A Fast Track Approach to Fusion Power

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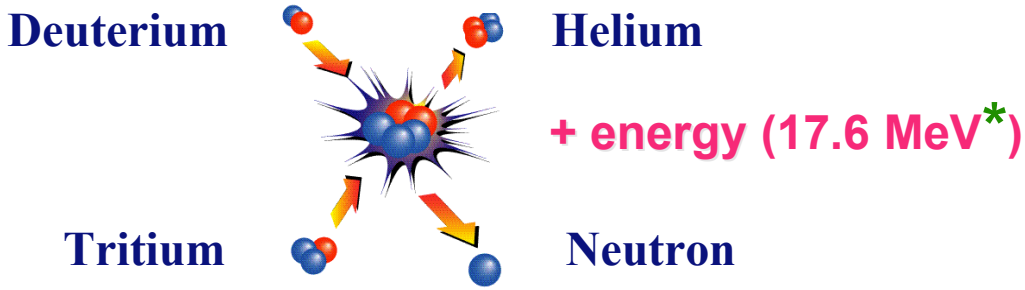
WHAT IS FUSION ?

Fusion is the process that produces energy in the core of the sun and stars

It involves fusing light nuclei (while fission ⇒ splitting heavy nuclei)

The most effective fusion process involves deuterium (heavy hydrogen) and tritium (super heavy hydrogen) heated to above 100 million °C :



Magnetic Fusion Energy uses a "magnetic bottle" called a tokamak that keeps the hot gas away from the wall

Challenges: make an effective "magnetic bottle" (now done ?)
a robust container, and a reliable system

* ten million times more than in the chemical reactions in burning fossil fuels ⇒ a 1 GW fusion power station would use 1 Kg of D + T in a day, compared to 10,000 tonnes of coal in a coal power station

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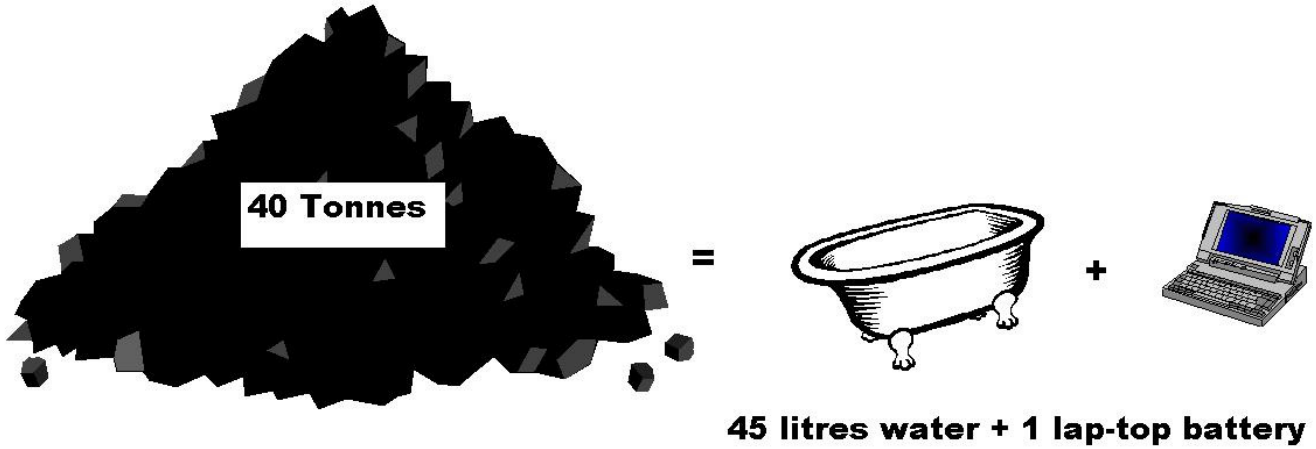
Fusion Fuel

Raw fuel of a fusion reactor is water and lithium*



Lithium in one laptop battery + half a bath-full of ordinary water (⇒ one egg cup full of heavy water) ⟹ **200,000 kW-hours**

= (current UK electricity production)/(population of the UK) for 30 years

* ⟹ *deuterium/hydrogen = 1/6700*

+ tritium from: neutron (from fusion) + lithium → tritium + helium

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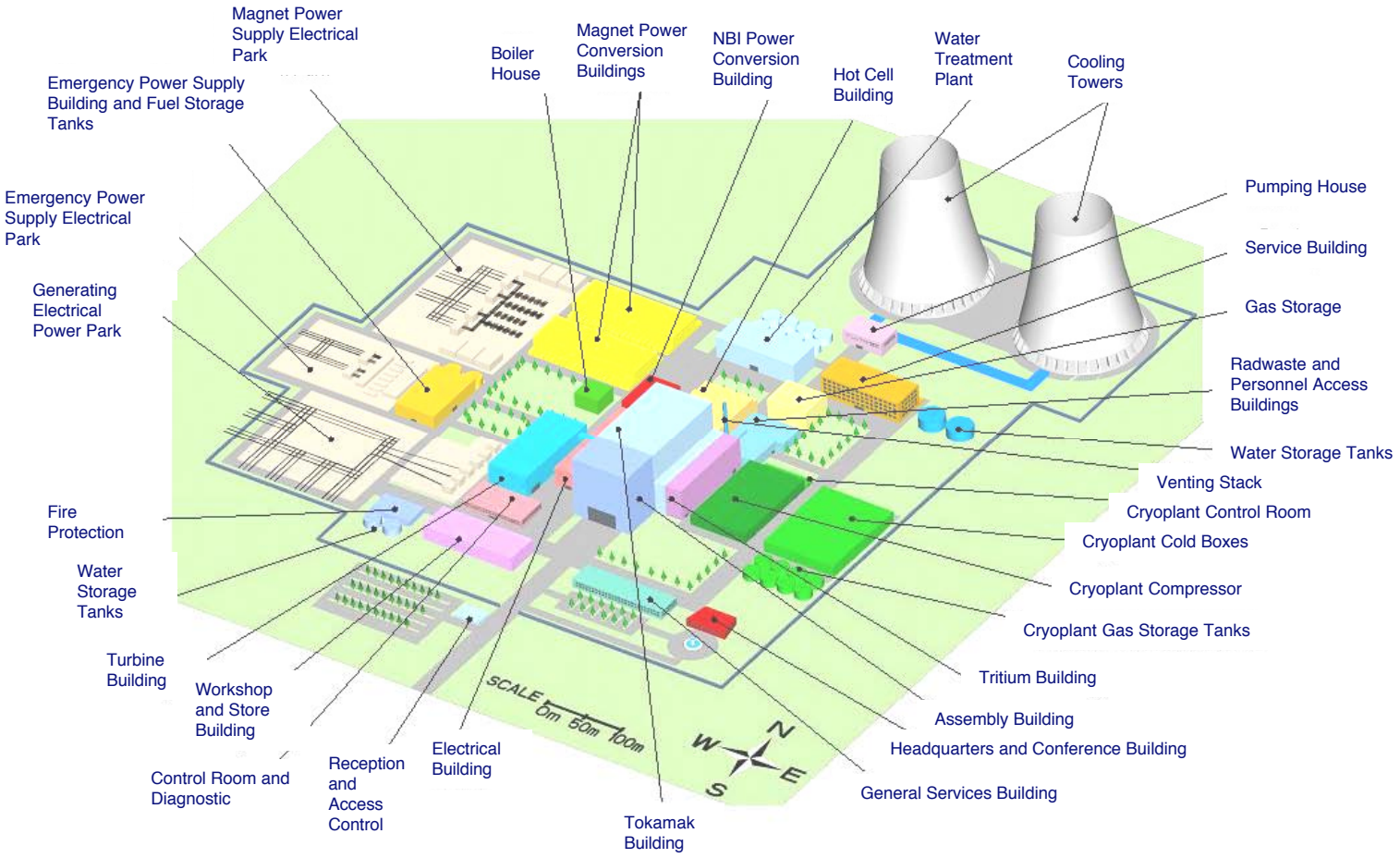
→ fusion looks potentially very attractive

- especially as it produces no CO_2 or pollution (SO_2, NOx, …), is intrinsically safe and (I will argue) has a good chance of working economically

Outline of rest of talk:

- What would a fusion power plant look like?
- Advantages of fusion
- Disadvantages of fusion
- State of the Art
- Next steps
- A fast track to fusion power

Layout of Power Plant



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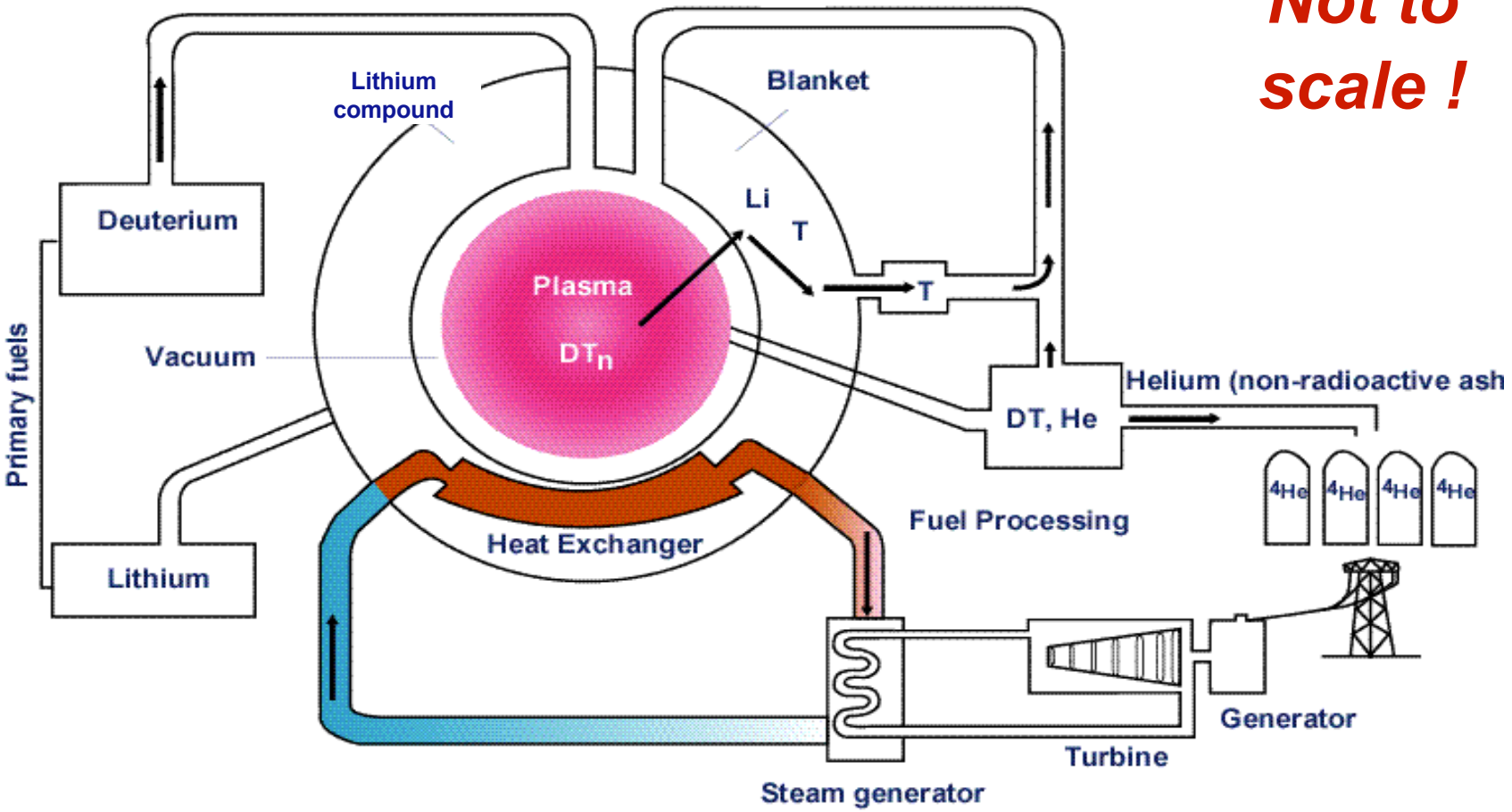
A Fusion power plant would be like a conventional one, but with different fuel and furnace

Not to scale !



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FUSION ADVANTAGES

- unlimited fuel
- no CO_2 or air pollution
- major accidents impossible
- no radioactive “ash” and no long-lived radioactive waste
- competitive electricity generation cost, ***if*** reasonable availability (e.g 75%) can be achieved (and essentially zero “external” cost [impact on health, climate])
- meets an urgent need

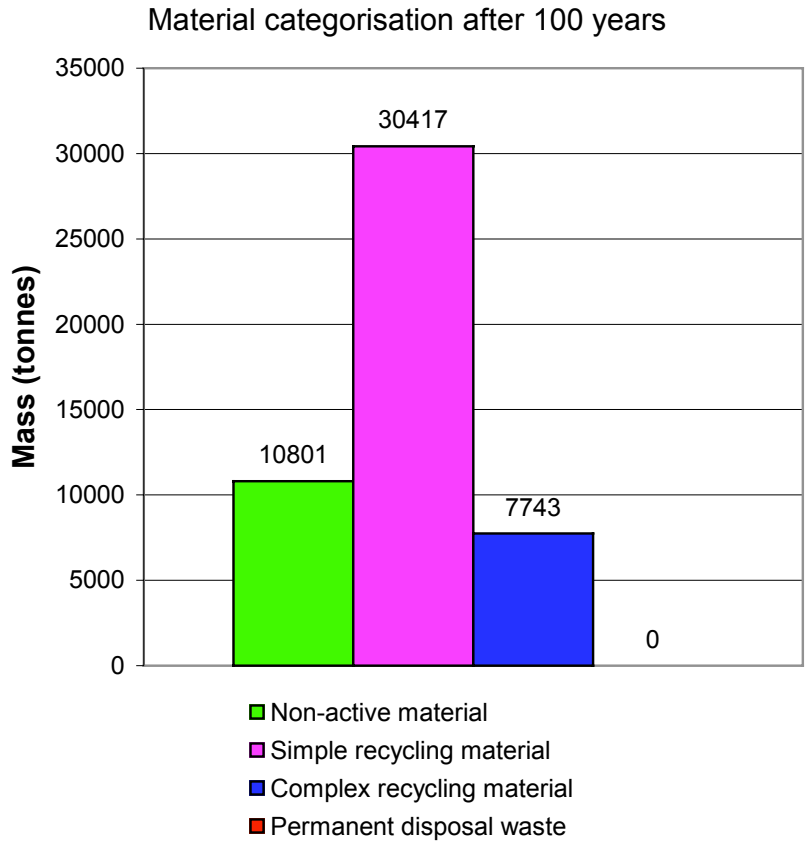
FUSION DISADVANTAGES

- More research and development needed
- Residual radioactivity in the blanket:

For ALL the Models considered in the recent European Fusion Power Plant Study:

- **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 a fusion power station with a net electrical output of 1.5 GW (Model B): others are similar)



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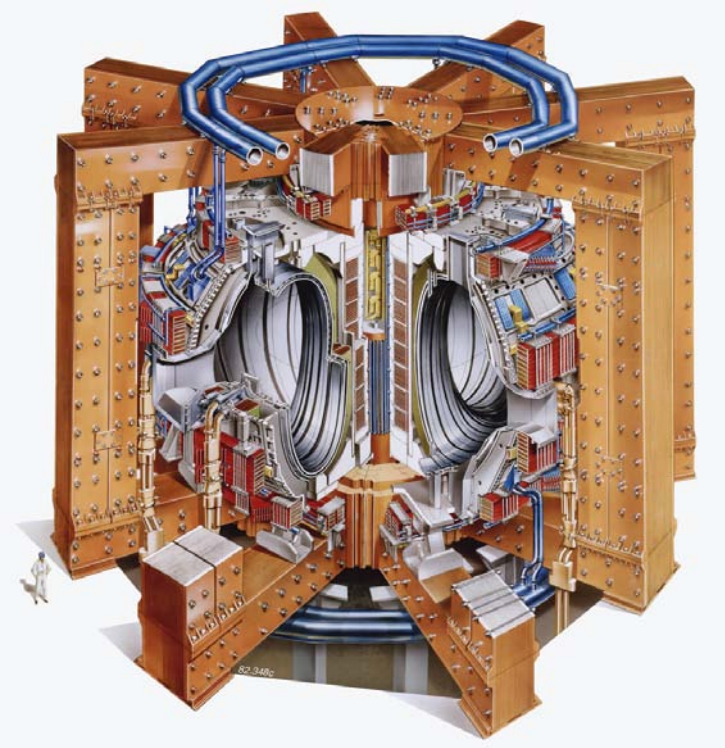
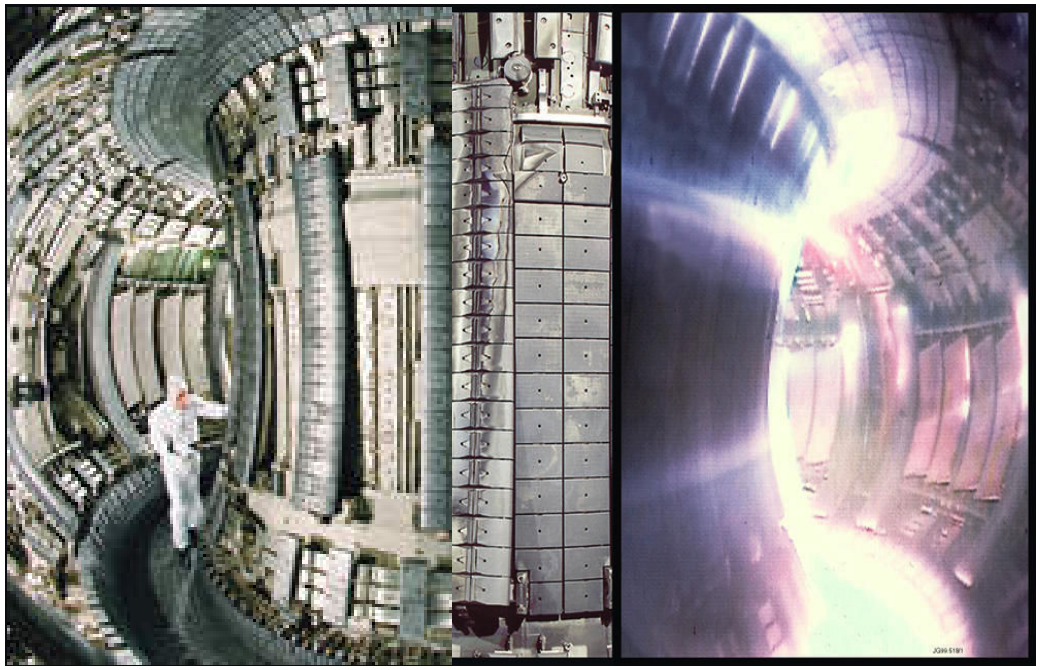
JOINT EUROPEAN TORUS (JET)

Currently the world's largest fusion research facility

Operated by UKAEA as a facility for European scientists





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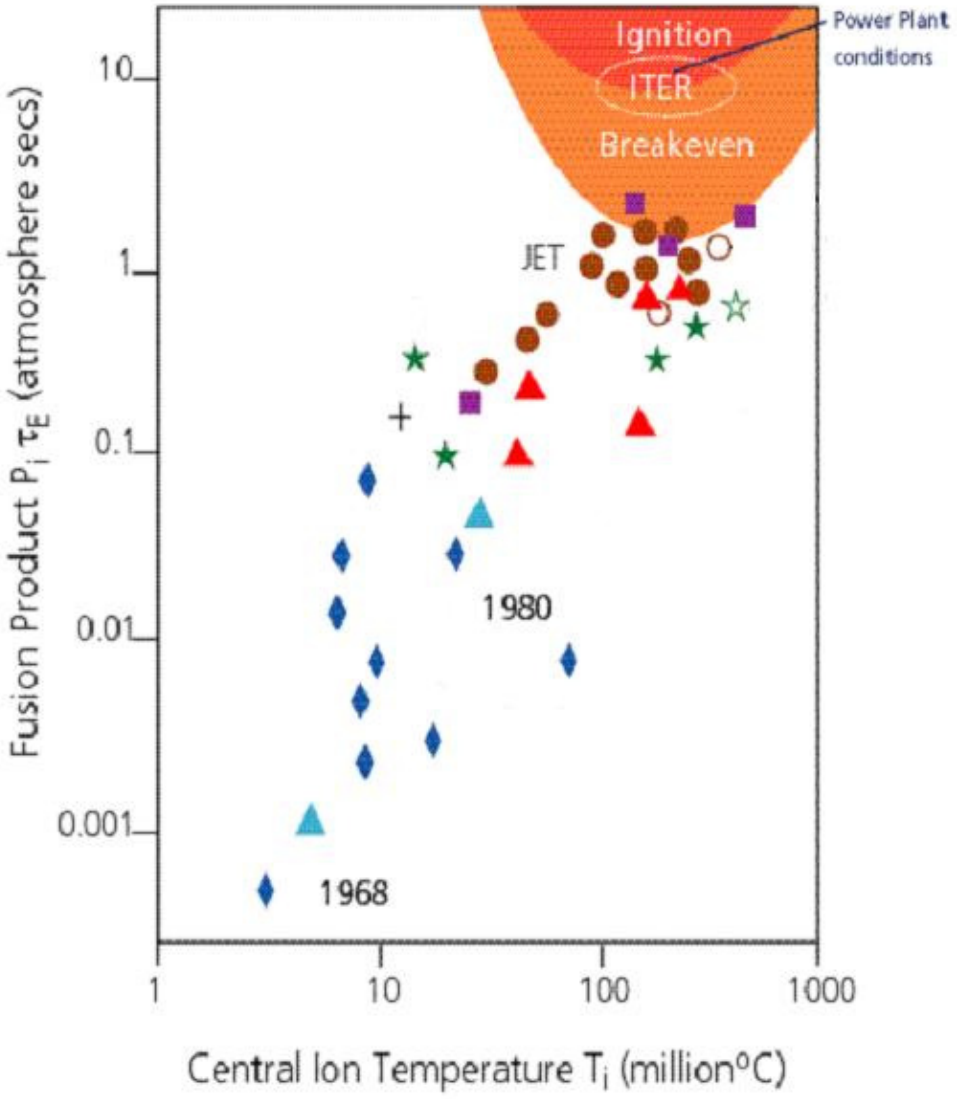
Major progress in recent years

- Huge strides in physics, engineering, technology
- **JET**: 16 MW of fusion power ~ equal to heating power. 21 MJ of fusion energy in one pulse
- Ready to build **ITER** - the next generation, Giga Watt-scale tokamak
- Scaling laws that fit data from existing tokamaks give confidence that ITER/power plants will achieve desired performance

[P_i=pressure in plasma;

τ_E= (energy in plasma)/(power supplied to keep it hot)]



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NEXT STEPS FOR FUSION

- **Construct ITER (International Tokamak Experimental Reactor)**

  ⇒ energy out = 10× energy in

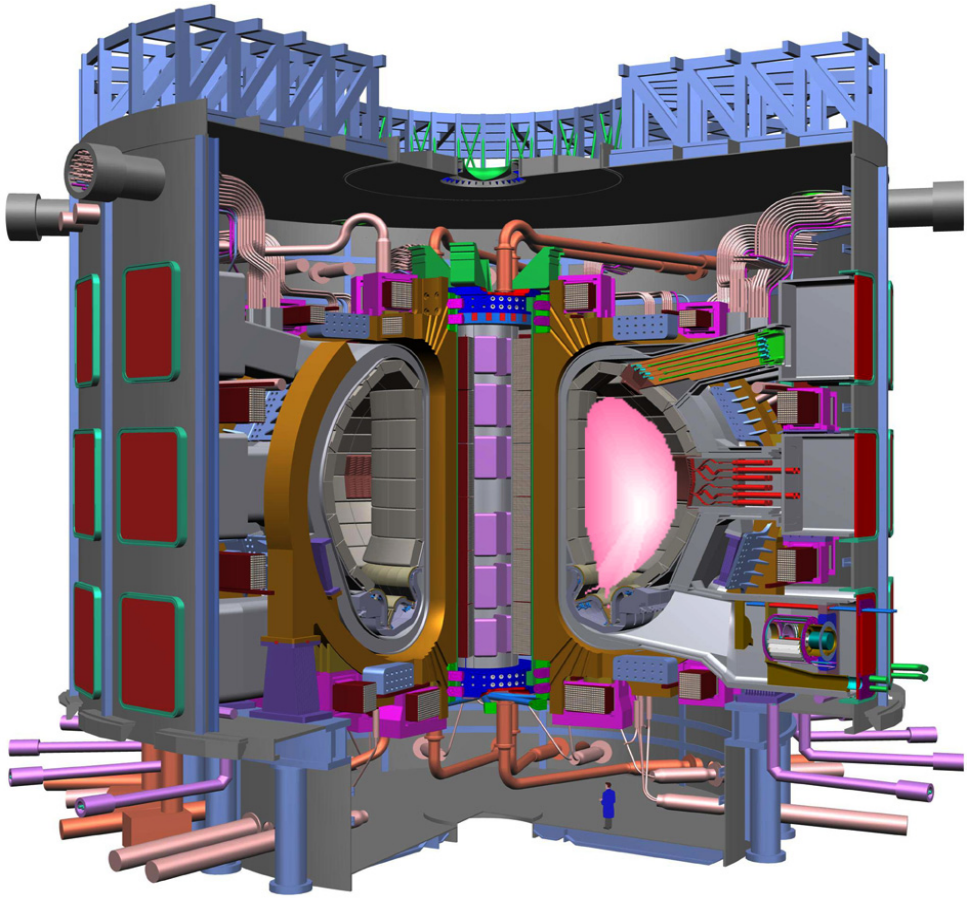
  ⇒ "burning" plasma

  During construction further improve tokamak performance in experiments at JET, DIII-D,…further develop technology, and continue work on alternative configurations

- **Intensified R&D on materials for plasma facing and structural components and test of materials at the proposed International Fusion Materials Irradiation Facility** (IFMIF)

ITER

- Aim is to demonstrate integrated physics and engineering on the scale of a power station
- Key ITER technologies fabricated and tested by industry
- 4.5 Billion Euro construction cost
- Partnership between Europe, Japan, Russia, US, China, South Korea (India?).
- Will be built at Cadarache in France
- Site choice, with USA on-board (⇒ key intellectual contributions) is great news



MATERIALS

- **Structural materials – subjected to bombardment of 2 MW/m^2 from 14 MeV neutrons**

- **Plasma facing materials subjected to an additional 0.5 MW/m^2 from hot particles and electromagnetic radiation** (much more on 'divertor')

- **Various materials have been considered, and there are good candidates, BUT:**

- **Further modelling + *experiments essential*:**

Only a dedicated (€800M) accelerator-based test facility - the **International Fusion Materials Irradiation Facility (IFMIF)** - can reproduce reactor conditions: *results from IFMIF will be needed before a prototype commercial reactor can be licensed and built*

FUSION FAST TRACK: WHAT IS NEEDED

(Recent Culham fast-track study; input from the European Power Plant Conceptual Study)

- **During ITER construction**
  - operate JET, DIII-D, JT60… → speed up/improve ITER operation
- **In parallel intensify materials work, approve and build IFMIF**
- **Then build a Prototype Power Plant ('DEMO')**

In parallel to fast track to (conventional tokamak-based) DEMO need: **Concept Development**: stellarators, spherical tokamaks,…: additional physics (feed ⇒ fast track) + alternative DEMOs/power stations, for which ITER will provide burning plasma physics and blanket testing + insurance policy

⇒ **Fusion a reality in our lifetimes**

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European Fusion Power Plant Conceptual Study

- **Four designs** (small to large extrapolations in physics and technology) **studied** (note: P_e~ 1.5 GW - hydrogen off-peak?)

  Optimised (within physics and technical limits) to give lowest generation costs

- **Results: confirm good safety and environmental features; dependence of cost of electricity on parameters - use this to prioritise future R&D**

Costs look reasonable (9 €-cents/kW-hour for early model A; 5 €-cents for early model D - lower with mature technology) **even now in some other countries**

This is encouraging

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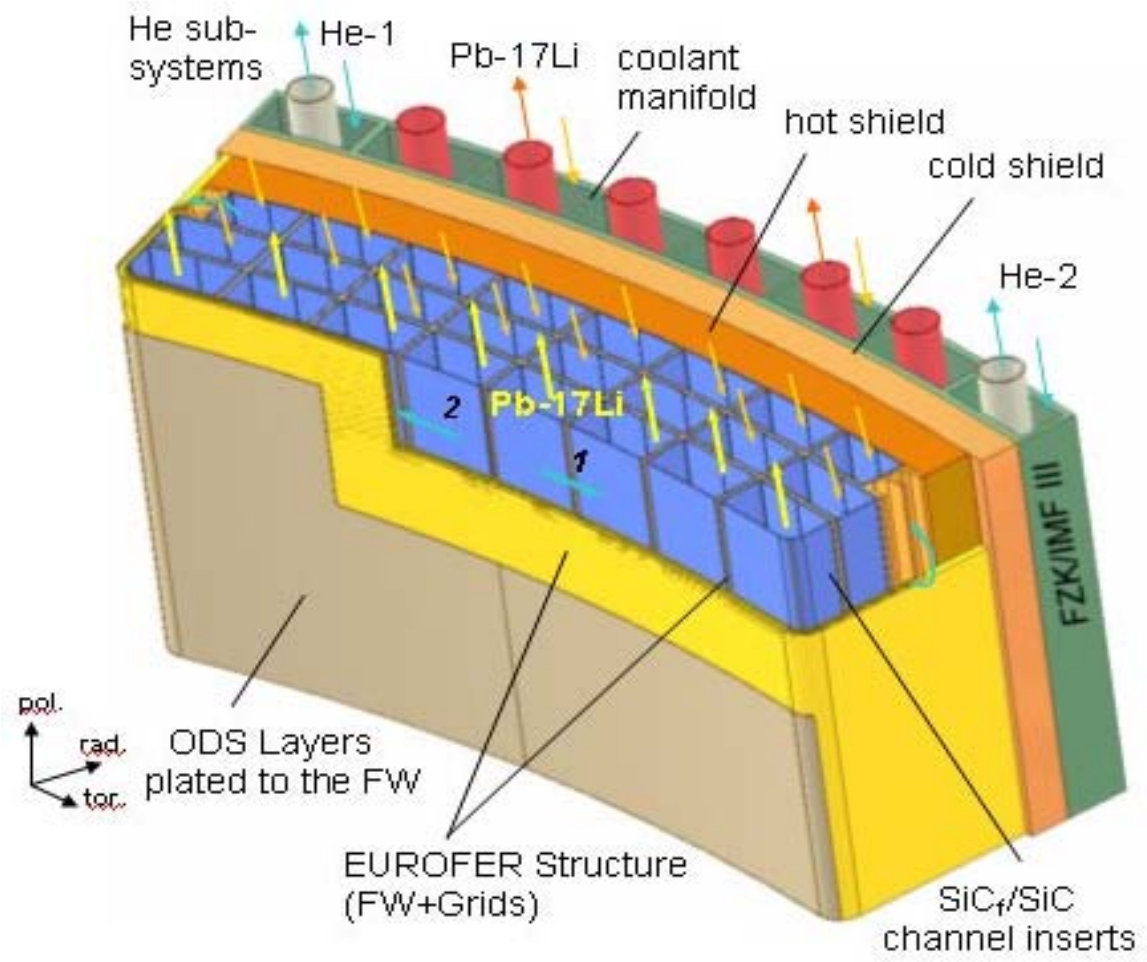
BLANKET DESIGN FOR MODEL C



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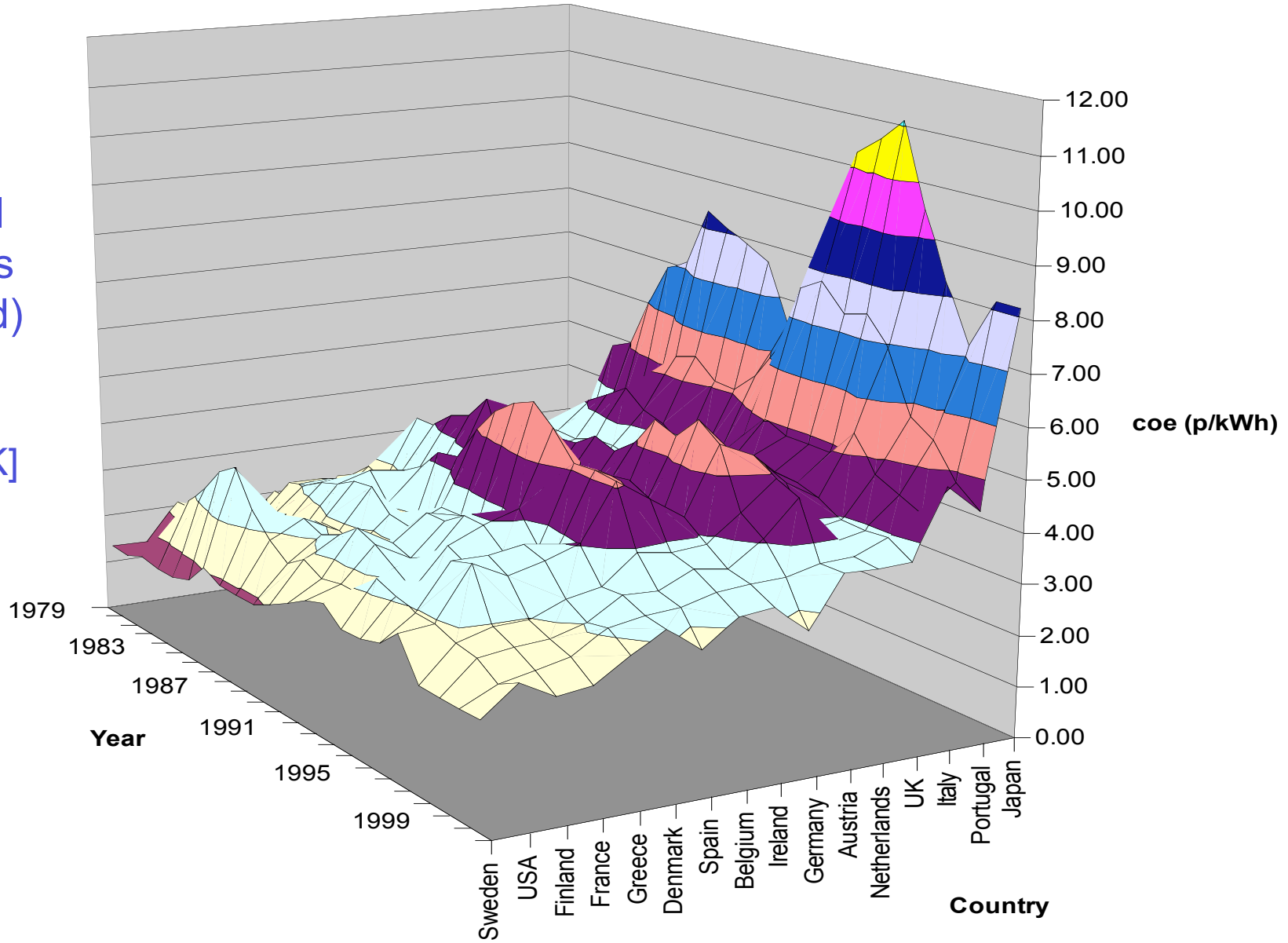
What is the cost target for a new energy source?

World industrial electricity prices (taxes excluded) in p/kWh

[1p = 1 penny UK]



Cost targets for a new energy source are

- **Moving** (UK electricity price has increased from 2p/kWhr to ~ 5p/kWhr in the last year; who knows what it will be 35 years from now)
- **Very country dependent** at any moment
- **Sensitive to introduction of carbon tax or equivalents:**

  EU Emissions Trading certificates (introduced earlier this year) were recently trading at €30/(tonne of CO2) _ 3€cents/kWhr for coal generation (1.5€cents for gas)
- **Philosophy dependent** – European studies target cost of more expensive power sources for which there is a market (ARIES targeted cheapest)

Culham Fast Track Study

- **Study of critical path + timing of necessary steps ⇒ DEMO ⇒ commercial power stations, with just-in-time information flow from ITER/IFMIF**

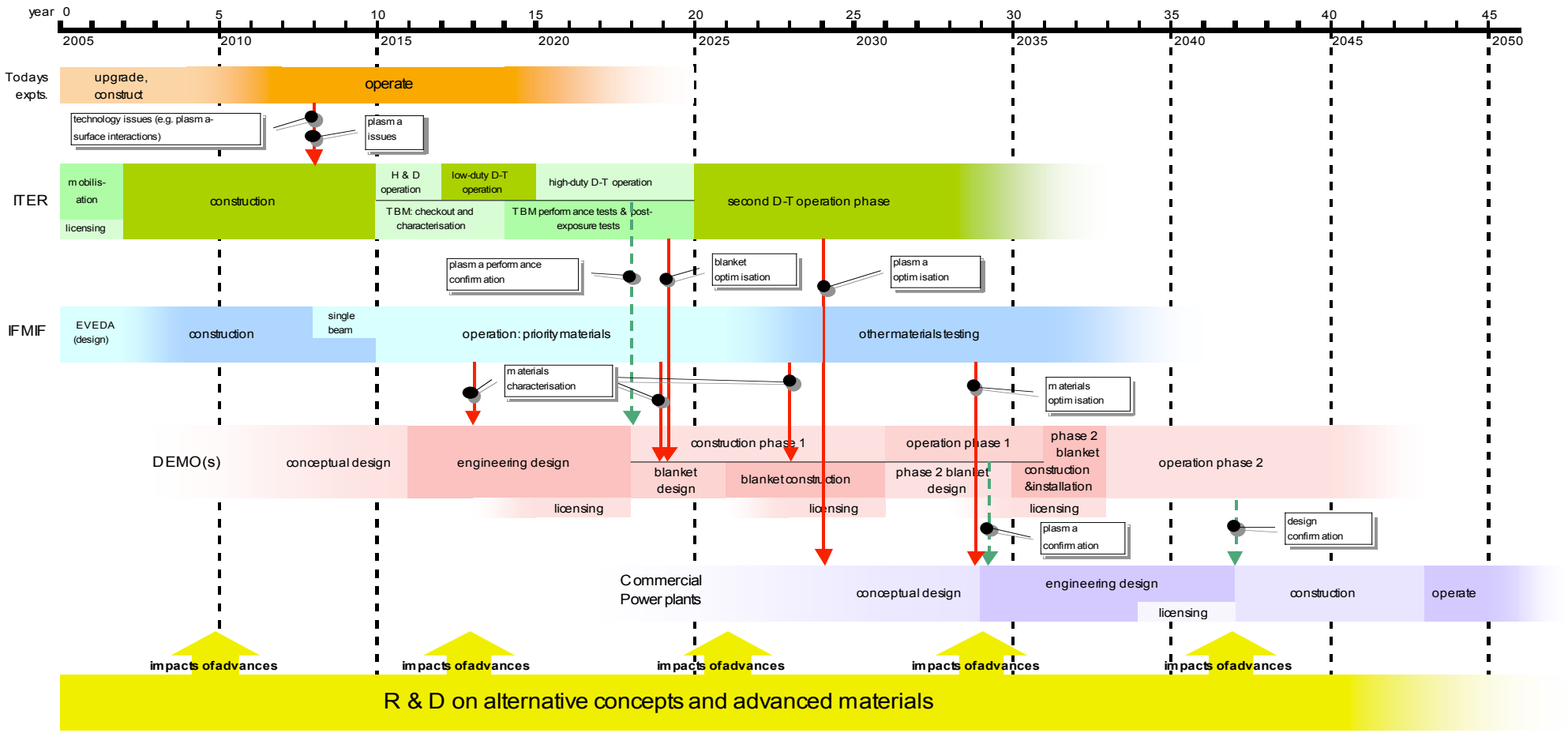
- **Minimal version: DEMO Phase I (power to grid) 2031, commercial power 2048**

- **With Component Test Facility* ⇒ commercial power could be available ~ 5 years earlier**

* highly desirable if not essential: in 'minimal model' (shown only because it is simpler), DEMO Phase I is effectively a very expensive CTF

Should be used (together with cost of electricity ~ parameters) **to guide/prioritise future work**

Fast Track - Pillars Only



Fusion Agenda in Parallel to Building ITER

- **The ITER construction budget will go mainly to industry**
- **It should ideally be accompanied by *increased* funding for accompanying fusion activities:**

- prepare for rapid exploitation of ITER
- train fusion scientists and engineers for the ITER era

capitalise on ITER investment

- push forward fusion while ITER is being built: in particular
  - _ increased work on technology and materials, and ***start building IFMIF***

Sir David King (Chief Scientific Advisor to UK Government)

"It would be a total dereliction of the case for ITER if the material project was not up and running in parallel"

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European Commission's Proposed Specific Fusion Programme during Seventh Framework Programme

- "To develop the knowledge basis for, and to realise, ITER as the major step towards the creation of prototype reactors for power stations"

The proposal includes

- The realisation of ITER
- R&D in preparation for ITER, including ITER focussed programme at JET
- Technology activities in preparation for DEMO, *including establishment of a dedicated project team and implementation of the EVEDA to prepare for construction of IFMIF* + materials and technology work
- R&D for the longer term (including concept development, theory, socio-economic studies)

- Proposed that the budget will double (⇒ half to ITER construction)

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CONCLUSIONS (I)

- **ITER site choice is great news, but in addition to ITER we need to**
  - **start IFMIF as soon as possible**
  - **increase work on materials and technology**
  - **continue to work on alternative concepts**
- **ITER investment almost all ⇒ industry; must meanwhile maintain or increase level of other fusion activities in order to maximise return from ITER**
- **DEMO could be putting fusion power into the grid in under 30 years, given**
  - Funding* to begin IFMIF in parallel with ITER, plus technology development and start of design of DEMO
  - No major adverse surprises

** cf world electricity (energy) market ~ $1 trillion ($3 trillion) p.a.*

CONCLUSIONS (II)

- **The cocktail of energy sources that we need* to meet the energy challenge must include large-scale sources of base load electricity – fusion is one of very few options**
  - ***plus improved efficiency***

- In view of the impending energy crunch (supply, climate change), the relatively small cost, and the promising outlook:
  - Fusion power should be developed even if the chance of success is not 100%

A suitably organised and funded programme can and should make fusion a reality in our lifetimes

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