European Fusion Power Plant Studies

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Background

From 1990 to 2000, several European studies examined

- the safety and environmental impacts, and
- the economic potential

of fusion power.

These were not fully consistent with one another.

There have been many advances in fusion science since the original basis of the studies.

Therefore, a new, more comprehensive and integrated, study was launched - the PPCS. This reported in 2004..

Objectives of PPCS

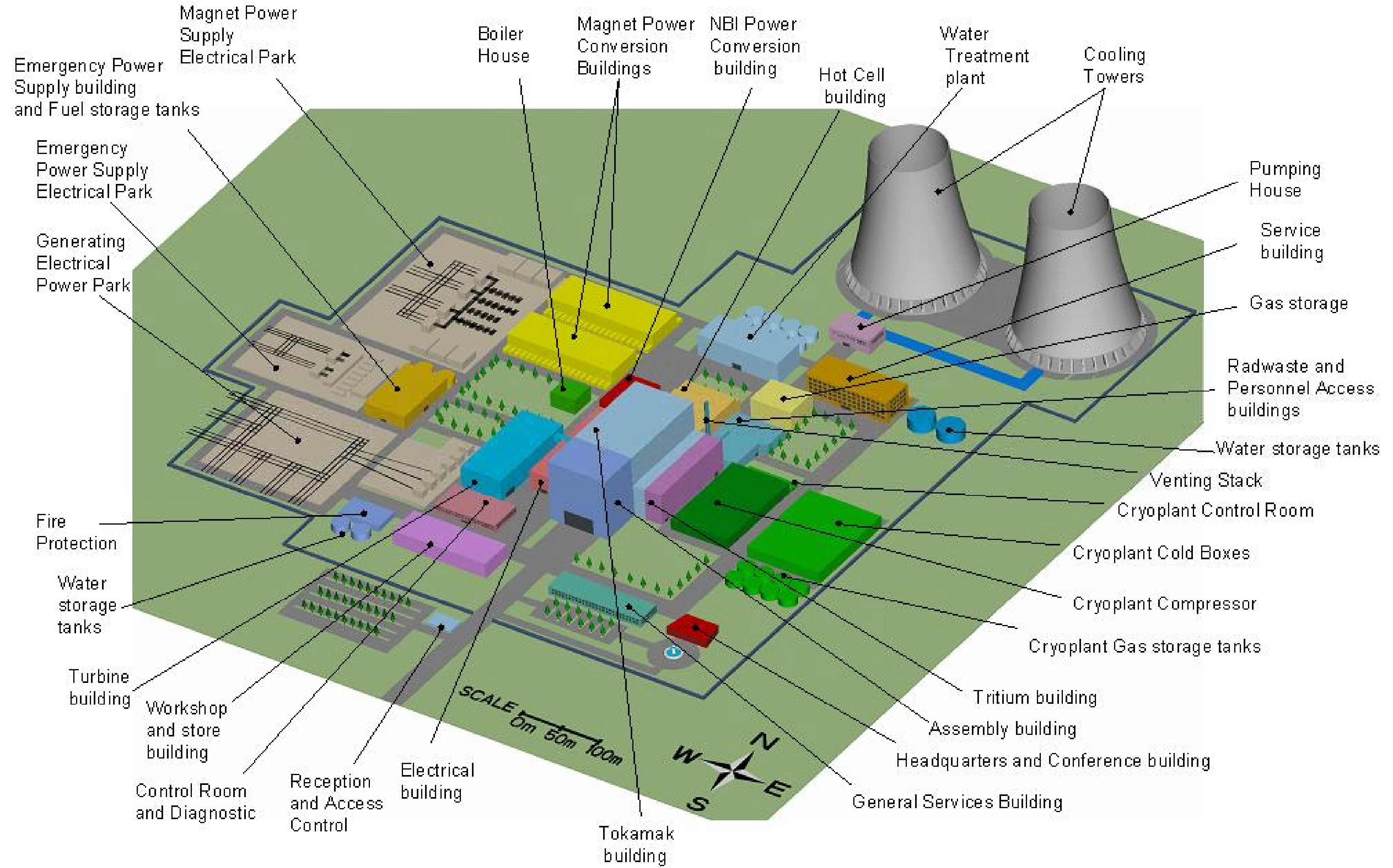
1. Compared to earlier European studies:

- Ensure the designs satisfy economic objectives.
- Update the plasma physics basis.

(For both reasons, the parameters of the designs differ substantially from those of the earlier studies.)

2. Maintain the excellent safety and environmental features of fusion power.

General layout



Selection of model parameters

- Four "Models", A - D, were studied as examples of a spectrum of possibilities.
- Ranging from near term plasma physics and materials to advanced.
- Systems code varied the parameters of the possible designs, subject to assigned plasma physics and technology rules and limits, to produce economic optimum.

Plasma physics basis

- Based on assessments made by expert panel appointed by European fusion programme.

- Near term Models (A & B): roughly 30% better than the conservative design basis of ITER.

- Models C & D: progressive improvements in performance - especially shaping, stability and divertor protection.

Materials basis

Model	Divertor	Blanket structure	Blanket other
A	W/Cu/water	Eurofer	LiPb/water
B	W/Eurofer/He	Eurofer	Li_4SiO_4/Be/He
C	W/Eurofer/He	ODS/Eurofer/ SiC	LiPb/SiC/He
D	W/SiC/LiPb	SiC	LiPb

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Technical innovation

Two notable innovative features:

- A **maintenance scheme**, evolved from the ITER scheme, capable of supporting high availability (at least 75%).

- Two concepts for **helium-cooled divertors, which permit peak heat loads of 10 MW/m2.**

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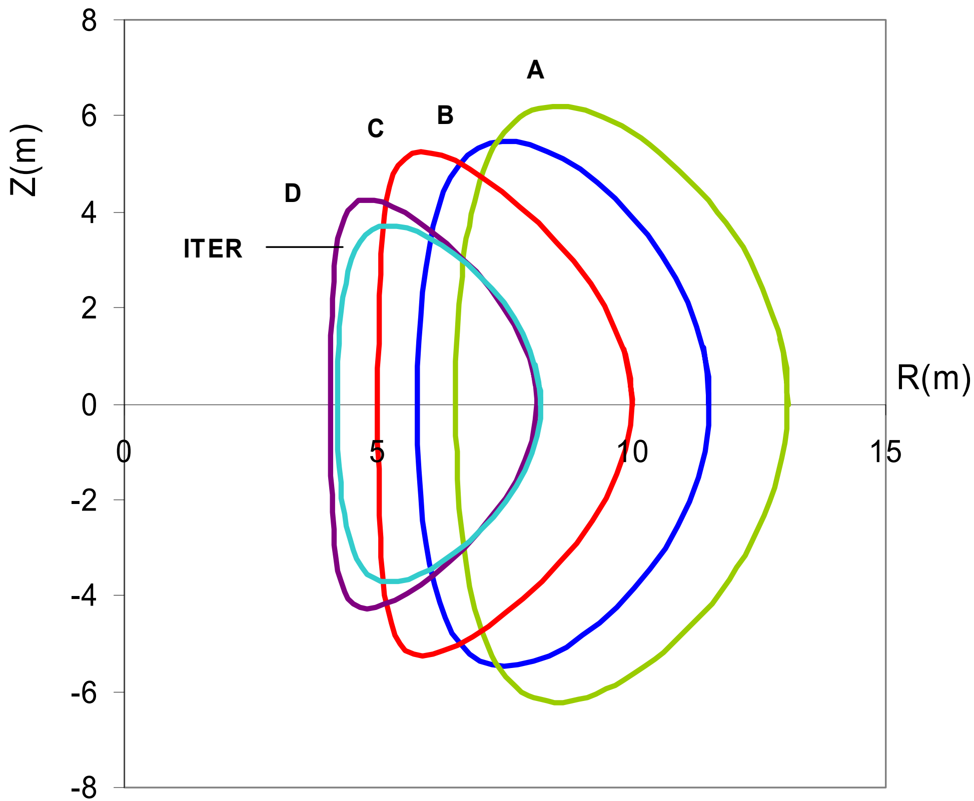
Key issues and dimensions

- All close to 1500 MWe net output.
- Fusion power determined by efficiency, energy multiplication and current drive power.
- So fusion power falls from A to D.
- Given the fusion power, plasma size mainly driven by divertor load constraints.
- So size falls from A to D.



Other key parameters

Parameter	Model A	Model B	Model C	Model D
Fusion power (GW)	**5.0**	3.6	3.4	**2.5**
Q	**20**	**13.5**	30	35
Current drive power fraction	**0.20**	**0.21**	**0.11**	**0.06**
Wall load (MW/m^{2})	**2.2**	2.0	2.2	**2.4**

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Direct and external costs

For any power source, there are two contributions to the cost of electricity:

- Direct costs: constructing, fuelling, operating, maintaining, and disposing of, power plants.
- External costs: environmental damage, adverse health impacts.

Direct costs: scaling (1)

- The variation of direct cost of electricity with the main parameters is well fitted by:

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

where, in descending order of relative importance to economics:

- A is the plant availability, which primarily depends upon the **lifetime of the blankets**, before they need to be replaced, and the **reliability of all the systems**, especially the in-vessel components;
- η_{th} is the thermodynamic efficiency, which primarily depends upon the operating temperature and energy multiplication of the blanket;
- P_e the net electrical output of the plant, which can be chosen;
- β_N is the **normalised plasma pressure**;
- N is the **ratio of the plasma density to the Greenwald density**.

It may be seen that there are no "show-stopping" target minimum values associated with any of these parameters, but they are all potential degraders of economic performance.

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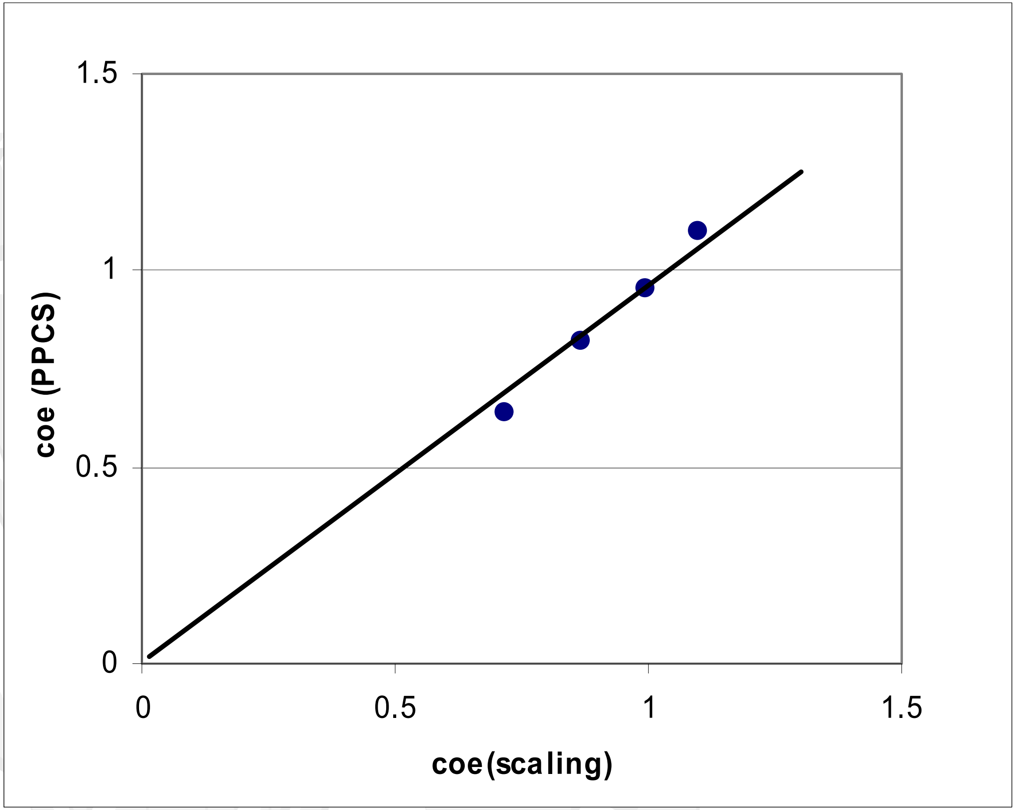
Direct costs: scaling (2)

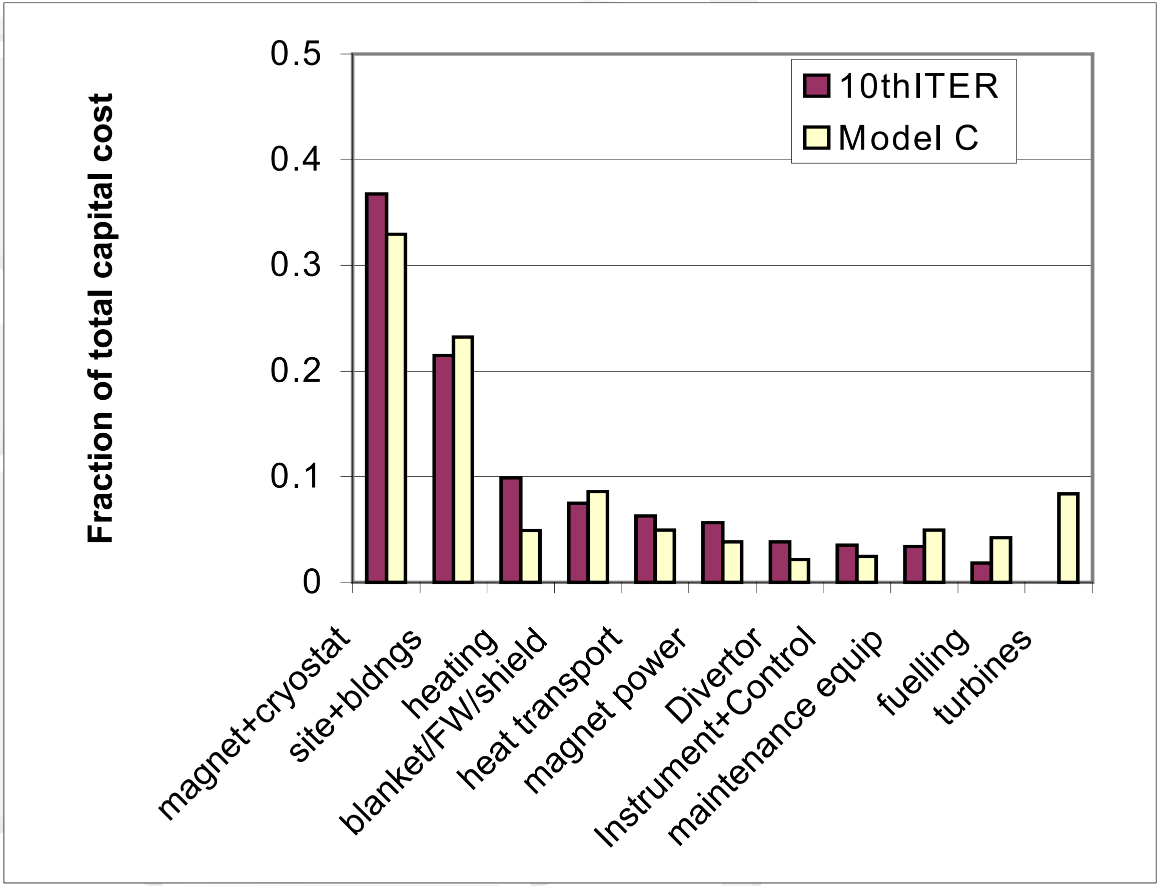
- Cost of electricity is well represented by the scaling opposite.
- The figure shows systems code calculations for Models A to D, against the scaling.
- Shows that PPCS Models are good representatives of a much wider class of possible designs.



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

Capital costs: comparison with ITER

- **Comparison between ITER and Model C fractional capital costs on the same basis.**
- **Good agreement, illustrating robustness of analyses**



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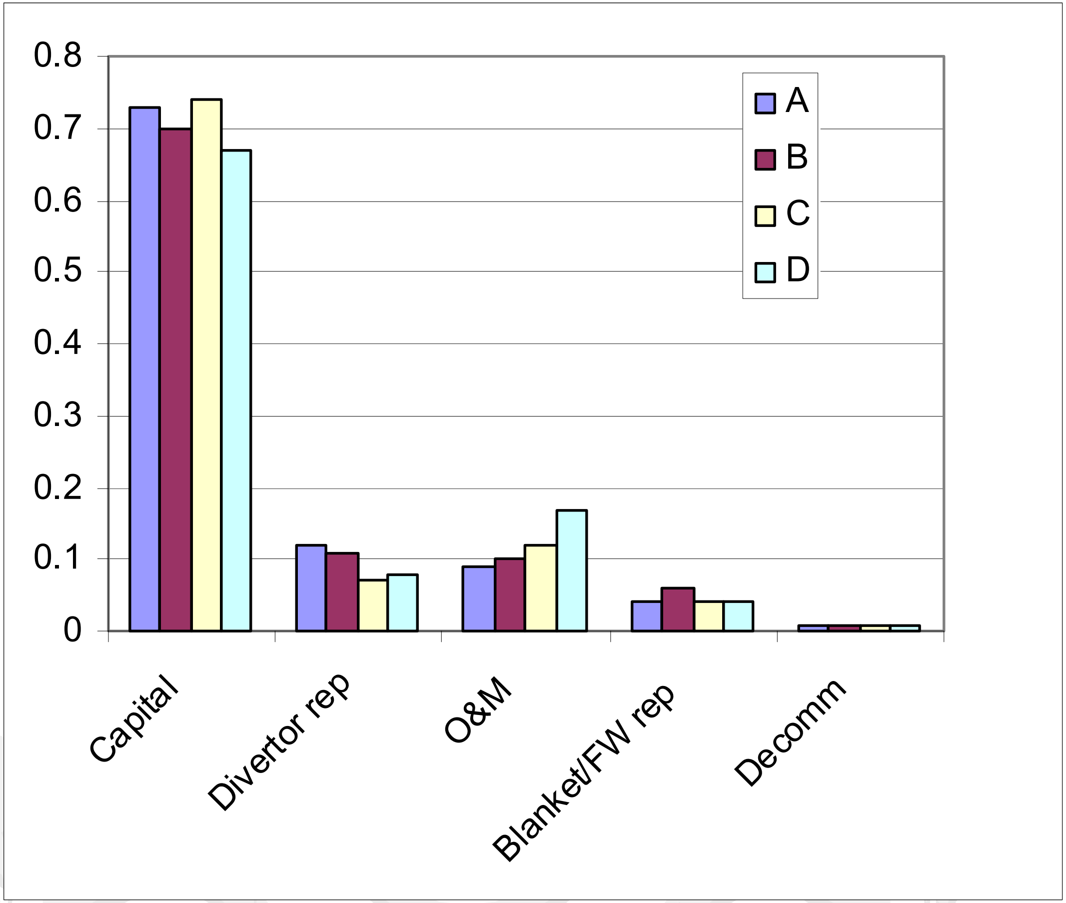
Breakdown of direct cost of electricity



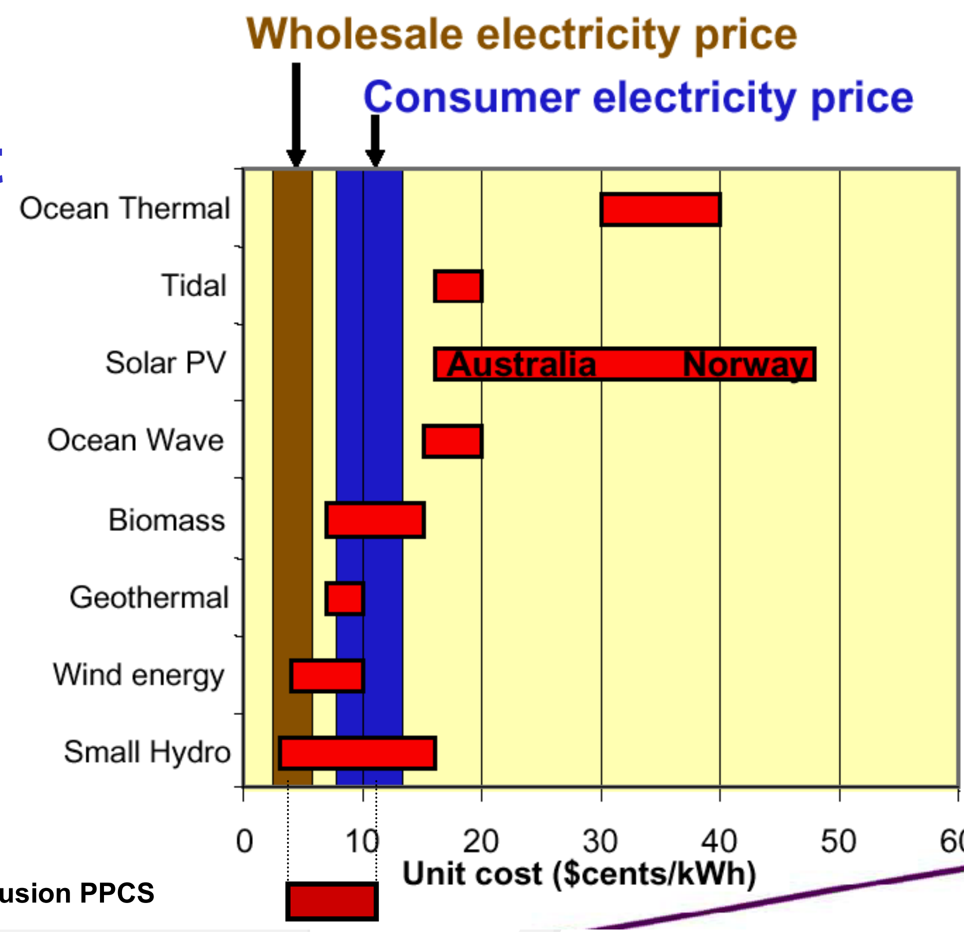
The main components of the cost of electricity for each Model, expressed as a fraction of the total.

Direct cost of fusion electricity

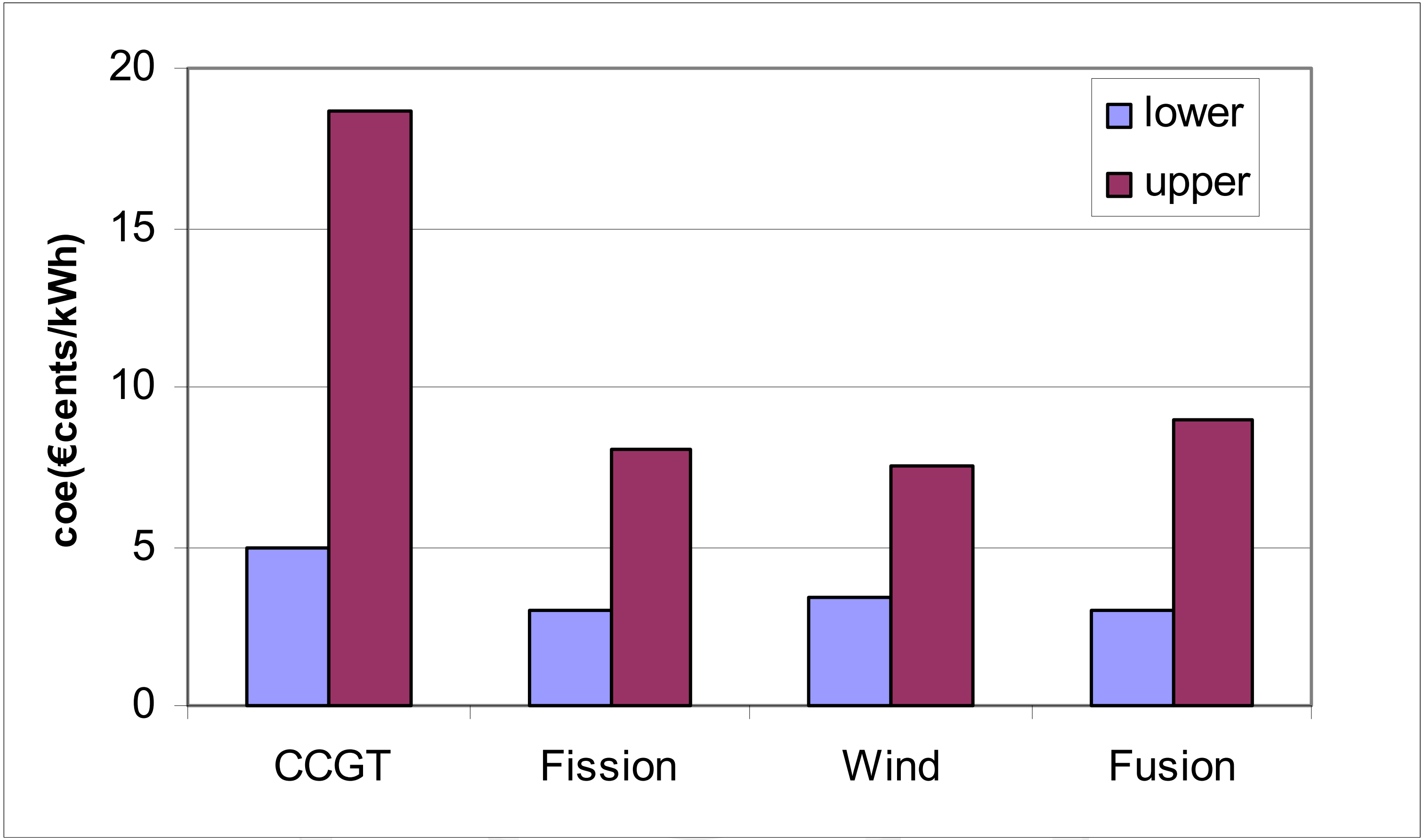
Model	Cost of electricity (Eurocents/kWh)
PPCS A	5 -9
PPCS B	4 - 8
PPCS C	4 - 7
PPCS D	3 - 5

Direct costs: comparisons (1)

- Depending on the Model and learning effects, PPCS direct cost of electricity ranges from 3 to 9 Eurocents/kWh.
- Even the near-term Models are acceptably competitive.



Direct costs: comparisons (2)



Even the near term Models are acceptably competitive.

External costs

Model	External cost (Eurocents/kWh)
A	0.09
B	0.07
C	0.06
D	0.06

- These are all small: comparable to wind power.
- Arises directly from environmental advantages of fusion.
- Conventional construction accidents are major contributor!

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Safety and environment: key questions

Given that:

- The designs satisfy economic objectives;
- The plasma physics basis is new;
  and so the parameters are substantially different than in earlier European studies:

- Do the good safety and environmental features still hold?

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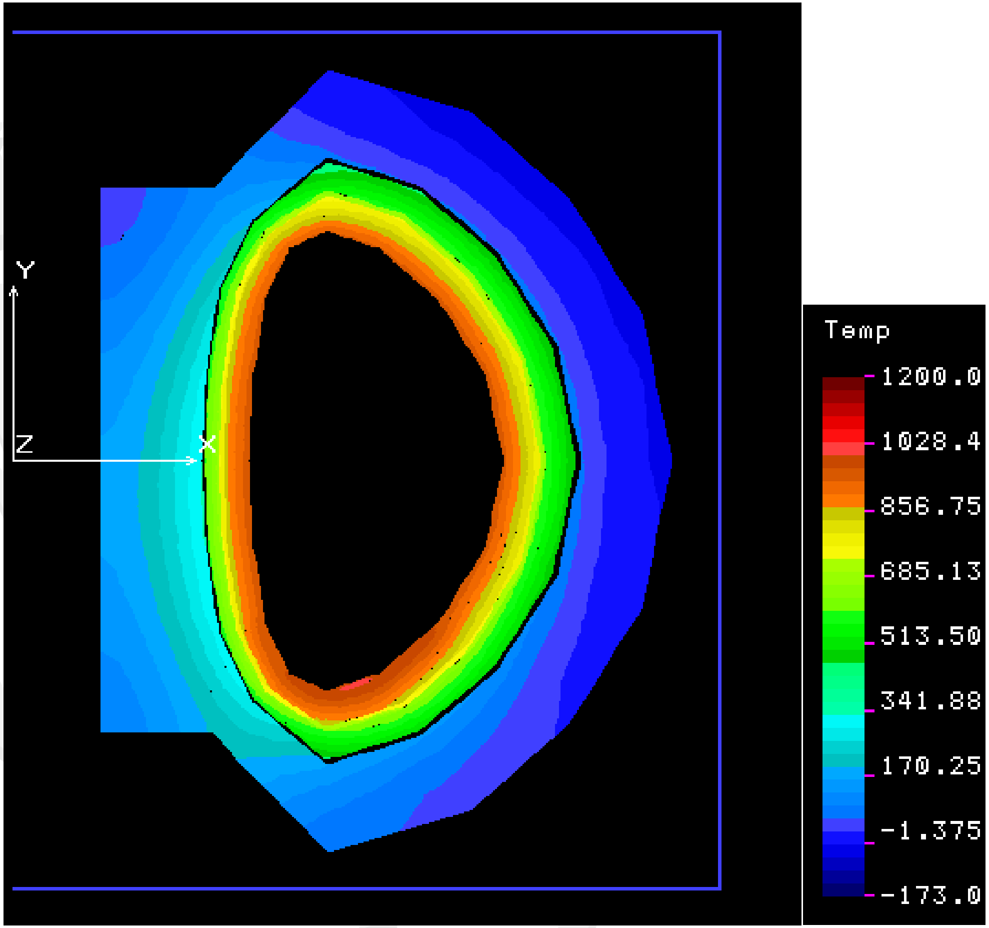
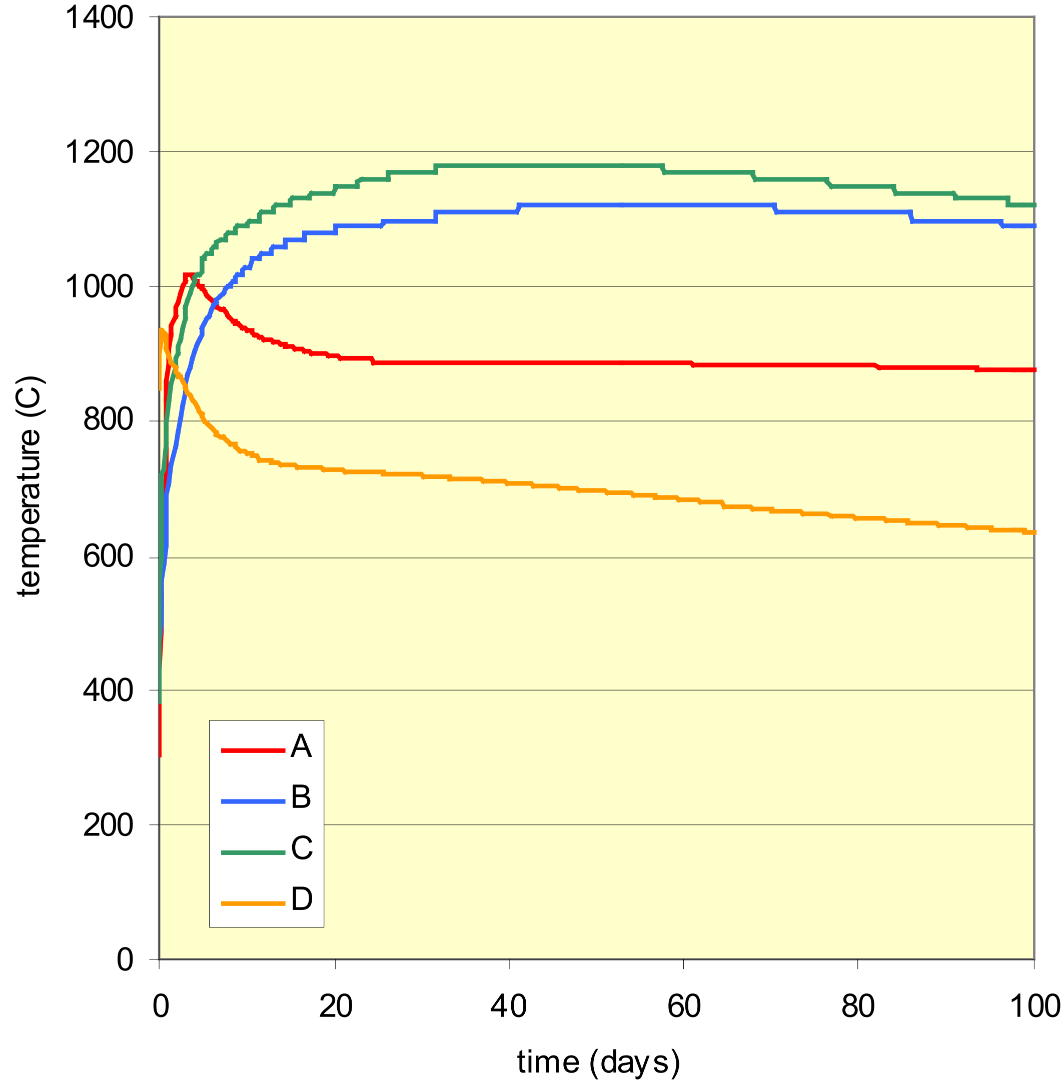
Bounding accident (1)

- <u>Worst case accident analysis</u>: complete unmitigated loss of cooling; no safety systems operation; conservative modelling.
- Temperature transients: example opposite - Model A after ten days.
- <u>Maximum temperatures never approach melting.</u>



Bounding accident (2)

Temperature histories in the outboard first walls of PPCS A - D, in the bounding accident scenario.



- **Maximum temperatures never approach melting.**

Bounding accident: maximum doses

The bounding accident analysis continues with:

- mobilisation; transport within the plant; release and transport in environment; leading to:

CONSERVATIVELY CALCULATED WORST CASE DOSES FROM WORST CASE ACCIDENTS

MODEL A: 1.2 mSv

MODEL B: 18.1 mSv

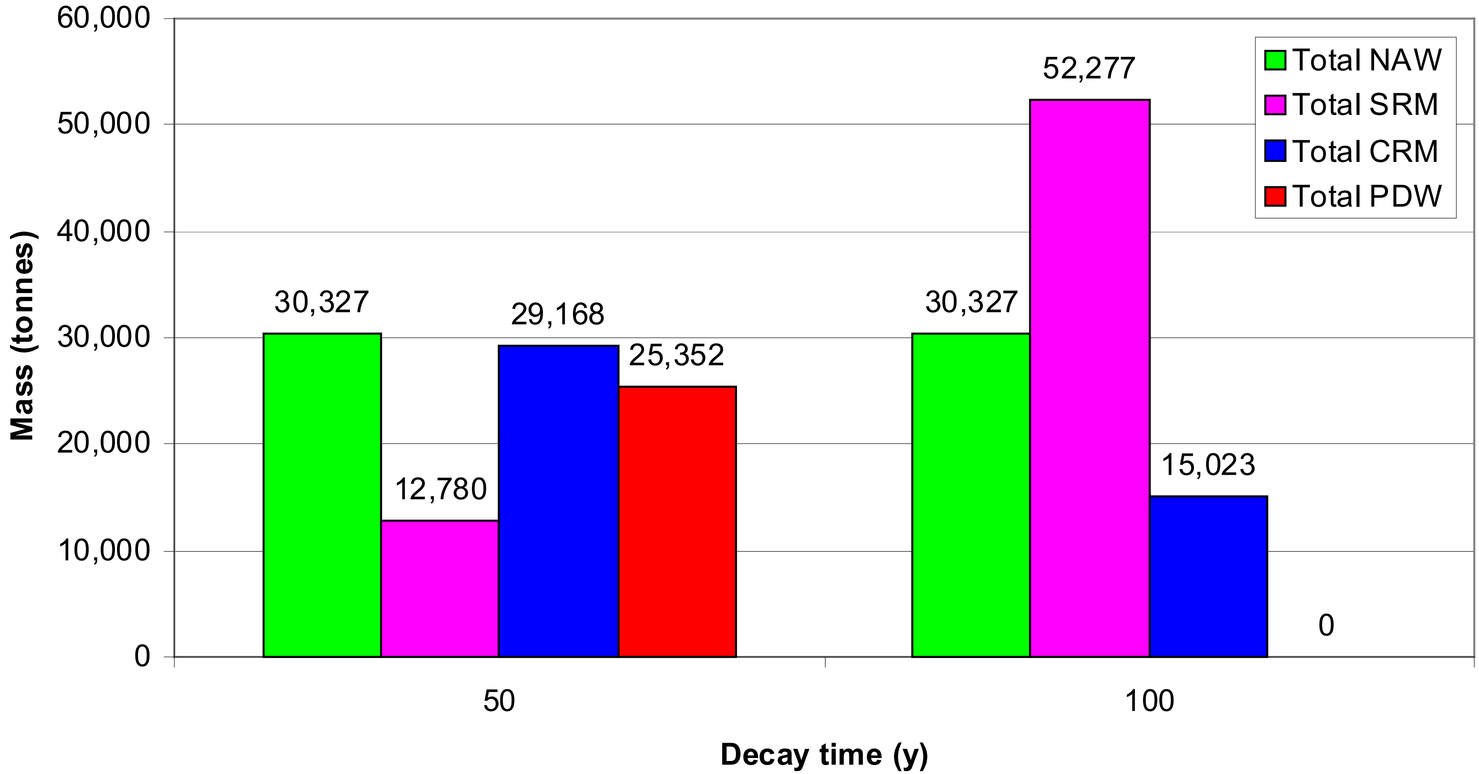
- Not much greater than - or comparable with - typical annual doses from natural background.
- Model C and Model D worst case doses assessed to be similar or lower.

Effluents

- <u>Doses from effluent releases are extremely low, even on a conservative basis of evaluation.</u>

- The calculated doses were among the inputs to the assessment of external costs. As stated earlier, these are very low.

Categorisation of activated material at 50 and 100 years after shutdown



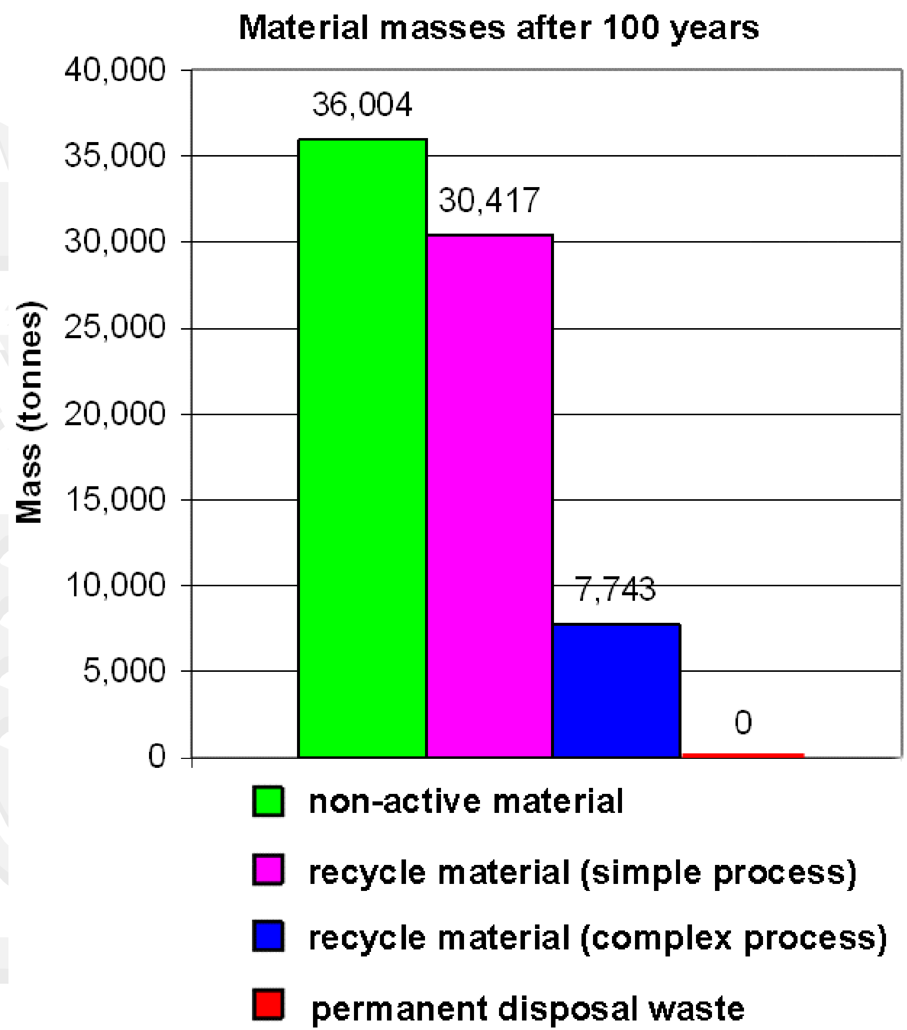
Masses for Model C. Note that all replacements of components are included.

Disposition of activated materials

For ALL the Models:

- **Activation falls rapidly: by a factor 10,000 after a hundred years.**
- **No waste for permanent repository disposal.**
- **No long-term waste burden on future generations.**

(Figure shows data for Model B: others are similar.)



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Overall summary

- Even near-term Models have acceptable economics.
- All Models have very good safety and environmental impact, now established with greater confidence.
- Studies suggest that helium-cooled lithium-lead (without SiC) is probably a very promising additional near term Model: a study is under way.

Strategic implications

PPCS shows that:

- **The main thrusts of the European fusion programme are on the right lines.**
- **Economically acceptable fusion power plants, with major safety and environmental advantages, are now accessible by a "fast-track" development of fusion, through ITER and without major materials advances.**
- **There is potential for a more advanced second generation of power plants.**

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