Performance, Safety and Economy of a Fusion Reactor

J. Rapp
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Contents

• Introduction
• Performance
• Safety
  – Availability
  – Efficiency
  – Plasma Pressure
  – Plasma Density

• EU Power Plant Conceptual Studies
• Conclusions
Introduction: EU fusion strategy

Next Step

Scientific and technological feasibility of fusion energy

ITER + IFMIF

DEMO

Qualification of components and processes

DEMO Studies

Fusion Plant (1st of a kind)

• High availability
• Safe and environmental-friendly
• Economically acceptable

Power Plant Conceptual Studies (PPCS)
Introduction: power plant requirements*

- **Safety / Environment**
  - no need for emergency evacuation, no active systems for safe shut-down, no structure melting following LOCA (loss of coolant accident)
  - minimum wastes to repository

- **Operation**
  - steady state, ~ 1 GWe, base load
  - availability 75 ÷ 80 %, with only few unplanned shut-downs/year

- **Economics**
  - public acceptance could be even more important than economics
  - economic comparison among equally acceptable energy sources

* Recommendations from EU utilities/industry
Introduction: fusion reactor
Performance

History:

Future: Uncertainty is physics of alpha particle heating

- **JET 1991 (EU):** 1.7 MW
  - First controlled DT fusion experiments on earth

- **TFTR 1994 (US):** 11.5 MW

- **JET 1997 (EU):** 16 MW
  - Energy amplification Q~0.65
  - Alpha particle heating clearly observed and consistent with theory

- **ITER 2015-2020:** 500-700 MW
  - Energy amplification Q>10

- **Power plant:** 1500-2000 MW (thermal)
  - Q~30-40
Introduction
Performance
Safety
Economy
EU Power Plant Conceptual Studies
Safety: requirements

- Total loss of coolant: no melting, without relying on any active safety system
- Doses to the public after most severe accident driven by in-plant energies: no evacuation
- No long term disposal of rad-waste, if adequate recycling implemented

- Minimize in-vessel hazards: Tritium and Dust inventory
- Low activation structural materials
Two basic mechanisms for long term fuel retention:

- Deep Implantation, Diffusion/Migration, Trapping
- Codeposition

Short term retention (Adsorption: dynamic retention)
~ Recovered by outgasing

Safety: tritium inventory
Safety: tritium inventory

Tritium inventory is strongly linked to material migration

- Largest erosion in outer divertor, but material mainly stays in outer divertor locally
- Main erosion source in main chamber
- Poloidal flow brings material to inner divertor
- Inner divertor is net deposition zone
- Material builds up as Tritium-rich hydro-carbon layers
- Materials eventually flakes off and becomes dust
Safety: tritium inventory

All C reaches tritium limit (350g) in less than 25 discharges

All-W eliminates tritium problem, but neutron effects need to be considered

Tritium retention in Reactor will be different, because of hot walls and is very likely to be lower
Safety: dust

Potential release in environment

W is the major radioactive source
Dust contains trapped Tritium

Hydrogen production when hot dust reacts with steam

Be major contributor
with carbon: \( \Rightarrow 6 \text{ kg C}, 6 \text{ kg Be}, 6 \text{ kg W limit} \)
without carbon: \( \Rightarrow 11 \text{ kg Be}, 230 \text{ kg W limit} \)

Possible pure Dust or Hydrogen/Dust explosion

Be, C, W involved
Safety: dust

Dust in ITER

- Total dust limit not reached before scheduled maintenance and exchange of divertor cassettes
- Dust will be vacuumed from divertor floor during maintenance period
- Hence dust is unlikely to be problem

![Graph showing Gross erosion in ITER (g) vs. Time (s)]

- 1 ton cold dust limit
- 230 kg W hot dust limit
- 6 kg C hot dust limit
- Disruption estimate
- Number of 400s ITER discharges: 2,500 to 25,000

Hence dust is unlikely to be a problem.
Safety: radioactive waste

Radioactive waste not inherent to the reaction

Several choices possible
Economy: cost of electricity

Most of the plant is conventional, not fusion specific!
Economy: cost of electricity

Composition of direct costs

Fuel costs are only accounting for 0.5%! 
Economy: cost of electricity

Capital cost for fusion power plant

Major costs:
- Blanket
- Super-conducting coils

Site-Buildings

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost 1990 MECU (PROCESS MODEL)</th>
<th>Cost 1990 MECU (ITER-TAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diverter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-conducting PF Coils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-conducting TF Coils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote Maint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I&amp;C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Supplies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum Systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site+Buildings</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The plant must be an affordable, reliable, maintainable energy source and all of these factors are contained in the cost of electricity:

\[\text{coe} = [C_{AC} + (C_{O&M} + C_{SCR} + C_F) \times (1 + y)^Y + C_{D&D}, \text{ where}]

\[(8760 \times P_E \times P_f)\]

- \(C_{AC}\) is the annual capital cost charge (total capital cost \times Fixed Charge Rate)
- \(C_{O&M}\) is the annual operations and maintenance cost
- \(C_{SCR}\) is the annual scheduled component replacement cost
- \(C_F\) is the annual fuel costs
- \(y\) is the annual escalation rate
- \(Y\) is the construction and startup period in years
- \(P_E\) is the net electrical power (MWe)
- \(P_f\) is the plant capacity factor
- \(C_{D&D}\) is the annual decontamination and decommissioning converted to mills/kWhr
Economy: cost of electricity

Scaling of cost of electricity with plant capacity

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

A: Availability
\( \eta_{\text{th}} \): thermodynamic efficiency
\( \beta_N \): normalized plasma pressure
N: normalized plasma density
Economy: availability

Operational Time is the power production time over a set period of time.

Scheduled Down Time is the sum of regularly scheduled maintenance periods for the power core, other reactor plant equipment, and balance of plant equipment.

The Unscheduled Down Time is the summation of maintenance times to repair unexpected operational failures that cause the plant to cease power production.

\[
\text{Availability} = \frac{\text{Operational Time}}{\text{Operational Time} + \text{Scheduled Down Time} + \text{Unscheduled Down Time}}
\]
Economy: availability

Lifetime of components

Main driver of scheduled maintenance: divertor and blanket
Economy: availability

Transient heat losses will limit the divertor lifetime of a reactor here ITER:

8.5MJ

- Transient heat losses of 1 ms duration are caused by edge instabilities (so called ELMs)
- Large ELMs are unacceptable
- Mode of Operation should avoid ELMs

Energy loss from plasma due to transients

F. Federici et al., PPCF 45 (2003) 1523
Economy: availability

• Reduction of transient heat loads possible, but most probably only on the expense of performance

➢ Trade-off between availability and unit size
Economy: availability

Improvement of availability as tolerable blanket neutron fluence is increased
Economy: availability

Number and length of maintenance shutdowns is important factor

Optimum major radius as a function of shutdown length to maintain high availability
## Shutdown Timeline

<table>
<thead>
<tr>
<th>Maintenance Action</th>
<th>Duration of Serial Operations, h</th>
<th>Duration of Parallel Operations, h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shutdown and preparation for maintenance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooldown of systems, afterheat decay</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>De-energize coils, keep cryogenic</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Pressurize power core with inert gas</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Drain coolants, fill with inert gas</td>
<td>6.0</td>
<td>30</td>
</tr>
<tr>
<td>Subtotal for shutdown and preparation</td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>

## Startup Timeline

<table>
<thead>
<tr>
<th>Maintenance Action</th>
<th>Duration of Serial Operations, h</th>
<th>Duration of Parallel Operations, h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Startup tasks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Move transporters and casks to hot cell</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Evacuate core interior</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Initiate trace or helium heating</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Fill power core coolants</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Bake out (clean) power core chamber</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Checkout and power up systems</td>
<td>4.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Subtotal for startup</td>
<td>34.0</td>
<td></td>
</tr>
</tbody>
</table>

Assumes streamlined processes for core evacuation, bakeout, and coolant fills

Dominated by cooldown of systems and core

= 2.6 days

Each shutdown/start-up results in ~0.7% availability decrement
Economy: availability

Remote handling is of very importance to improve shutdown efficiency.

Example: In-Vessel Transporter/Blanket Module Demo

Example: Blanket segment
Economy: thermal efficiency

$$\eta = 1 - \sqrt{\frac{T_c}{T_h}}$$

Conclusion:
- Increase temperature on hot side of conversion system
- Helium or Lithium cooling
- Hot in-vessel walls
Economy: thermal efficiency

Helium cooled divertor

Finger unit

W alloy

18 mm

ODS Steel

9-Finger-Unit

Stripe-Unit

Panel

Divertor

1-finger mock-up

Radial cooling - basic principle

Heat transfer promoter

inlet/outlet separation cartridge

Strip structure / manifolds
Economy: plasma pressure

Normalized pressure $\beta_N$: ratio of kinetic energy to energy stored in magnetic field
Economy: plasma pressure

Standard tokamak operation: the H-mode scenario

With additional power:
Steep edge pressure gradient: H-mode scenario
Standard tokamak operation: the H-mode scenario

Advantages:
Natural plasma state in the divertor tokamak configuration with additional heating power.
Minimal control requirements.

Disadvantages:
Limited plasma pressure achievable $\beta_N \sim 2-3$.
Instabilities associated to large edge pressure gradient ("ELMs").
Economy: plasma pressure

Advanced Tokamak modes of operation with internal transport barrier

Advantages:
Improved core confinement and better stability properties leading to higher plasma pressure achievable $\beta_N \sim 4$, as required for high DEMO efficiency.

Challenges:
Operation in steady state with advanced control techniques:
- Plasma Profiles
- Plasma Instabilities
Economy: density limit

\[ Q = \text{fusion power out} \]
\[ \text{ext. power in} \]

\[ T \]
\[ n \]
\[ \tau_E \]

\[ Q_{\text{DT}} = 1 \]

Ignition

ITER

optimal

sub-optimal

Challenge

Lawson parameter, \( n \tau_E \left(10^{20} \text{ m}^{-3} \text{ s}^{-1}\right) \)

Central ion temperature, \( T_i(0) \) (keV)

D-T

D-D

\( \tau_E \)

\( N = n/n_G \)

density limit

Economy: density limit
Power Plant Conceptual Study

5 different plant concepts have been studied

Version A, AB and B are moderate concepts

Version C and D are advanced concepts with increased plasma pressure, density and thermal efficiency
## PPCS: Plant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A</th>
<th>B</th>
<th>AB</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Size ($GW_e$)</td>
<td>1.55</td>
<td>1.33</td>
<td>1.46</td>
<td>1.45</td>
<td>1.53</td>
</tr>
<tr>
<td>Fusion Power (GW)</td>
<td>5.00</td>
<td>3.60</td>
<td>4.29</td>
<td>3.41</td>
<td>2.53</td>
</tr>
<tr>
<td>Major Radius (m)</td>
<td>9.55</td>
<td>8.6</td>
<td>9.56</td>
<td>7.5</td>
<td>6.1</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>0.31/0.33</td>
<td>0.36</td>
<td>0.34</td>
<td>0.42</td>
<td>0.60</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>30.5</td>
<td>28.0</td>
<td>30.0</td>
<td>20.1</td>
<td>14.1</td>
</tr>
<tr>
<td>Plasma Density N</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Plasma pressure $\beta_N$</td>
<td>3.5</td>
<td>3.4</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Bootstrap Fraction</td>
<td>0.45</td>
<td>0.43</td>
<td>0.43</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td>$P_{add}$ (MW)</td>
<td>246</td>
<td>270</td>
<td>257</td>
<td>112</td>
<td>71</td>
</tr>
</tbody>
</table>
### PPCS: Nuclear Core

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
<th>Model AB</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>Eurofer</td>
<td>Eurofer</td>
<td>Eurofer</td>
<td>Eurofer</td>
<td>SiC/SiC</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>Helium</td>
<td>Helium</td>
<td>LiPb/He</td>
<td>LiPb</td>
</tr>
<tr>
<td>Coolant T in/out (°C)</td>
<td>285 / 325</td>
<td>300 / 500</td>
<td>300 / 500</td>
<td>480 / 700</td>
<td>700 / 1100</td>
</tr>
<tr>
<td>Breeder</td>
<td>LiPb</td>
<td>Li₄SiO₄</td>
<td>LiPb</td>
<td>LiPb</td>
<td>LiPb</td>
</tr>
<tr>
<td>TBR</td>
<td>1.06</td>
<td>1.12</td>
<td>1.13</td>
<td>1.15</td>
<td>1.12</td>
</tr>
<tr>
<td>Structural material</td>
<td>CuCrZr</td>
<td>W alloy</td>
<td>W alloy</td>
<td>W alloy</td>
<td>SiC/SiC</td>
</tr>
<tr>
<td>Armour material</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
<td>LiPb</td>
</tr>
<tr>
<td>Coolant T in/out (°C)</td>
<td>140 / 170</td>
<td>540 / 720</td>
<td>540 / 720</td>
<td>540 / 720</td>
<td>600 / 990</td>
</tr>
</tbody>
</table>

Optimisation of power conversion cycle allow to gain 4 percentage points in net efficiency.
PPCS: cost of electricity

Cost of electricity for the 4 power plant versions

![Graph showing the cost of electricity for the 4 power plant versions.](image-url)
PPCS: cost of electricity

Relative likelihood of the direct cost of electricity for range of assumptions on key physics and technology variables

Note: most optimistic case would be only half of lowest value
PPCS: cost of electricity

Internal cost of electricity ranges from 5-9 (model A) to 3-5 (model D) €cents/kWh

External cost ranges from 0.06 to 0.09 € cents/kWh

Even the near-term Models are acceptably competitive

Projected costs without subsidies Shell Renewables, 2003
To remember

Nuclear Fusion has made substantial progress

We are taking the next step now: ITER

ITER will demonstrate a burning plasma

Fusion Energy is safe

Fusion Energy will be competitive
 References and Acknowledgement

- EU Power Plant Conceptual Study, final report
  

- EU Socio-Economic Research on Fusion
  

- J. Roth et al., PSI-18, Int. Conference on Plasma Surface Interactions in Controlled Fusion Devices (Toledo, Spain, 26-30 May 2008)

- D. Maisonnier et al. 2006 Fusion Engineering and Design 81 1123-1130