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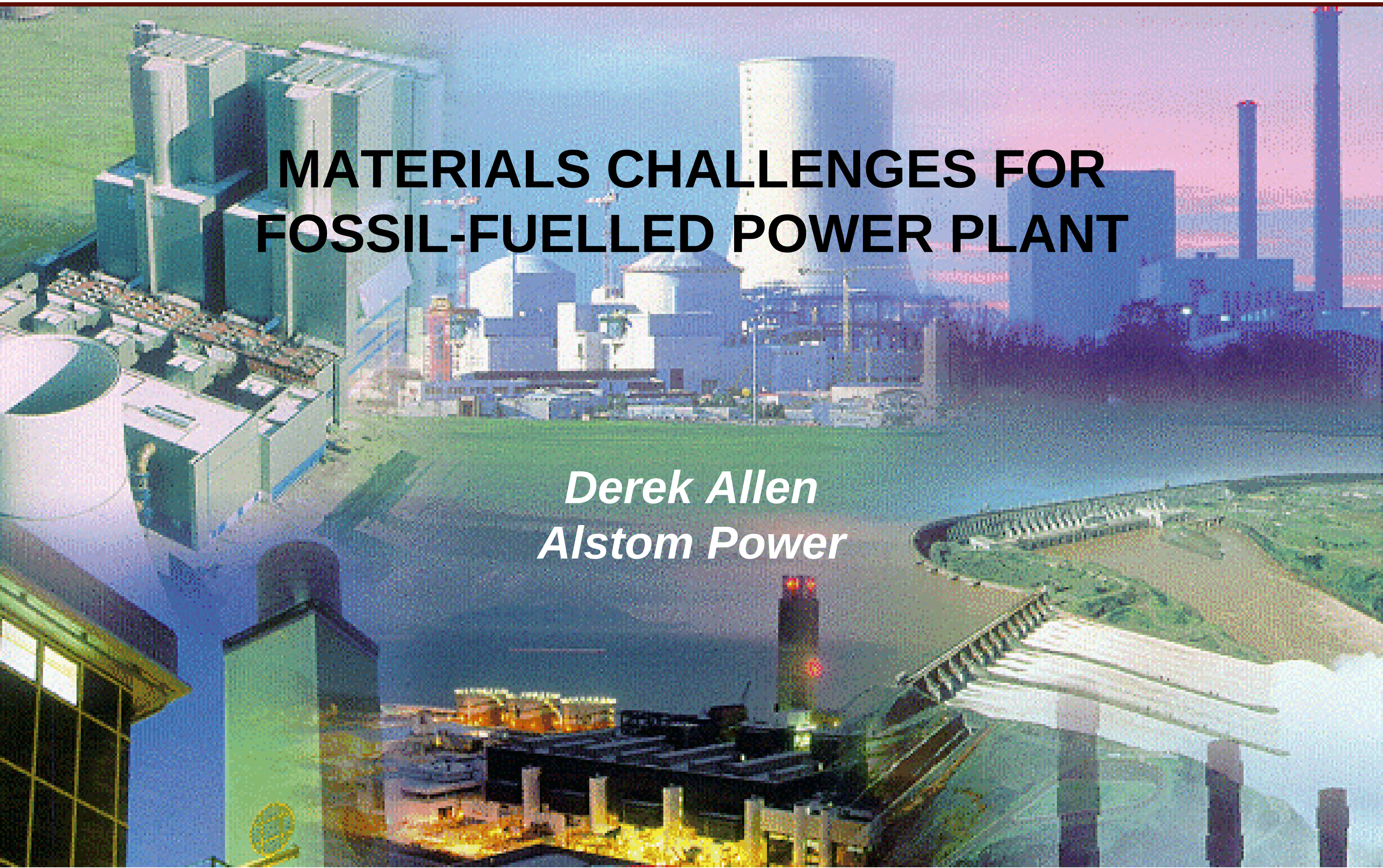
Energy Materials

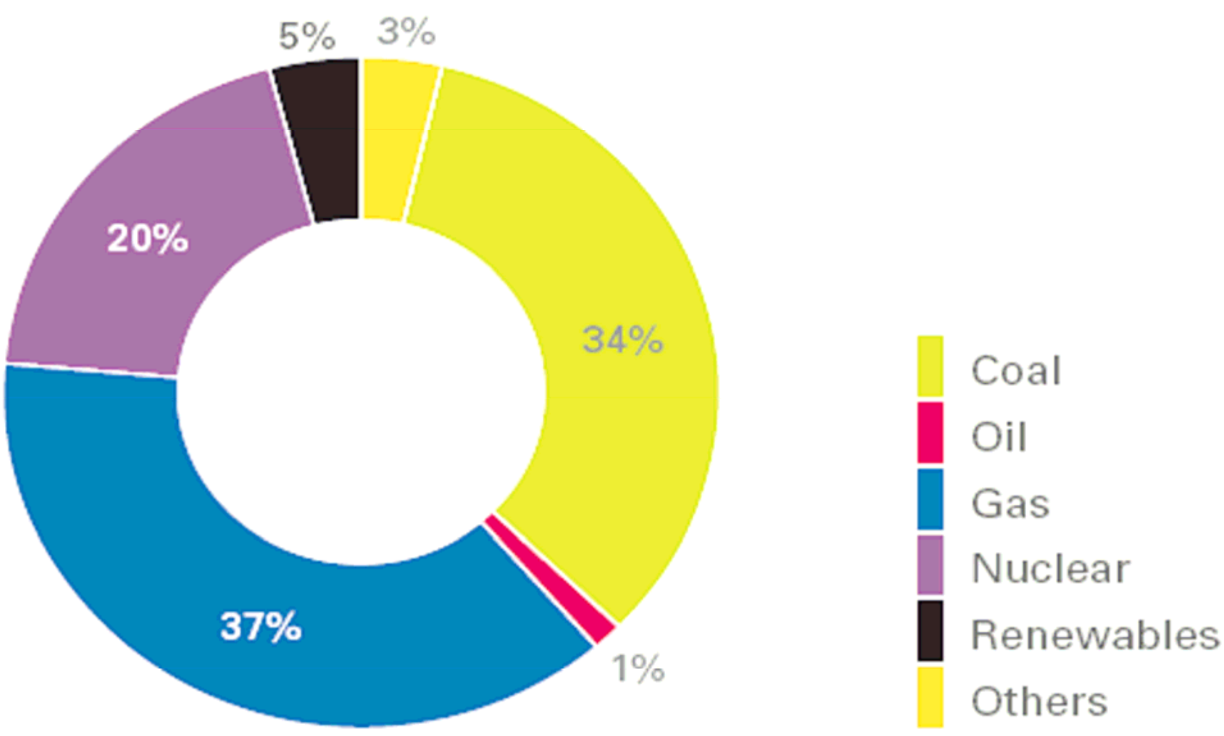


MATERIALS CHALLENGES FOR FOSSIL-FUELLED POWER PLANT

Derek Allen
Alstom Power

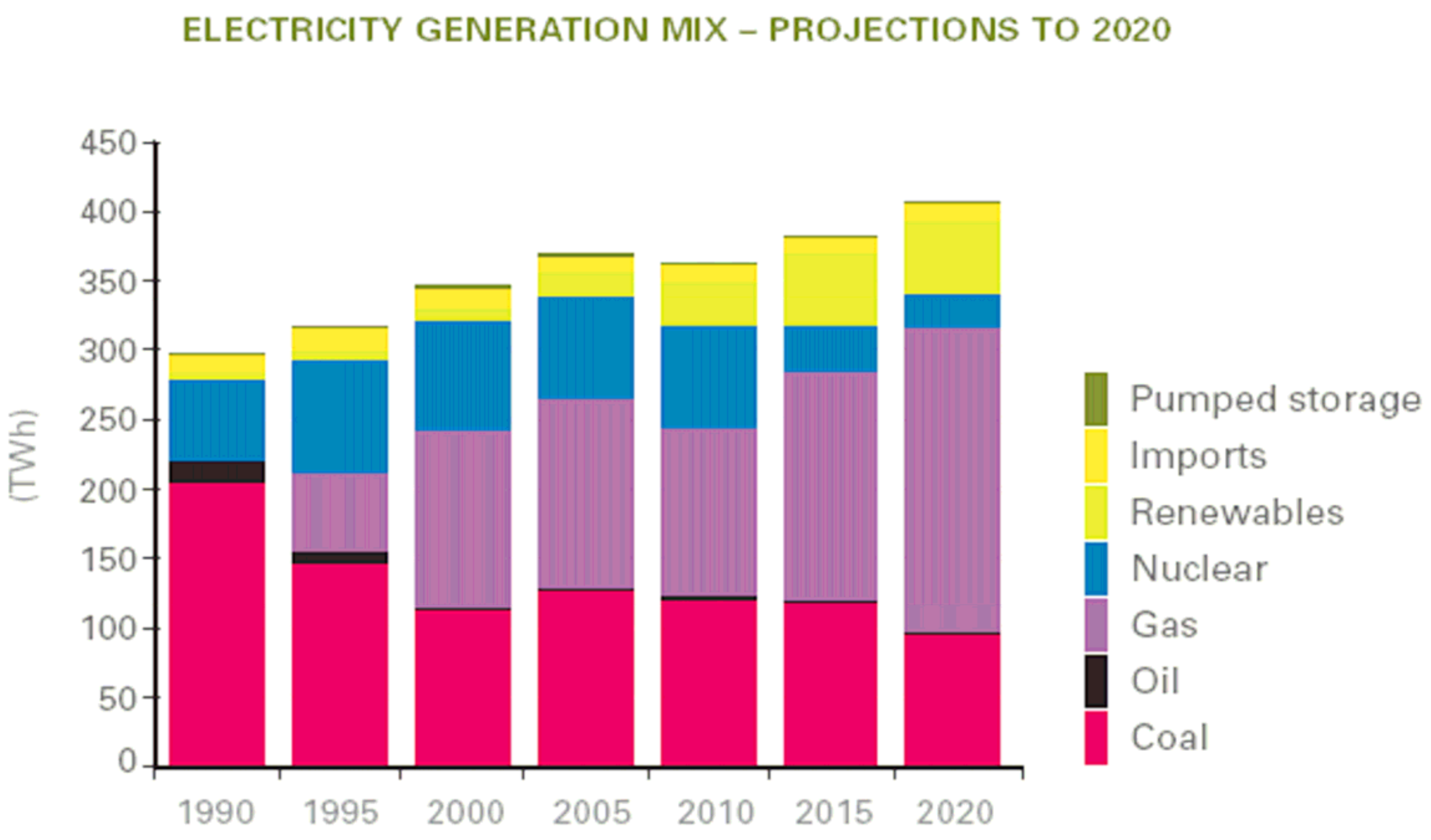
Fossil fuels in the energy portfolio

. UK ELECTRICITY GENERATION MIX (2005)



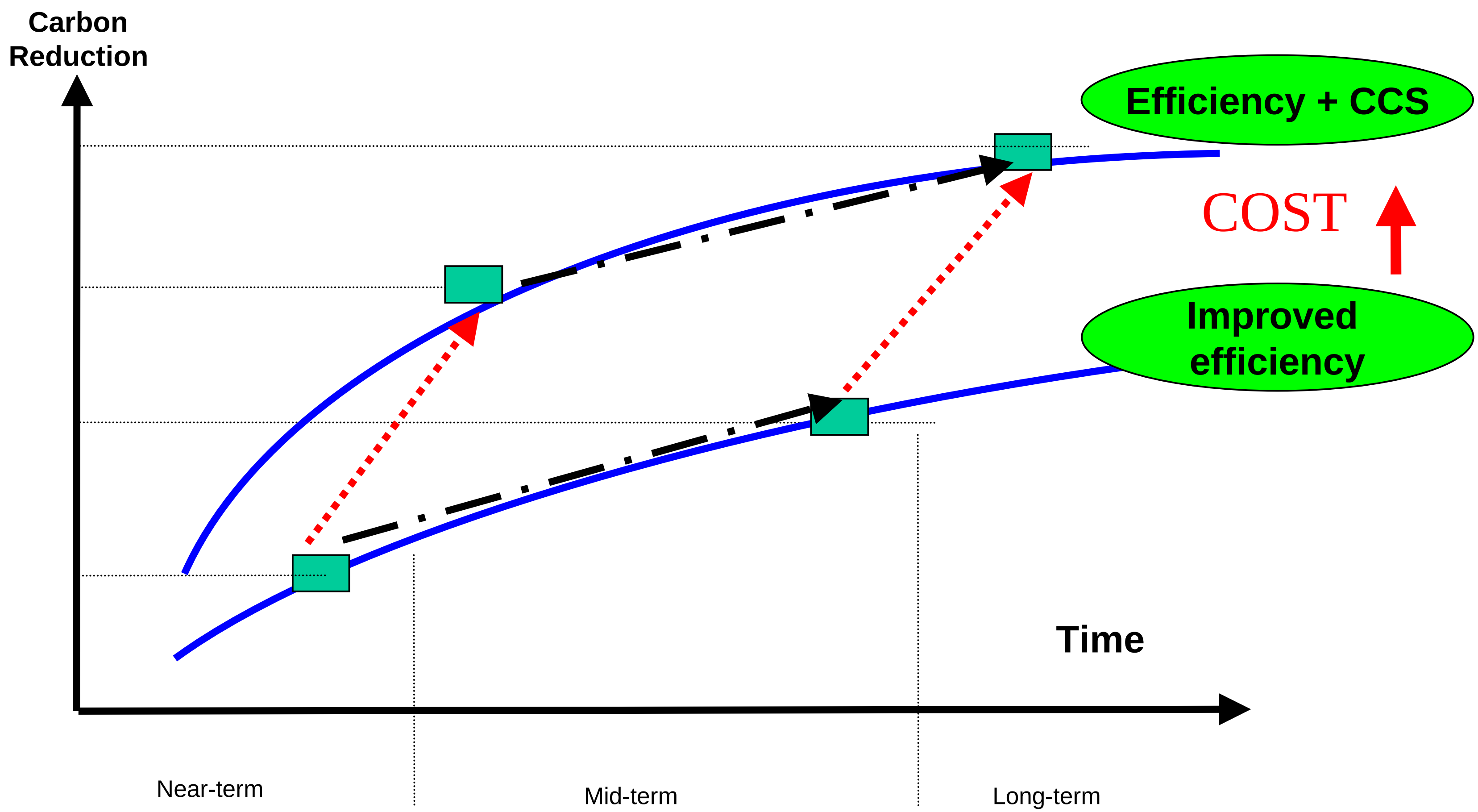
Source: DTI, 2006

Projections



Source: DTI, 2006

TWIN-TRACK APPROACH



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Emissions Reduction by Improvements In Plant Efficiency

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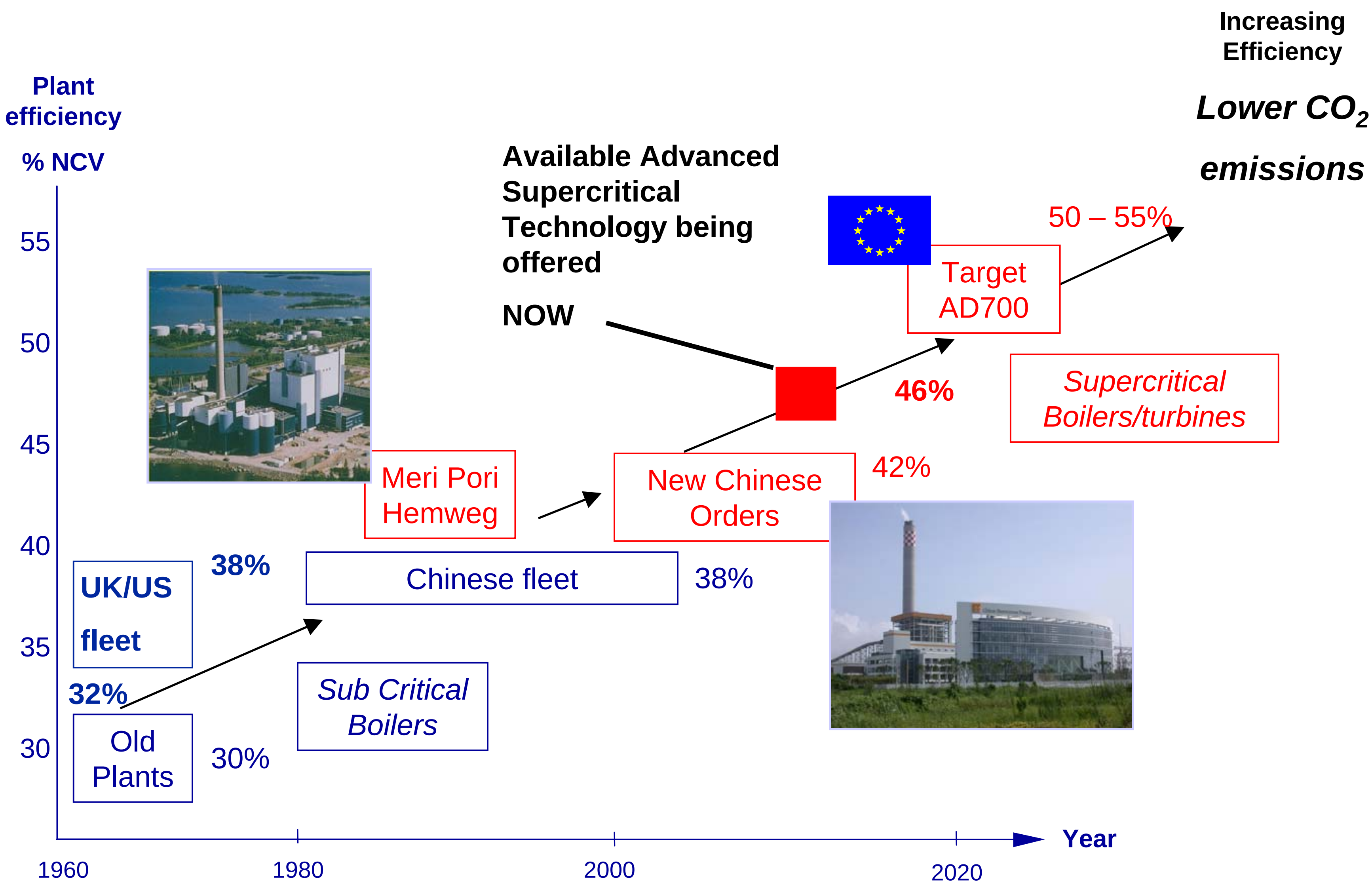
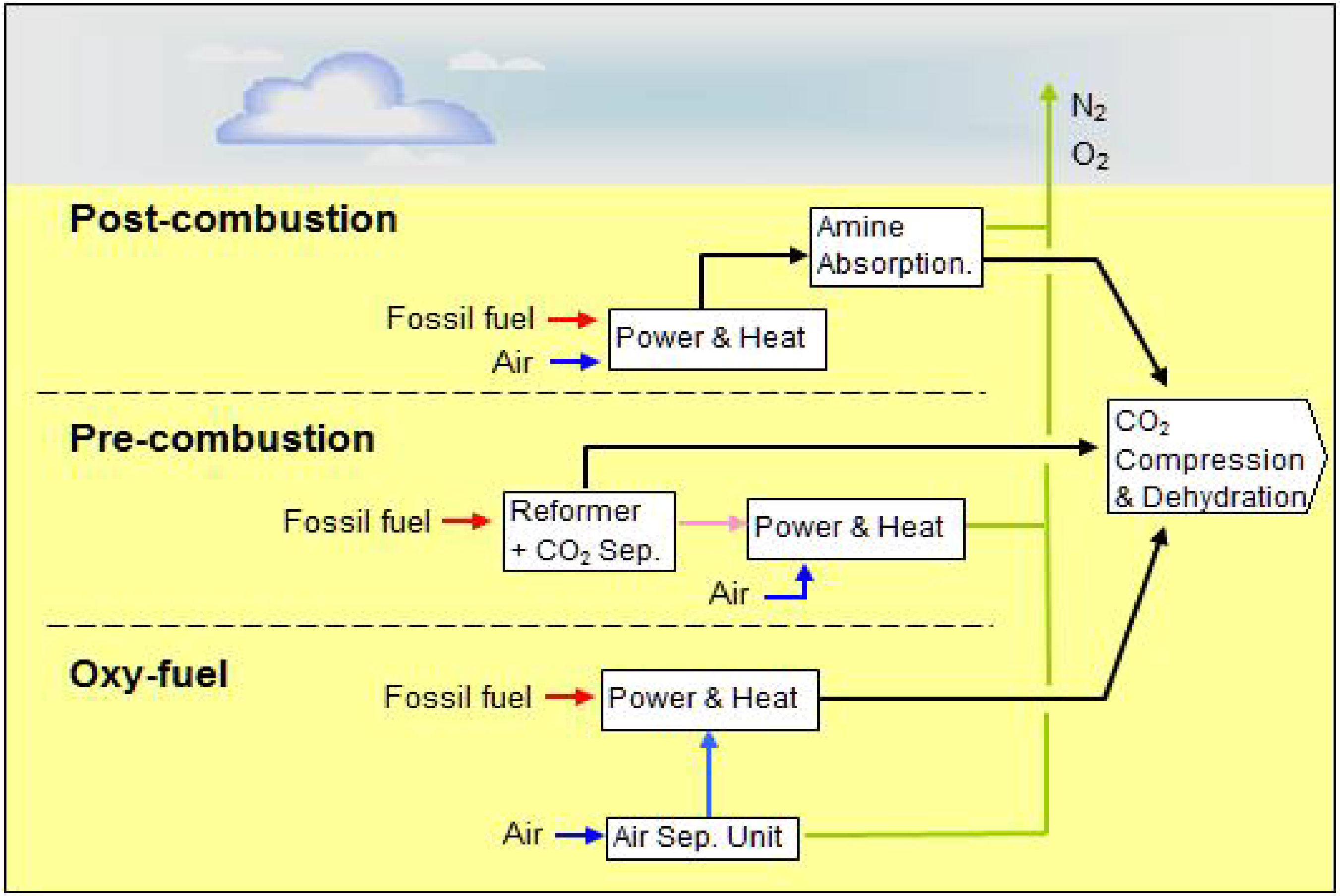
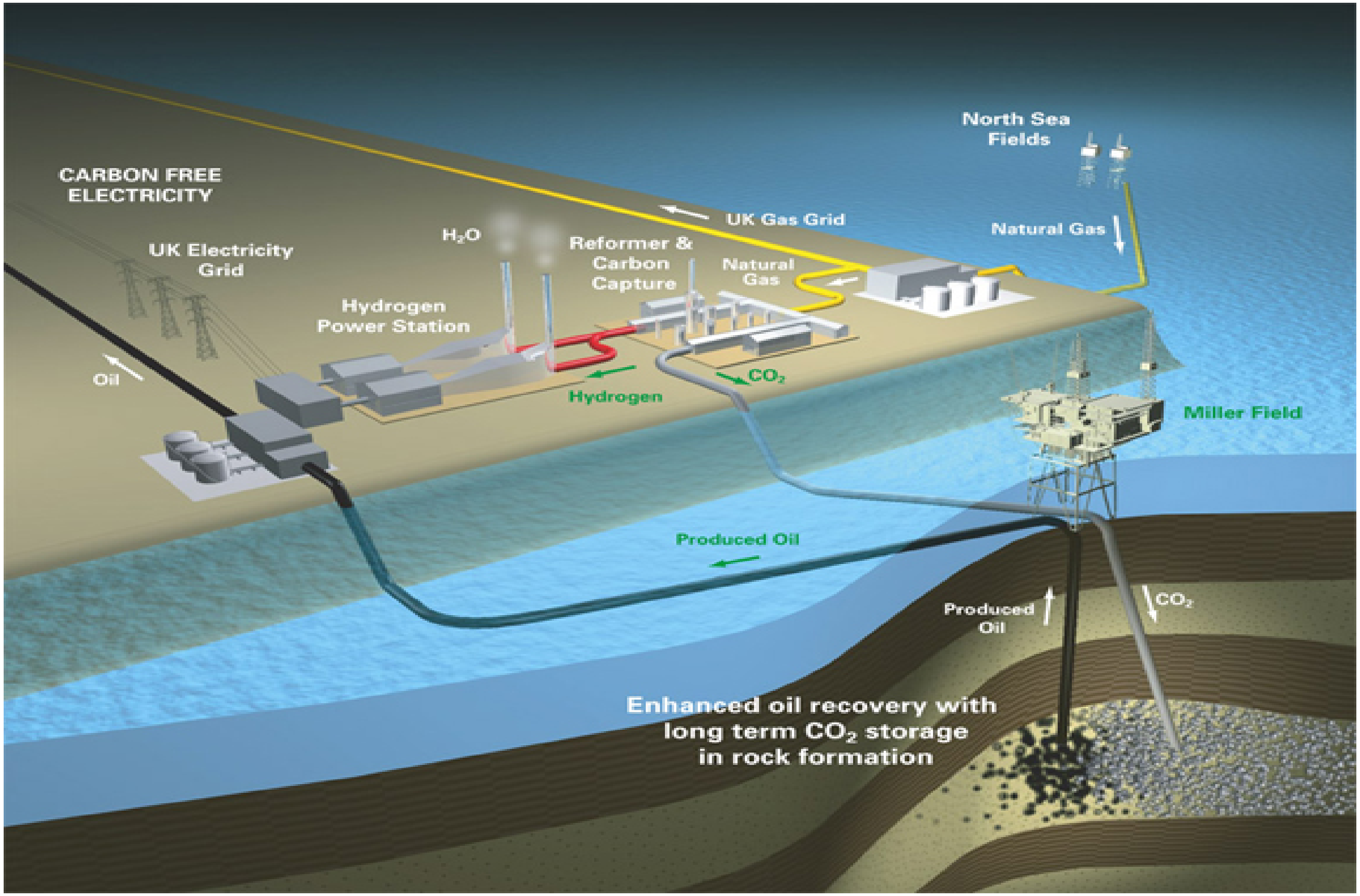


Carbon Capture and Storage



New fossil-fuelled power generation technology is becoming a complex, integrated power and chemical processing plant

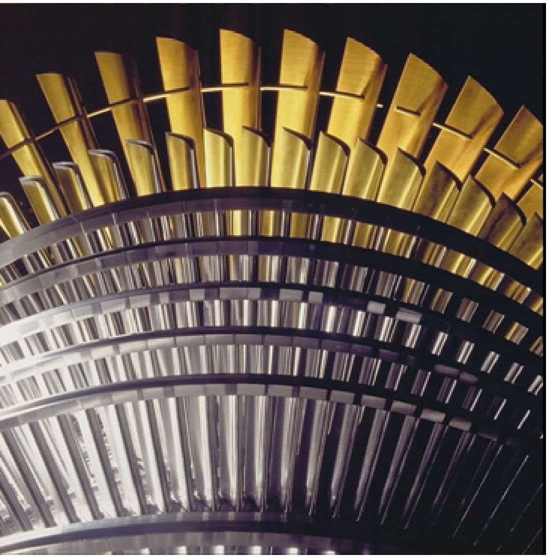


Key Challenges Facing Fossil Power Plant Materials

- Life extension of existing plants

- Increasing Temperatures

- The aggressive nature of the environment particularly for CCS plant options



Steam turbine materials

Operation at higher temperatures

- Improved creep performance
- More aggressive environment
- More demanding surface properties (steam oxidation, wear)-coatings development

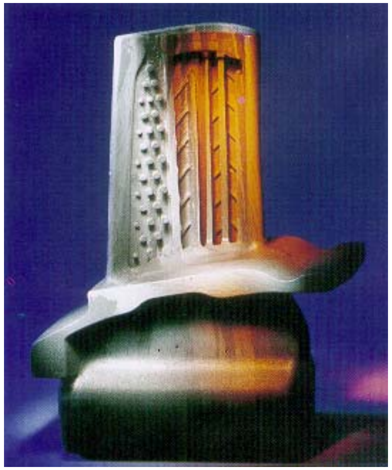
Enable more aerodynamic steam path

- Highly stressed low temperature steam path
- Stronger rotors and blades coupled with resistance to SCC

Incremental developments are vital

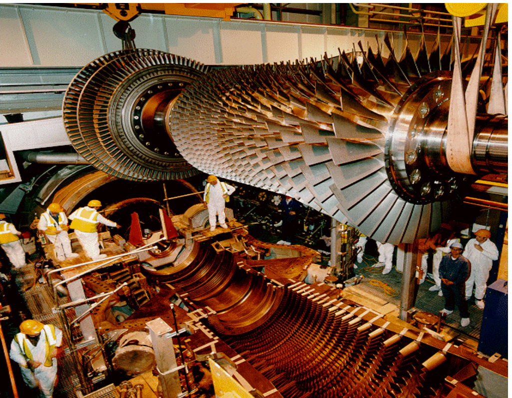
Boiler materials

- Ferritic materials with operational temperatures to 650C either through intrinsic properties or a combination of this and surface engineering
- Austenitic materials capable of temperatures up to 700C and then beyond
- Superalloys materials capable of temperatures up to 750C and beyond in aggressive environments
- Materials modelling capabilities to reduce lead time for new alloys to hit the market place

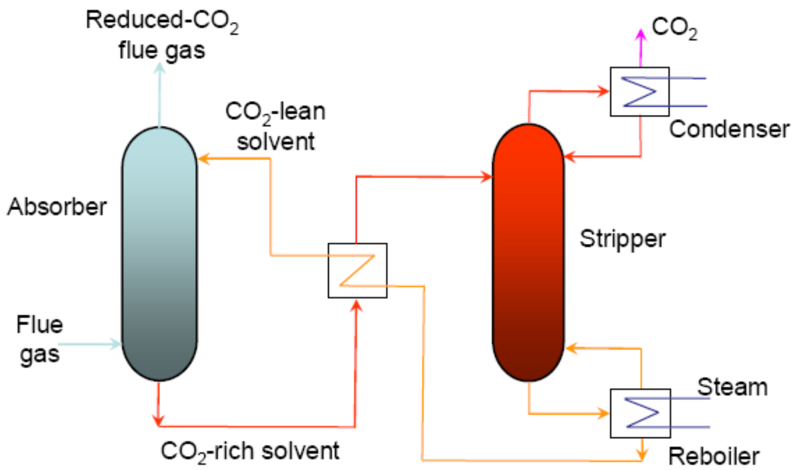


Gas Turbine Materials

- Higher temperature blading/combustors
  - Thermal cycling
- Combustor & blading alloys for aggressive environments
- Coatings (corrosion, oxidation, TBC, SMART)
- Stronger disc alloys
- Lightweighting (last stage blading)



Post Combustion Capture – Amine Scrubbing



CO_2 recovery from flue gas with chemical solvent (MEA)

Materials and related issues

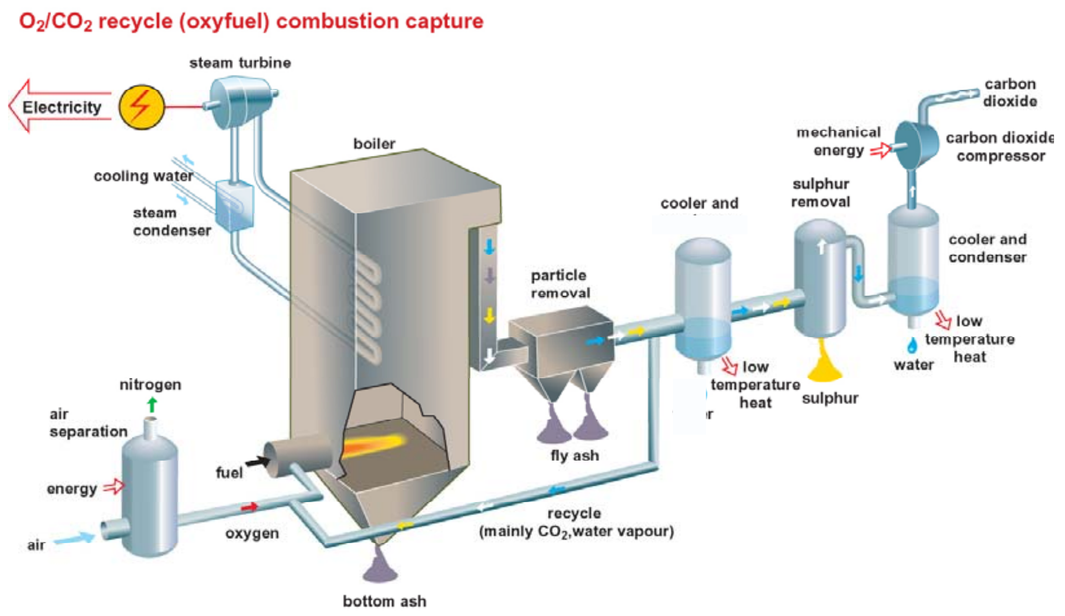
- Scale-up to power plant requirements
- Durability of scrubber
- Life of amine solvent
- Operational flexibility

Oxy-Combustion – Pulverised Coal Plants

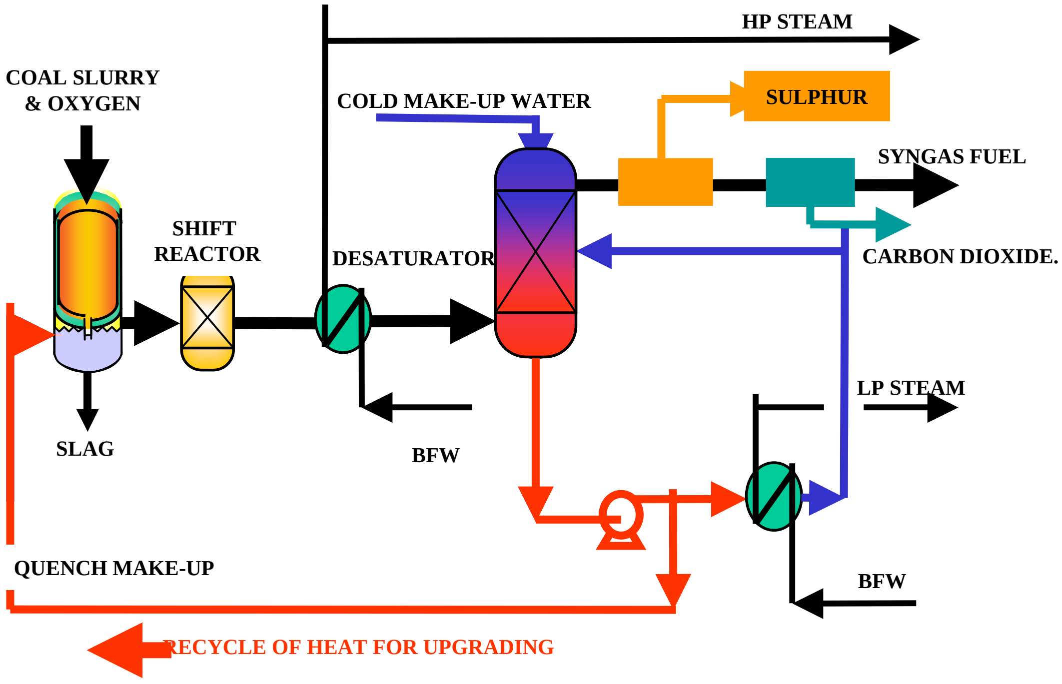
Materials and related issues

- Water wall and superheater materials – fouling, slagging and corrosion
- Concentration of contaminants with flue gas recycling
- CO_2/H_2O condenser durability
- Contaminants in the CO_2 stream for disposal

30 MW_{th} Schwarze Pumpe (Vattenfall) Pilot Plant



Entrained Flow Gasification – with CO_2 Capture

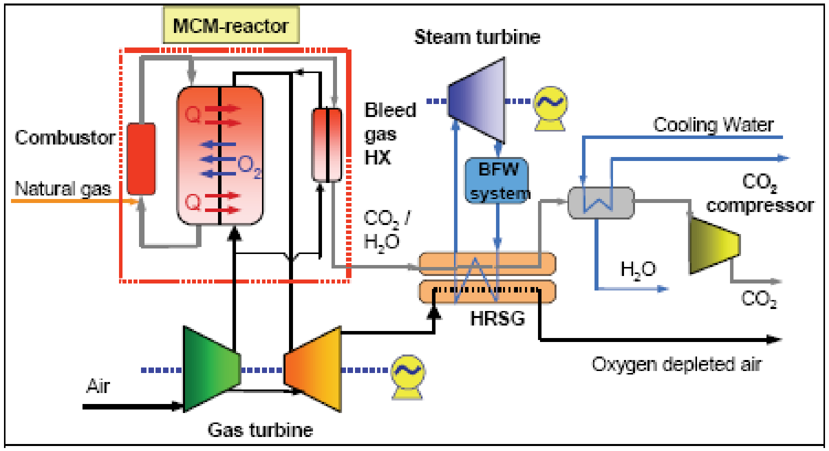


JACOBS CONSULTANCY

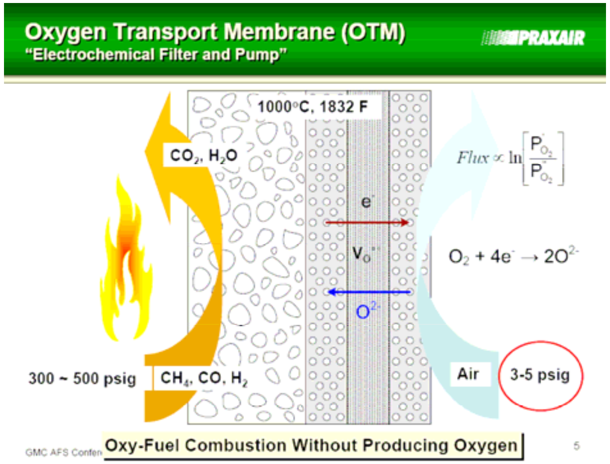
Materials and related issues

- Syngas cooler conditions
- Syngas cooler materials
- Gasifier refractory linings
- Gas cleaning technology options
- Gas turbine durability
- H_2 separation membranes
    - Pd/Ag
    - Polymer
    - Ceramic

Oxygen separation membranes (ceramic) for CCS systems



Norsk Hydro AZEP system for Natural gas firing



Praxair integrated system

Materials issues

Need tolerance to $CO_{2,}$, good mechanical properties, chemical stability at high temperature

CO_2 Transport - pipelines

CO_2 pipelines:

- 3500 km in use today
- Capacity > 45 Mt/y

Weyburn

- Pipeline length 325 km
- 19 MtCO2 over 15 years of EOR.

Materials and related issues

- Pipeline/compressor materials – corrosion
- Corrosion inhibitors
- CO_2 contaminant levels

Photo: Dakota Gasification

SUMMARY

- Improved efficiency of ‘Conventional’ and existing plant
  - High temp materials & coatings
  - Life extension & modelling (full life cycle)
  - Low cost manufacture & processing
  - Incremental developments are important

- New plant-including CCS
  - Aggressive environments
  - High Temp
  - Novel materials development (eg filters, membranes, sorbents)
    - Disruptive technologies
  - Life cycle considerations

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Materials challenges in power generation by nuclear fission

Alan Turnbull

NPL

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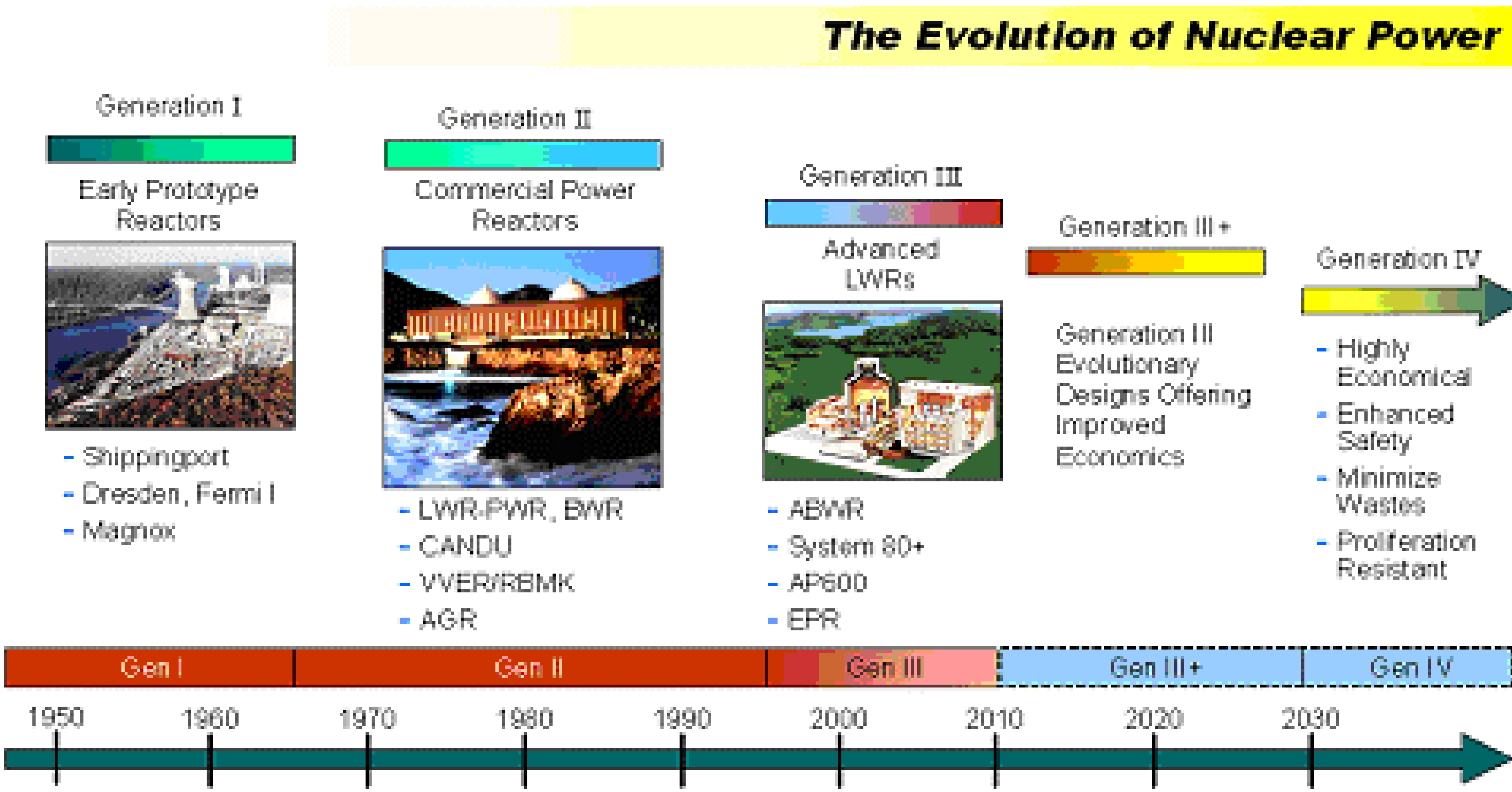
Nuclear fission - civil



Nuclear fission - civil

440 nuclear plants in 31 countries; about 30 plants currently being constructed, mostly PWR. China is proposing to start building 25 nuclear plants in next 5 years – includes pebble-bed HTR

UK: Magnox reactors →2010?; AGRs →2023?; Sizewell PWR →2040s

Commitment to nuclear submarine new-build reactors but not yet civil

In short term, any new UK civil plant will be "off-the-shelf" evolutionary PWR design with 60-year+ life expectancy

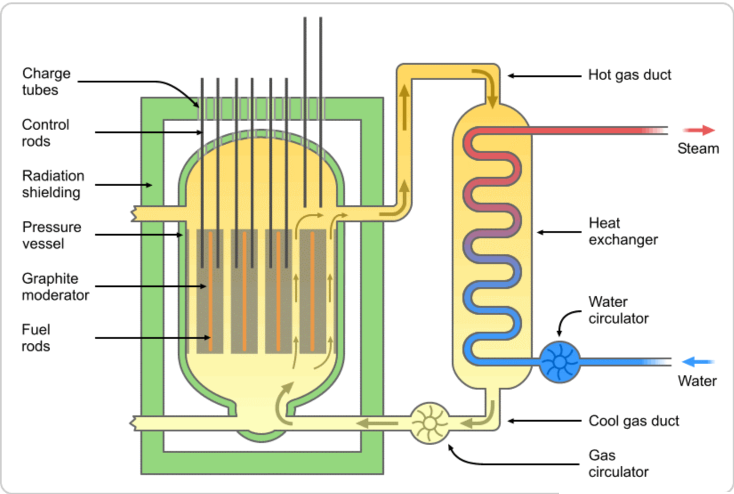
Westinghouse 1100 MW AP1000?

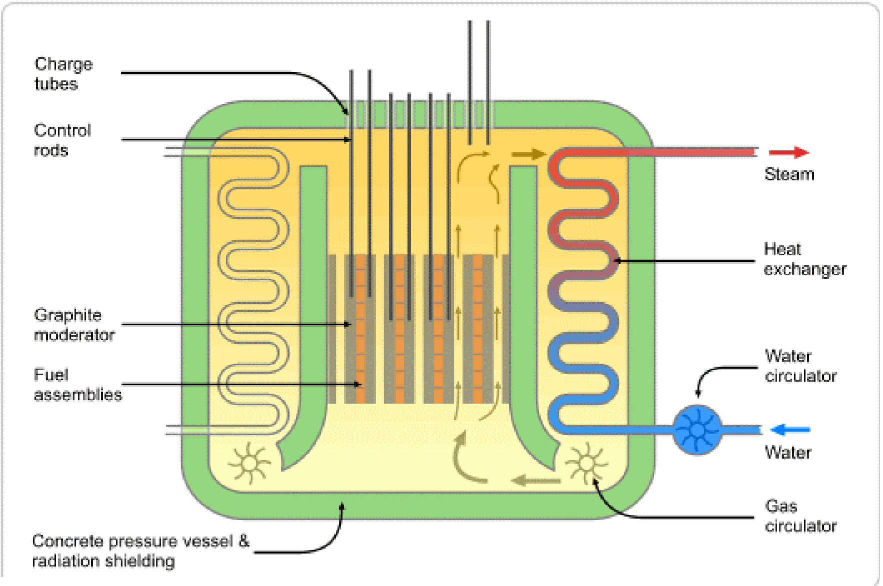
- **50% fewer valves; 83% less piping, 35% fewer pumps etc….**

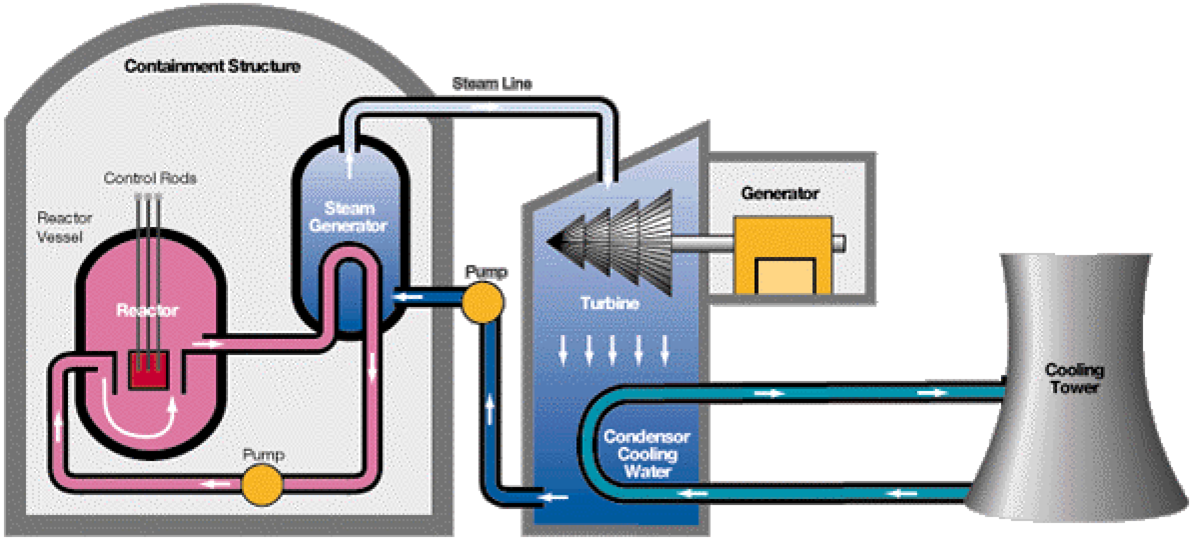
European Pressurised Water Reactor 1600 MW?

- **Innovative design features to prevent core meltdown (no power or switching required)**

Nuclear fission – UK reactor types







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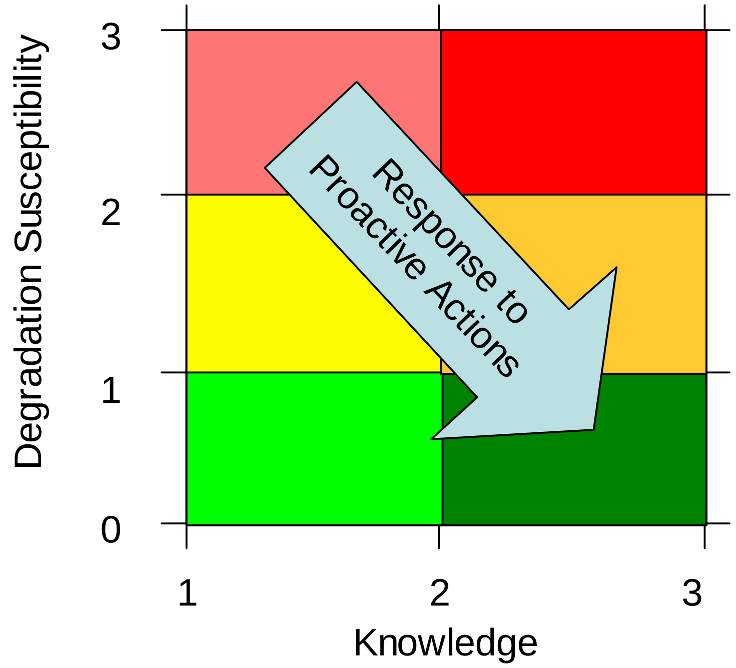
Statement from a 2004 Nuclear Energy Institute (NEI) presentation to U.S. utility management (courtesy of EPRI)

"Primary system materials will degrade at your plant"

The problem can be characterised:

- ***What is going to crack next?***
- ***Where will it crack?***
- ***When?***
- ***Can you live with it?***



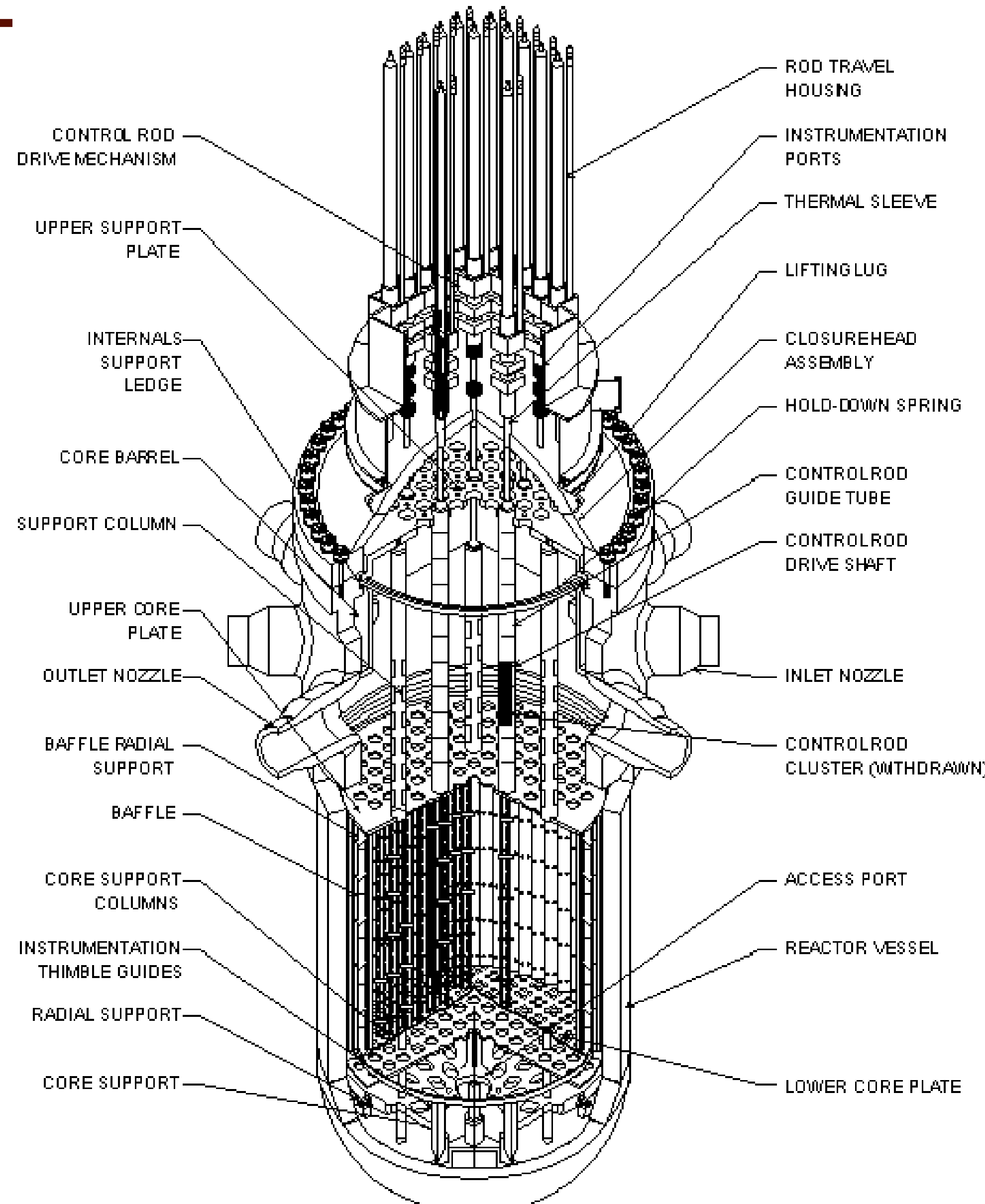
Nuclear fission – PW reactor

Inlet water 290 °C

Outlet water 325 °C

H_2, LiOH, H_3BO_3, O_2<10ppb

pH=6.8 – 7.4 at 300°C



Nuclear fission – irradiation

Neutron irradiation can generate point defects in metals and lead to transmutation of some elements

In the case of low-alloy steels, neutron irradiation induces hardening and embrittlement as a function of :

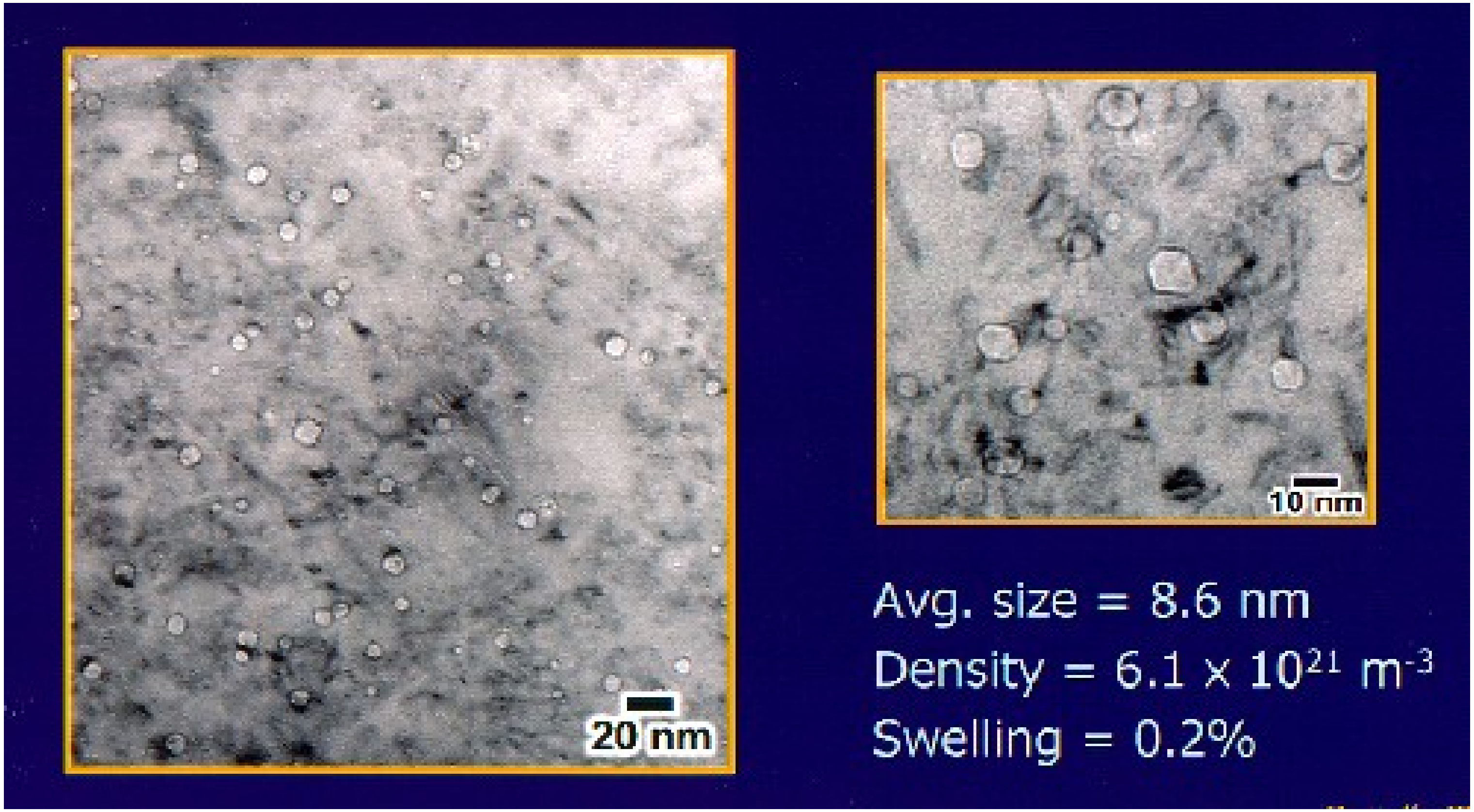
- **Irradiation temperature**
- **level of impurities (Cu, P …)**

RPV internals materials are subjected to a very high fluence (up to 1000 times the fluence on the RPV wall) which leads to major modifications of their properties

- **Hardening (YS can be multiplied by 5)**
- **Decrease in ductility and toughness**
- **Changes in microstructure (grain boundary chemistry, dislocation density and intragranular precipitates)**

Nuclear fission – PWR (courtesy of Areva NP)

Voids and helium/hydrogen bubbles in a baffle-bolt extracted from Tihange 1 (TEM examinations – PNNL)



Cavities in 316 SS

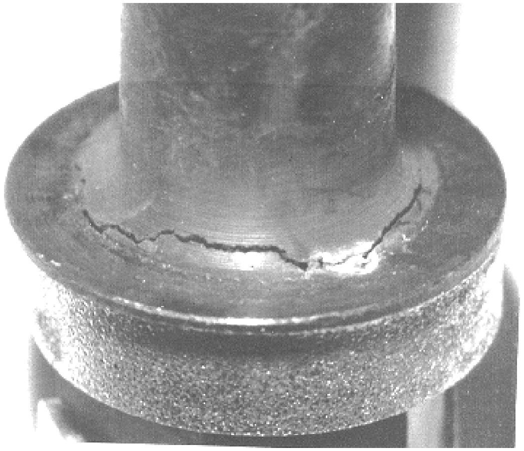
Degradation of core internals

Potential degradation mechanisms for irradiated stainless steel and nickel alloy core components include

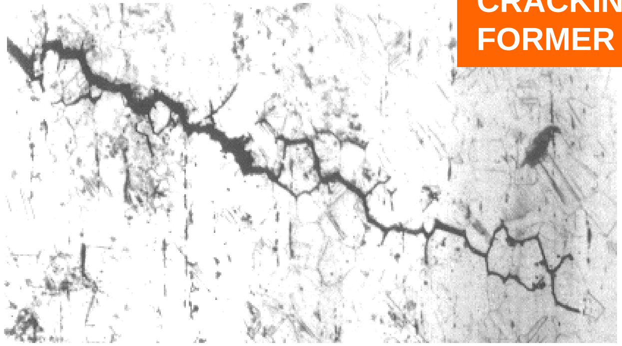
- **-irradiation embrittlement**
- **-void swelling**
- **-irradiation assisted SCC**

IASCC has caused a number of failures

- **-baffle-former bolts**
- **-control rod cladding**



CRACKING IN PWR BAFFLE FORMER BOLT



PWSCC Experience Outside of SG (courtesy of EPRI)

1980s
- Leak - pressurizer instrument nozzle
- Leak - pressurizer heater sleeve
- Leak - two steam generator drain nozzles
- Leaks - 20 pressurizer heater sleeves
- Fail - steam generator tube plug
- Leaks - pressurizer instrument nozzles (non-US)

1990s
- Leak - control rod drive mechanism nozzle (non-US)
- Leak – replaced pressurizer instrument nozzle (original nozzle involved)
- Cracks - two hot leg piping instrument nozzles
- DE of Leaking CRDM nozzle - indications near the top of the J-groove weld (included OD circ crack and cracks in weld)
- Leak - circ crack pressurizer relief valve nozzle safe end.
- 7 mm deep crack - CRDM nozzle

2000s
- Shallow ID cracks - hot leg nozzle butt welds (non-US).
- Leak - reactor vessel hot leg nozzle pipe butt weld
- Leaks - CRDM nozzle and five thermocouple nozzles
- Through-wall circ crack - in CRDM nozzle above the J-groove weld
- Leaks - two CRDM nozzles - significant boric acid wastage of the reactor vessel top-head surface.
- Several CRDM nozzle leaks – after full inspection, most of the welds had cracks with many requiring repair.
- Leaks - Two bottom mounted instrument (BMI) nozzles
- Circ through-wall cracks five pressurizer heater sleeves
- Cracks – CRDM Nozzle weld
- Leaks and Cracks – pressurizer relief nozzle and safety nozzles
- Crack – surge line butt weld
- Cracks – hot leg drain line butt weld and cold leg drain line butt weld

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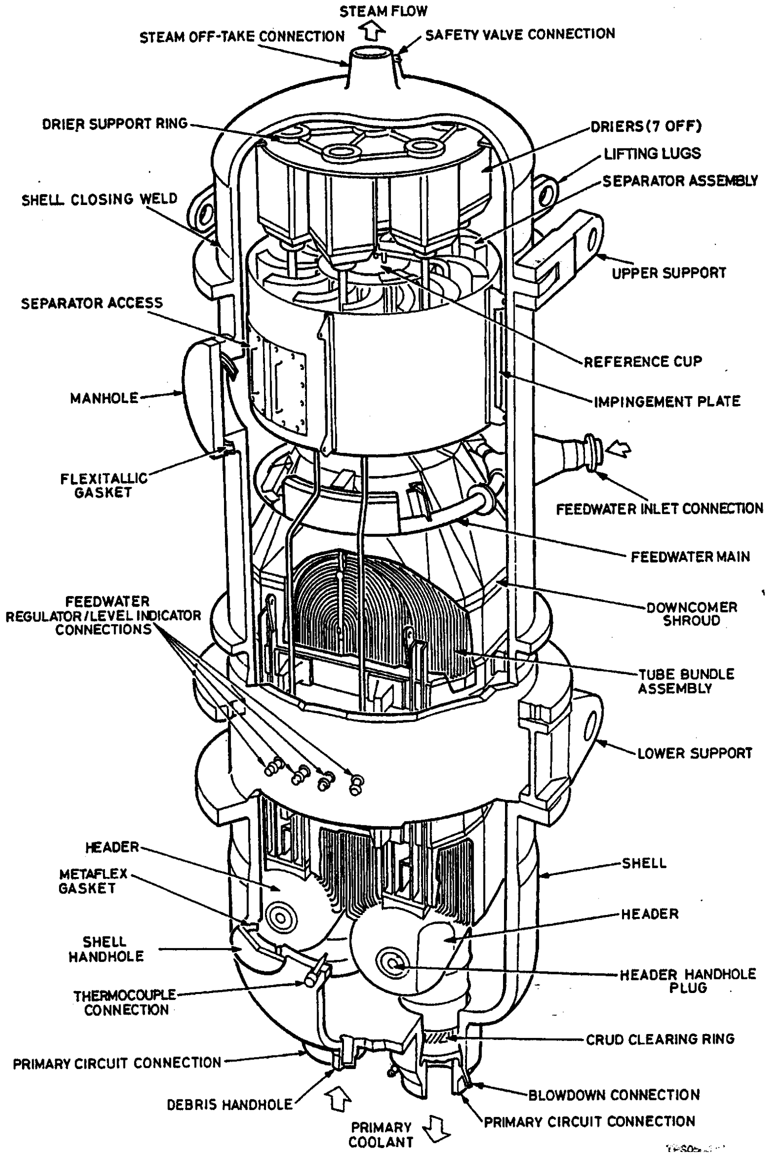
Nuclear fission – Steam generator

NH_3, N_2H_4, morpholine,
O_2<3ppb
pH=9.2 – 10.0 at 25°C



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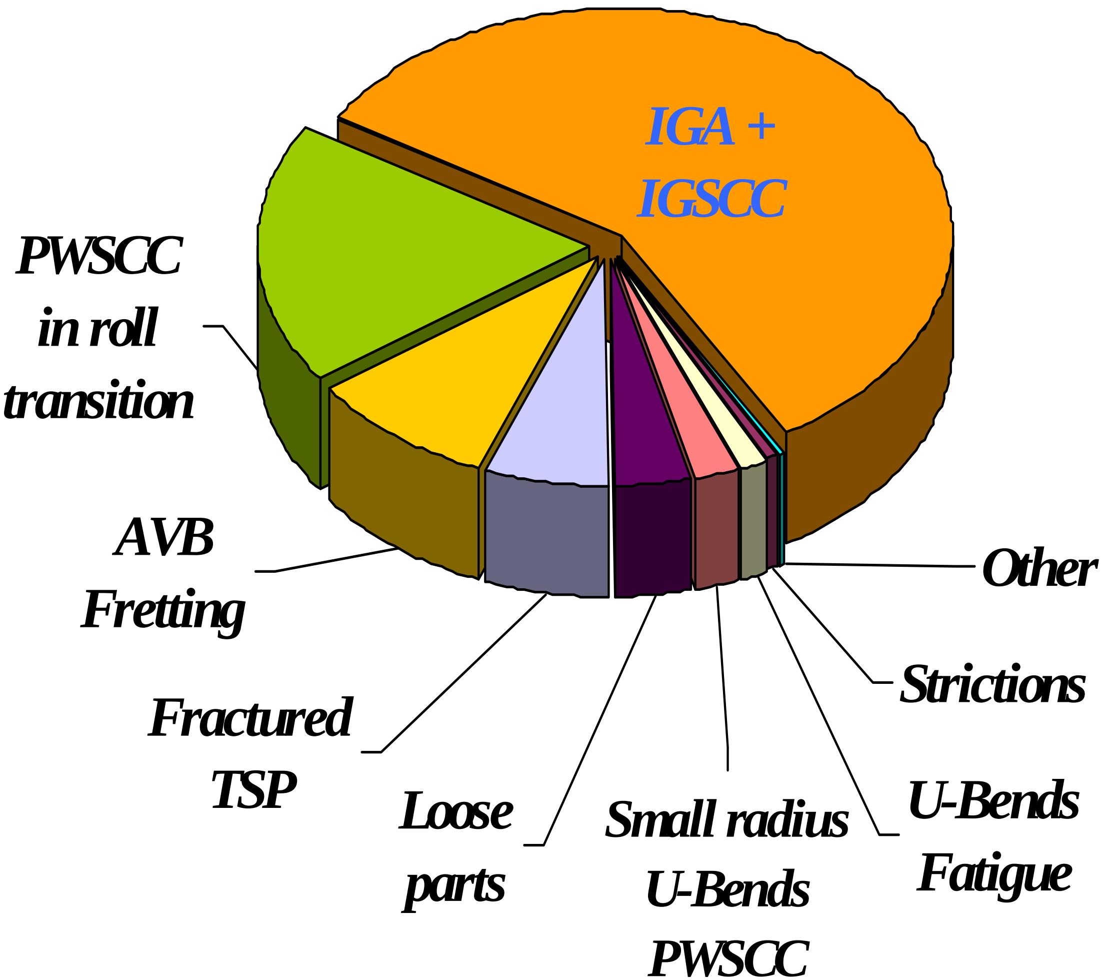
Nuclear fission – Steam generator (courtesy Areva NP)

Plugged tubes in France in 1999



Nuclear fission –PWR challenges

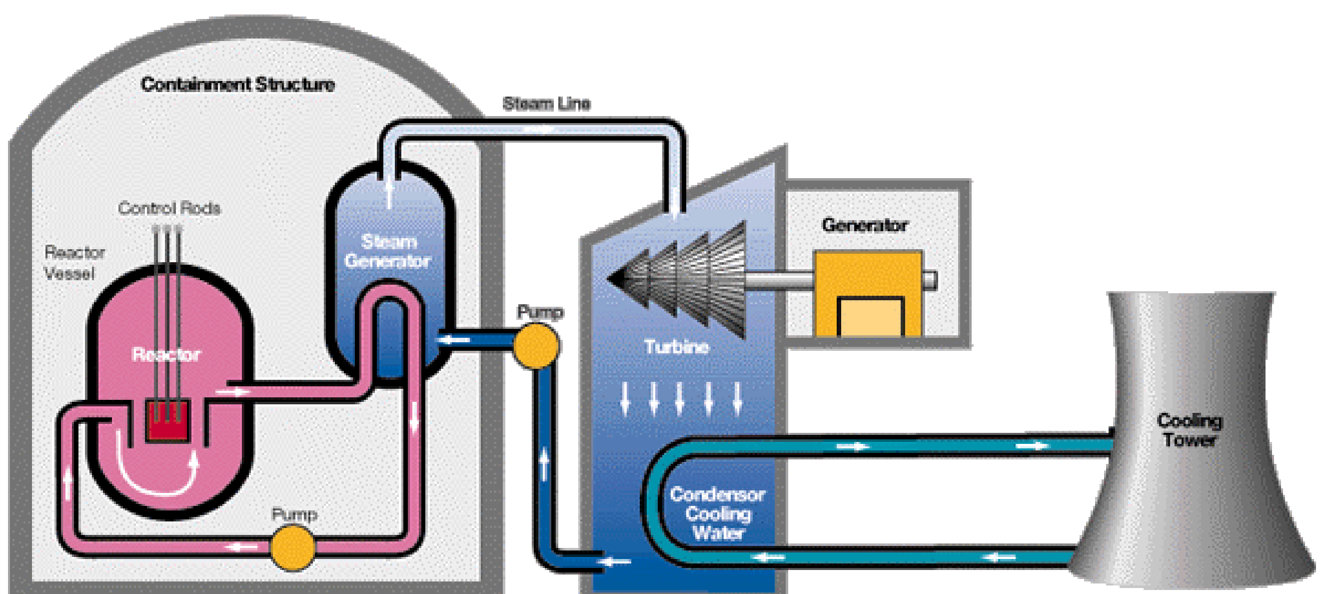
EIC: design & fabrication factors; start-up/shut-down; water chemistry transients, occluded regions; irradiation induced stress corrosion cracking; corrosion fatigue; corrosion-erosion

Thermal fatigue; thermal ageing; irradiation toughness loss; void swelling

Monitoring of strain, temperature and chemistry would be ideal

Risk-based management+NDE (considered at design stage)

Multi-scale modelling critical



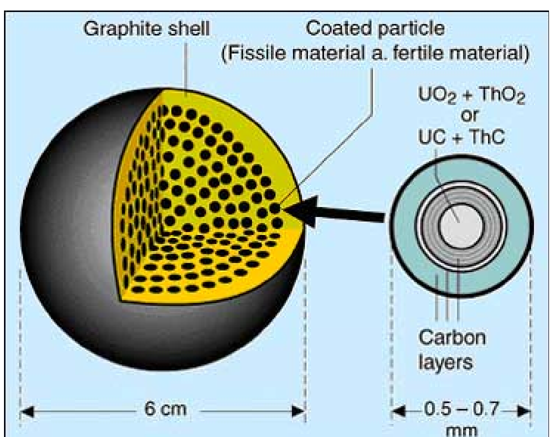
Nuclear fission – the future

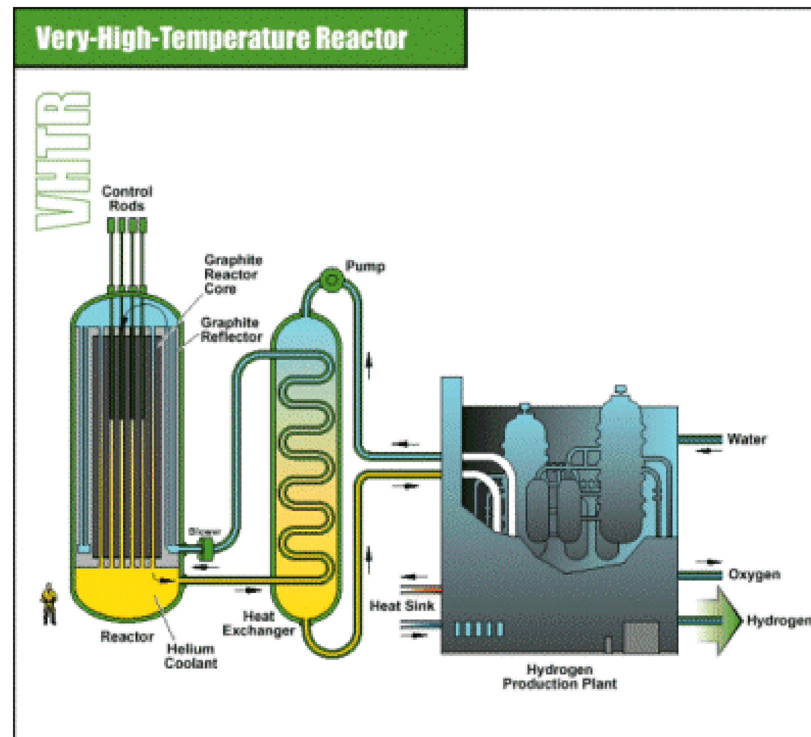
High temperature reactors (Coolant outlet T >900 °C)

- -Modular pebble bed
- -Prismatic modular reactors
- -Fast reactors
- -VHTR

H_2 production

Gas turbine



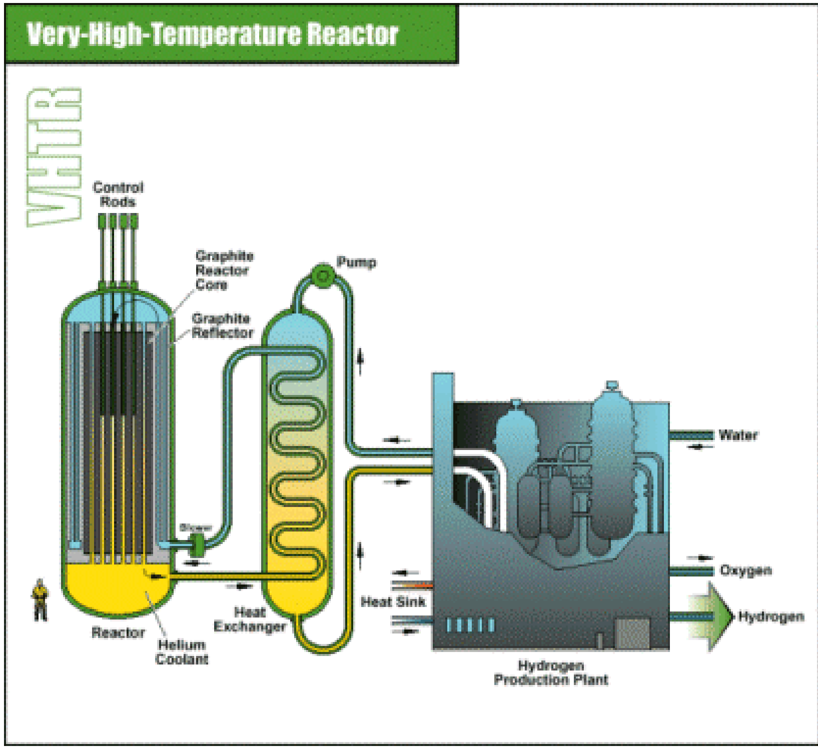


Nuclear fission – the future

High temperature reactors - Material needs

Materials lifetime at elevated temperatures

- Reactor pressure vessel
- Internals components
- Hot gas ducts and components
- Impurities in He gas
- Dimensional behaviour of graphite at high fluences



Nuclear fission – Other issues

Steam turbines

- Higher temperature inlet steam
- Higher strength blades in last stage LP turbine

Waste containment

Energy Materials

Workshop on energy materials, DTI 24/11/06

Fusion Materials

Drivers, Challenges and Opportunities

Synergies With Other Areas

Barriers

Ian Cook

EURATOM/UKAEA Fusion Association

(See: I. Cook, 'Materials research for fusion energy', Nat. Mat. 5, 77-80, Feb. 2006.)

Drivers (1)

"Fast Track" commercialisation of fusion will bring a large payoff:

•Almost unlimited fuel

•Competitive economics

•No significant emissions

•No potential for major accidents

•Only short-lived waste.

So, a big contribution to:

•World economic development, while avoiding dangerous climate change.

•Energy security.

Drivers (2)

Huge progress in fusion science and technology

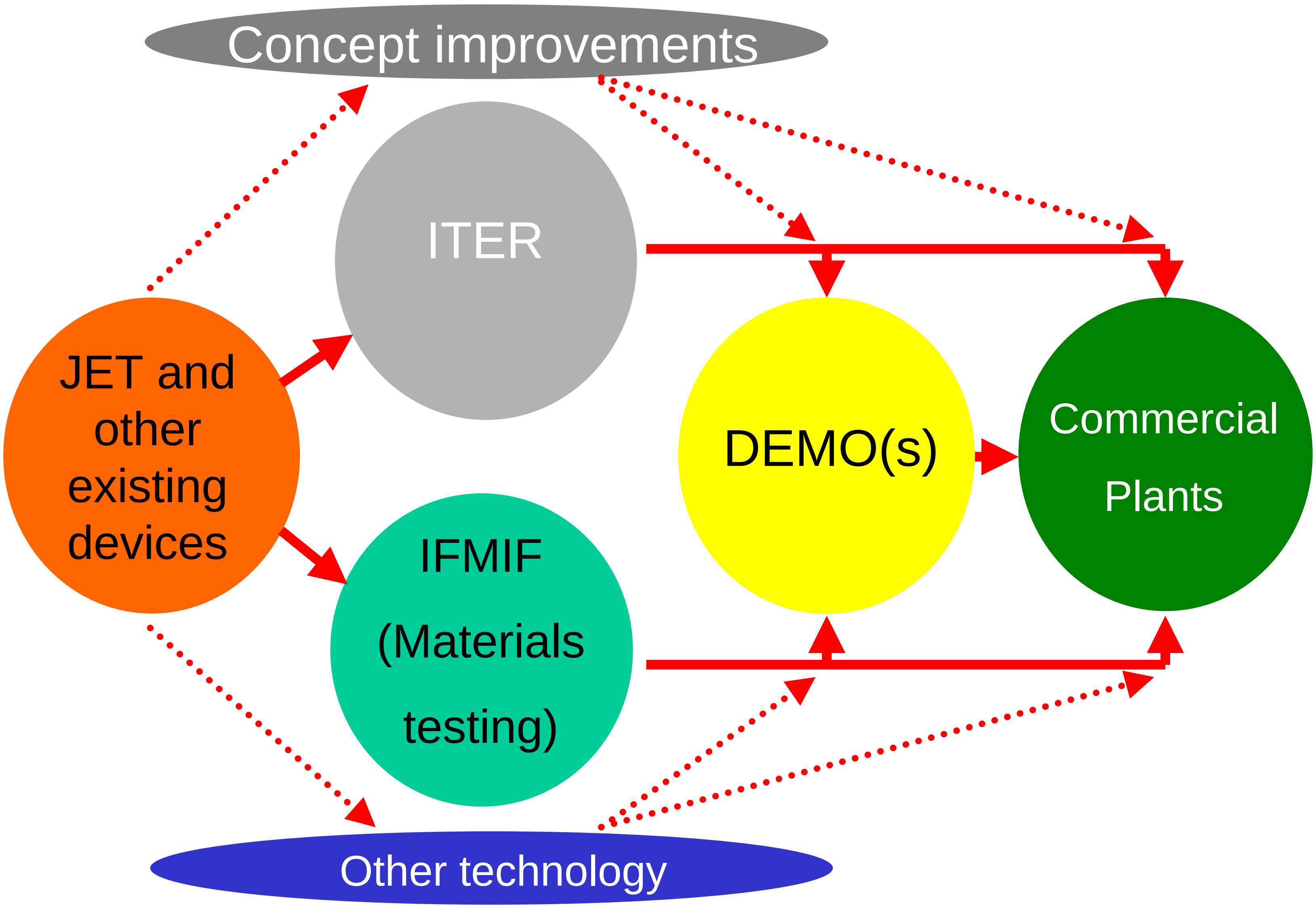
Fusion has just passed a major decision point:

- **We are taking the 'Next Step' - ITER**
- **In addition, there is a major materials initiative**

This marks the transition from the 'research' phase of fusion power development to the 'demonstration' phase

European Fusion Fast Track Strategy

(The ‘King Report’ to the EU Council of Ministers, 2002)



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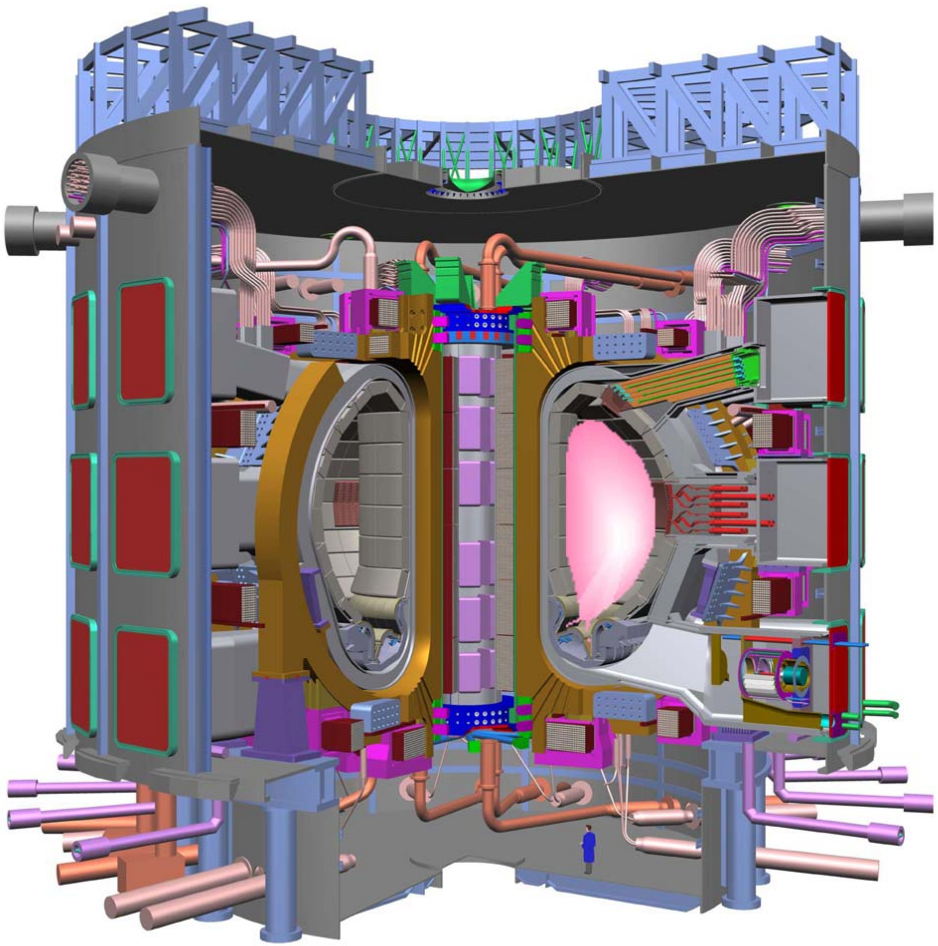
ITER

- Integrated physics and engineering on the scale of a power station
- Key technologies have been fabricated and tested by industry
- 500 MW
- Europe, Japan, Russia, China, India, USA and South Korea.
- <u>Construction has begun at Cadarache in France.</u>
- <u>Treaty signed on Tuesday, in the Elysee Palace.</u>



ITER will address many materials issues

- Effects of fluxes of particles and energy on plasma-facing materials.

- Short-term effects of fusion neutrons on materials.

- Corrosion, permeation and stress-related phenomena in materials.

- Many others.

Some materials issues cannot be addressed by ITER

ITER cannot address:

- **Damaging effects of many years exposure to fusion neutrons**
- **Associated development of alloys &composites.**

To address these challenges, we need to:

- **Construct IFMIF, the fusion neutron source, quickly and use it to test the most promising materials.**
- **Develop real understanding, and models with predictive capability, to optimise the initial choice of alloys to be tested, and to extrapolate from IFMIF results to DEMO.**

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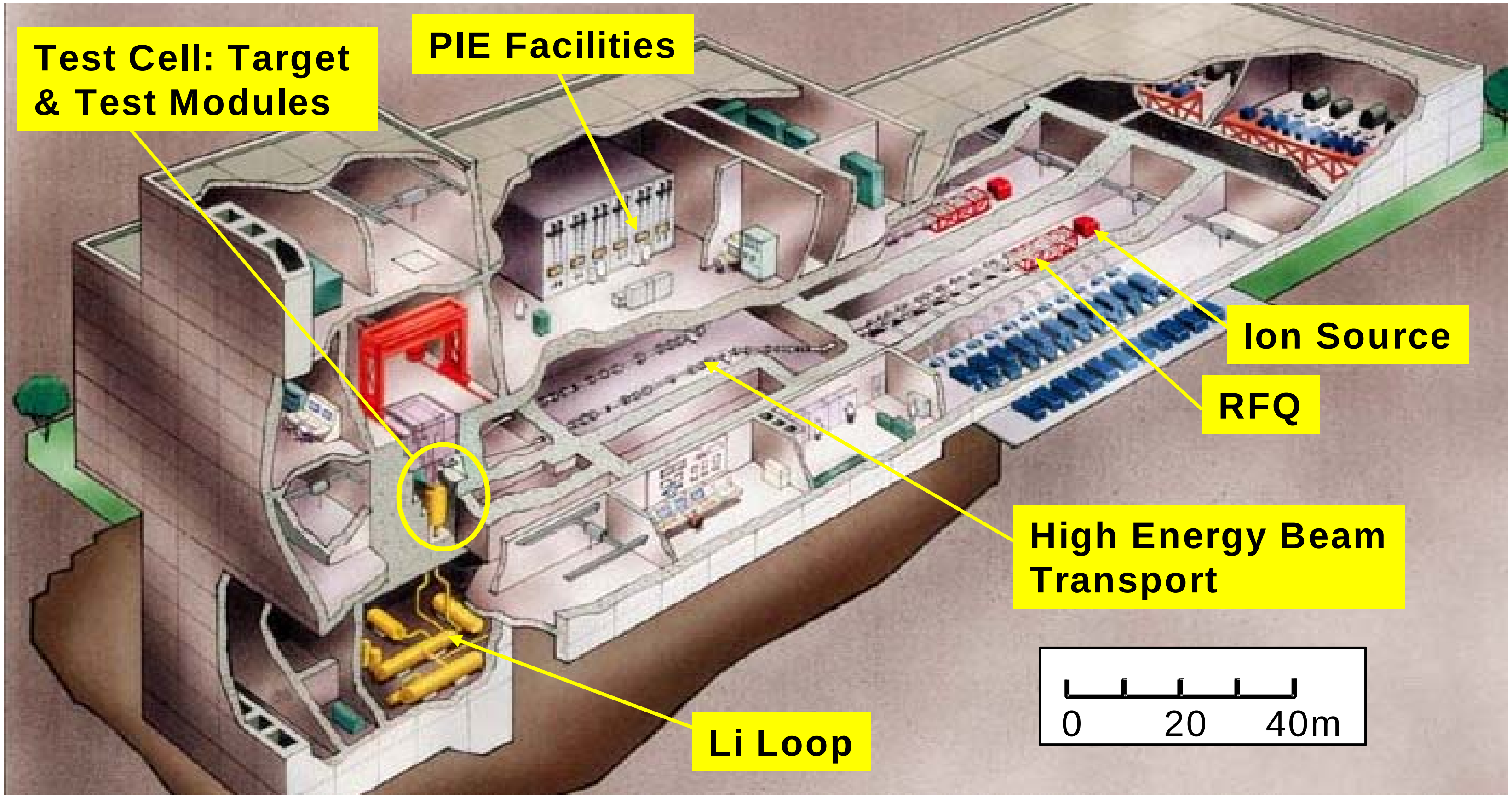
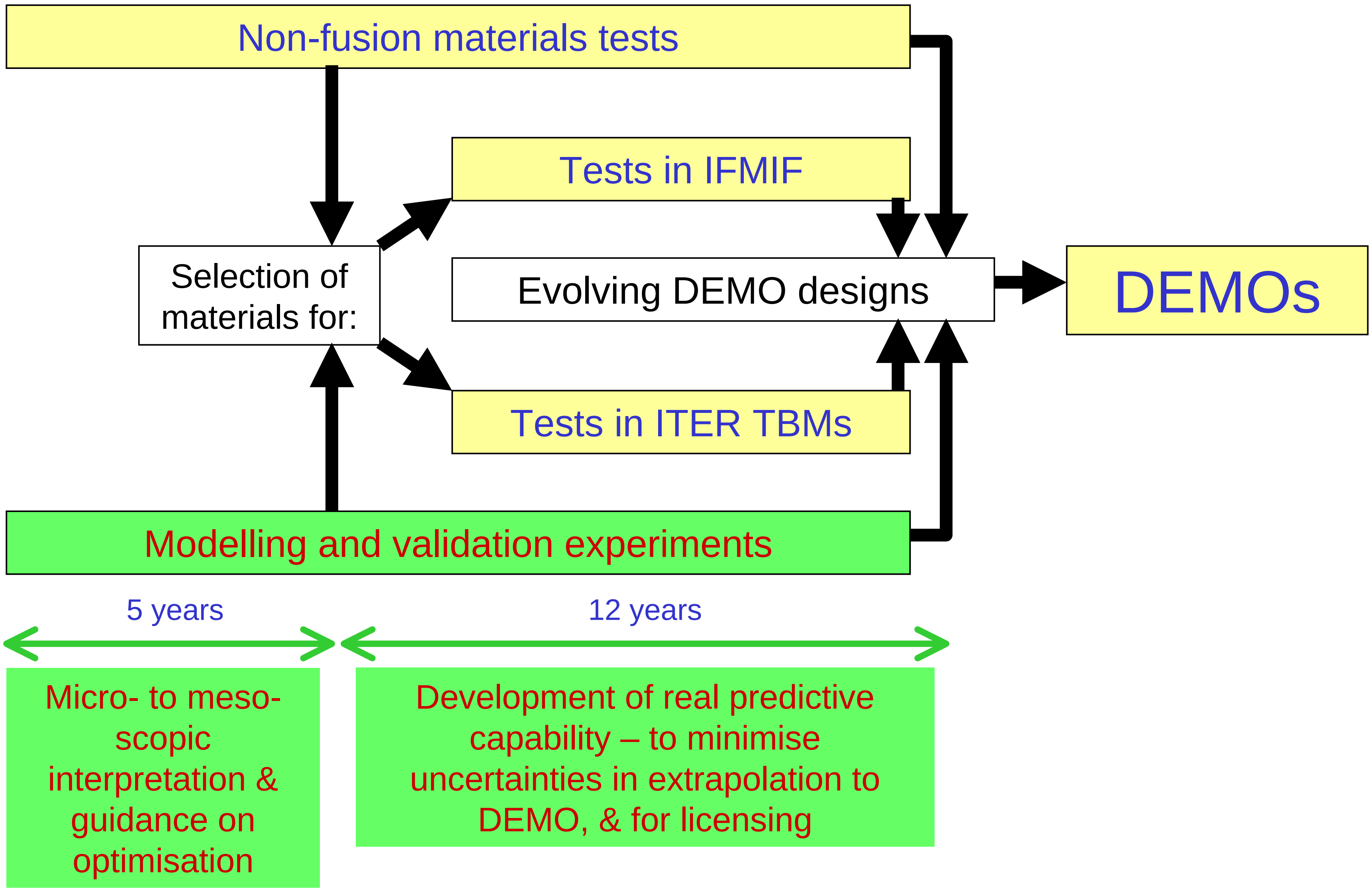
IFMIF



Accelerated completion of the design of IFMIF: JP/EU treaty, agreed on Wednesday in Brussels.

Roles of modelling and validation in the fast track fusion materials development programme



Main R&D Priorities

First priorities are the following promising materials:

- Ferritic-martensitic steels (neutron–resistant structural materials); Oxide-dispersion-strengthened steels.
- Tungsten-based (plasma-facing material).

These are body-centred-cubic (bcc). So are chromium, molybdenum, tantalum, vanadium and niobium: all of which have fusion interest, either as alloying elements or in niche roles.

So, we primarily study the bcc metals and alloys! Comparisons between these are also of great scientific value.

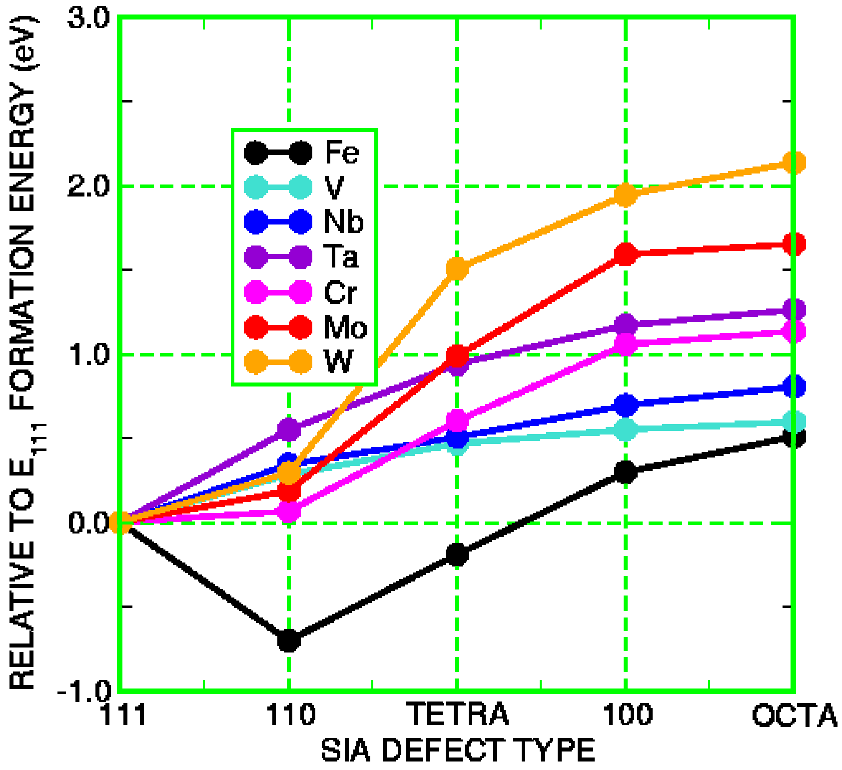
A wide variety of other materials, including ceramics, are also relevant.

Opportunities

- Real predictive modelling capability, based on understanding, is rapidly becoming possible. We are going through a phase change in this respect. Transatlantically competitive!
- Needs experimental facilities (e.g. multi-ion-beam irradiations, TEM) for inexpensive clever model validation.
- Can accelerate and cheapen materials design and optimisation, and permit licensing without the need for excessive design conservatism.

These developments have major potential in other areas.

Identification of Material Damage ‘Viruses’



Structures and energies from calculations used:

■As input to constructing *correct* interatomic potentials for molecular dynamics.

■As input to kinetic Monte Carlo modelling, on the mesoscale.

■Systematic quantum-mechanical calculations of small interstitial defects in the body-centred cubic metals.

■Has revealed anomalous nature of defects in iron: driven by magnetism.

■These are the ‘viruses’ of irradiation-driven materials damage.

■May always be inaccessible to observation.

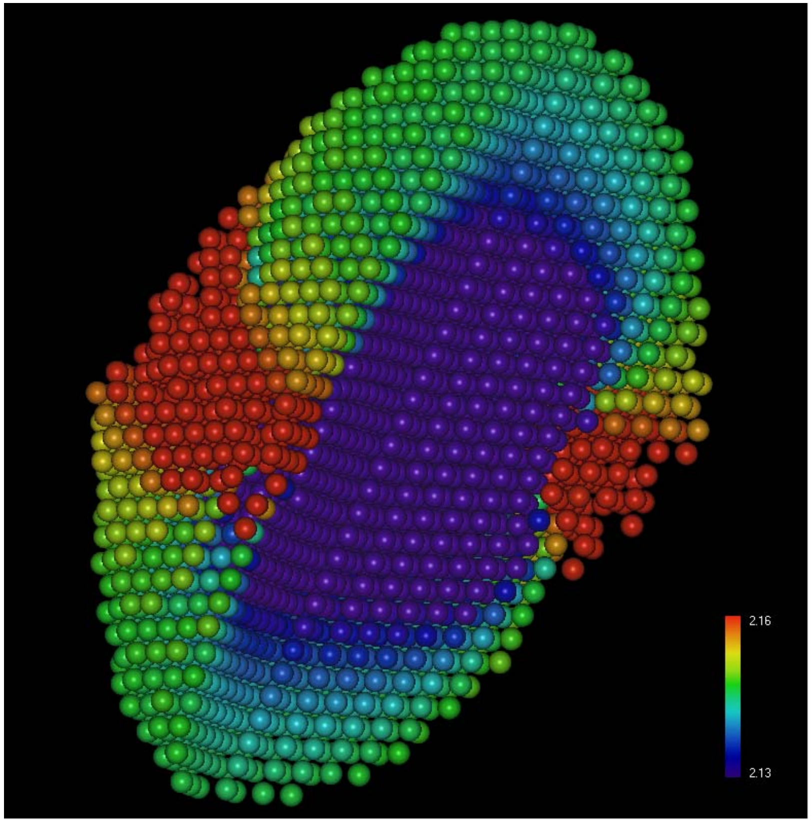
New interatomic potential for magnetic iron

Defect configuration	'Ab initio' calculation	Calculated from Potential
100	4.64eV	4.60eV
111	4.34eV	4.24eV
110	3.64eV	3.65eV

[Note that in the previous viewgraph, the 111 value has been set as the zero.]

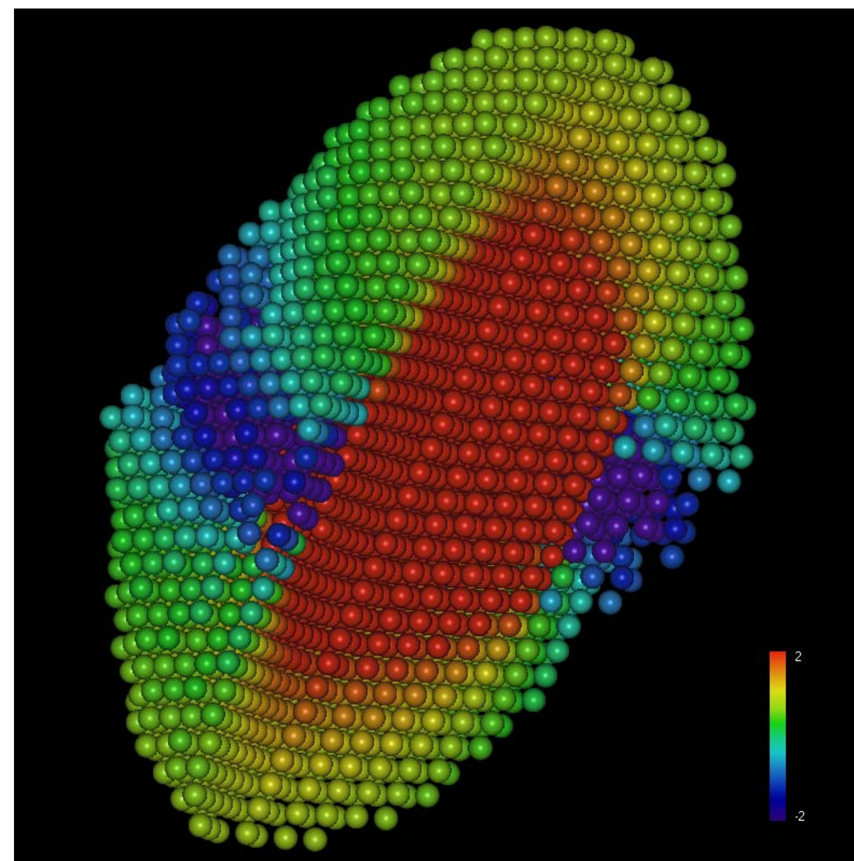
- New quantum-mechanics-based classical interatomic potentials.
- Allows accurate efficient simulations on million-atom scale.
- Significant result, likely to have implications in other fields.

Example results from the new potential

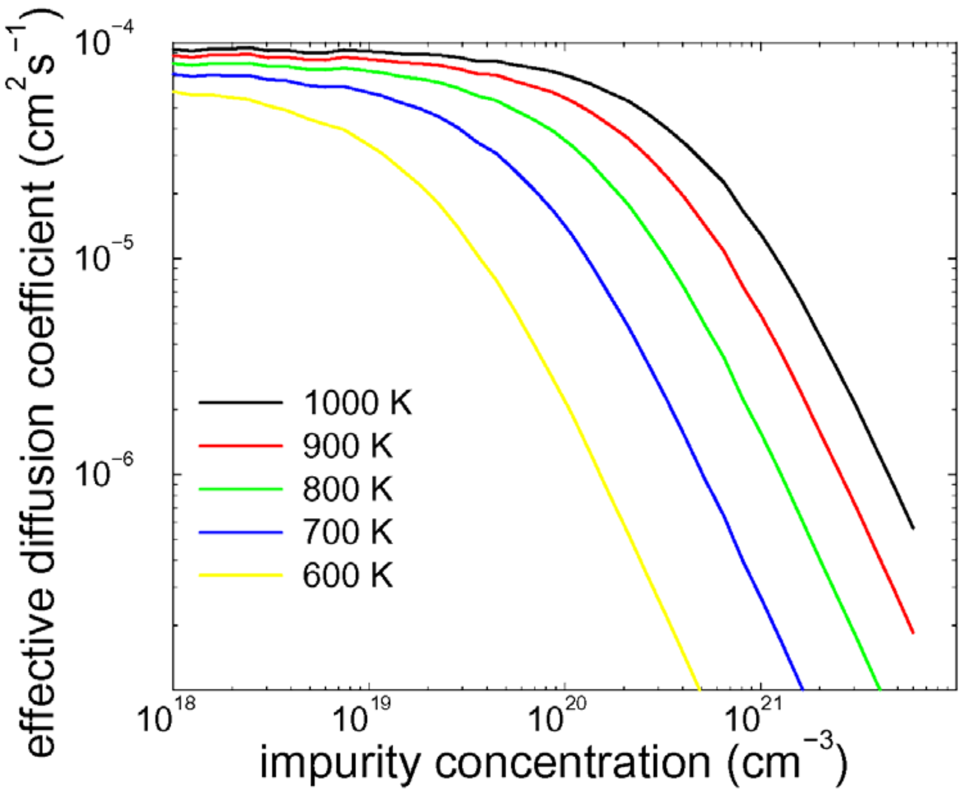


The distribution of magnetic moment (above) and pressure (below) around a dislocation loop in iron.

Pressure and magnetisation are almost perfectly anticorrelated, highlighting the importance of magnetoelastic effects in the microscopic picture of radiation damage in iron and ferritic steel.



Inhibiting Defect Migration



- Kinetic Monte Carlo and analytical investigations of effect of impurity atoms on migration of defect clusters in metals.
- Strong inhibition of diffusion – so defects are more likely to re-combine.
- May lead to ways of doping materials to suppress swelling etc.

Ongoing Work

- **Extending the modelling to alloys (iron-chromium, steels, tungsten alloys)**

- **Extending the modelling in theoretical scope (electronic effects, mesoscale modelling of defect evolution, dislocation mobility, phase changes).**

- **Validation of models to greatest possible extent. (*Fission* irradiations in European fusion programme. UKAEA-funded experimental programme at Oxford U. Prepare for interpretation of CEA/CNRS JANNUS multi-beam experiments, and facility to be set up at Salford U.)**

All work will continue to be within integrated European programme.

Main Synergies

Fusion and fission are very different in most respects. However, there are strong synergies in fission (Gens. 3.5 & 4) and fusion materials development:

- Similar underlying materials physics
- Similar candidate structural materials
- Similar desire for high temperature and long life in neutron bombardment
- Similar methods of theoretical and experimental investigation
- Similar need for real understanding

Joint approach would bring significant benefits. Benefits also to lifetime extension of existing plants and understanding the long time behaviour of fission repository waste.

More widely, synergies to materials for extreme environments (e.g. high heat flux.)

Barriers

•Low funding levels*.

•No *UK* integrated (or even loosely co-ordinated) *cross-cutting* R,D&D programmes.

•Few facilities (especially in UK) for experimental validation.

* Total public-funded world annual spending on energy R&D is equal to *one day* of consumer spending on energy.