy, Spain, Sweden and the United Kingdom.

REFERENCES

[1] J. Raeder, I. Cook, F.H. Morgenstern, E. Salpietro, R. Bunde and E. Ebert, “Safety and environmental assessment of fusion power (SEAFP)”, European Commission DGXII, Fusion Programme, report EUR-FUBRU XII-217/95, June 1995.

[2] Cook, G. Marbach, L. Di Pace, C. Girard, P. Rocco and N.P. Taylor, “Results, conclusions and implications of the SEAFP-2 programme”, *Fusion Eng. Des.* 51-52 (2000) 409-417.

[3] Cook, G. Marbach, L. Di Pace, C. Girard and N.P. Taylor, “Safety and environmental impact of fusion”, European Fusion Development Agreement report EFDA-S-RE-1, April 2001.

[4] “Socio-economic aspects of fusion power”, EUR (01) CCE-FU 10/6.2.2, European Fusion Development Agreement Report, April 2001.

[5] I. Cook, R.L. Miller and D.J. Ward, “Prospects for economic fusion electricity”, *Fusion Eng. Des.* 63-64 (2002) 25-34.

[6] G. Marbach, I. Cook, and D. Maisonnier, “The EU power plant conceptual study”, *Fusion Eng. Des.* 63-64 (2002) 1-11.

[7] D Maisonnier, I Cook, P Sardain, R Andreani, L Di Pace, R Forrest, L Giancarli, S Hermsmeyer, P Norajitra, N Taylor, D Ward, “A Conceptual Study of Commercial Fusion Power Plants: Final Report of the European Power Plant Conceptual Study”. European Fusion Development Agreement (EFDA) Report EFDA-RP-RE-5.0, September 2004.

[8] I. Cook, T.C. Hender, P.J. Knight and D. Ward, “Direct cost of electricity from fusion power plants”, Proc. 26th EPS conference, Maastricht, 1999.

[9] T.C. Hender, P.J. Knight and I. Cook, UKAEA FUS 333 (1996).

[10] T.C. Hender, P.J. Knight and I. Cook, “Key issues for the economic viability of magnetic fusion power”, *Fusion Techn.* 30 (1996) 1605.

[11] D. J. Ward, “International benchmarking calculations on key issues of fusion economics”, UKAEA report SERF/UKAEA/DFCA3.1, 2002.

[12] R.J. Miller et al., Fusion Technology19 (1991) 802.

[13] F. Najmabadi et al., Fusion Engineering and Design, 38 (1997) 3.

[14] F. Najmabadi et al., 17th Fusion Energy Conference (1998) Yokohama, FTP/08.

[15] “Technical basis for the ITER final design report, cost review and safety analysis”, ITER EDA Documentation No. 16, IAEA, Vienna (1998).

[16] “ITER physics basis”, *Nuclear Fusion* 39 (1999), 2175.

[17] U. Samm et al., “Report of the ad-hoc group to assess the physics assumptions underlying the power plant conceptual study (PPCS)”, unpublished June 2001, published as Annex 2 of reference 7.

[18] S. Malang et al., “ARIES-RS maintenance approach for high availability”, Fusion Engineering and Design, 41, 1998.

[17] D J Ward, I Cook, Y Lechon, R Saez, “The economic viability of fusion power”, Proceeding of the 2004 SOFT conference, to appear in Fusion Engineering and Design.

19] R. Saez et al., “Externalities of fusion: SERF (1999-2000)”, Coleccion Documentos CIEMAT (2001).

[20] 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).