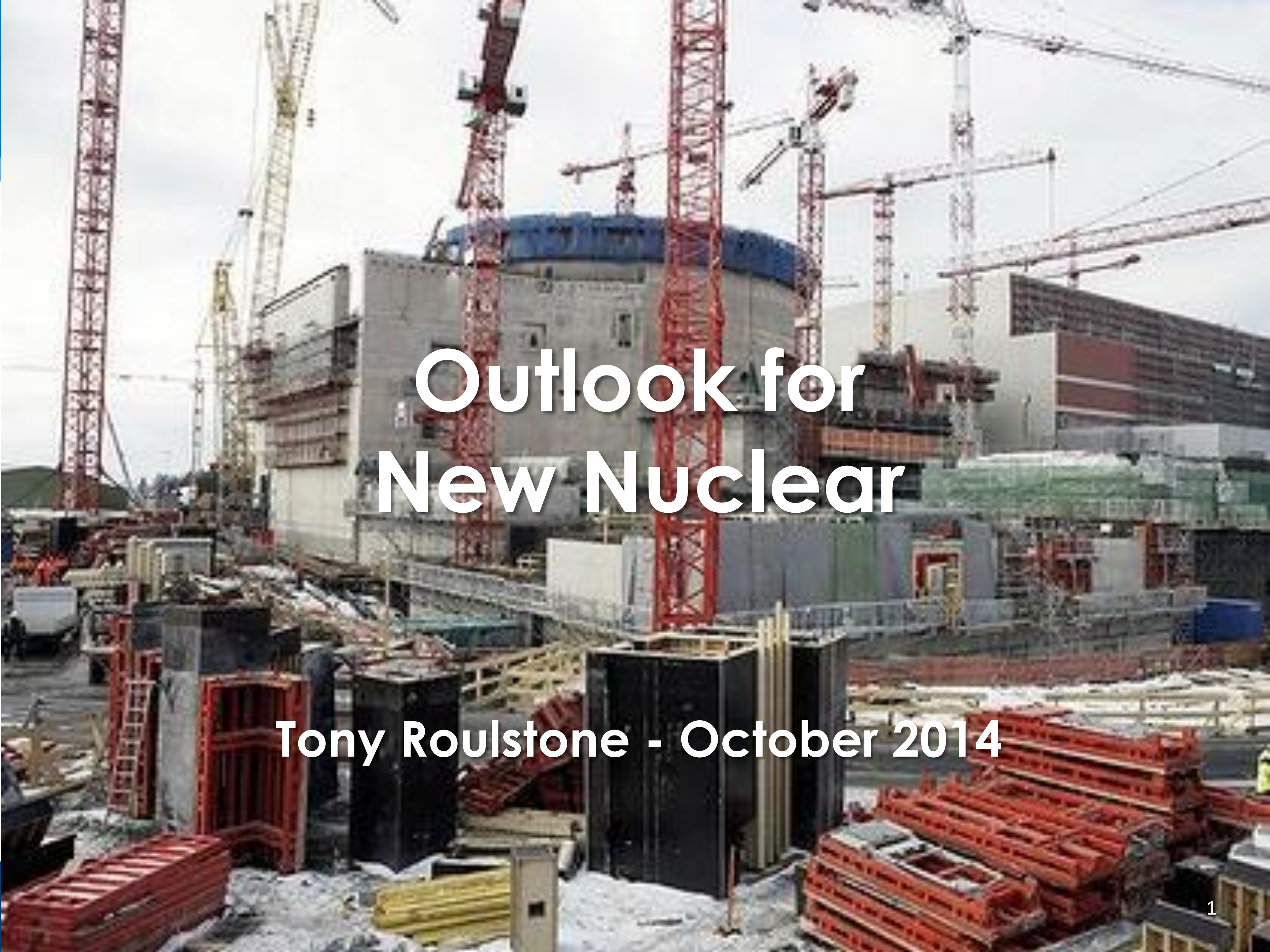


Outlook for New Nuclear

Tony Roulstone - October 2014

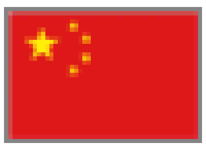
Scope

- Nuclear build plans around the world;
- What is driving these plans?
- New lines of nuclear development:
  - Waste burning
  - Nuclear costs.
- Questions

Nuclear Around the World

- Today: 435 nuclear power reactors are operating in 31 countries, plus Taiwan, with a combined capacity of 370 GWe - providing 11% of world electricity;

- 72 reactors being built around the world (76 GWe) – all but eight being LWRs



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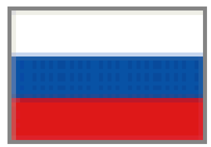

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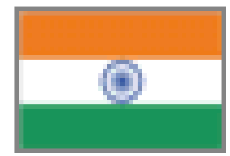

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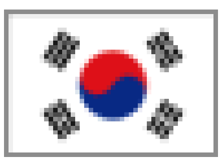

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- 174 reactors planned (190 GWe), a further 299 proposed (329 GWe), with largest numbers in China (59/118), Russia (32/18) and India (22/35).

- Also, new nuclear countries: UAE (2/10), Turkey (4/4), Vietnam (4/6), Saudi Arabia (16), Bangladesh (2) and expansion in South Africa (8), Brazil (2) etc.

Why Nuclear in 21st Century? – Climate Change

- **Global targets** set for total carbon dioxide (and other GHG) emissions;

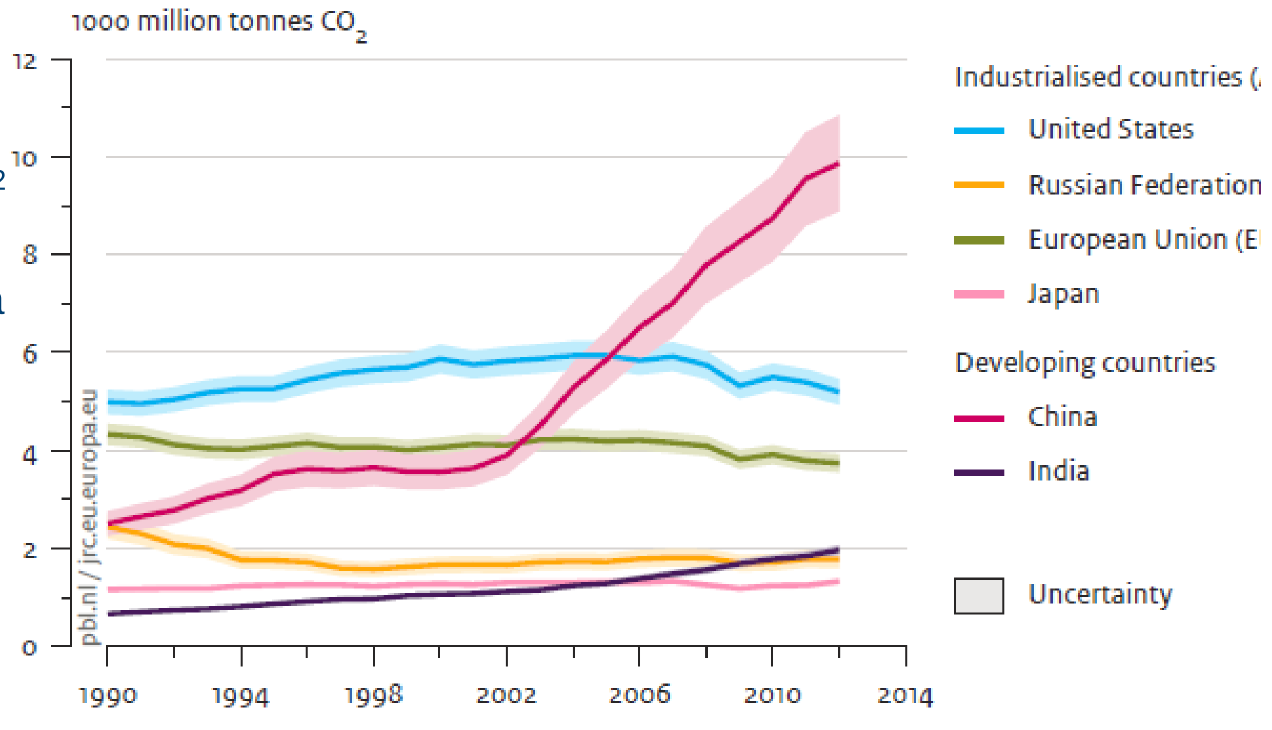
  2 deg C consistent with IPCC global **3,200 bn tne of** CO_2

  Emitted to date **2,000 bn** tne

  Current rate **40 bn tne** pa growing at 2.2%

- **Specific targets for 2050**:

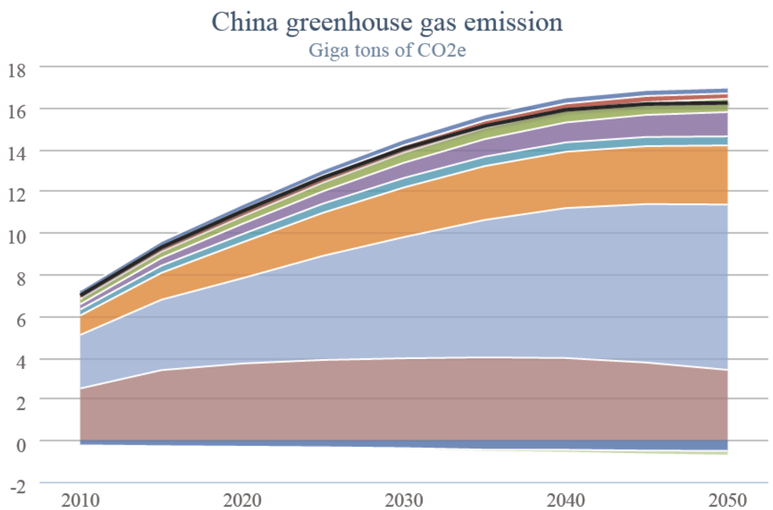
  - Developed countries - 80% cuts from 1990 levels, and
  - Global average **< 2 tne** CO_2 per head, world wide.



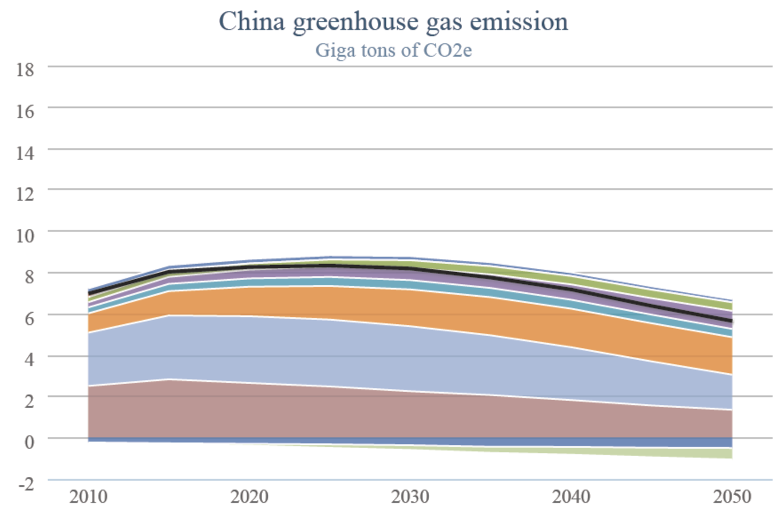
EDGAR 4.2FT2010 (JRC/PBL, 2012); BP, 2013; NBS China, 2013; USGS, 2013; WSA, 2013; NOAA, 2012

Challenge of Climate Change - China

- Without wholesale change increase emissions of CO_2 per head from **~6 tne** today to **>12** tne in 2050 – versus target global average **2 tne** per head by 2050;
- Any successful strategy will include: Radical energy saving; Step change in efficiency – electricity, materials, industry and heating, and electrification of heating and transport;
- Even with extremely ambitious renewables (1,000 GWe) and very large amounts of nuclear (350 GWe) emissions curtailed only to **~5 tne** per head in 2050;



China 2050 Pathway 'Pessimistic' scenario

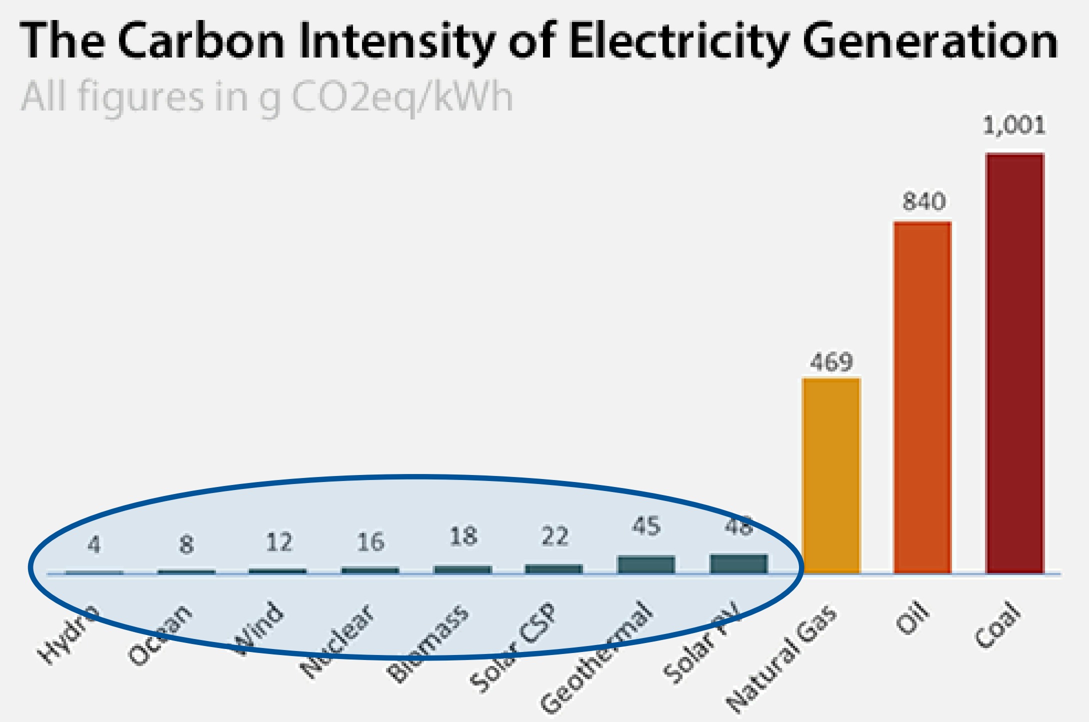


Dr Yang Yufeng scenario with added nuclear

Why Nuclear in 21st Century? – Climate Change

Only Renewables and Nuclear are clean enough

- UK carbon intensity has come down from 800g/kWh in 1990 to below 500g/kWh;
- Target of 80% cut across all energy uses - electricity needs to cut 90% to below 80g/kWh;
- CCS potentially reduce carbon by 80% on whole system basis:
  - CCS - Coal ~200g/kWh
  - CCS – Gas ~90g/kWh
- Only renewables and nuclear meet the carbon criterion.



Note: Data is the 50th percentile for each technology from a meta study of more than 50 papers
Source: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

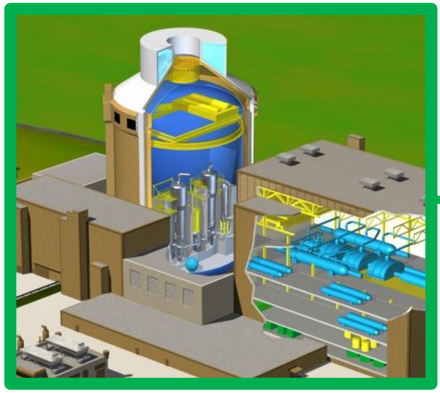
UK Energy Policy – a mix of clean sources

UK Government **energy policy is now:**

- **Double the scale of electricity** in our energy mix by 2050: - supplied by:
  - 30,000 large **wind**mills ~80GWe (nominal) or 20-25 GWe (mean)
  - Some **gas** to fill the gap, balance the system and set the price level;

- Committed plan for 16 GWe by ~2035, plus for 2050 either:
- Scenario **0** – no more nuclear - CCS?
- Scenario **1** – 50% of supply 40 GWe
- Scenario **2** – Max possible? 75 GWe

Nuclear New Build Sites – 16 GWe



Westinghouse AP1000

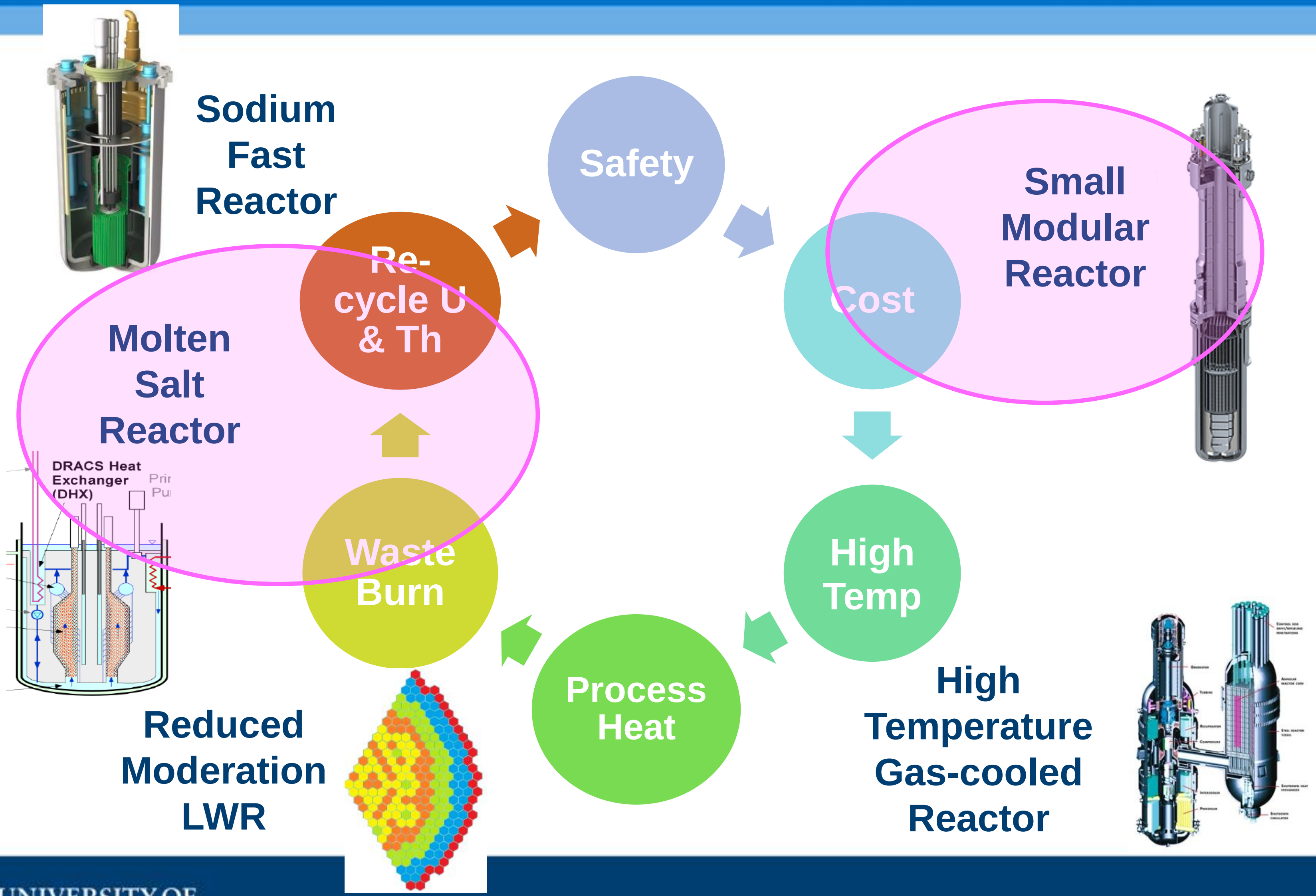
AREVA - EPR

Hitachi - ABWR

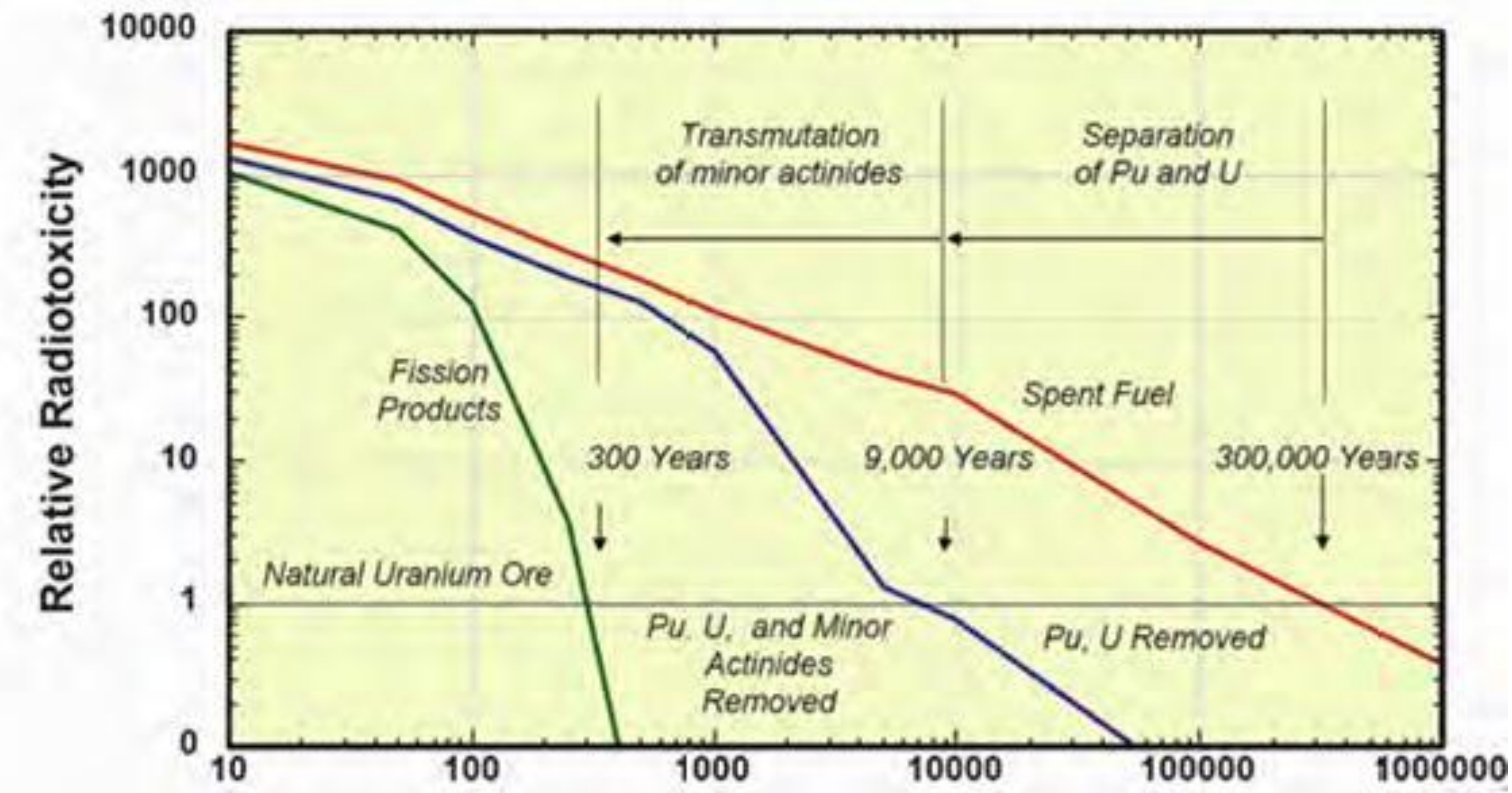
UK Nuclear - What could go wrong?

- **Public opinion** – driven by a possible nuclear accident, or loss of confidence in industry's ability to deliver;
- **Construction failures** – major delays, or poor quality leading to safety concerns;
- **Funding** of programme - £100bn up to 2030, with a further >£100bn afterwards
- **Lower costs** of alternatives – 'fracking', or solar - effect on electricity prices;
- **New competitors** – CCS or super-cheap PV + large-scale storage by 2030;

Lines of Nuclear Development



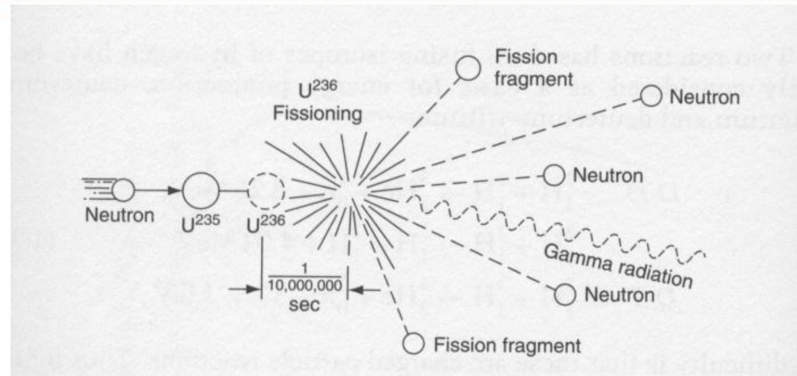
Nuclear Waste Radio-toxicity v Time

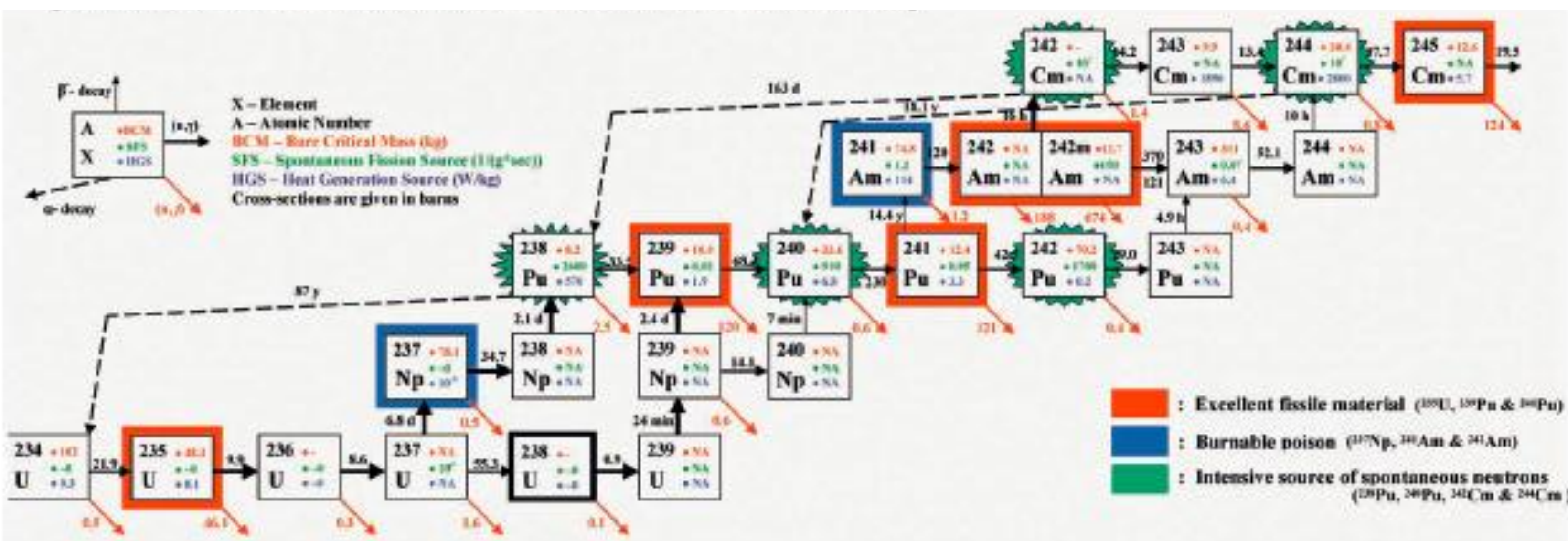


Nuclear Waste – Trans-uranics/Actinides

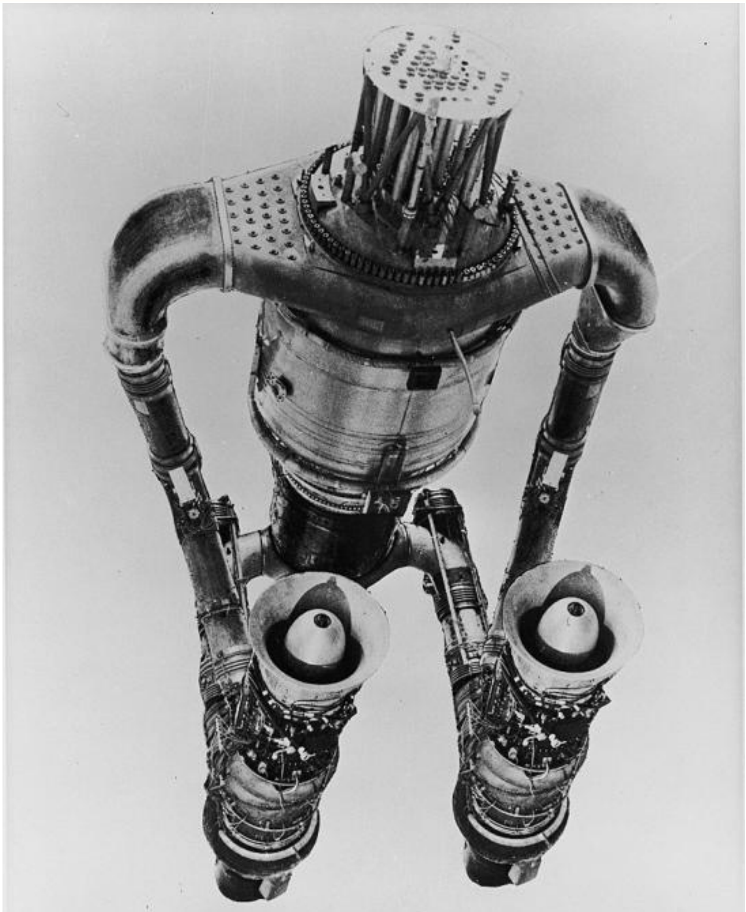
Creation & Destruction

Successive capture of neutrons
create a complex mixture of trans-uranics,
which can destroyed by fission.

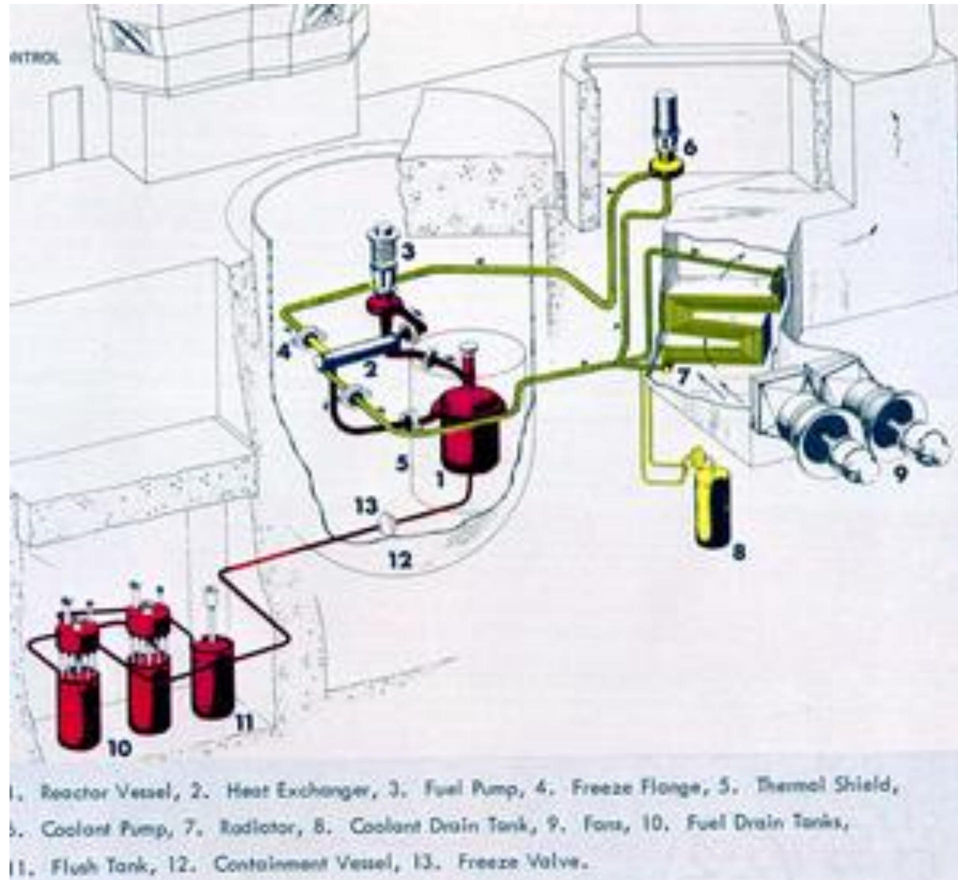




Origins of Molten Salt Reactor Technology

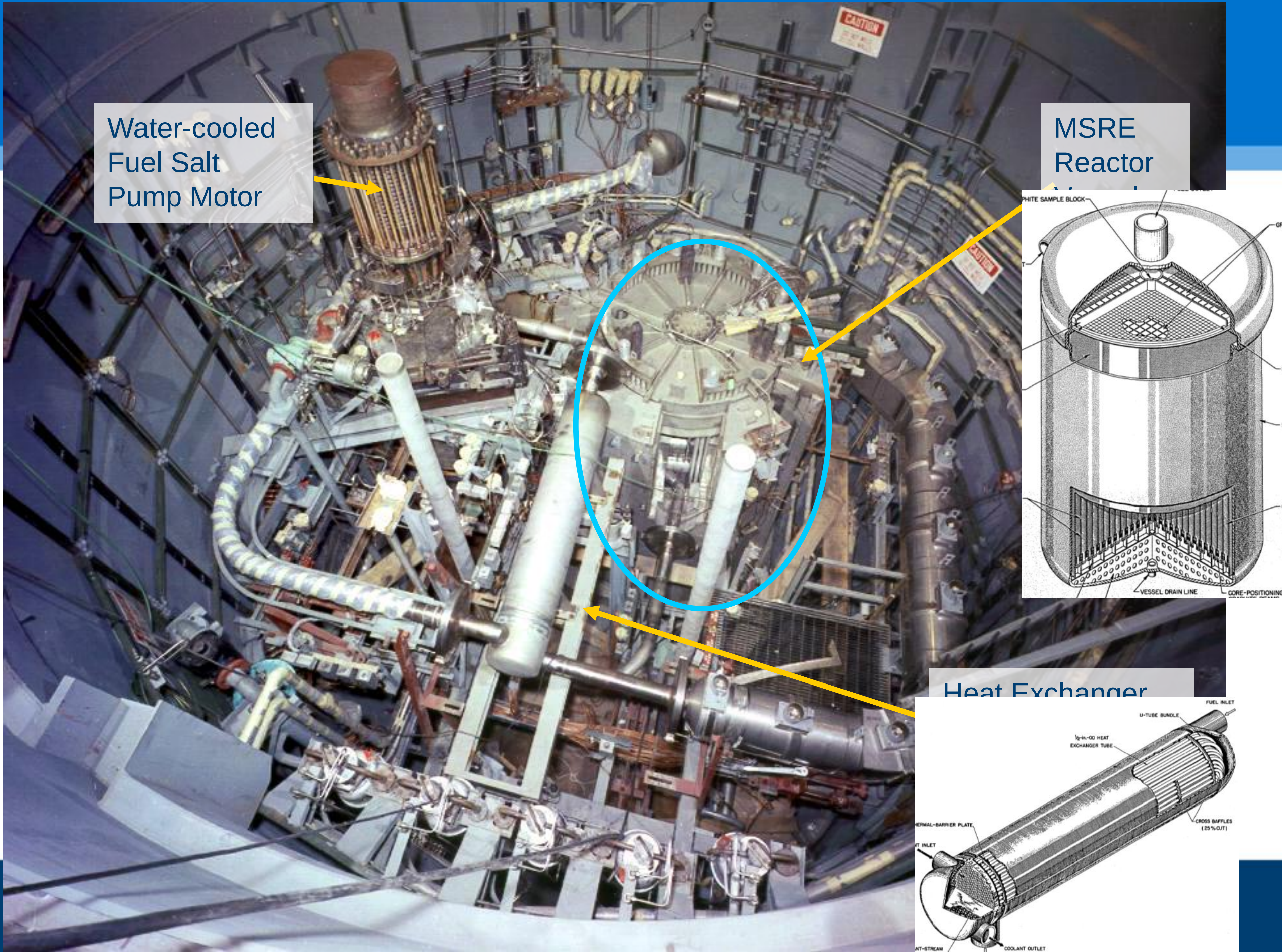


Aircraft Reactor Experiment 1954



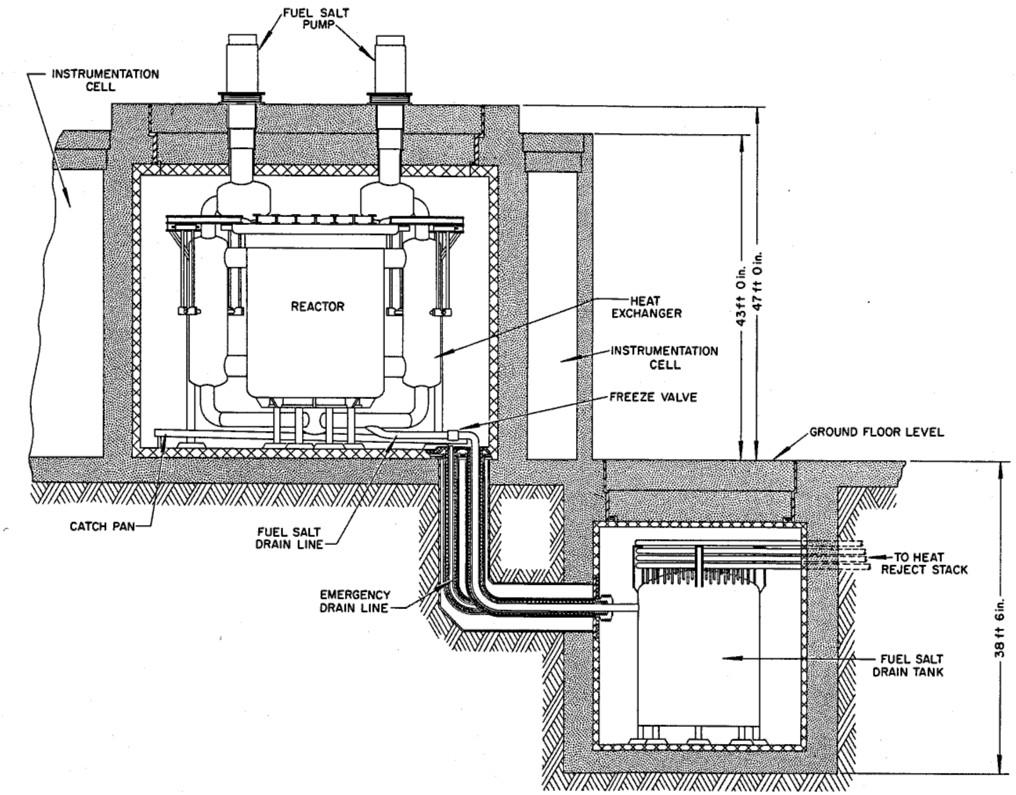
Molten Salt Reactor Experiment 1965-9

UNIVERSITY OF CAMBRIDGE

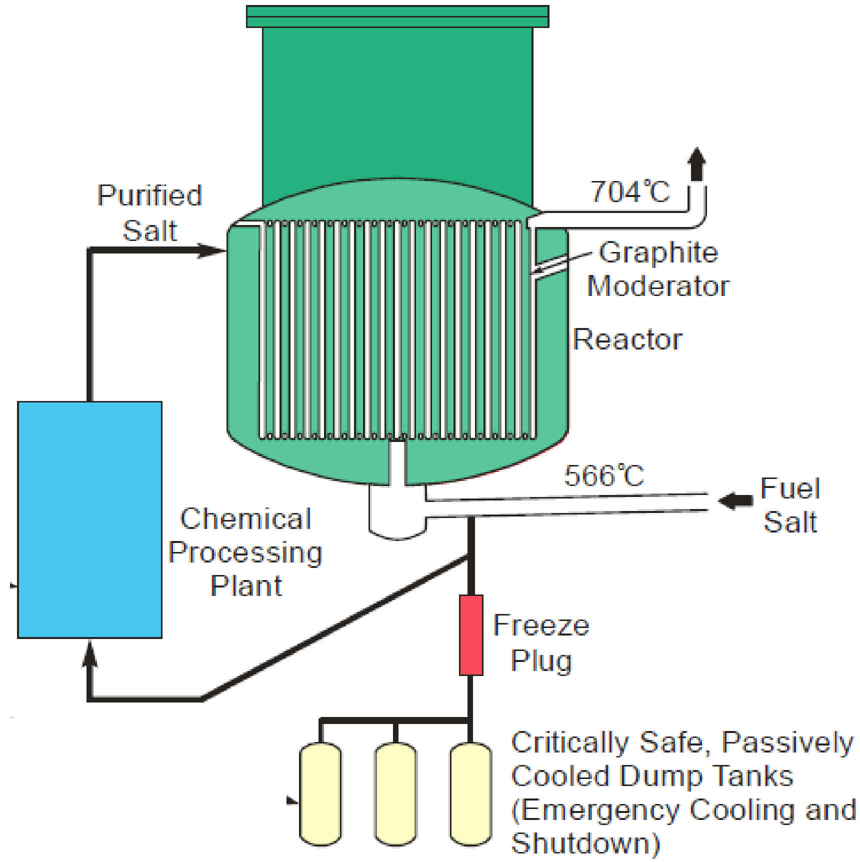


Water-cooled Fuel Salt Pump Motor
MSRE Reactor
VESSEL DRAIN LINE
Heat Exchanger
FUEL INLET
U-TUBE BUNDLE
CROSS BAFFLES (25% CUT)
COOLANT OUTLET

Molten Salt Reactor Designs



MSRE Design

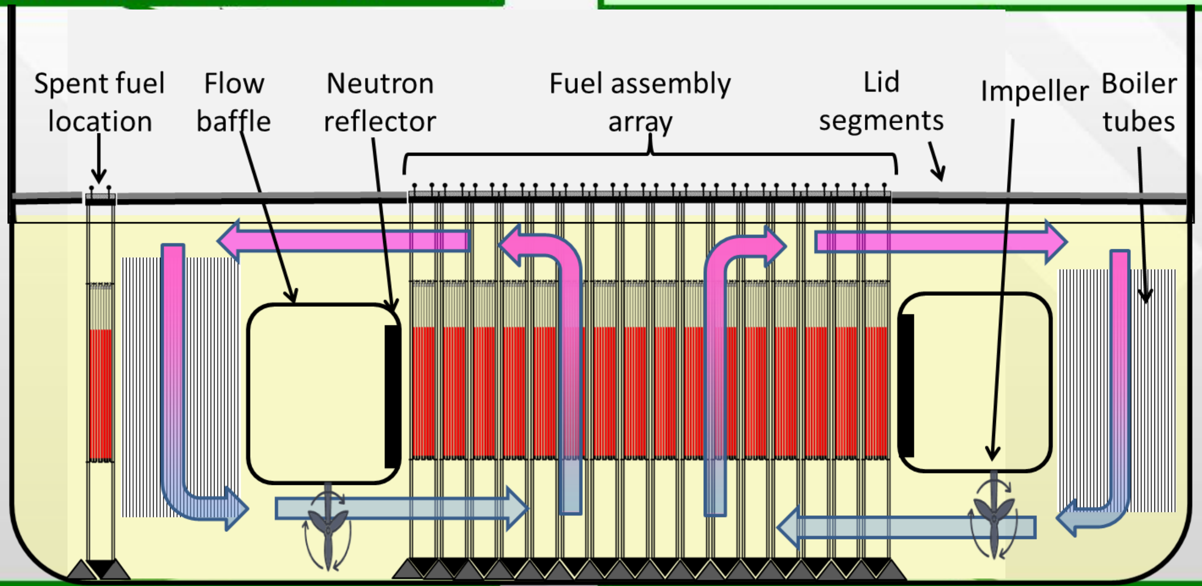


Molten Salt Studies

Moltex - Simplified Molten Salt Reactor

- **MOLYBDENUM FUEL TUBES**
- Used in crucibles to 2000°C
- Thermodynamically resistant to molten salts
- Lower neutron damage than nickel or carbon
- Practical to manufacture, no new materials

- **NICKEL SUPERALLOY BOILER TUBES**
- Low corrosion in molten salt up to 750°C
- Already used in coal fired boilers
- Excellent manufacturability



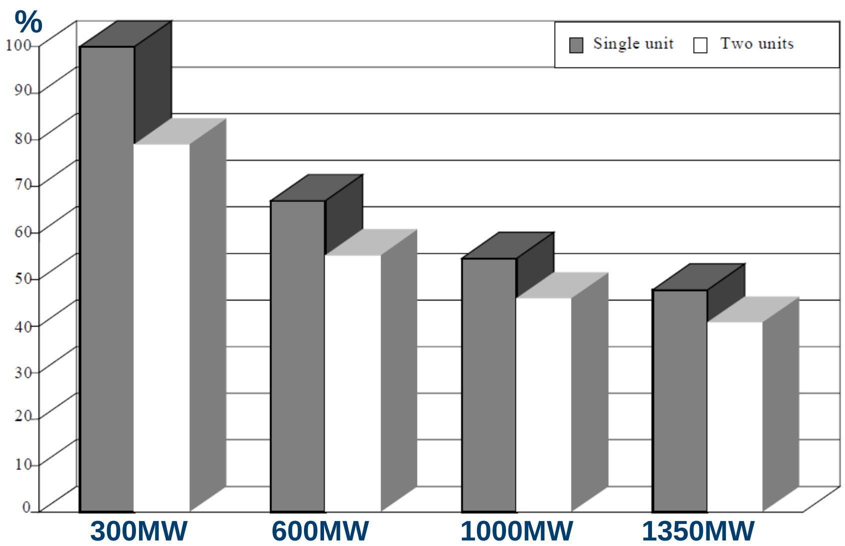
- **COOLANT SALT**
- 10% NaF/48% KF/42% ZrF_4
- Melting Pt 385°C, Boiling Pt ~ 1150°C
- Viscosity 0.47 cP
- Hafnium content in Zirconium shields neutrons
- Low cost (<£5 million)

- **FUEL SALT**
- ~80% UCl_3/20% reactor grade $PuCl_3$
- Melting point ~750°C, Boiling Pt ~1700°C
- ~2% (UCl_4/$AlCl_3$/$ZrCl_4$ (Vapour M. Pt. <600°C)
- High delayed neutron fraction – ^{238}U fission
- Viscosity 2-3 cP

Reactor Costs

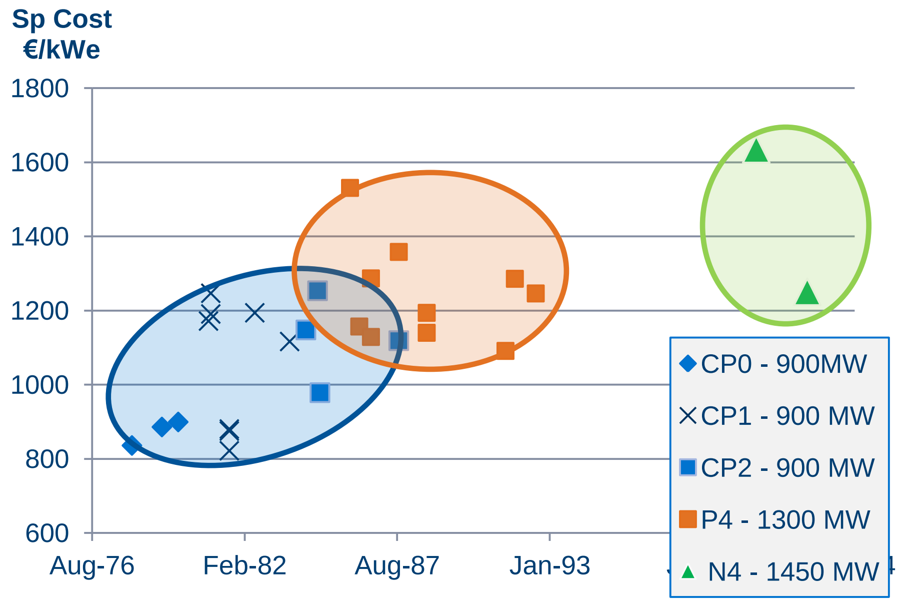
Cost Scaling: Forecasts meet Reality

- Cost forecasts based on an assumed power scaling effect.



Forecast Scaling Effect - France

OECD-NEA Reduction of Capital Costs in NPP 2000 [2]



French Data - Specific Construction Costs €/kWe 2010

Cour de Compte (2012) [13]

LWR Reactor Costing Models

$$Specific\ Cost/Specific\ Cost_0=(Power/Power_0)^a*(y)^b$$

Scaling + Learning + Regulation

Specific Cost:

a = 0 no scaling

a <0 scaling effects:

a is often taken to be in range **-0.5 to -0.35**

Wright Progress index [8]

y % man-time saving for *b* doublings of unit/volume, *y* in the range 70-100%

where $b = Ln(n)/Ln(2)$ for ***n*** units

Nuclear Industry: Learning rate (1-*y*) = **3-5%**

LWR Economics – Cost Data Analyses

Country (plants)	Sp. Power	Learning	Comment	Reference
US (67)	0.14	3-5%	Extended build duration of larger units absorbs any scale savings. Learning offset by regulatory changes. FOAK +20%	Cantor & Hewlett 1988 [11] U of Chicago 2004 [12]
France (58)	0.15	0-10%	Extended build duration larger units absorbs any scale savings. Onsite learning high 10% but programme effects offset by regulatory changes	Cour de Compte [13] Rangel & Levesque [14]
Japan (34)	0.07	as US above	Better correlation with total cost than overnight – learning derived statistically – fit data. FOAK +20%	Marshall & Navarro [15]
UK Magnox (8)	-0.14	~5%	Some scale & learning effects – AGRs little evidence of either!	Hunt [16]
S Korea (12)	0	5%	OPR 1000 benefited from strong drive for learning. No scale effect is evident.	Adjusted published KEPCO data - APR1400 estimates as not complete.
Canada (12)	0	0%	No consistent power scaling or learning effects evident.	Thomas [17]

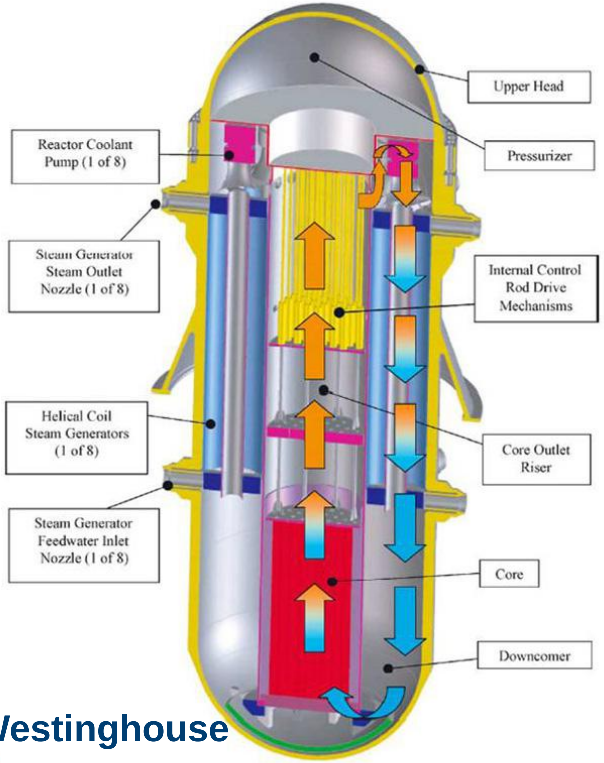
Learning is Present in Many Capital Industries

With manufacturing conditions, learning at rates 8-20% is normal

Industry	Learning Rate	Comment	Source
Aircraft	19%	Original work by Wright in aircraft manufacturing confirmed by Archian, 1950 and Benkard, 2000	Chen & Goldberg [19] Appendix A
Shipbuilding	10-15%	Stump 2012 & Smallman 2011 with variations by type of work: 5-25%	Man-time learning
Semi-conductors	20%	Irwin 1996, dependant on low process losses	
PV	20-35%	Margolis, 2002 wide range of values depending on degree of investment in automation	
Wind turbines	4-12%	NEEDS 2006, depending on scale	
Gas pipelines	4-24%	Zhao, 1999 onshore & offshore in US to 1997	McDonald & Schrattenholzer [20] pg. 257
Gas turbines	10%	MacGregor, 1991 world-wide to 1980	
Coal Power	8%	Kouvaritakis, 2001 OECD to 1993	
GTCC	26%	Claeson, 1997 world-wide to 1997	Learning rates on overall cost, they include all times of improvement
Wind	17%	Kovaritakis, 2001 OECD to 1995	
Ethanol Prod.	20%	Goldemberg, 1996 Brazil	
Solar PV module	20%	Harmon, 2000 world-wide to 1998.	

Small LWR Reactor Costing

$$\textit{Specific Cost/Specific Cost}_0=(\textit{Power/Power}_0)^a*(y)^b$$



IRIS - Westinghouse

Scaled SMR £7k/kWe

Large LWR £3k/kWe

1. Design simplification
2. Multiple units one site
3. Production learning
4. Standardisation
5. Short build schedule
6. Finance savings

SMR £2.4k/kWe

Break-even Volumes (Reactor Units)

SMRs can be cost competitive

200MW Sp. Power Learning	-0.35	-0.3	-0.25	-0.2	-0.15	-0.1
3%	>500	>500	>500	>500	>500	>500
4%	>500	>500	>500	>500	>500	3
5%	>500	>500	>500	>500	32	2
6%	>500	>500	>500	95	10	2
7%	>500	>500	218	27	6	2
8%	>500	>500	63	13	4	2
9%	>500	146	29	9	3	2
10%	445	62	17	6	3	2

100MW Sp. Power Learning	-0.35	-0.3	-0.25	-0.2	-0.15	-0.1
3%	>500	>500	>500	>500	>500	>500
4%	>500	>500	>500	>500	>500	3
5%	>500	>500	>500	>500	>500	2
6%	>500	>500	>500	>500	77	2
7%	>500	>500	>500	>500	23	3
8%	>500	>500	>500	121	12	3
9%	>500	>500	>500	48	8	2
10%	>500	>500	262	25	6	2

Modelled values:

- Comparison between LR - 1000MW with SMR - 100/200MW unit size;
- Reactor costs split 50/50 labour & materials, Materials learning rate 2% applied to all cases;
- LR comparator with overall learning rate of 3%, including 2% for materials;
- Project interest rate 8% for construction periods assumed: SMR: 36 months, LR: 60 months.

Outlook for Nuclear

- Outlook for nuclear is positive both in UK and many other countries;
- UK Industry needs to deliver the current 16GWe reactor programme;
- Key problems that need to be addressed:
  - Continued public acceptance;
  - Dealing with long-lived nuclear waste – through international collaboration;
  - High capital cost & long construction schedule of current designs.

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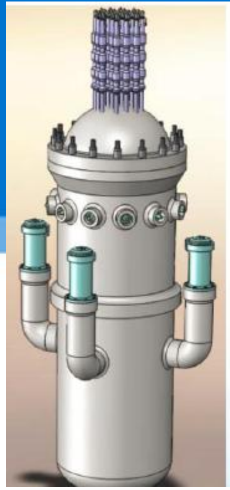
Conditions for Cost Competitive of SMRs


ACP100

Scaling:

- Simplify the design, less components, less systems;
- Operate within current LWR & steam technology understanding, not at the edge;
- Design plant for manufacture, not construction: whole plant and systems, not just the reactor vessels and components.
- One design that can accommodate most of world's requirements – a global standard 50/60 Hz
- Alignment of design certification standards, with a level stability of regulation.

Learning:

- Design for factory manufacture and site assembly - whole plant and all systems;
- Detailed design for manufacture done with global suppliers/partners;
- Manufacturing engineering, jigs, tools and fixtures as part of development;
- Launch and forward order profile that support a minimum supply chain 'drum beat';
- Global supply chain that ensures 'learning by doing' – 10 per year minimum?

These are the skills of low volume manufacturing rather than construction?

Is Nuclear Safe?

- More than 14,000 reactor years of experience of commercial power reactors – but:

Release:	
Core damage + Containment by-pass	
Less than once in:	
1,000 years	1970 LWRs as built
10,000 years	1970 reactors upgraded
100,000 years	Modern e.g. Sizewell B
1,000,000 years	Gen III+ designs

- Latest reactor designs - at least 100* safer than the old BWRs at Fukushima because of:
  - **Inherently stable cores** with design for defence in depth against incidents;
  - **Multiple and redundant and/or passive safety** systems;
  - **Robust protection** against external events.

Progress in Nuclear Safety

- Hazard to the Public: **Core Damage + Containment by-pass**;

Core damage frequency improvements:

~1 in 1,000 yrs

LWRs as built in 1970s

Designed for limited set of standard accident, plus containment for DBEs

<1 in 10,000 yrs

Post TMI build or as modified

Probabilistic Risk Analysis
LOCA protection & better control systems

<1 in 100,000 yrs

Modern Systems 1990s: ABWR, Sizewell B

Designed-in LOCA prevention & protection
Common cause addressed

~1 in 1,000,000 yrs

Gen III+: EPR, AP1000

Design for External & Internal hazards
Whole core accident prevention/mitigation
Improved Containments

- Design safety performance has been **improved by at least factor of 100** since 1980.