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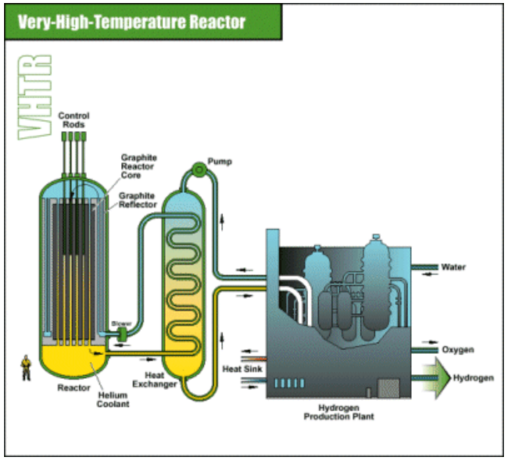
EPR

AP1000



VHTR

Nuclear Reactors – New Build, Future Designs and Novel Applications

Presentation to: **Engineering Department Nuclear Energy Seminars**

Venue: **University of Cambridge**

Presented by: **Dr John Lillington, Serco, Winfrith**

Thursday 23rd February 2012

Summary of Presentation

- Status of New Build Activities in the UK
- Currently available Advanced LWRs (in general)
- New Build deployment and status in Rest of World
- Advanced 'Small Reactor' developments
- Future reactor developments and applications

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 for 80% of energy use have agreed to cut or limit carbon emissions by 2020
- Other issues with reliance on fossil 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

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 60% reduction by 2050
- Reduction in generating capacity
  - Magnox. Only one Magnox station will remain in operation after 2012), Wylfa (to 2014); others at various stages of decommissioning.
  - AGRs. Life Extensions in train giving last station (Torness) closure in 2023), but other stations closing much earlier. Ageing and obsolescence issues becoming 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

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New Nuclear Sites and Potential Licensees

- At the beginning of 2009, the UK government invited industry to nominate sites for the first wave of New Build. After a consultation period, from 2010 developers were able to apply for planning permission
- 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 (E.ON UK & RWE npower) have interest in Oldbury and Wylfa, target is to develop 6GW of new capacity for the UK
- NuGen (GDF Suez & Iberdrola) looking to develop a further 3.6GW of capacity at Sellafield

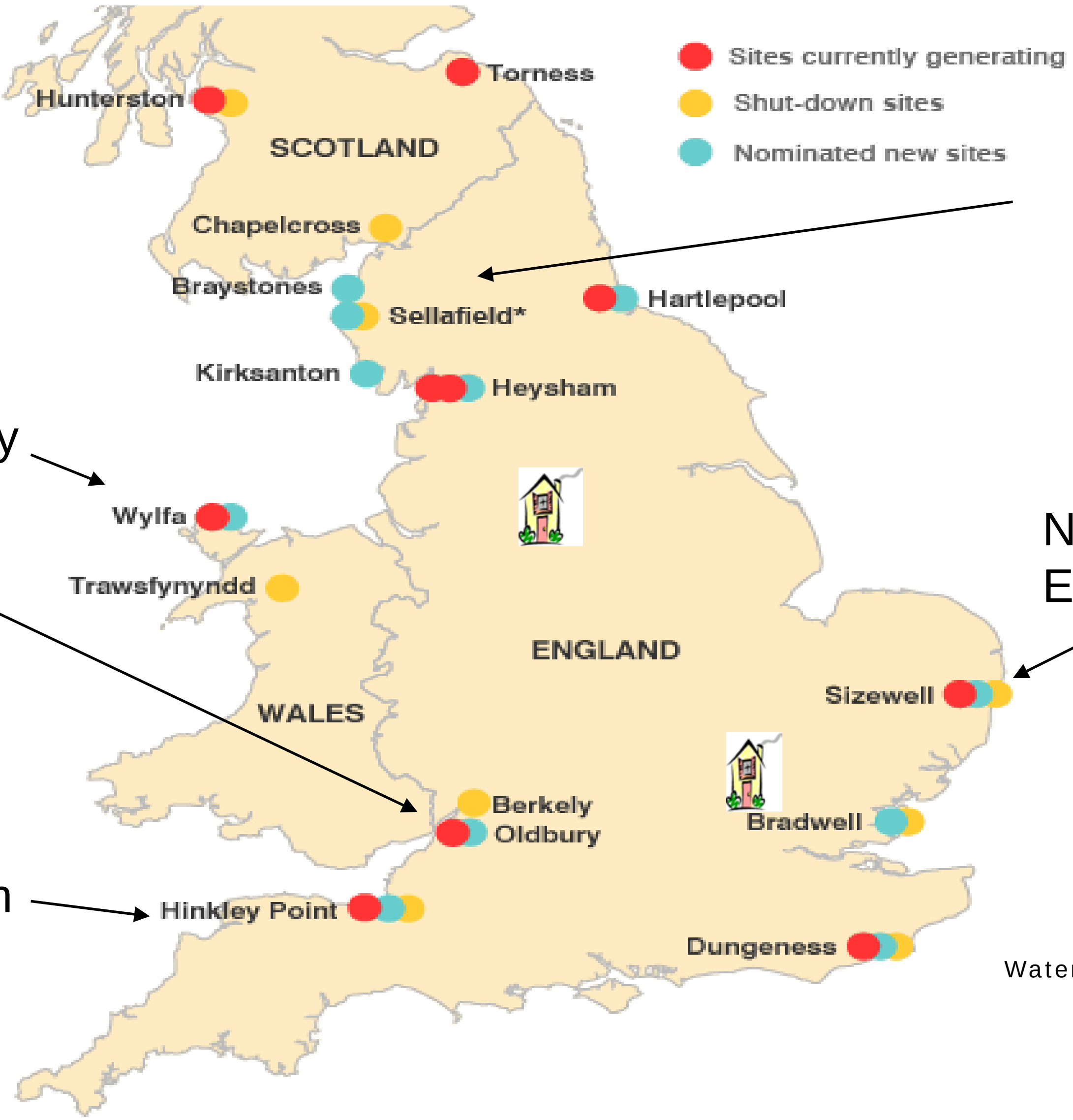
UK Civil New Build Sites

NuGen
No technology choice yet

Horizon
No technology choice yet

NNB Genco
EPR (1 & 2)

NNB Genco
EPR (1 & 2)
Lead Station

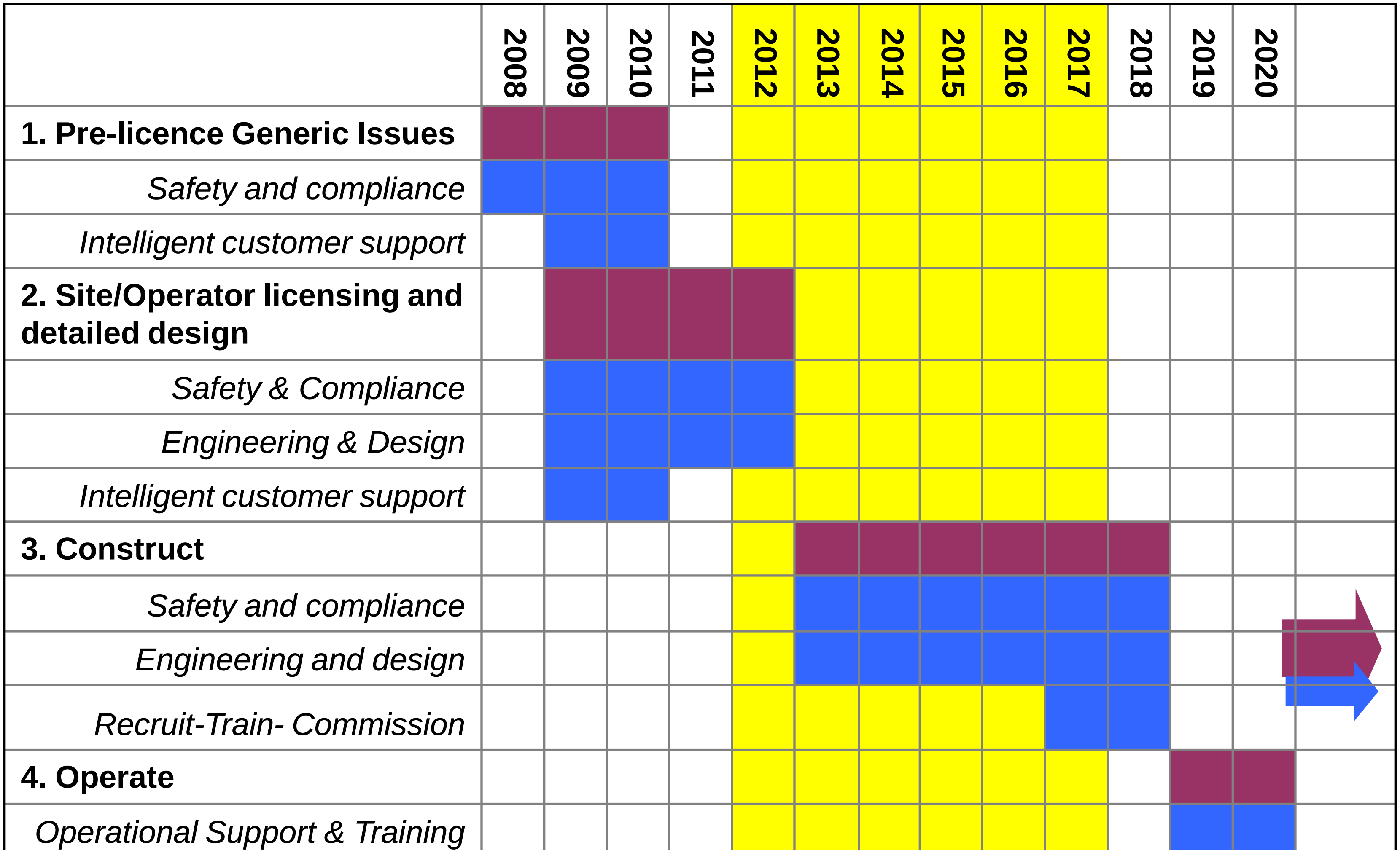


*Shut-down site known as Calder Hall

SOURCE: DECC

Waterlooville

New Build Time Line – UK



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Advanced Water Reactors （New Build）

- **PWR candidate designs:**
  - **EPR (AREVA)**
  - **AP1000 (Westinghouse)**
- **Status**
  - **First plants under construction**
    EPR (Finland, France), AP1000 (China)
- **UK**
  - **ONR &EA have granted**
    ‘interim approval’ to both designs (Dec 2011)
- **Evolutionary approach:**
  - **Extension from current designs**
- **Safety:**
  - **Inherent safety features in design**

EPR

AP1000

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UK Candidate 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

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EPR Design Features

- THE EPR™ REACTOR EVOLUTIONARY FEATURES
- **An axial economiser inside each steam generator allows a higher level of steam pressure and plant efficiency.**
- **A heavy neutron reflector surrounding the reactor core lowers uranium consumption.**
- **An outer shell covering the reactor building, the used fuel building and two of the four safeguard buildings provides protection against a large commercial or military aircraft crash.**
- **A core catcher allows passive collection and retention of the molten core should the reactor vessel fail in the unlikely event of a core melt.**
- **Digital technology and a fully computerized control room with an operator-friendly human-machine interface improve the reactor protection system**

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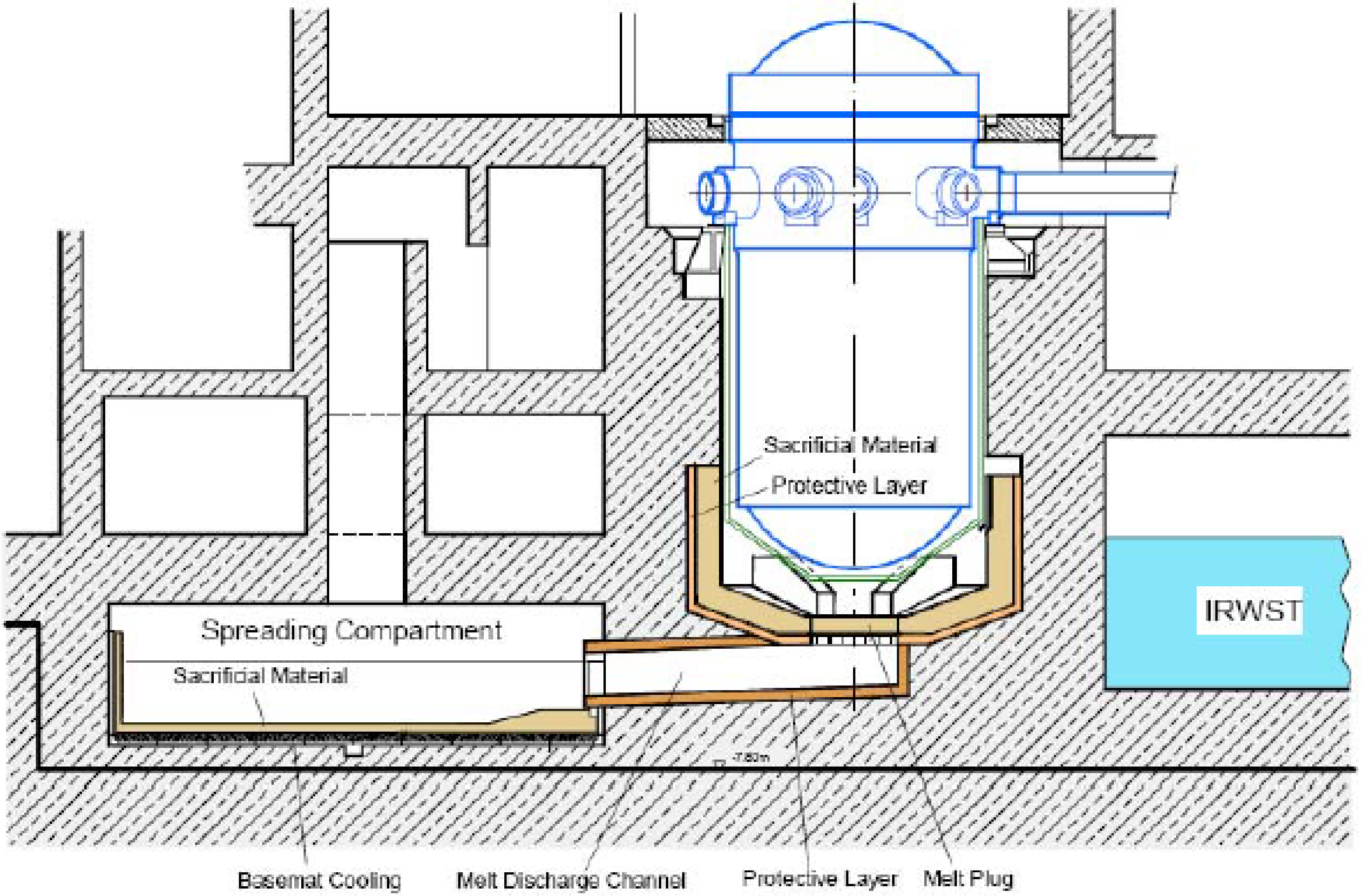
EPR Design Basis

- Advances in technology have changed the design basis (Examples)
- Loss of coolant accidents (LOCA)
  - Large break ruled out due to the ‘break preclusion’ concept (though retained for containment design)
  - Small breaks treated by secondary side measures; emergency core cooling systems redesigned
- Severe Accidents
  - Claim that the core meltdown frequency is reduced by a factor of 10 compared with plants presently in operation
  - External core melt retention system (core catcher) to enable melt spreading, cooled by a passive flooding system.

EPR Containment



Status of EPR – UK

- ONR granted ‘interim design acceptance’ in December 2011
- ONR have confirmed the plans in place to resolve outstanding issues and matters raised by HM Chief Inspector’s report following Fukushima
- NNB Genco have applied for planning approval (consent) by the Infrastructure Planning Commission (IPC) to operate two new reactors at Hinkley Point, Somerset
- Still to do:
  - Apply to ONR for a Nuclear Site Licence
  - Obtain environmental authorisation from EA
  - Prepare POSR for submission to ONR to start operation

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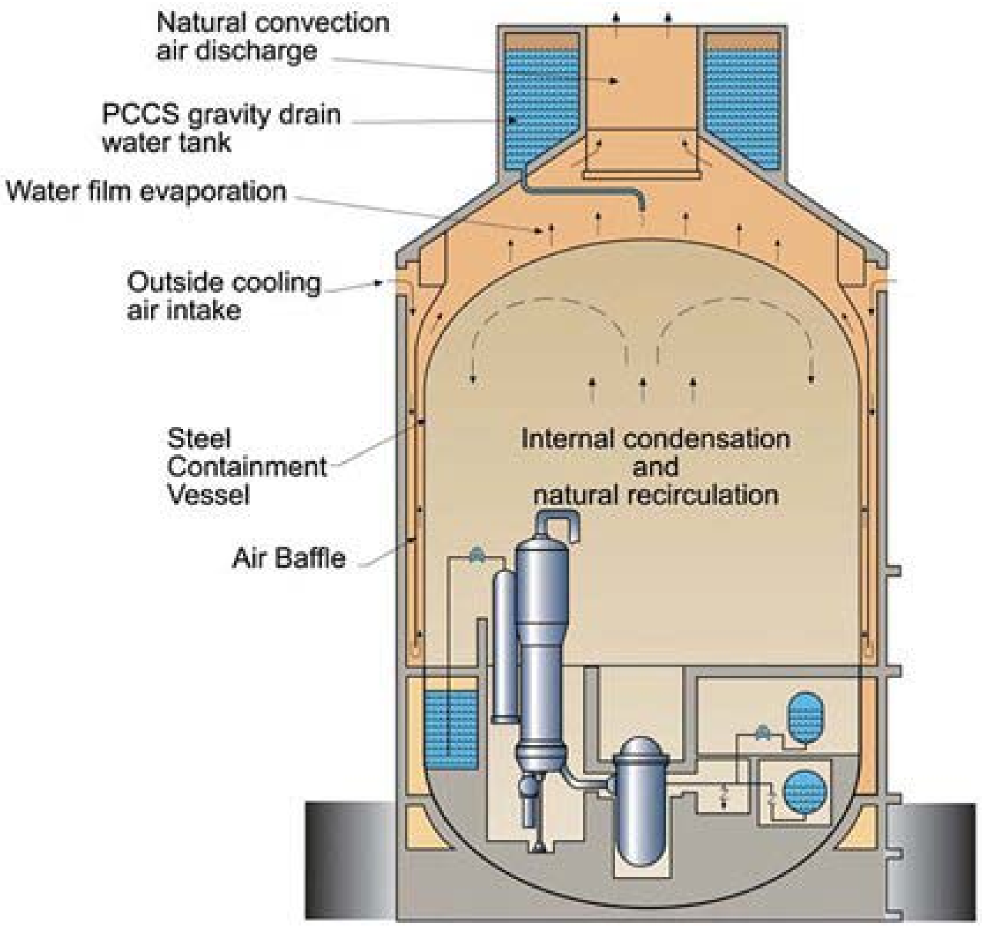
AP1000 Design Features

- Design uses proven components and technology which greatly facilitates the construction, operation and maintenance of the AP1000.
- The distinguishing safety enhancement of the AP1000 over existing PWR technology is the adoption of passive protective safety measures
- Modular construction techniques means that the construction process is safer, simpler and more predictable, leading to reduced costs.
- Separation, segregation, redundancy and diversity provided by the design minimise the effects of internal and external hazards and human errors.
- Simplifications in the design mean that operator doses are significantly reduced during operation, maintenance and inspection activities.

AP1000 Design Basis

- ‘More’ evolutionary design basis (Examples)
- Passive concept of safety systems, which eliminates operator actions to mitigate design basis events.
  - New systems added, automatic depressurisation system (ADS) and passive containment cooling system (PCCS) to take decay heat out of the containment.
  - Gravity driven safety systems.
  - All design basis and probabilistic targets are met using passive safety systems alone.
- Severe Accidents
  - Claim that water from the in-reactor water storage tank will prevent reactor pressure vessel melt-through via external cooling of the vessel
  - Evolutionary containment concepts

AP1000 Passive Containment Cooling system

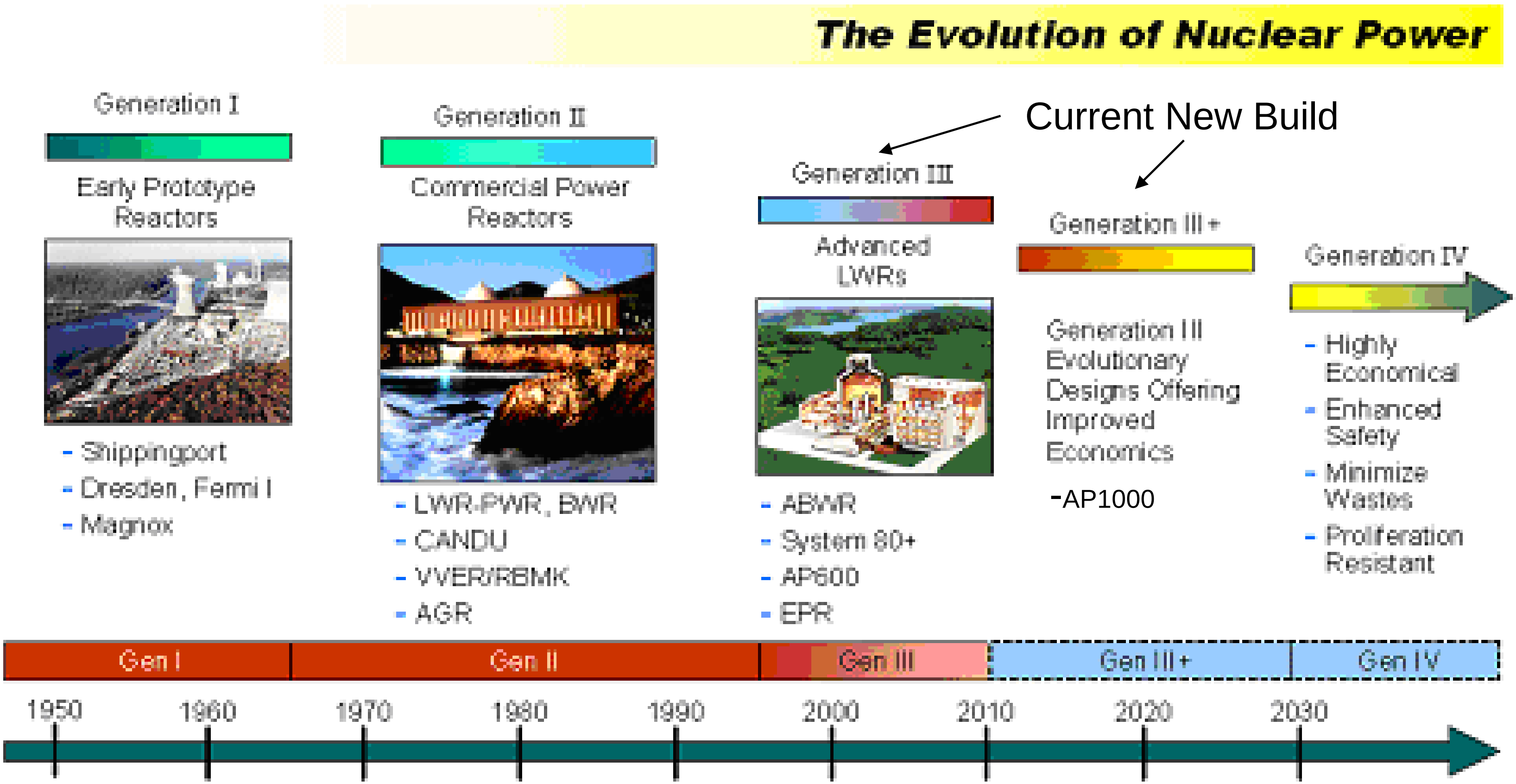


AP1000 Passive Containment Cooling System

Status of AP1000 – UK

- ONR granted ‘interim design acceptance’ in December 2011
- ONR have confirmed the plans in place to resolve outstanding issues and matters raised by HM Chief Inspector’s report following Fukushima
- No utility orders in the UK yet but Westinghouse focusing on Horizon Nuclear Power (near term) and NuGen (longer term)
- Significant work in engaging UK supply chain

The Evolution of Nuclear Power



Source: USDOE

Gen III/III+ Reactors （Design Objectives）

- Standardised design to expedite licensing, reduce capital cost and reduce construction time
- Simpler and more rugged design, making them easier to operate and less vulnerable to operational faults
- Higher availability and longer operating life - typically 60 years
- Further reduced possibility of core melt accidents
- 72-hour grace period, so that following shutdown the plant requires no active intervention for 72 hours
- Resistance to serious damage that would allow radiological release from an aircraft impact
- Higher burn-up to reduce fuel use and the amount of waste
- Greater use of burnable absorbers ("poisons") to extend fuel life.

Advanced Thermal Reactors on the Market

Reactor	Type	Capacity (MWe) Gross	Developer
EPR	PWR	1750	Areva NP, Europe. French design approval. Undergoing US certification
AP1000	PWR	1200	Westinghouse, USA. US design certification.
APR-1400	PWR	1450	KEPCO, derived from Westinghouse, South Korea. KINS design certification 2003
APWR	PWR	1530-1700	Japanese utilities, Mitsubishi. Japan certification. Submitted for design certification in US.
VVER-1200	PWR	1290	Gidropress, Russia. Certified as meeting EUR standards

Advanced Thermal Reactors on the Market （Cont.）

Reactor	Type	Capacity (MWe) Gross	Developer
ESBWR	BWR	1600	GE Hitachi, Undergoing US design certification, expected shortly.
ABWR	BWR	1380	GE Hitachi, Toshiba. Design certification in US.
ACR	PHWR	1080	AECL, Canada. Undergoing certification in Canada
CANDU-6 (EC6)	PHWR	750	AECL, Canada. Design certification in Canada.

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NEWBUILD – Worldwide Interest

Rest of the World – New Build

- EPR – Areva NP
  - The first EPR unit is being built at Olkiluoto in Finland, the second at Flamanville in France, the third European one will be at Penly in France.
  - Two further units are under construction at Taishan in China.
- AP1000 - Westinghouse
  - Under construction, two units at Sanmen and two units at Haiyang in China. First 'concrete poured' in March 2009, first electricity in late 2013.
  - Further six orders in the US, initial units at Vogtle site.
- APR1400 – KOPEC, South Korea
  - The first APR-1400 units - Shin Kori 3 & 4, are under construction, and operation is expected in 2013 and 2014.
  - Four APR-1400 reactors in UAE planned.

Rest of the World – New Build （Cont.）

- VVER-1000 – Gidropress
  - Build in Russia and China.
  - Russia's Atomstroyexport is building India’s first large nuclear power plants, comprising two VVER-1000 (V-392) reactors.
- ABWR – GE-Hitachi & Toshiba
  - Two units under construction in Japan, others planned in US. Plans for ABWR in Lithuania. No orders for ESBWR as yet.
- AHWR
  - Indian indigenous PHWR reactors will be 700 MWe gross (640 MWe net) are under construction. Four are being built, due on line by 2017.
  - AECL focussing on ACR – 1000. Not aware of orders yet.

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Rest of the World – New Build （Cont.）

- FBR
  - 500 MWe prototype fast breeder reactor (PFBR) is under construction in India. Four further oxide-fuel fast reactors are envisaged.
  - Two Russian designed fast reactors (BN-800) due to start construction in China

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Gen III/ III+ Small Reactors

- **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:**
  - Light water reactors for marine propulsion
  - Modular designs
  - Integral systems
  - Mainly driven by US vendors

Small Reactors with Well-Advanced Designs （Examples）

Reactor	Type	Capacity (MWe) Gross	Developer
IRIS SMR	PWR PWR	100-335 225	Westinghouse consortium, USA. Westinghouse.
mPower	PWR	125	Babcock & Wilcox, USA. Design certification application in 2012.
NuScale	PWR	45	NuScale Power, USA
ANTARES	HTR	600 (MWt)	Areva NP, Prismatic
HTR-PM	HTR	2*105	INET & Huaneng, China. Construction in China approved. Pebble bed.

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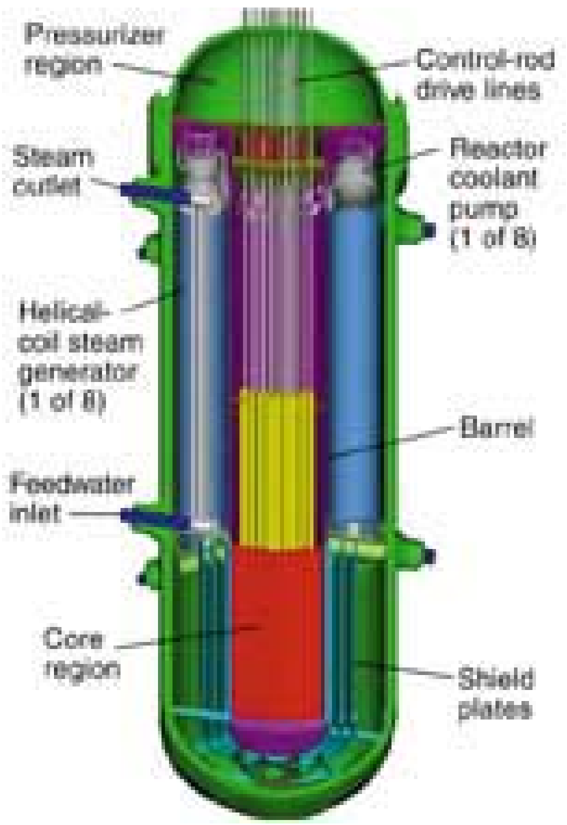
IRIS Pressurised Water Reactor

- The International Reactor Innovative and Secure (IRIS) reactor is being developed by an Westinghouse and academia
  - as a near-term advanced reactor that is economic to build and relatively quick to license.
- Modular pressurised water reactor with modest sized units of 100-350 MWe
- Integral reactor, with its steam generators inside the reactor vessel. Therefore attractive safety characteristics
  - This design feature eliminates the classical large pipe break accident risk
- IRIS is also resistant to proliferation because there is must less frequent access to its fuel
  - The fuel residence time is 5-8 years, other today's reactors are opened every 18 months or so to remove and replace fuel.
- US design certification is at a pre-application state.



Source: ORNL

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mPOWER

- Babcock & Wilcox is developing the B&W mPower™ reactor
- Scalable, modular, passively safe, advanced light water reactor system. Multi -unit (1 – 10)
- Capacity to provide 125 - 750 MWe
- Integral nuclear system design
- Passive safety systems
- Underground containment
- 4.5-year operating cycle between refuelling
- Pre-design certification stage in USA

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Applications

- **Realisation**
- Electricity production
- Process heat (low temperature)
  - District heating
  - Desalination?
- Propulsion
  - Naval
  - Civil (ice-breaker)
- Medical (Isotope production)
- Research applications

- **Concept**
- Electricity (high efficiency)
- Transmutation
  - Waste (actinide destruction)
  - Weapons grade Pu burning!
- Process heat (medium - high temperature)
  - Oil refining, coal gasification
  - Cement/ glass manufacture
- Hydrogen production
    - From natural gas, methane
    - pyrochemcal

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Future Designs – Gen IV

- Generation IV
  - Attempts to prioritise medium and long term design options that are worthy of investment.
  - Generation IV (GIF) Forum of interested countries.
  - Roadmaps to achieve objectives.
  - Wide ranging applications including power generation, high temperature applications, actinide management.
  - Thermal and fast spectra systems.

Generation IV Reactors

Reactor	*Application*
Supercritical Water Reactor (SCWR)	Electricity generation/Waste and plutonium management
Very High Temperature Reactor (VHTR)	Electricity generation/Hydrogen production/Process heat
Gas Cooled Fast Reactor (GCFR)	Electricity generation/Waste and plutonium management/Hydrogen/ Process heat
Sodium Cooled Fast Reactor (SCFR)	Electricity generation/Waste and plutonium management
Lead/Lead Bismuth Cooled Fast Reactor (LCFR)	Electricity generation/Waste and plutonium management/Hydrogen
Molten Salt Reactor (MSR)	Electricity generation/Waste and plutonium management

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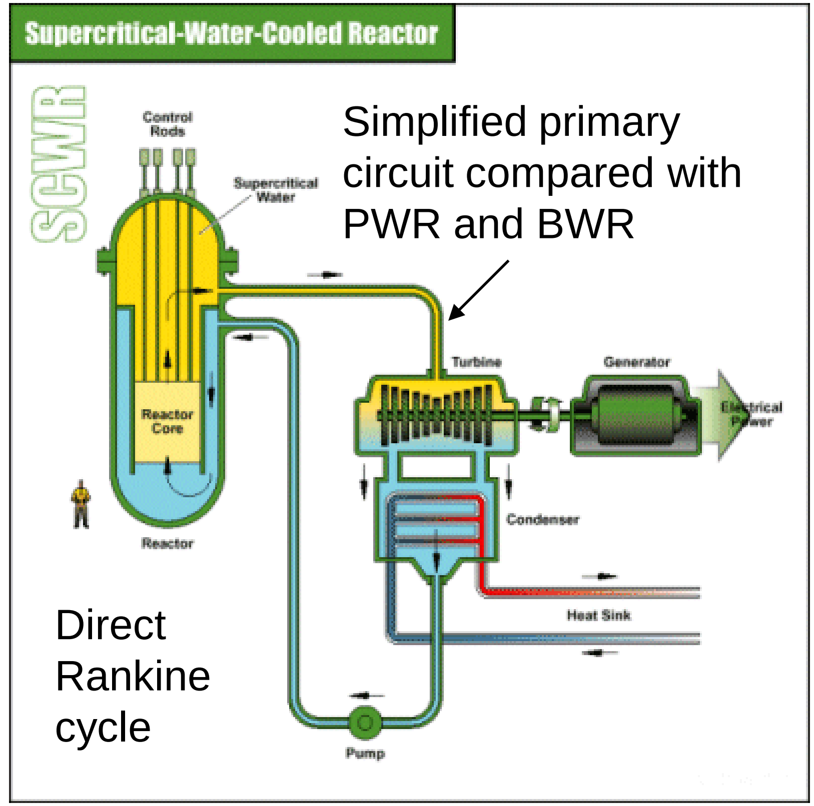
Super Critical Water Reactor （SCWR）

- Main characteristics and applications
  - Super critical water system pressure (25MPa)
  - Reference power (1700MWe)
  - Core outlet temperature (510 - 550 deg C)
  - 50% efficiency for electrical power generation
  - Light and heavy water systems proposed
  - Once-through fuel cycle
  - Thermal spectrum
  - Fast spectrum option for actinide and plutonium management with closed fuel cycle



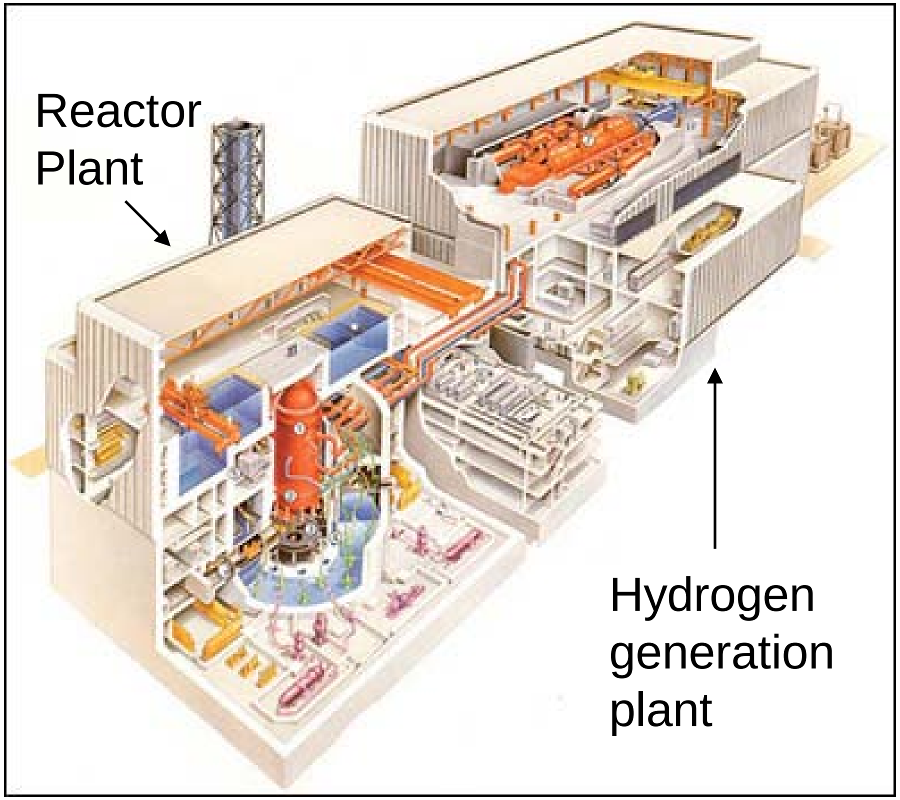
Source: USDOE

Research requirements

- Baseline of very extensive water reactor experience
- Research requirements
  - Significant materials development (corrosive high temperature water environment)
  - Developments required to address some operational safety issues
  - Heat transfer, radiolysis and water chemistry
  - Crack growth research
- Status
  - A system research plan has been developed by the GIF SCWR System Steering Committee that outlines the R&D requirements for the SCWR development1. The GIF members that are currently active in the SCWR R&D include: Canada, EURATOM, France, Japan, Republic of Korea, and China (as observer).

Very High Temperature Reactor （VHTR）

- Main characteristics and applications (VHTR)
  - Helium cooled, Reference power (600 MWt)
  - Coolant outlet temperature (1000 deg C)
  - 50% efficiency (at this efficiency it could produce 200 metric tonnes of hydrogen/ day
  - Very high temperature reactors, evolution on earlier HTR technology
  - Envisaged for power generation and high temperature applications such as hydrogen generation and process heat
  - Thermal spectrum, Once-through fuel cycle



Source: USDOE

Gas Reactor Operating Experience

- Build on extensive previous experience:
- HTR in the 60s & 70s
  - Research reactors
    - US work on Peach Bottom HTGR (40 MWe), UK consortium Dragon project (20MWt), German AVR reactor (15 MWe)
  - Prototype reactors
    - Fort St. Vrain (330MWe) in US, THTR-300 in Germany, UK gas reactors
- Also Magnox and AGR power reactor experience to date

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VHTR Research Requirements

- **Basic research, or design and deployment areas**
- **Fuel & Core**
  - Fuel materials and fabrication
  - Research and development was carried out on HTR fuel during the UK Dragon programme, along with that from other prototype reactors
  - For temperatures exceeding 1000^{o}C, very little experience. For silicon carbide coated particle technology, advanced coatings based on zirconium carbide
- **Gas Circulation**
  - Direct cycle design unproven. Indirect experience from UK Magnox and AGR. US NGNP and Chinese HTR PM prototypes now propose indirect cycle

VHTR Research Requirements （Cont.）

- Reactor Vessel
  - Technology requires advances in high temperature materials, alloys, ceramics and composite materials (Open).
  - Current proposals are based around steel pressure vessels, materials understood but no direct experience at the required temperatures. UK Magnox and AGR experience for concrete vessel experience.
  - Helium thermal conductivity significantly greater than carbon dioxide, Fort St Vrain, THTR and Dragon addressed this.
- Hydrogen production technology
- Graphite technology
- Waste Management and Decommissioning
  - Disposal of coated particle fuels received little attention compared with metal clad fuels. Large quantities of graphite (as in some of today's reactors) an issue.

Status of Technology

- Present day
  - Concept
    - PBMR(200MWe)- SA, GT-MHR as part of NGNP – US, HTTR – Japan, ANTARES-France
  - Operational reactor
    - HTR-10 – China,
  - Under construction and being marketed commercially
    - HTR – PM (2*105 MWe) – China
- Currently the only HTR project proceeding is the Chinese HTR-PM.

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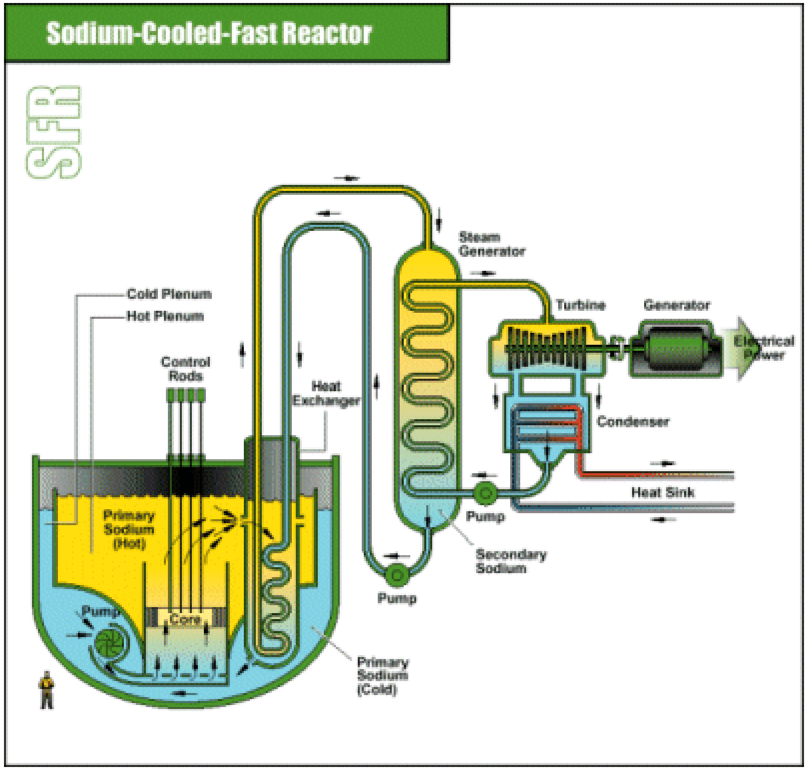
Sodium Cooled Fast Reactor （SCFR）

- SFR
  - Sodium cooled
  - Reference power (150-500 MWe (small), 500-1500 (large))
  - Electricity generation in the past; future - actinide waste and plutonium management
  - Fast spectrum
  - Closed fuel cycle
  - 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.



Source: USDOE

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Fast Reactor Operating Experience

- UK
  - Research reactors (ZEPHYR, ZEUS, ZEBRA (zero-energy))
  - Demonstration and prototype reactors (DFR (15MW), PFR(250MWe))
- France
  - PHENIX, SUPER-PHENIX
- Russia
  - BN-600
- Japan
  - Joyo (experimental reactor), Monju (280 MWe)
- India
  - Fast breeder test reactor (40MWt)

Since the 1950s , about 20 FBRs have already operated with 300 reactor-years experience.

Research requirements

- Research requirements
  - Fuel cycle technology
  - Plant simplification
  - Core design
  - Materials chemistry
  - Nuclear steam supply system
  - Safety (void coefficient issue)
- French CEA ASTRID research programme addressing a number of these issues

Status of Technology

- BN 600 is currently operating in Russia. BN-800 is under construction (880 MWe gross). For electricity and burning Pu from dismantled weapons. BN-800 has been sold to China, and two units are due to start construction there in 2012. GenIV capability BN-1200 being developed.
- Research continues in India on the use of thorium as nuclear fuel. Construction of a 500 MWe prototype FBR underway, expected operation in 2012, fuelled with (U,Pu) oxide with a thorium blanket to breed fissile U-233.
- Small reactor designs well developed (PRISM (311MWe), Hyperion PM (25MWe))

Gas Cooled Fast Reactor （GCFR）

- Characteristics
  - 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

- Status
- No GCFR constructed to date
- Assessments in 70s
  - Switzerland (PSI)
  - UK (Winfrith)
- More recent work
  - Progress of CEA pre-conceptual design studies
  - UK This work was sponsored by BNFL as part of the EC CAPRA/CADRA project.

Lead / Lead Bismuth Cooled Fast Reactor (LCFR)

- Characteristics
  - Reference power (50-1200 MWe)
  - Coolant outlet temperature (550 – 800 deg C)
  - Closed fuel cycle
  - Option of a long (30 year) core life
- Applications (additional to high efficiency electricity generation)
  - Propulsion
  - Hydrogen
  - Actinide waste and plutonium management
- Status
  - Russia has experimented with several lead cooled reactor designs
  - Lead Bismuth cooling in submarine reactors
- More recent work
  - Euratom supported programme for European system
  - Russian medium and small scale designs

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Molten Salt Reactor （MSR）

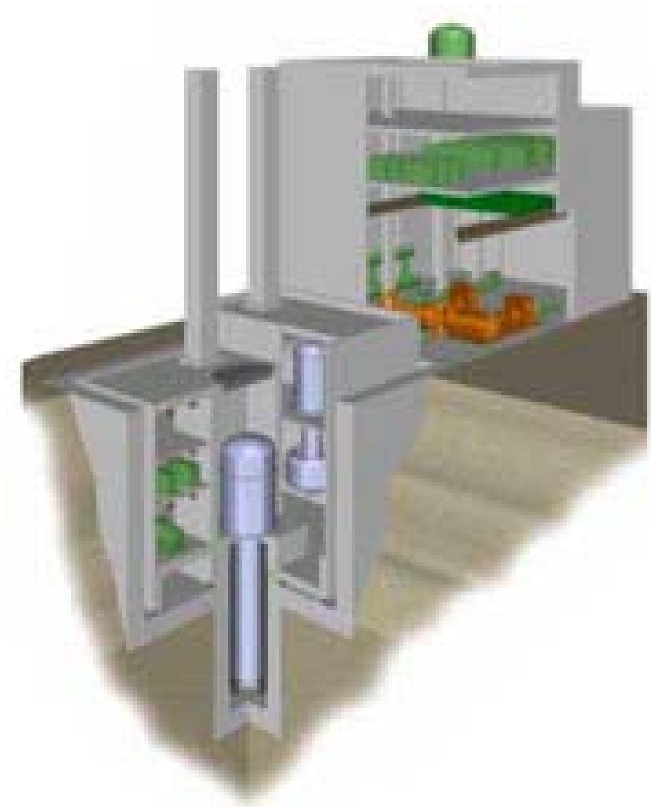
- Characteristics
  - Liquid mixture of sodium, zirconium and uranium fluorides
  - Reference power (1000 MWe)
  - Low pressure/ coolant outlet temperature (700 deg C)
  - Fast spectrum, closed fuel cycle
  - Other design concepts
- Applications (additional to high efficiency electricity generation)
  - Electricity/ actinide and plutonium management
- Status
  - No large scale commercial prototype MSRs have ever been built
  - ORNL conducted work from the 1970s on a breeder concept with a uranium/ thorium fuel cycle
- More recent work
  - No well defined design ideas but ORNL work continues
  - Some US work on an advanced HTR but with molten fluoride as the primary coolant
  - Chinese Academy of Sciences developing the Thorium) MSR

Future Small Reactors

- **Small and medium nuclear power Gen IV type reactors for generating electricity from nuclear power, for process heat, and other applications.**
- **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 larger larger scale reactors already mentioned)
  - Aqueous homogeneous reactors

4S （Super，Safe，Small and Simple） Reactor

- The 4S (Toshiba) is a novel small molten sodium-cooled reactor (current design 10-50MWe)
  - Being considered for remote locations and without refuelling over its 30 year life
  - It also has virtually no moving parts, is small scale (~20 metres long)
- For the above reasons, the reactor has been referred to as a nuclear ‘battery’
- There are plans for the design to be put forward for certification in the US
- Potential site(s) under consideration in Alaska



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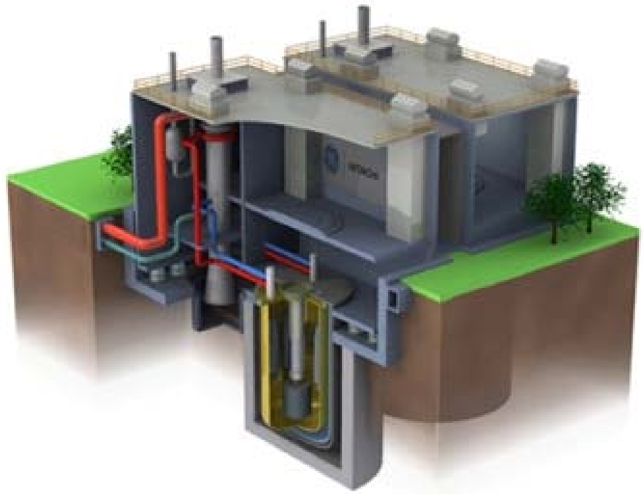
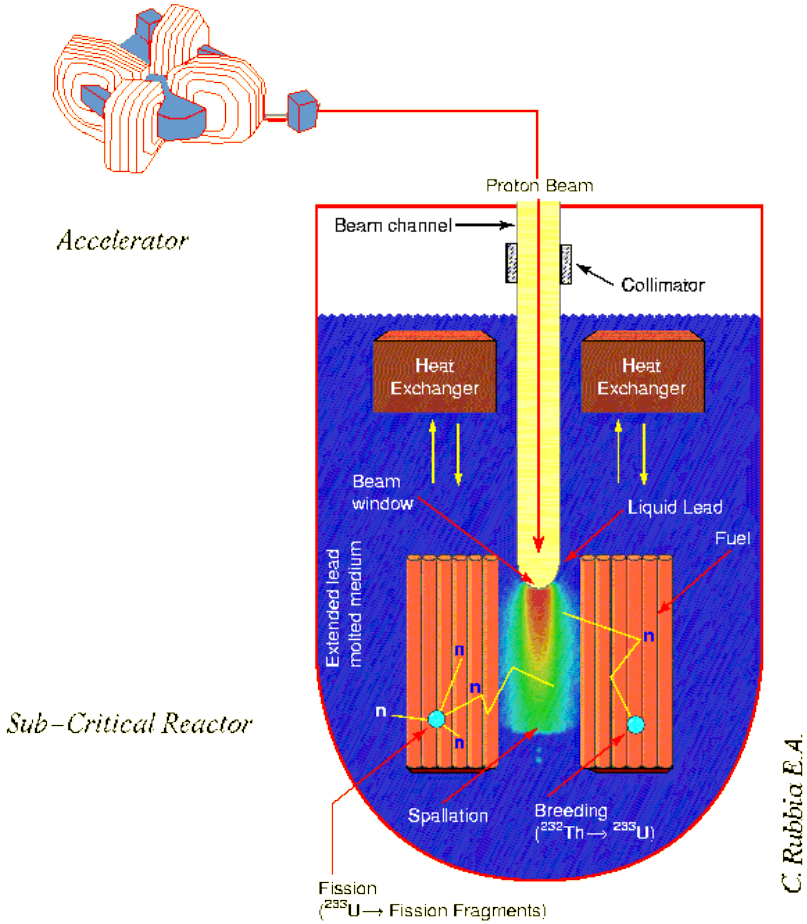
PRISM

- GE - Hitachi have proposed their PRISM fast reactor for the UK for destruction of the UK reactor grade Pu stockpile
- For construction at Sellafield
- Characteristics
  - Each reactor consists of two units, reference power 311MWe/ unit
  - Compact modular pool-type FR
  - Operating temperature over 500 deg C
  - 30 years of development
  - Gen IV solution



Accelerator Driven Systems （ADS）

- Concept been known for several decades
- Has all the applications of fast reactor technology for 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)



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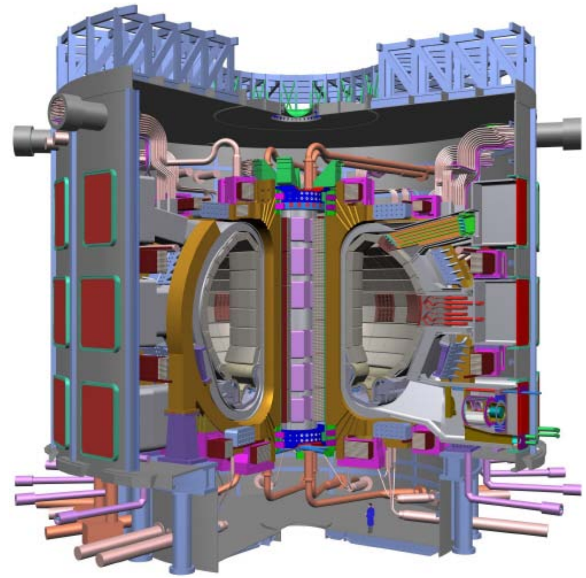
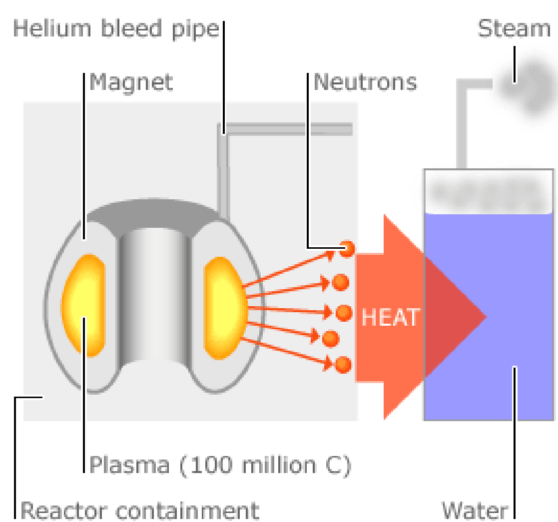
ITER

- 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.





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SUMMARY

- New Build civil power reactors 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 a number of hurdles to cross. Interim approval of UK designs achieved, site licensing to come. Generation ~ 2018, so gap in nuclear generation apart from Sizewell-B.
- General features of current New Build designs. Standardised, simpler and robust designs. Longer life. Higher fuel burn-up. Improved safety. Extension of design basis. Improved resilience against severe accidents.

SUMMARY Cont.)

- Globally the most ambitious New Build programmes proceeding are in China, India and South Korea. Impacts from Fukushima on New Build progress are very country specific with significant differences across Europe.
- There are medium term designs (high temperature gas and liquid metal cooled reactors) that would build on proven experience (with prototypes) that could support more efficient electricity generation, hydrogen production and high temperature process heat applications.
- There are longer term conceptual designs to support the thorium fuel cycle, also waste management partitioning and transmutation and plutonium burning. These applications generally require more R & D and the technologies have not yet been demonstrated at prototype scale.

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