Nuclear Reactors – New Build, Future Designs and Novel Applications

Presentation to: Engineering Department Nuclear Energy Seminars
Venue: University of Cambridge
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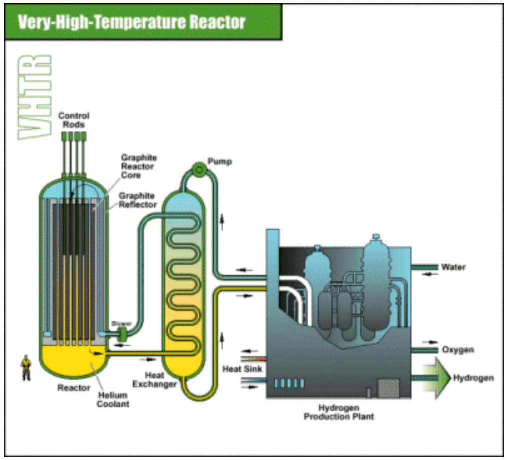
EPR


AP1000



VHTR

Why Global Nuclear Renaissance?

- Increasing energy demand
  - Doubling of global electricity consumption from 2007 by 2030 driven by population growth
- Impact of global warming and carbon emission targets
  - 75 countries accounting of 80% of energy use have agreed to cut or limit carbon emissions by 2020
- Other issues with reliance on fission fuels
  - Uncertainty on (increasing !) fossil fuel prices
  - Comparatively high impact of fossil fuel costs on electricity generation
- Security of supply
  - National energy autonomy – interruption of fossil fuel supplies across international boundaries is a concern
- Renewables
  - Cannot deliver reliable base load electricity

Why Nuclear Renaissance in the UK?

- Global factors also apply. In particular, regarding carbon emissions, the UK Government has set targets of cutting CO_2 emissions by 33% from 1990 to 2020 and 80% reduction by 2050
- Reduction in generating capacity
  - Magnox. Only one unit of one Magnox station remains in operation: Wylfa (to 2014); others at various stages of decommissioning.
  - AGRs. Life Extensions giving last station (Torness) closure in 2023) but other stations closing earlier. Ageing and obsolescence issues become more prominent with length of operation.
  - PWR (Sizewell-B). Only PWR currently operating in the UK, operating until 2035.
- Nuclear New Build required to redress the likely ‘dip’ in generating capacity around 2015 – 2023, as new plants will not yet be on stream
- Electrical grid ~85GWe today, forecast 300 GWe by 2050

Current Nuclear Power Plant Operations in the UK

- Gas Reactors
  - Magnox
  - AGR

Wylfa Magnox

Torness AGR

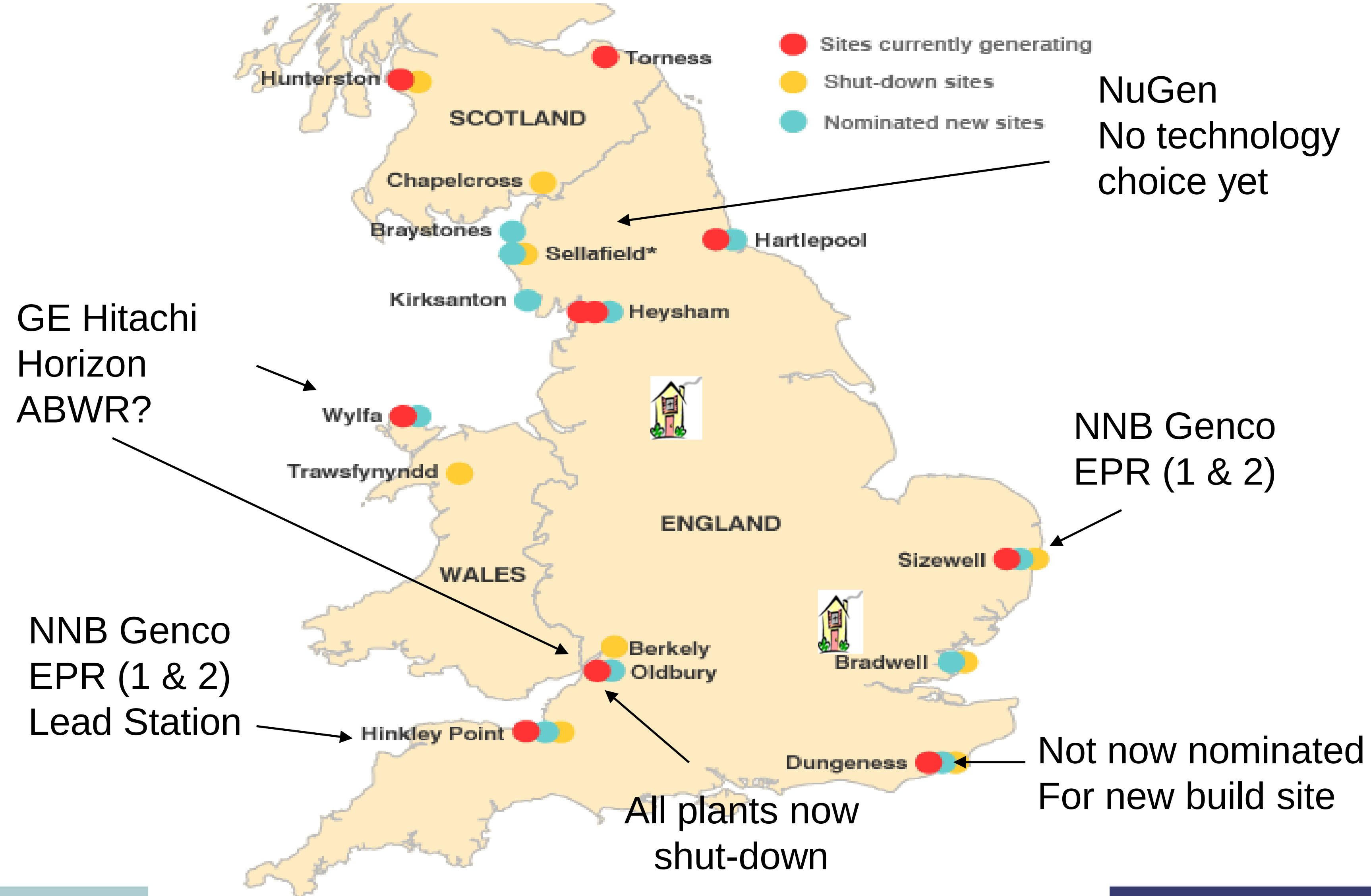
- UK PWRs
  - Sizewell-B
  - Naval PWRs

Sizewell-B PWR

Milestones for New Build

- In March 2008, the Department for Business, Enterprise & Regulatory Reform (DBERR) invited the nuclear industry to put forward applications for a Justification Decision, required by UK and EU law.
- Sites for new build have been proposed and potential licensees have come forward.

UK Civil New Build Sites



*Shut-down site known as Calder Hall

SOURCE: DECC

New Nuclear Sites and Potential Licensees

- NNB GenCo (EDF Energy + Centrica) has plans for 4 new reactors, 2 at Hinkley Point and 2 at Sizewell, comprising 6.4GW of capacity
- NDA has nominated the sites Wylfa, Oldbury, Bradwell and Sellafield for New Build.
- Horizon Nuclear Power, has secured sites at Oldbury and Wylfa to develop 6GW of new capacity.
- GE-Hitachi recently purchased Horizon; after RWE/ E.ON pulled out earlier in the year
- NuGen (GDF Suez + Iberdrola) looking to develop a further 3.6GW of capacity.
- NB. Russia's state atomic energy corporation Rosatom also remains interested in the UK nuclear market.

Advanced Pressurised Water Reactors (New Build)

- PWR candidate designs:
  - EPR (AREVA)
  - AP1000 (Westinghouse)
- International status
  - International design standards
  - First plants under construction
- UK:
  - Designs under UK licensing process
- Evolutionary approach:
  - Extension from current designs
- Safety:
  - Inherent safety features in design

EPR

AP1000

UK Candidate PWR Designs

- EPR
- Nominal rating: 1,650 MWe
- Evolution of N4 (French) & Konvoi (German) designs
- Meets European Utility Requirements (EURs)
- Meets Technical Guidelines (TGs) established by the French Nuclear Regulatory Agency (DGNSR)

- AP1000
- Nominal rating: 1117 MWe
- Evolution of Westinghouse PWR technology over 35 years
- Meets US Advanced Light Water Reactor Utility Requirements (URDs) and European Utility Requirements (EURs)
- Achieved USNRC design certification approval

NEWBUILD – Status of UK Licensing Process

- Pre-licensing of new PWR designs by Safety, Security and Environmental Regulators – Generic Design Assessment (GDA) in progress 2009 – 2011:
  - Detailed safety review of EPR and AP1000 candidate designs – interim design acceptance for both designs achieved in December 2011

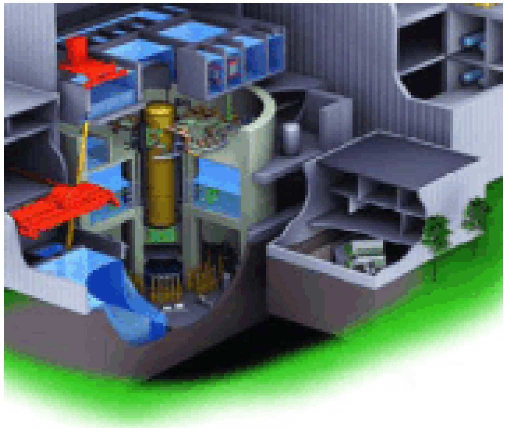
- Site licensing assessments and operator specific evaluations still required (for EPR, in progress in 2012):
  - Planning approval (consent) by the Infrastructure Planning Commission (IPC)
  - Nuclear Site Licence applications with ONR
  - Site based authorisations for radioactive waste disposal (EA, SEPA)

New Build Time Line - UK

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1. Pre-license Generic Issues														
Safety and compliance														
Intelligent customer support														
2. Site/Operator licensing and detailed design														
Safety & Compliance														
Engineering & Design														
Intelligent customer support														
3. Construct														
Safety and compliance														
Engineering and design														
Recruit-Train- Commission														
4. Operate														
Operational Support & Training														

Advanced Boiling Water Reactors (New Build)

- ABWR (GE – Hitachi)
  - Nominal rating: 1,350 MWe
  - Gen III evolution of earlier BWR designs
  - Achieved USNRC design certification approval in 1997
  - ABWRs operating in Japan, under construction in the USA and Taiwan
- ESBWR (GE)
  - USNRC design certification application submitted
  - Originally submitted for GDA in the UK but withdrawn after preliminary stage

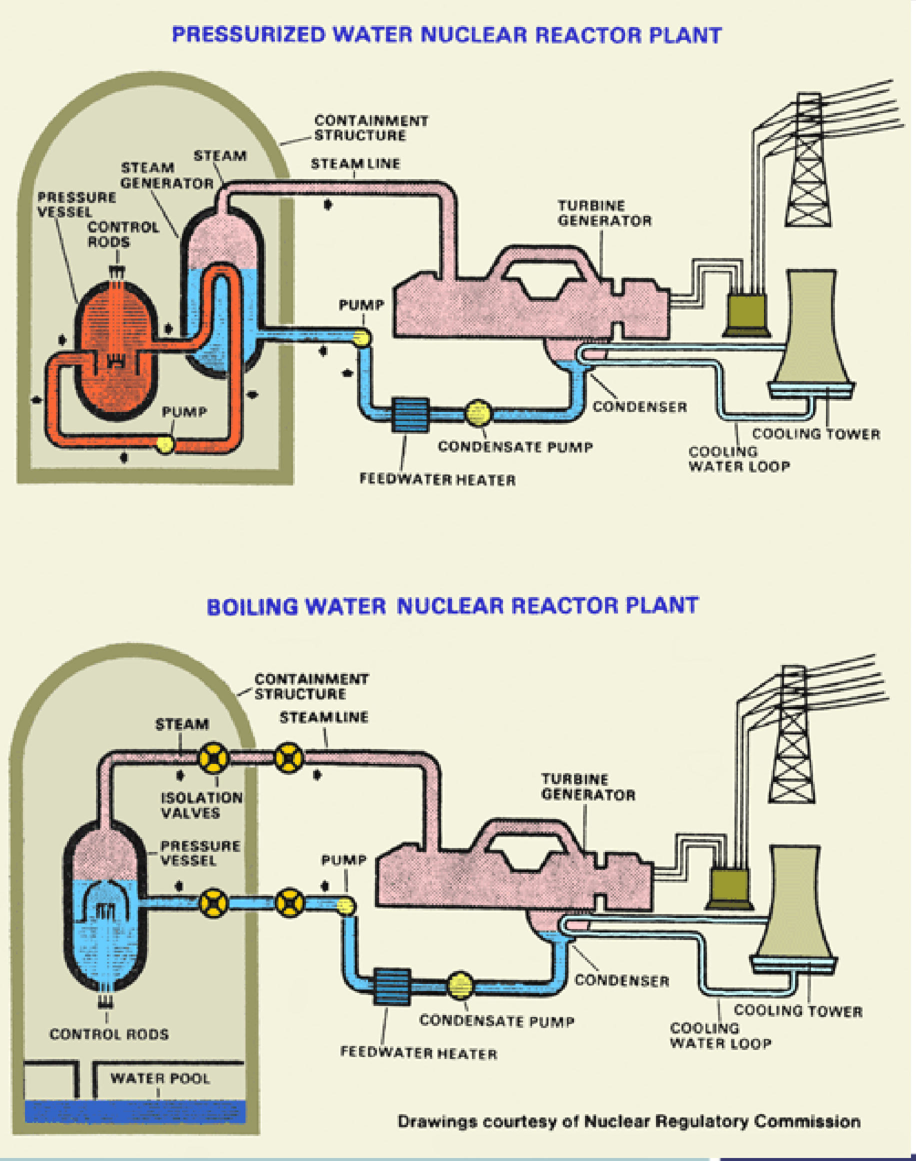


Difference between the PWR and BWR

In the PWR, heat is transferred from the primary circuit to the secondary circuit and steam is generated within the steam generator connecting between the primary and secondary circuits.

In the BWR, steam is produced in the vessel and goes straight to the turbine generator. This has implications for the emergency cooling systems design and radiological implications in the event of fuel clad rupture.

Ref: www.nrc.gov



Summary Status of UK New Build

- Private sector view of financial risk
  - Increase in building capital cost
  - Guarantee price for nuclear comparable with other carbon free generation!
- Following interim design acceptance in 2011, EDF are progressing the ‘permissioning‘ phase with ONR to commence building two EPR units at Hinkley C but final investment decision pending (end 2012 anticipated)
- GE-Hitachi acquisition of Horizon Nuclear Power signals a ‘vote of confidence on UK nuclear’ but:
  - Additional financial backing required; and
  - ONR acceptance of ABWR design would be needed and this would take several! years
- There is currently no utility planning to proceed with the AP1000 in the UK, though NuGen have not made a technology choice
- Impacts from Fukushima still require work
- Economic crisis impacts

NEWBUILD - Worldwide Interest

Rest of the World

- Europe
  - As of March 2012 there is a total of 186 nuclear power plant units with an installed electric net capacity of 162 GWe in operation in Europe
  - Significant nuclear reactor/ operations of different types of reactors (PWRs, BWRs, PHWRs, VVERs, RBMKs, Also small reactors e.g. isotope production)
  - First EPR under construction in Finland. Two further in France. New build programmes halted in Germany and Switzerland; impact from Fukushima events.
- North America
  - The US is the world's largest producer of nuclear power, accounting for more than 30% of worldwide nuclear generation of electricity. As of 2011, there are 69 PWRs with combined capacity of about 67 GWe and 35 BWRs with combined capacity of about 34 GWe.
  - Orders for six AP1000s in the US, initial units at the Vogtle site in Georgia. Orders for two ABWRs in the US at the South Texas site.
  - Canada focussing on their Candu plants, for new build on the advanced Candu (ACR-1000).

Rest of the World (Cont.)

- Asia
  - China is embarking upon a huge increase in nuclear capacity to 70-80 GWe by 2020; Two EPRs under construction at Taishan. Two AP1000 at Sanmen and two at Haiyang under construction. First electricity in late 2013.
  - India's target is to add 20 to 30 new reactors by 2020. Russia's Atomstroyexport is building India’s first large nuclear power plants, two VVER-1000 (V-392) reactors. Four PHWR reactors (640 MWe net) are under construction. due on line by 2017. 500 MWe prototype fast breeder reactor (PFBR) in construction, four further fast reactors are envisaged.
  - Japan has put significant investment into nuclear power but major ramifications from Fukushima. As from 2008, Japan had 55 reactors operating around the country with a total output of 49 GWe, including four ABWRs. All shut-down immediately after Fukushima but some are now restarted.
  - South Korea already has substantial programme. The first new APR-1400 units - Shin Kori 3 & 4, are under construction, and operation is expected in 2013 and 2014. ABWR under construction in Taiwan.

Rest of the World (Cont.)

- Middle East and North Africa
  - In consultation with IAEA, a number of countries in these areas are considering nuclear power programmes
  - UAE plans to build 4 commercial nuclear power reactors, South Korean APR-1400s, total 5.6 GWe, by 2020. Further reactors are planned.
  - Jordan intends to license the operation of the country's first nuclear research facility, for training purposes, followed by a first 1GWe scale power reactor later.
- Latin America
  - Brazil has two nuclear reactors generating 3% of its electricity, and a third under construction. Four more large reactors are planned to come on line by 2025.
  - Argentina has two nuclear reactors generating; completion of a 3rd reactor is expected by early 2011.
- South Africa
  - South Africa has two nuclear reactors generating 5% of its electricity. Strong commitment to nuclear energy but financial constraints. Construction of a demonstration Pebble Bed Modular Reactor was cancelled.

Fukushima Events

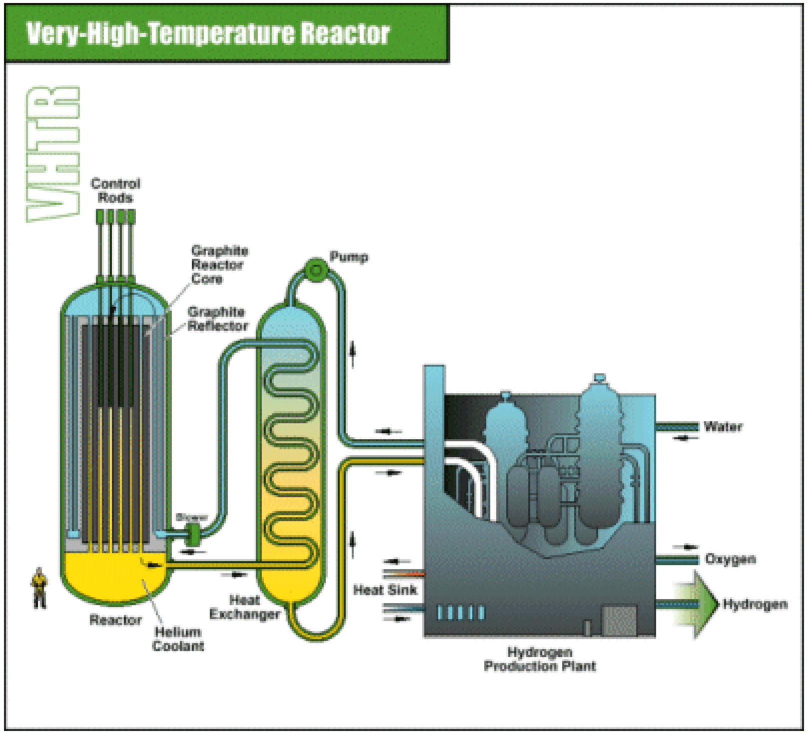
- Scenario
  - The earthquake and ensuing tsunami on March 11, 2011 resulted in loss of power supplies (including diesel generator back-up) over an extended period in four of the six Fukushima Daiichi reactors
  - Cooling systems to the plant's reactors and spent fuel ponds were therefore not functional
  - Fuel rods overheated which resulted in fuel cladding material reacting with steam to produce hydrogen
  - A series of explosions occurred which caused significant difficulties in stabilising the badly affected reactors.
- Governments around the world immediately ordered reviews of their nuclear programmes in regard to:
  - Existing nuclear operations
  - New Build planning

UK Response to Fukushima

- UK Government COBRA office and the Chief Scientist initiated a study on the unfolding events in the immediate aftermath of the Fukushima accident on March 11th, 2011
- HM Chief Inspector of Nuclear Installations initiated an in-depth review on the implications for the UK nuclear industry (interim recommendations (May 2011), final report (September 2011)
- In mid 2011, EU Governments required industry to carry-out 'Stress Tests'; severe accident resilience studies on all nuclear reactors in the EU. Globally, other governments required similar responses
- The Office of Nuclear Regulation (ONR) implemented these mandates in the UK for all reactor plant but also, in addition, required reviews covering all supporting nuclear facilities (e.g. fuel ponds, waste management facilities, etc) and also reviews on the UK candidate new build designs

Very High Temperature Reactor (VHTR)

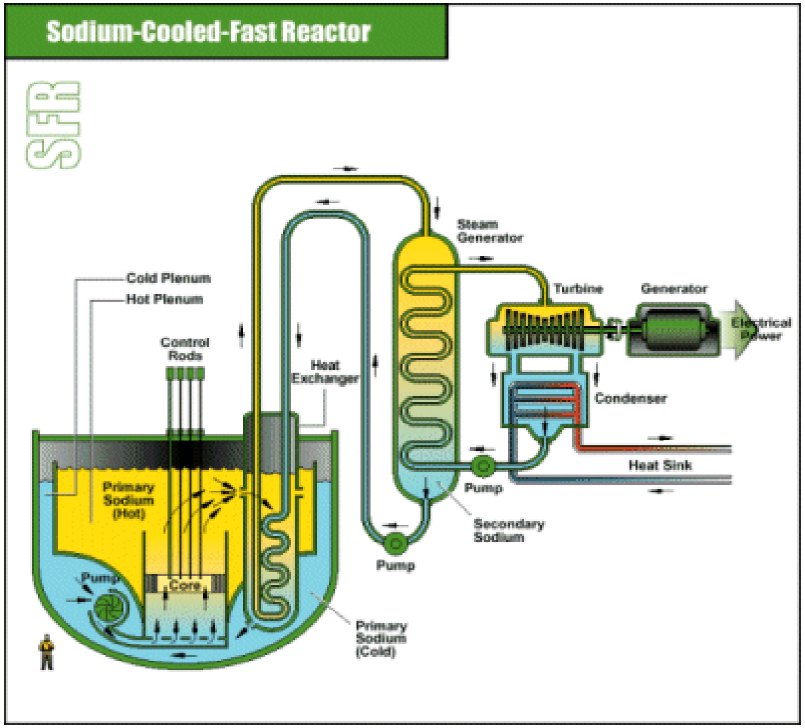
- Extend HTR technology to very high temperature operation for new applications (additional to high efficiency electricity generation)
  - Hydrogen generation
  - High temperature process heat applications
- Very High Temperature Reactor (VHTR)
  - Helium cooled, Reference power (600 MWt)
  - Coolant outlet temperature (1000 ^{0}C)
  - 50% efficiency (at this efficiency it could produce 200 metric tonnes of hydrogen/ day
- Research requirements
  - Technology requires advances in high temperature materials, alloys, ceramics and composite materials.
- Timeline
  - 2030+



Source: USDOE

Sodium Fast Reactor (SFR)

- Extend existing experience in sodium cooled fast reactor technology
  - Electricity generation in the past;
  - Future - actinide waste and plutonium management
  - Prototype sodium cooled fast reactors have been built and operated successfully in US, UK, France, Russia and Japan
  - Concept fallen out of favour at the present time due to high capital cost, proliferation concerns.
- Sodium Fast Reactor (SFR)
  - Reference power (150-500 MWe (small), 500-1500 (large))
  - Fast spectrum
  - Closed fuel cycle
- Research requirements
  - Fuel cycle technology
  - Plant simplification
- Timeline
  - 2030+



Source: USDOE

Other Gen IV Reactors (Long Term)

- Super Critical Water Reactor (SCWR)
  - Water cooled
  - Extend widely used light and heavy water reactor technology
  - Thermal or fast spectrum
- Gas Cooled Fast Reactor (GCFR)
  - Helium cooled
  - Coolant outlet temperature (1000 ^{0}C)
  - Gas cooled fast reactors considered in the past, e.g. by UKAEA
- Combine the benefits of gas reactor and fast reactor technology
- Applications (additional to high efficiency electricity generation)
  - High temperature process heat
  - Actinide waste and plutonium management

- Lead/ Lead Bismuth Cooled Fast Reactor (LCFR)
- Application
  - Enable 30 year life fuel
  - Attractive for propulsion
- Molten Salt Reactor (MSR)
- Application
  - Capability to utilise thorium
  - Attractive as a means for extending fuel resources
- Timeline
  - 2030+

Small Reactors

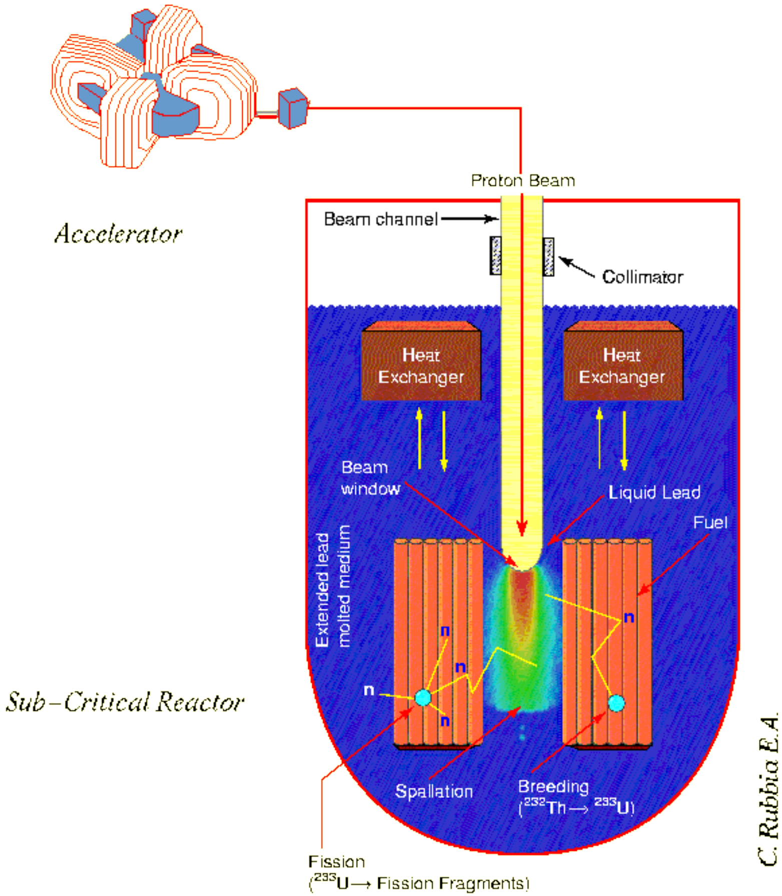
- A new interest in developing small and medium nuclear power reactors for generating electricity from nuclear power, for process heat, and other applications.
- Drivers:
  - Reduce capital costs ($100M, not $5b) and quicker to build;
  - For smaller power requirements(10 – 200MWe) and for smaller scale grid systems.
- Technologies and applications being studied very diverse:
  - Light water reactors for marine propulsion, cogeneration (electricity and district heating/ desalination), floating power units and submerged power units)
  - High temperature gas cooled reactors for high efficiency power generation, process heat applications. A modified version uses fast neutrons and so is a gas-cooled fast reactor enabling it to reduce nuclear waste by transmutation.
  - Other small reactors (Liquid metal cooled fast neutron, molten salt) akin to the larger scale reactors already mentioned)
  - Small reactor designs well developed (PRISM (311MWe), Hyperion PM (25MWe))

Future Research - Partitioning and Transmutation

- Partitioning is a chemical process applied to spent nuclear fuel to separate the constituents for transmutation
- Transmutation is a nuclear reaction to change certain isotopes into more stable or shorter lived isotopes
- Isotopes of plutonium and other actinides generally long-lived with half-lives ~many thousands of years
- Radioactive fission products generally shorter-lived with half-lives ~ 30 years
- Therefore, transmutation of actinides in waste substantially reduces very long-term radiotoxicity by a much shorter-term radiotoxicity problem

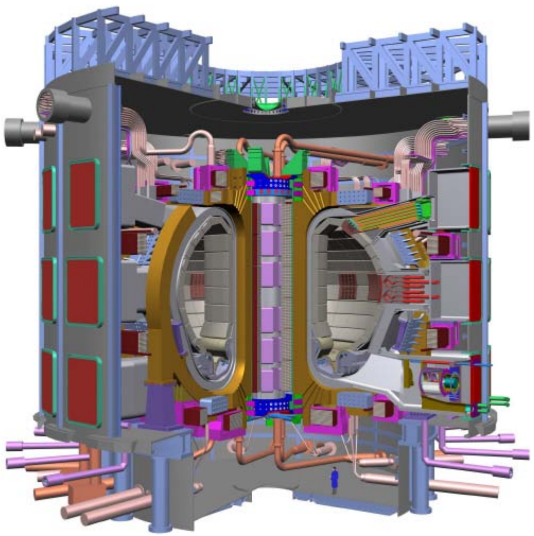
Accelerator Driven Systems (ADS)

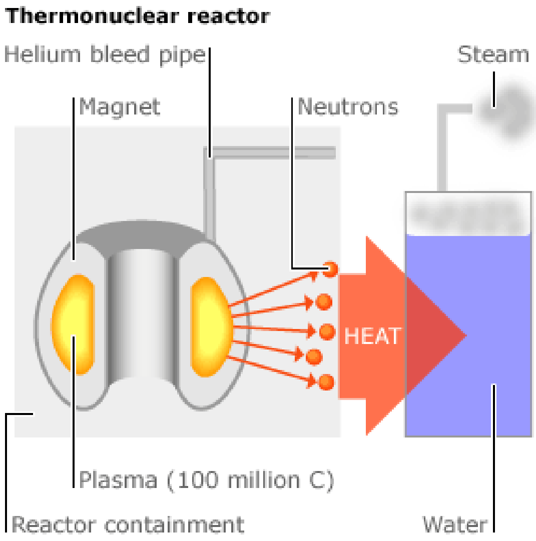
- Concept been known for several decades
- Has all the applications of fast reactor technology including actinide transmutation and Pu burning
- Additional safety features
- Applicable to a thorium fuel cycle
- International activities
  - Towards prototypes with thorium (UK, Switzerland)
  - R & D. Japan, India, Belgium (MYRRHA)



ITER

- A global project The International Thermonuclear Experimental Reactor (ITER is a collaboration between the EU, the US, Japan, Russia, China, South Korea and India.
- The aim is to design and build a fusion reactor in about a decade at a cost of five billion euros.
- ITER will implement decades of research in a test facility that will bridge the gap to a commercial plant.





Summary

- Current plant has an important role to play in carbon free electricity generation for the next decade, but requires strong support to deal with ageing and obsolescence issues. Legacy waste issues still require resolution
- Current and New Build civil power reactor will focus primarily on electricity generation over the next one to two decades. Water reactor technologies will predominate. Other applications include propulsion (naval), low energy applications
- New Build has fuelled the nuclear renaissance but still some hurdles to cross. In the UK interim design licensing for two candidate designs achieved, site licensing to come. Open public scrutiny of process. First generation ~ 2020, so gap in nuclear generation apart from Sizewell-B

Summary (Cont.)

- There are medium term designs (e.g. high temperature gas reactors) to support more efficient electricity generation, hydrogen production and high temperature process heat applications
- Long term designs can support fuel breeding in both uranium and thorium fuel cycles within a fast reactor context, also waste management transmutation and plutonium burning
- Significant investment in fusion technology to support the ITER prototype development project but major engineering challenges to be overcome. Large scale prototype under construction in France.