The Fast Track to Fusion Power

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OUTLINE

■ The Looming Energy Crisis

- world energy use predicted ⇒ double by 2045; 80% currently from fossil fuels ⇒ climate change + running out (oil first)

■ What must be done?

- increased energy R&D (currently negligible [and decreasing] on $3 trillion p.a. scale of world energy market): improve efficiency, develop renewables, …

but apart from fossil fuels, solar (in principle) and nuclear fission, only fusion can ⇒ large fraction of need

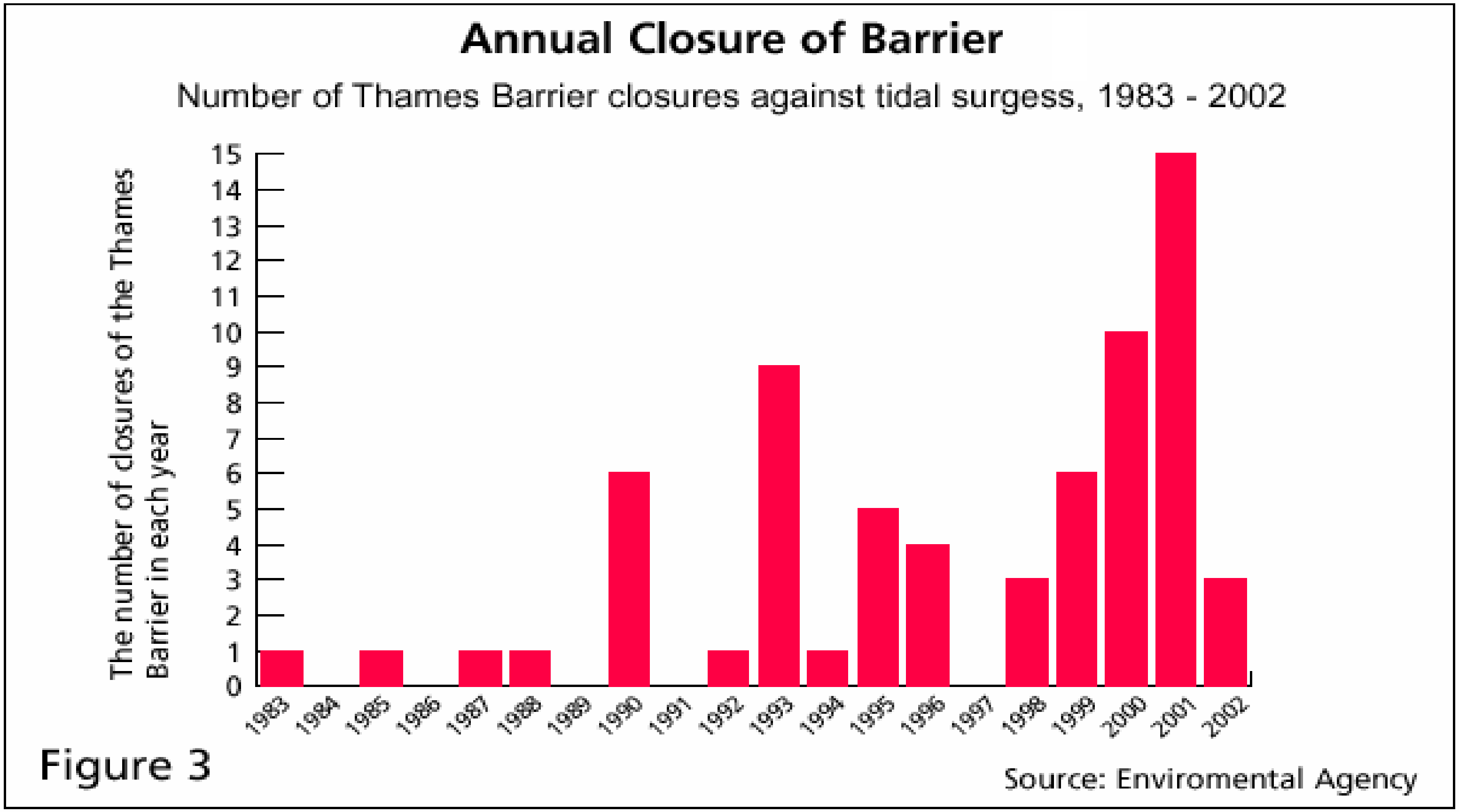
■ Prospects for fusion

- recent European Power Plant Study ⇒ power stations with acceptable performance accessible without major advances (barring surprises)

■ Fast Track to Fusion (model being developed at Culham)

+ argue programme with i) project-orientated fast track ⇒ DEMO (assumed conventional tokamak) ⇒ operation in ⊆ 30 years, plus ii) concept development: stellarators, spherical tokamaks,…: additional physics (feed ⇒ fast track) + insurance policy + alternative DEMOs/power stations?

Another Example of the Many Effects of Climate Change: Thames Barrier Now Closed Frequently to Counteract Increasing Flood Risk



ABATEMENT OF CLIMATE CHANGE?

Ambitious goal for 2050 (when total world power market predicted to be 30TW)

- limit CO_2 to twice pre-industrial level

Will require 20 TW of CO_2-free power (compared to today's world total power market of 13 TW)

US DoE "The technology to generate this amount of emission-free power does not exist"

Saudi saying "My father rode a camel. I drive a car. My son flies a plane. His son will ride a camel".

Is this true?

Very likely yes

Even using the US Geological Survey's estimate of the amount of remaining oil (which is significantly larger than all others), the peak of oil production cannot be much more than 20 years away (and many predict that production will peak in 5-10 years, and then fall ~ 3% p.a.)

Not much time to develop and deploy alternatives for transport [hydrogen - whence?;…], or introduce large scale conversion of coal to oil [+ CO2]

Note: gas will last longer; coal much longer

WHAT MUST BE DONE?

- **Recognise the problem, and that**
  - only new/improved technology can → solution (although fiscal measures ⇒ change behaviour of consumers + stimulate work by industry also essential)
  - increased investment in energy research essential*

    reasonable scale set by size of energy market ~ $3 trillion p.a. (so, e.g., 10% cost increase → $300 bn p.a.)
  - global co-ordination and collaboration (→ necessary funding and expertise; prevent duplication) essential

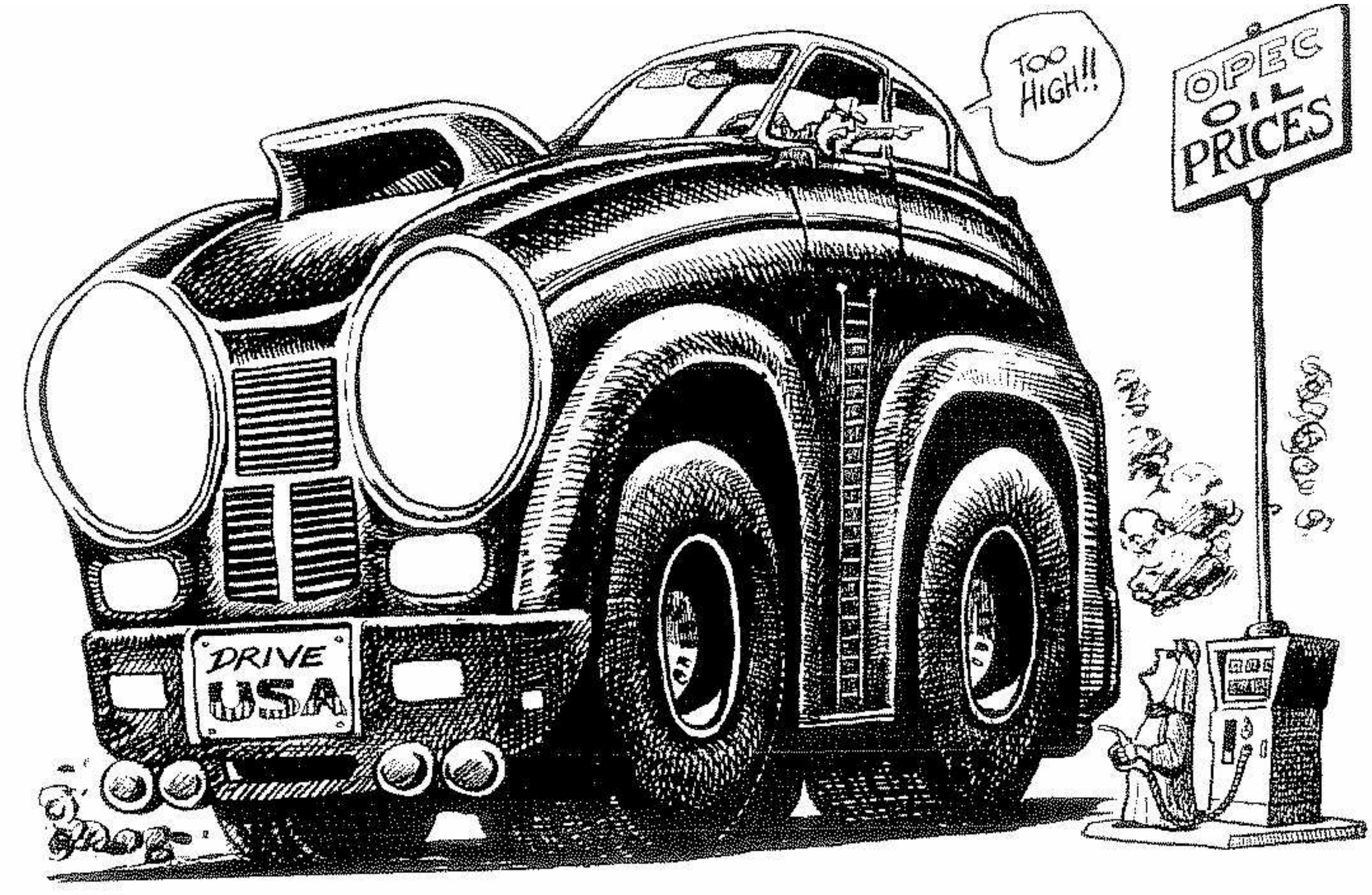
** public funding down 50% globally since 1980 in real terms; private funding also down, by (e.g.) 67% in USA in 1985-98*

FOCUS FOR RESEARCH

Must explore all avenues (solution = cocktail). Note - highly interdisciplinary: socio-economic, biological and physical sciences

- **Energy efficiency - yes** (will ameliorate but not solve problem)
- **CO_2 capture and sequestration - yes** (but big challenges, risks, and will add costs)
- **Renewables - yes** (but, apart from solar, do not have potential to meet large fraction of global demand). **Solar - yes** (enough in principle, but currently very expensive and mostly not where needed)
- **Energy storage* - yes** (essential for large scale use of intermittent sources)
- **Nuclear fission - yes** (at least until fusion available)

*** energy storage/retrieval inevitably ⇒ significant losses**



The Economist 29/5/04

■ Fusion - yes

Apart from fossil fuels (as long as they last), **solar** (not [yet?] viable/economical except for niche uses) **and nuclear** (→ fast breeders in the future), ***fusion is the only known technology capable in principle of producing a large fraction of world's electricity***

With so few options, I believe we must develop fusion as fast as possible - although success is not certain

The Joint European Torus (JET)/TFTR have produced 16/11 MW and shown that fusion can work

The big question is whether/when we can develop the technology → robust, reliable (⇒ economic) fusion power stations

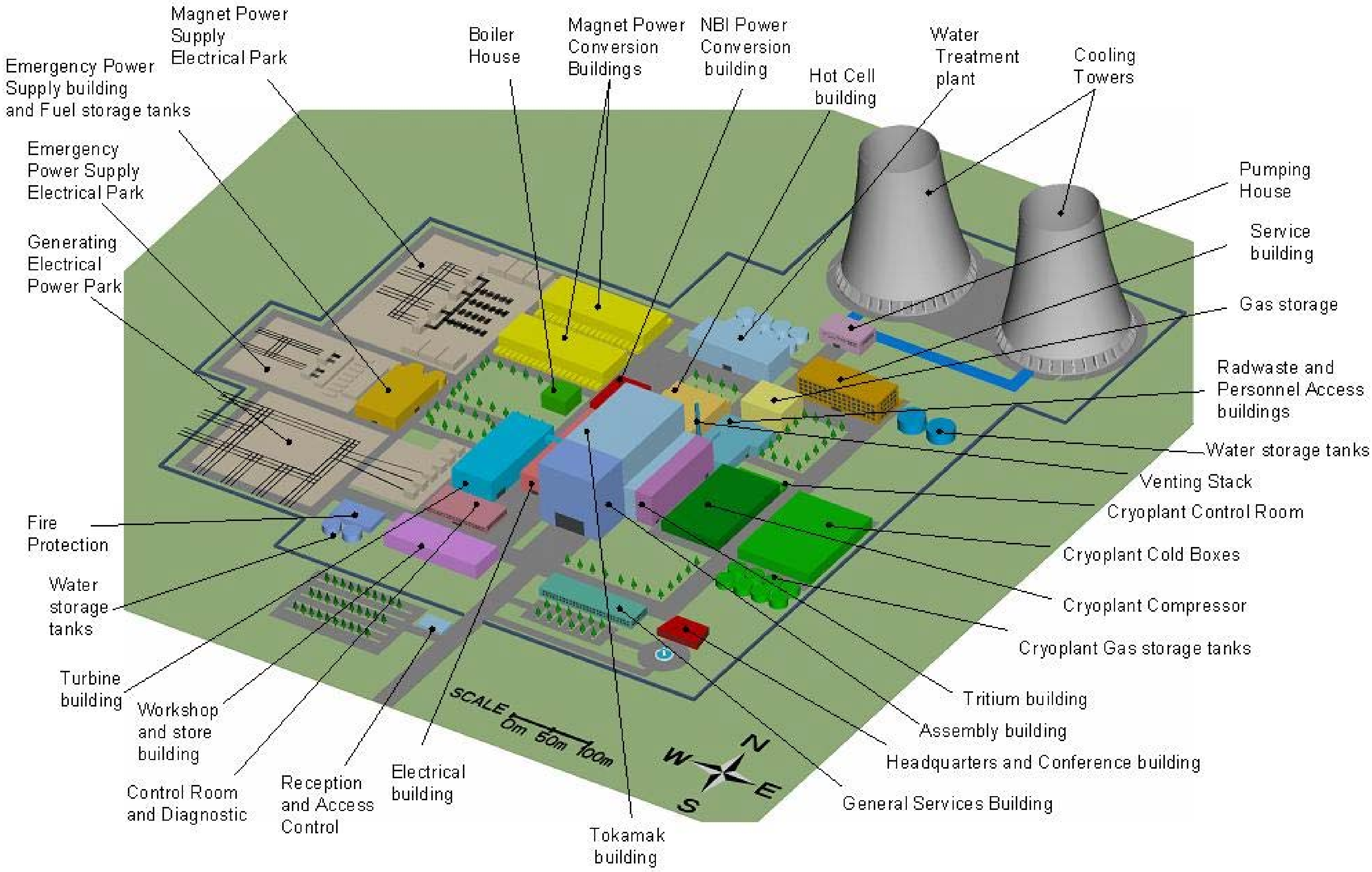
Before turning to the European Fusion Power Plant Studies, note that

some of the first studies of fusion power plants and fusion economics were initiated by the great fusion pioneer R S (Bas) Pease (former Director of the UK Fusion Programme & Director of Culham and Chairman of the IFRC) who died two weeks ago. Bas's concluding summary of a 1956 symposium included the remark

"…Our vision is of a power station, sited perhaps on the coast, with a pipe bringing water from the sea, helium leaving by the chimney and electrical power flowing into the grid. We do not know what to put inside the power station (*laughter*)**…"**

We have come a long way since then...

General layout



European Fusion Power Plant Studies
(to be published shortly)

- **Four "Models", A - D, were studied** as examples of a spectrum of possibilities (parameters differ substantially from earlier studies)
- **Models range from near term plasma physics and materials (A) to advanced (D)**
- **Systems code varied the parameters** of the possible designs, subject to assigned plasma physics and technology rules and limits, **to produce economic optimum**

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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**

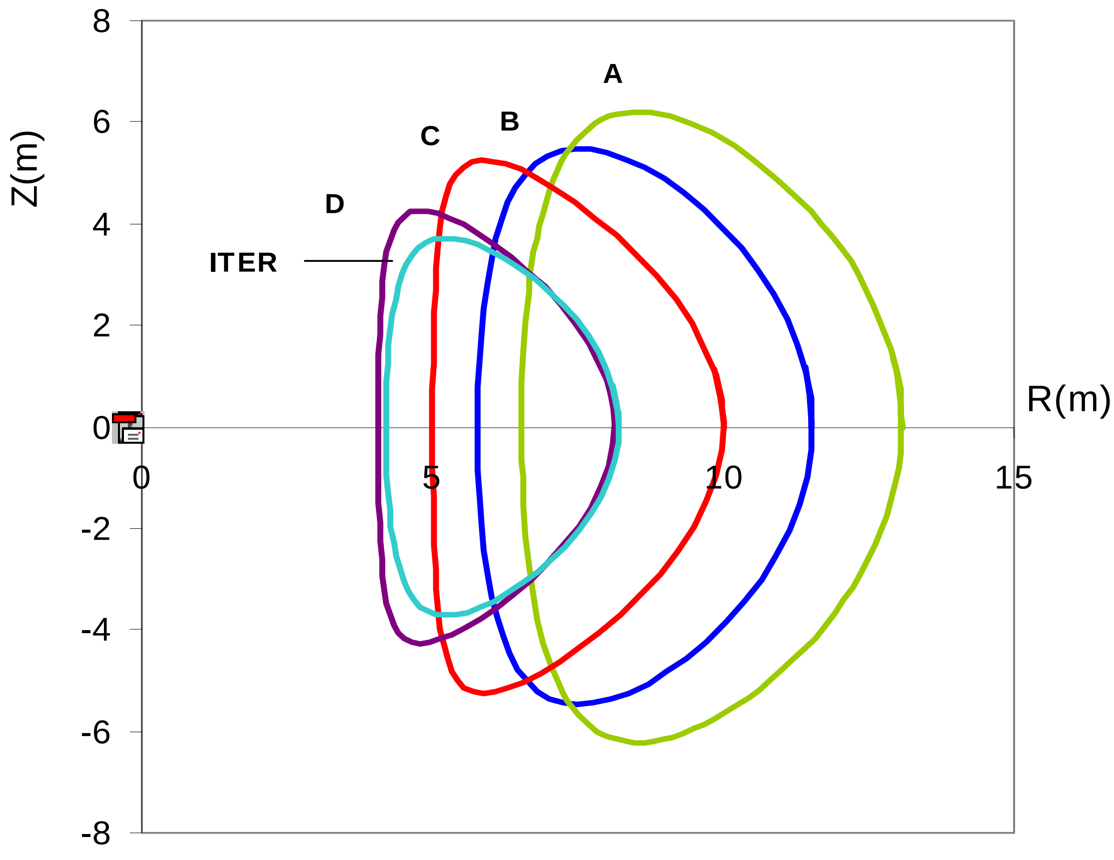
- Models C & D: progressive improvements in performance - especially shaping, stability and divertor protection

Materials basis

Model	Divertor	Blanket structure	Blanket other	Blanket Temperature
A	W/Cu/water	Eurofer	LiPb/water	300C
B	W/Eurofer/He	Eurofer	Li_4SiO_4/Be/He	300-500C
C	W/Eurofer/He	ODS steel & Eurofer	LiPb/SiC/He	450-700C
D	W/SiC/LiPb	SiC	LiPb	700-1100C

Fusion power and dimensions

- **All close to 1500 MWe net output**
- Thermodynamic efficiency increases with temperature (A⇒D)
- So **fusion power falls from A (5.0 GW) to D (2.5 GW)**
- and **size (and cost) falls from A to D**



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Outcome of European PPCS

- **Cost of electricity falls**

A (5-9 euro-cents/kW-hr) ⇒ D (3 - 5 cents)

[remarks on costs vs. parameters later]

- **Safety and environmental features excellent** (external costs [to health, environment] ~ wind power)

- **Economically acceptable fusion power stations**, with major safety and environmental advantages, **seem to be accessible on a fast- track** through ITER + material testing by IFMIF (but without major material advances)

CULHAM FAST TRACK STUDY*

(Builds on important work of Lackner, Andreani, Campbell, Gasparotto, Maisonnier, Pick)

- **Idea ⇒ develop fast track model + critical path analysis for development of fusion**

⇒ prioritise R&D

⇒ motivate support for, and drive forward, rapid development of fusion

Work needs to be taken forward by wider community (e.g in framework of EFDA)

* Preliminary ⇒ public soon

Essence of the Fast Track (I)

First stage

ITER

IFMIF on the same time scale

Second stage

DEMO (assumed to be a conventional tokamak): for final integration and reliability development

Realistically, there may be several DEMOs, roughly in parallel

Third stage

Commercial power

Essence of Fast Track (2)

Assume a major change of mind-set, to a disciplined project-oriented “industrial” approach to fusion development + adequate funding

Compare fusion with the way that flight and fission were developed! There were the equivalents of many DEMOs and many materials test facilities (~ 24 materials test reactors).

Approach

- Motives and opportunities (from power plant studies)
- Issues, and their resolution by devices
- Prioritisation, focus and co-ordination to speed the programme
- "Pillars" - ITER + IFMIF + existing tokamaks (JET,JT60,…)
- "Buttresses" to reduce risks (and perhaps speed up the programme)

Technical targets from safety & environmental and economic requirements

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

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

In descending order of relative importance to economics:

A - plant availability

η_{th} - thermodynamic efficiency

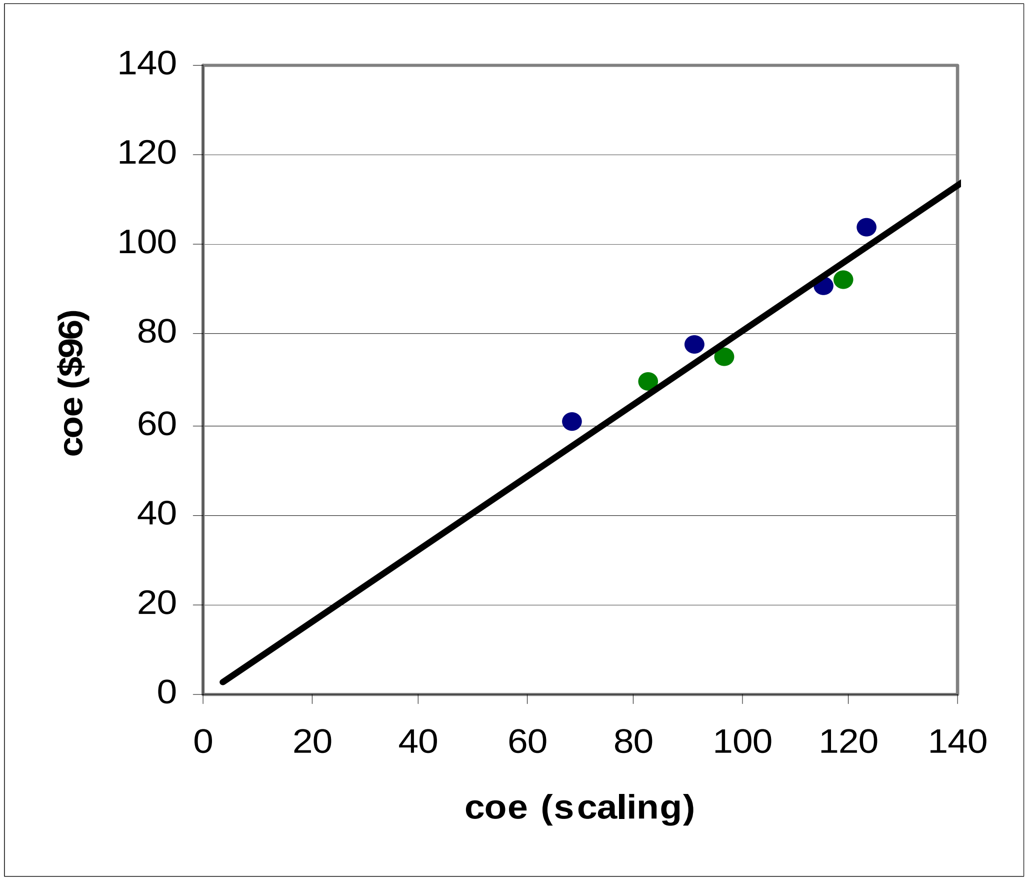
P_e - net electrical output of the plant (which can be chosen)

β_N - normalised plasma pressure

N - ratio of the plasma density to the Greenwald density.

It seems there are no “show-stopping” minimum values associated with any of these parameters, although all are potential degraders of economic performance

PPCS and ARIES (1,RS,AT) on Same Scaling*



* with divertor assumptions brought into agreement

Issues and their resolution: pillars only

Issue	Today's expts	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Disruption avoidance	2	3		3	R	R
Steady-state operation	1	3		3	r	r
Divertor performance	2	3		r	R	R
Burning plasma Q>10		3		R	R	R
Power plant plasma performance	1	3		3	R	R
T self-sufficiency		1		3	R	R
Materials characterisation			3	R	R	R
Plasma-facing surface lifetime	1	1		2	3	R
FW/blanket materials lifetime		1	2	2	3	R
FW/blanket components lifetime		1		1	3	R
Divertor materials lifetime		1	2	2	3	R
NB/RF heating systems performance	1	3		R	R	R
Electricity generation at high availability				1	3	R
Superconducting machine	1	3		R	R	R
Tritium issues	1	3		R	R	R

Key:

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
r	Solution is desirable
R	Solution is essential

BUTTRESSES

- **Multi-beam -** study damage from irradiation with heavy ions (Xe?) to material samples with implanted Helium (+ hydrogen?)

- **Satellite tokamak -** to be operated in parallel with ITER, as part of ITER programme, to test new modes of operation, plasma technologies,...

- **Component Test Facility (CTF) -** to test engineering structures (joints, …) in neutron fluences typical of fusion power stations (see talk on Friday by Howard Wilson on work at Culham and Princeton on spherical tokamak based CTFs)

Key assumptions: pillars

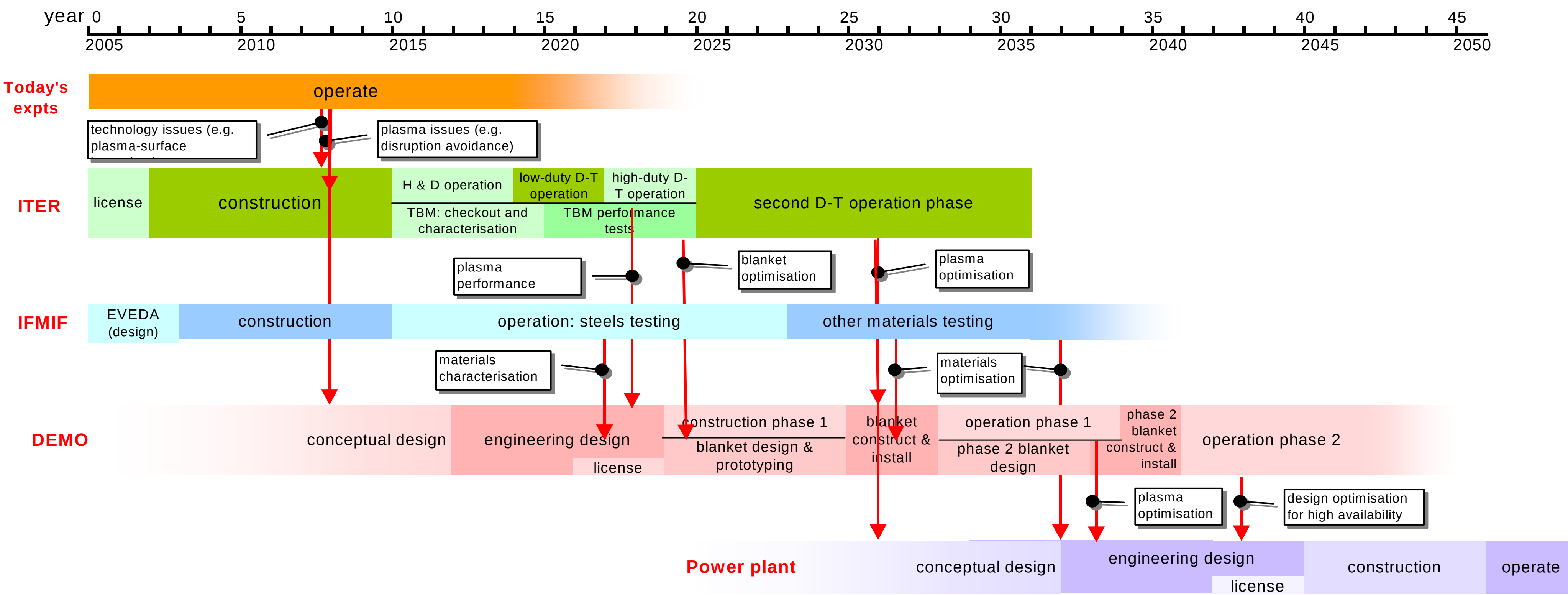
First stage

- ITER immediately!
- Acceleration of ITER exploitation, by focussing programme of existing Tokamaks (JET,…) on supporting rapid achievement of ITER's goals
- Acceleration of IFMIF design and construction (by using money)
- Prioritisation of ITER & IFMIF programmes, in favour of DEMO relevance

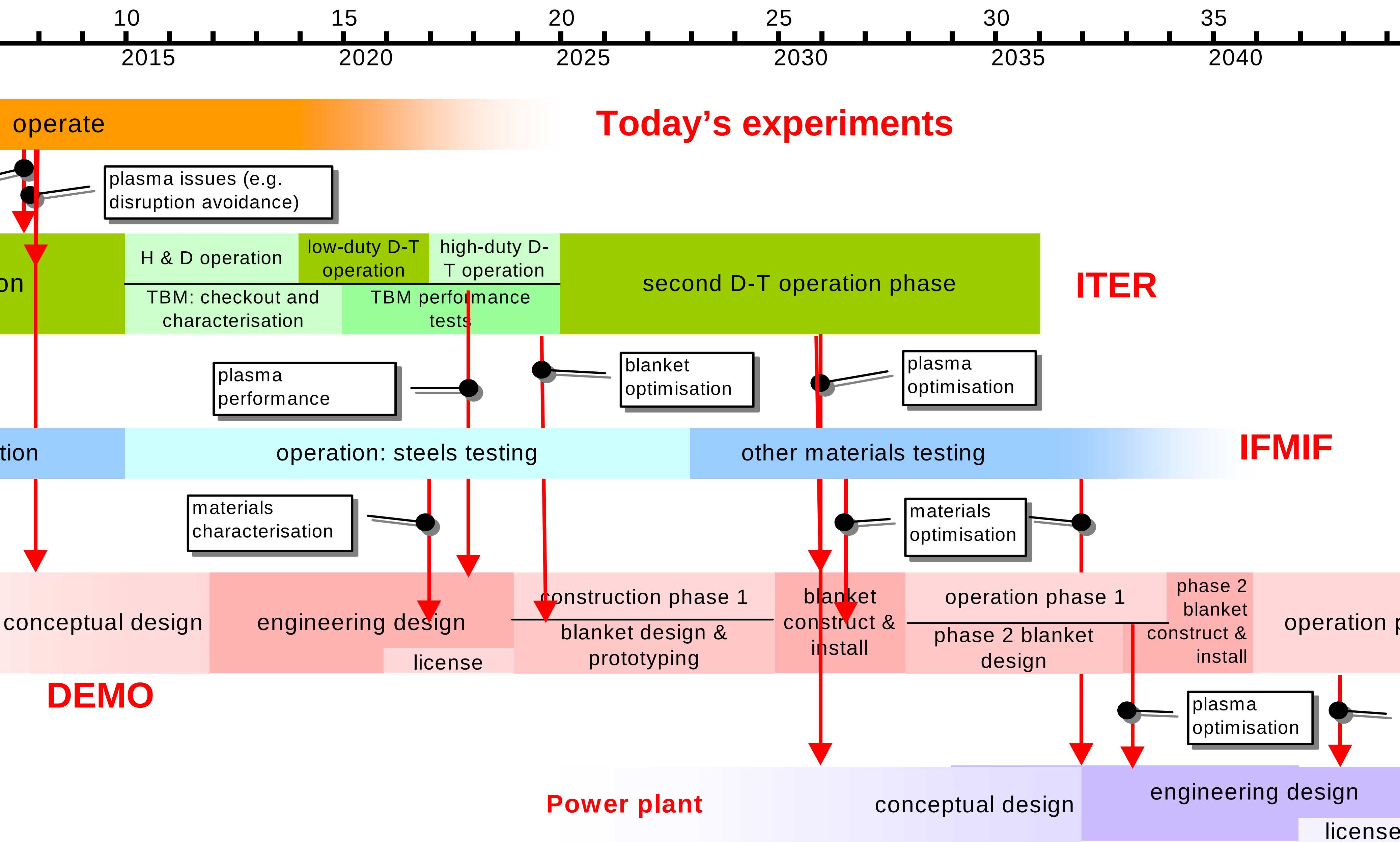
Second stage

Ex-vessel reliability developed in extended ITER and parallel programme

PRELIMINARY



PRELIMINARY



Risks and Benefits

The main risks are of:

delays, or, if the delay is unacceptable

having to back off to some extent from the economic performance of the first generation of power plants

The main benefit of the "buttresses" is risk reduction (could also accelerate the programme)

The benefit of the fast track development of fusion would be very much greater than the cost, even when discounted for both time delay and probability

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Conclusions

- **The world needs *major* sources of (environmentally responsible) energy**
- **Fusion is one of very few options**
- **Power Plant Studies ⇒ time to move to a project oriented approach ⇒ fast track ⇒ DEMO**
- **In parallel, 'Concept Development' line (stellarators, spherical tokamaks,…)** - additional physics (feed into fast track line) + insurance + alternative DEMO/power plants?
- **This will require a change in mind set, organisation and funding. First steps are**
  - **fusion community ⇒ agree an (aspirational) guiding fast-track model**
  - **persuade governments ⇒ funding to turn aspirations to reality**

Final Words

~ Lev Artsimovitch's celebrated reply to the question "When will fusion be ready?"

"Термоядерная энергия будет получена тогда, когда она станет необходима человечеству" *Детская энциклопедия. М., Педагогика, 1973, т.3, с.381.*

~ "Fusion will be ready when society needs it"

The need is clear

- must aspire and work to deliver fusion as fast as we can