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Small Modular Reactors and the UK

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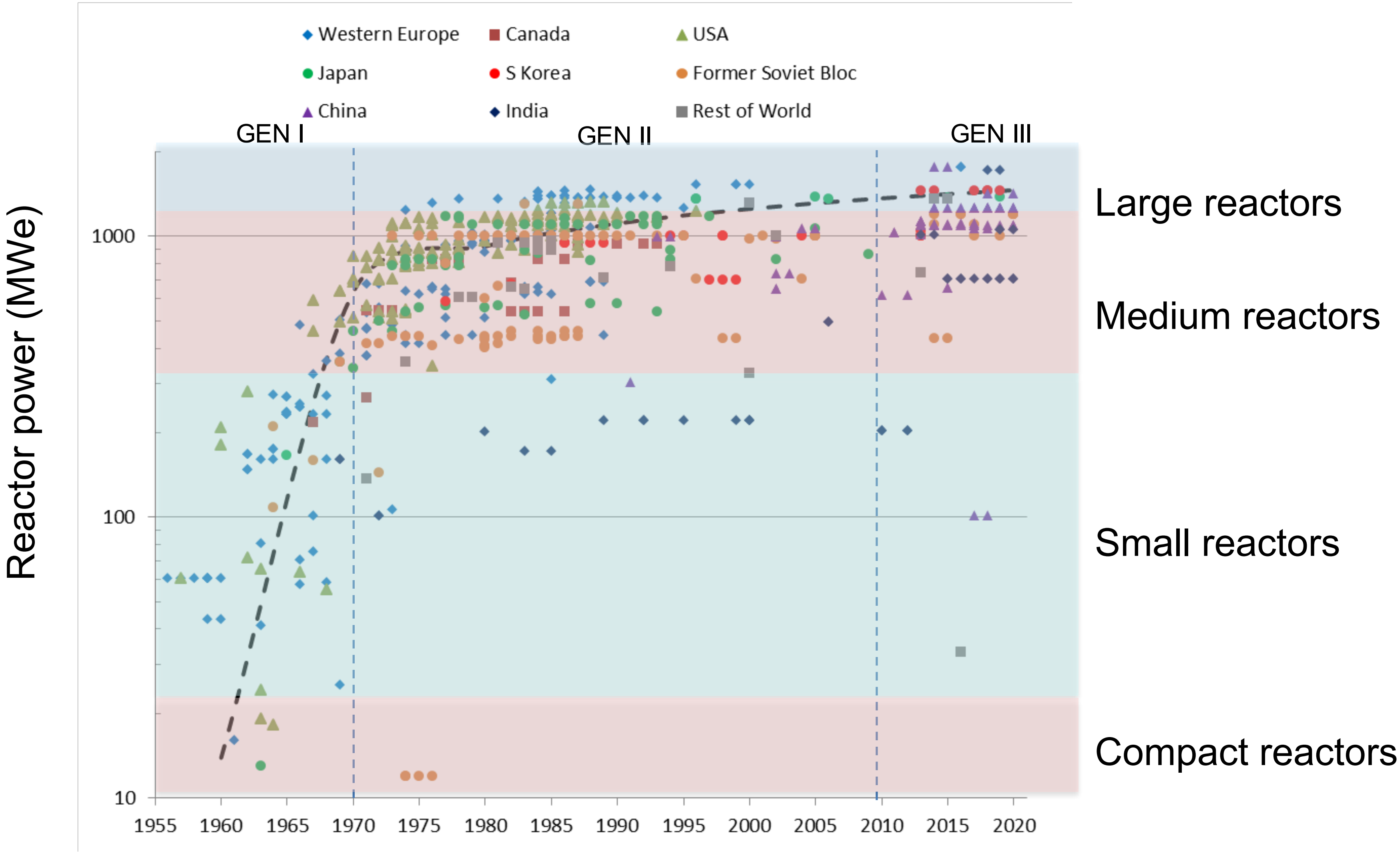
In the beginning there were just small reactors

- The first nuclear power plant were small (<100 MWe) but within 10 years, reactors were being built that were much bigger. This was because economies of scale favoured larger designs and the fixed costs associated with reactor construction and operation tended not to increase with reactor size.
- By 1980 most reactors were over 1000 MWe and the trend continued until today's reactors are typically between 1200 and 1700 MWe.
- Countries like Russia, India and China still build smaller reactors to fit in with local needs. In the developed world concern has been expressed on the increased time it takes to construct a reactor, the complexity of designs and the difficulty in finding the huge investment costs for projects. This is the background to the interest in SMRs.

Evolution of reactor size



Small reactor markets

There are are essentially two markets for small reactors:

1. Small Modular Reactors (SMRs)
   - Sizes from ~20 to 300 MWe
   - Designed for grid connection
   - Need to compete with other grid generation
2. Very small reactors (compact reactors)
   - Sizes from ~1 to 20 MWe
   - Designed mainly for off-grid and isolated generation but could be integrated into a grid
   - Need to be easily transportable and installed
   - Need to compete with diesel and other off-grid generation

The U-Battery is an example of 2, in this presentation we look at 1.

Origin of the SMR as a separate line of development

- As we have seen, to begin with all reactors were SMRs but the concept of separate streams of development arose in the period after the 3 Mile Island accident (1979) and was reinforced by the Chernobyl catastrophe (1986).
- There was a spurt of interest in developing reactors which could be cooled passively and the smaller the reactor size, the easier it was to do.
- There was also concern about making very small safe reactors to site near centres of population as well as the need for small reactors to meet developing markets

OECD Small and Medium Reactors

- In 1991 the OECD NEA published the results of an expert group into small and medium reactors https://www.oecd-nea.org/brief/brief-07.html
- The documentation listed 24 reactor concepts of which only the CANDU 6 (already established) and the Japanese small HTGR HTTR were ever built.
- Despite this, the review covered many of the issues were are discussing now and several of the designs were very influential in current developments
- The main difference was the interest in 7 designs for low temperature heat producing reactors.

UK first interest in SMRs

- UK Interest in SMRs dates back to the late 1980s when it was realised that the privatisation of the electricity supply industry would make the investment in large reactors difficult.
- Studies at that time looked at the effect of scale on cost and the industry was still firmly looking at large reactors.
- The UK (Rolls Royce and AEA Technology) joined the SIR project (Safe Integral Reactor) with ABB and Stone & Webster, but in the end the dash for gas won.

USA interest in SMRs

- The American interest in the 1980s for SMRs was driven by EPRI and the US Department of Energy on a strategic basis, looking at requirements for nuclear power both domestically and for export.
- Around 2000 the focus had changed to the need to replace coal fired power stations in a fragmented deregulated generation industry. This momentum has, at least temporarily, been broken by the availability of cheap shale gas.
- The US DoE is currently running an SMR Technical Licensing Support Program

USDOE view of SMR benefits

- **Modularity**: in two senses – factory fabrication of modules for a simpler assembly on site and reactor units as modules that can be added to match demand;
- **Lower Capital Investment**: lower unit of investment and lower investment per unit power from factory fabrication and shorter construction times;
- **Siting Flexibility**: smaller footprint, less demanding infrastructure and possibility of siting on existing fossil sites nearer habitation;
- **Gain Efficiency**: use of heat for industry and other applications and coupling with other generation sources for more efficiency;
- **Non-proliferation**: Depending on type of SMR could lead to reduced transport and handling of nuclear materials and longer refuelling times, possibility of sealed fuel units;
- **International Marketplace**: Opens a new nuclear market.

Other potential advantages of SMRs

- Multiple build enables reduced costs through learning;
- Enables existing licensed sites to be used where space is limited;
- Small reactors can fit into limited electrical grid in remote regions, islands and in developing countries;
- Small reactors are simpler and more able to use natural convection and passive safety features and to be located underground.

UK current interest in SMRs

- UK Nuclear Industrial Strategy, March 2013: "*To be a key partner of choice in commercialising Generation III+, IV and Small Modular Reactor (SMR) technologies worldwide*".
- NIRAB initiated a feasibility study with BIS support in 2014.
- The feasibility study was published in December 2014 and focussed on the integral PWR design
- A next stage study sponsored by DECC to be delivered in April 2016 has just started covering 5 lots (paraphrasing):
  - Detailed analysis for the direction of a UK SMR project (or not to go for SMR development);
  - How SMRs can be integrated into the UK electricity system;
  - Market assessment and a strategic view of future developments ;
  - Safety of SMRs;
  - Manufacturing of SMRs (this lot has not yet been allocated).

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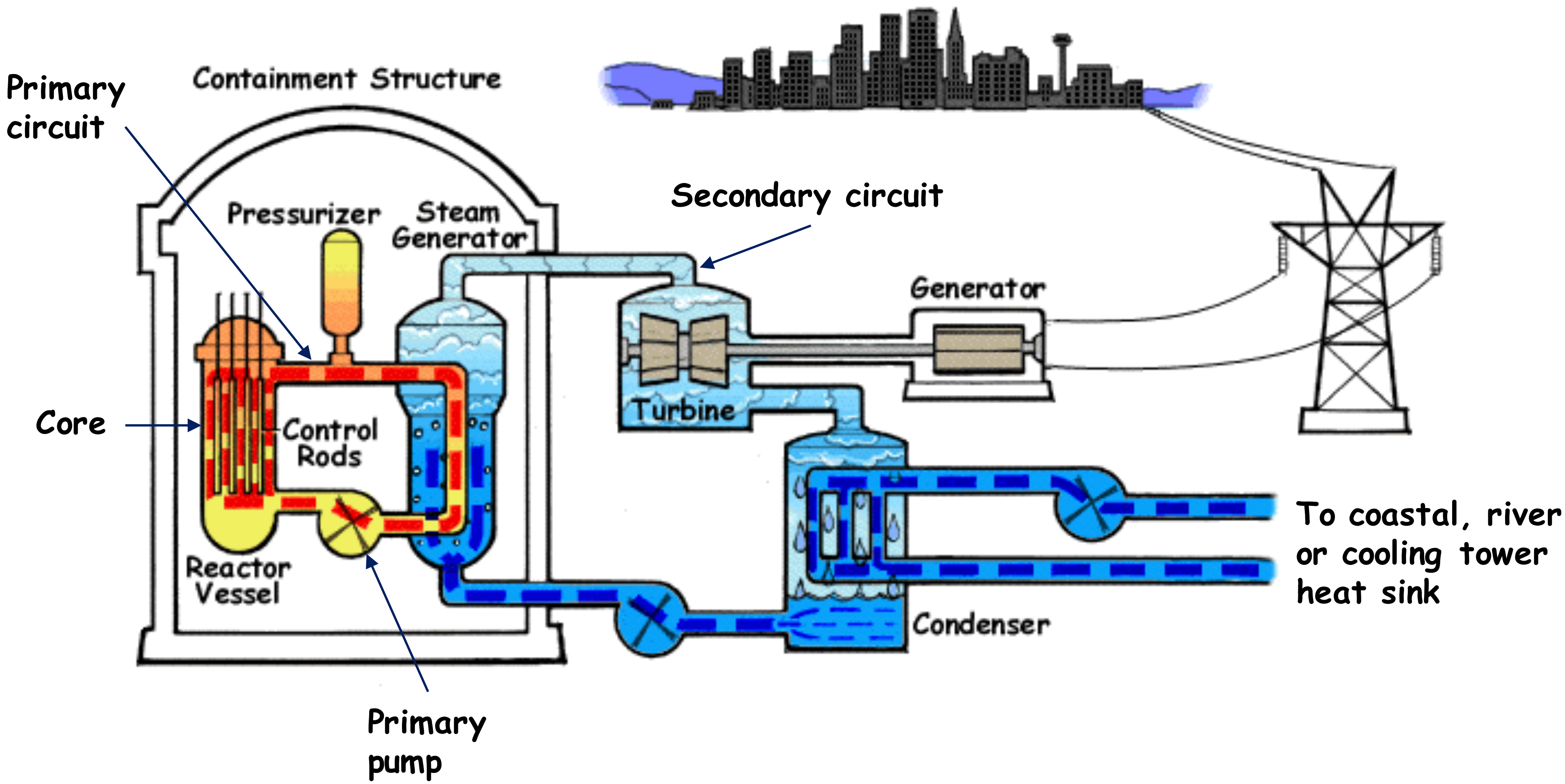
WHAT SMR DESIGNS ARE WE CONSIDERING?

Range of SMR concepts

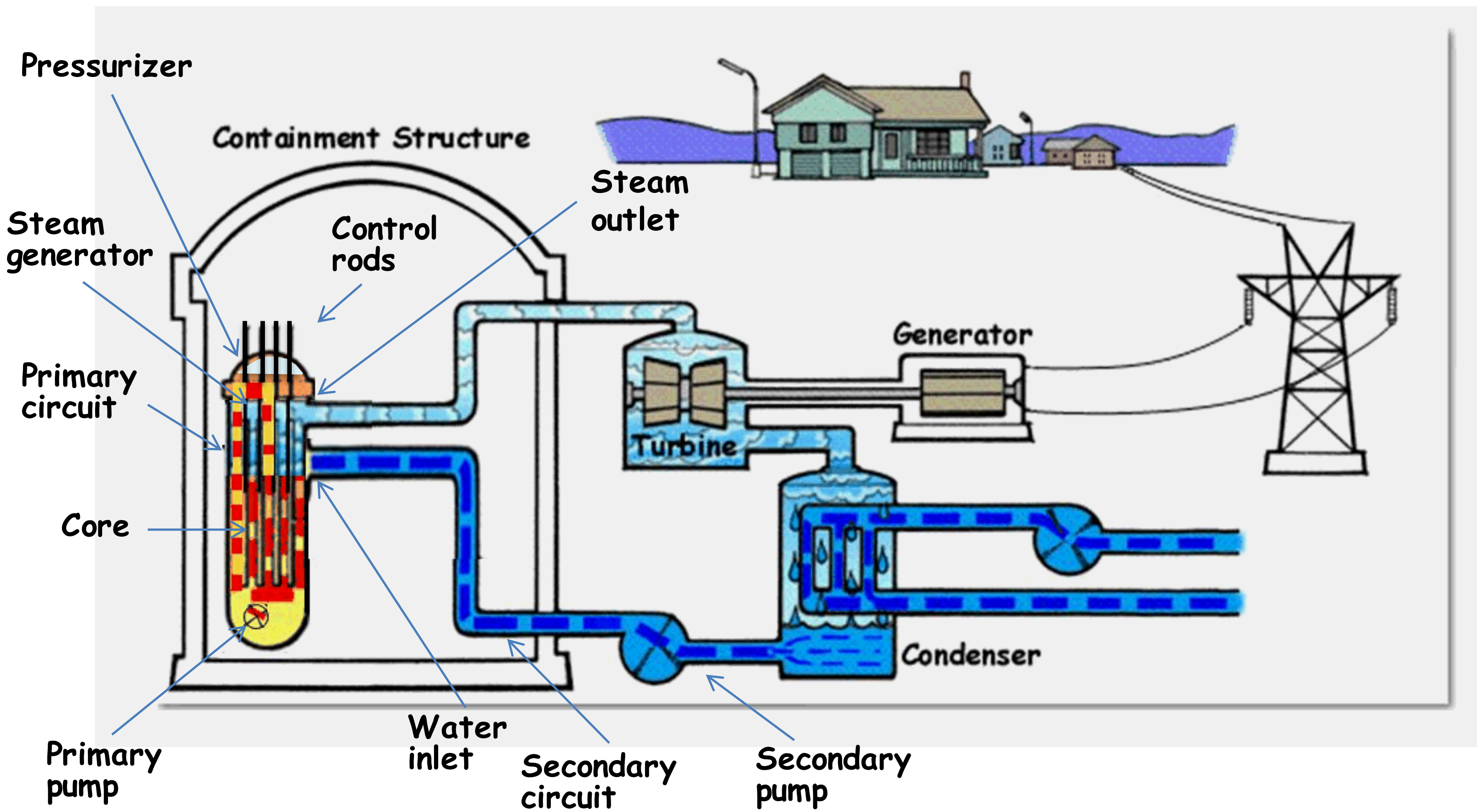
- In addition to small versions of current reactors, there are over <u>60</u> recent SMR concepts that have been studied in the last 10 years but few are likely to be built.
- The main thrust of recent SMR development is with *Integral PWRS* – PWRs where the steam generator is integrated into the reactor pressure vessel (RPV). We will focus on this direction as several designs are close to market
- High temperature gas cooled reactors are inherently small reactors to enable heat removal in loss of coolant accidents. We have the UK U-Battery very small reactor project and China is building a twin 105 MWe pebble bed reactor station.
- A number of small sodium and lead alloy cooled fast reactor designs at one time looked like they might be built but currently are seen as a step too far for SMR development.
- There is a recent interest in molten salt reactors, which would be in the SMR range. In particular the Terrestrial Energy Integral Molten Salt Reactor (~240 MWe) based on the the ORNL MSRE is well developed.

The basic components of a PWR



Source USNRC

Integral PWR



Apologies to USNRC for merging their PWR and BWR animated GIFs

Current Integral PWR concepts

There are several integral PWR projects active at the moment:

- CAREM (Argentina) – 25 MWe demonstration reactor being constructed
- ACP 100 (China) – 100 MWe first plant under construction
- SMART (S Korea) – 100 MWe completing licensing with passive cooling
- mPower (USA) – 180 MWe design being developed by Babcock & Wilcox
- NuScale (USA) – 45 MWe design being developed by Fluor
- Westinghouse SMR (USA) – 225 MWe design being developed by Westinghouse
- SMR 160 (USA) – 160 MWe design being developed by Holtec
- IMR (Japan) – 350 MWe design being developed by MHI
- ABV 6M (Russia) – 6 MWe marine reactor designed to be used in pairs and could be barge mounted
- RITM 200 (Russia) – 50 MWe marine reactor that can be used onshore or on a barge first example under construction

Integral PWR concepts

	Power MWth	MWe	RPV size (m) Diameter	Height	Core size (m) Diameter	Height	Primary circuit
SIR	1000	320	5.8	19.2	2.8	3.6	Forced
IRIS	1000	335	6.2	21.3	2.3	4.26	Forced
CAREM	100	250	3.2	11	1.1	1.4	Natural
ACP-100*	310	100	3.19	10	1.85	2.15	Forced
SMART	330	100	6.5	18.5	1.85	2.0	Forced
mPower	530	180	4	27	2.0	2.4	Forced
NuScale	160	45	2.9	17.4	1.5	2.0	Natural
Westinghouse SMR	800	225	3.7	28	2.3	2.4	Forced
SMR 160**	525	160	2.7	15	1.64	3.7	Natural
IMR (MHI)	1000	350	6.0	16.8	2.95	2.4	Natural
ABV 6M*	38	6	2.4	6	1.67	0.9	Natural
RITM 200*	175	50	3.3	8.5	2.2	1.65	Forced

*External pressuriser **Steam generators and pressurizer section of RPV offset with a dog leg

Advantages of the integral PWR concept

Careful design will give a considerable reduction in the NSSS cost but the main advantages are related to the safety of the system

- The primary circuit is kept entirely within the RPV, so no primary pipework and no active circuit outside RPV
- No penetrations of the RPV larger than 50 mm diameter so no large break loss of coolant accidents
- Increased shielding of RPV from fast neutrons
- Lower core power density and larger volume of water in RPV
- Larger surface area to power ratio, making passive decay heat removal easier

Safe Integral Reactor (SIR)

Power – 300 MWe

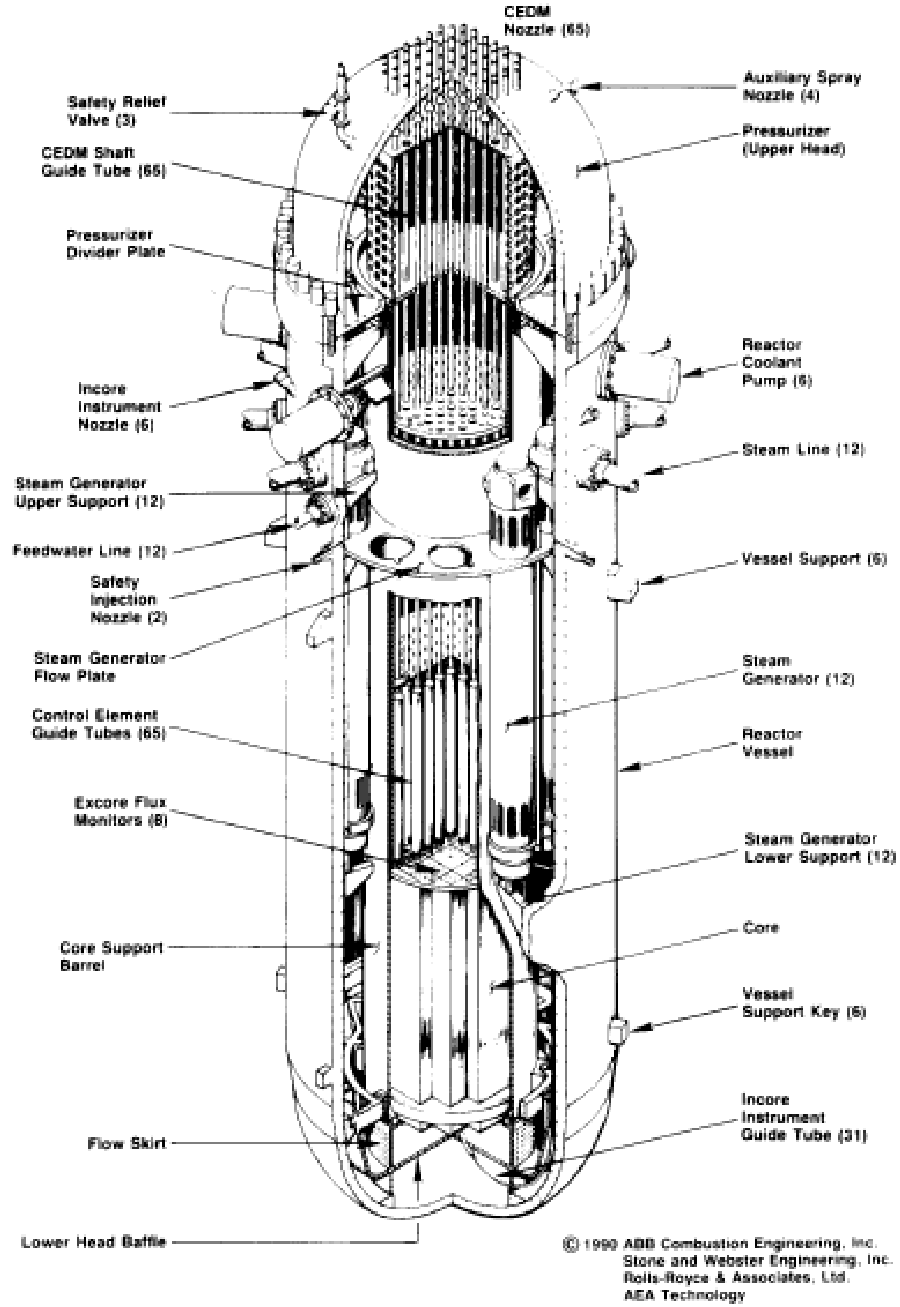
Power density – 55 MW/m3 (similar to BWR)

Special design features – 12 modular steam generators, integral with RPV

There is an extremely low fast neutron dose to the reactor pressure vessel because of the large water gap between the reactor core and the vessel wall.

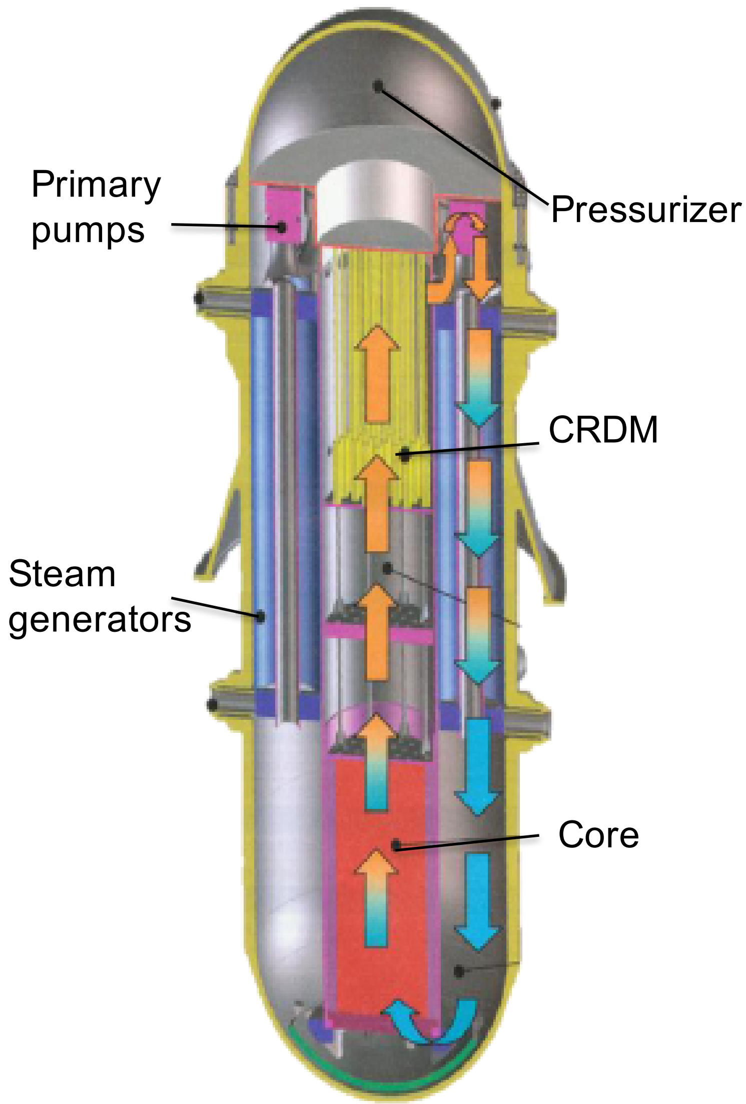
Vessel diameter – 5.8 m

Vessel height – 19.2 m



Source: Matzie et al, Nucl. Eng. and Design 136 (1992) 73

IRIS (IRIS, International Consortium)



- IRIS (International Secure and Innovative) was a collaboration led by Westinghouse that included BNFL in the UK and organisations in Italy, Spain, Russia, Brazil and Japan.
- The main design work was done in the early 2000s, but the influence of the project can be seen in all current integral PWR designs.
- The design is just outside the normal definition of an SMR at 335 MWe.
- IRIS has the features that can be seen in designs like the Westinghouse SMR, mPower, SMART, CAREM and some Russian designs
- IRIS is clearly influenced by the SIR design (Westinghouse acquired ABB Combustion Engineering) but the main innovation is the sealed CRDM inside the RPV.

Source: [IAEA]

Westinghouse SMR (Westinghouse, USA)

Illustration removed because of copyright Please look at Slide 3 on hyperlink below

Source: Westinghouse

- Westinghouse has moved on from its role in IRIS to create its own 225 MWe SMR design Claimed to be derived from the AP1000 design but clearly built on the IRIS experience
- The design is much longer and thinner than IRIS. One of the main innovations is to add a second flange below the steam generators to allow easier access to the core for fuel reloading. The coolant pumps are also located lower.
- The Westinghouse design is well developed and has advanced along the USNRC approval but there are no specific plans to build a first plant.

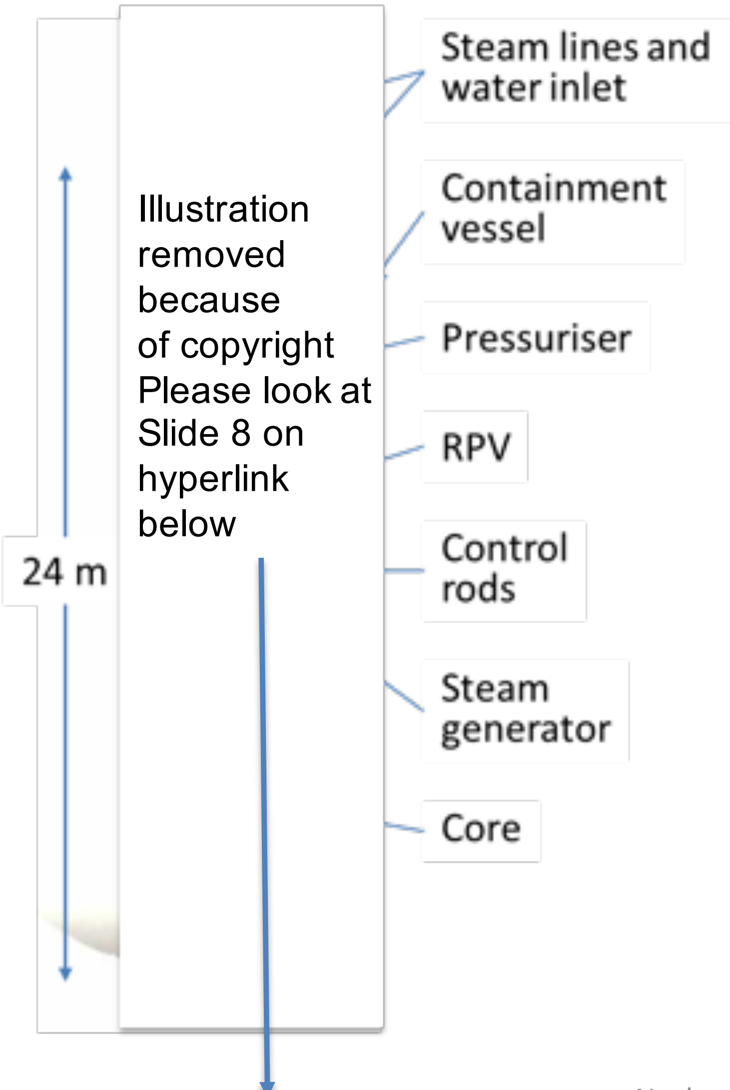
mPower (Babcock and Wilcox, USA)

Illustration removed because of copyright Please look at Slide 16 on hyperlink below

Source: Generation mPower LLC

- The mPower design comes from B&W in the USA and was being developed as a JV with Bechtel and is said to be based on its experience with US naval reactors, but the influence of IRIS is obvious
- The design has had various powers but currently aims to deliver 180 MWe. In many respects the design is very similar to that of Westinghouse but the coolant pumps are still located at the top of the RPV.
- The containment concept is less ambitious than Westinghouse, NuScale or ACP-1000, with a larger dry containment.
- After a very bullish start, several US DoE grants and substantial investment by B&W, the projects is now essentially mothballed. B&W are looking for a partner to take a majority stake, but still hopes to be the main manufacturer.

NuScale (NuScale Power Inc., USA)



Source: NuScale

- NuScale started as a concept at of Oregon State University and Idaho National Laboratory but is now being developed by Fluor. From the point of view of containment and heat removal it is the most innovative of the new designs.
- As the only design the UK is looking at that uses natural convection during normal operation, the reactor power is just 45 MWe. It is intended to be used in blocks of up to 12 modules (a total of only 540 MWe). Despite this an overnight cost of only $5000/kWe is claimed
- The CRDM system is external using conventional technology, which means the linkages are very long.
- Rolls Royce has given support to NuScale in its US DoE funding applications. Currently the plans are to build the first plant at Idaho and it is expected that the construction and operation licence application to USNRC will be made in 2017.

ACP-100 and ACP-100+ (CNNC, China)

Pressurizer

CRDM

Steam generators

Primary pumps

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Core

ACP-100+

Source: CNNC

- The most advanced Integral PWR project is the the Chinese ACP-100 design which is currently being assessed for safety by the IAEA and construction may have already started.
- The design for a 100 MWe reactor is being replaced with a 120 MWe development with several important design improvements, notably placing the CRDM and pressurizer inside the RPV.
- The new reactor is designated for the time being as ACP 100+ and this design is the one that the UK is looking at a possible development partnership.

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WHAT ARE THE SMR CHALLENGES FOR THE UK?

SMR R&D needs

- Integral PWRs mostly use the same technology as other LWRs and the same fuel reduced in length. So the materials, fuel and structural integrity issues are the same ones as being faced in BWRs and PWRs, eg Zr alloy oxidation and radiation damage of the RPV.
- The really distinct issues for SMRs are related to:
  - specific design features;
  - safety;
  - and manufacture.
- For lower power SMRs there is the possibility of cassette fuel replacement.

Design issues

- Primary coolant pump
  - The primary pumps are usually fixed externally in a "canned design" with a penetration through the RPV for the drive to the impellors. Some designs dispense with pumps and operate wholly on natural convection.
- Control rod drive mechanism (CRDM)
  - The long RPV and the location of steam generators and pressurizer makes design of the CRDM difficult. Some designs use a sealed internal CRDM.
- Steam generator
  - The steam generators have to be compact and efficient. Many systems use modular steam generators that can be isolated and separately removed if there is a tube leak.
- Pressurizer
  - The location and small volume available for the pressurizer is a challenge.

Westinghouse SMR CRDM

- The CRDMs are a high-temperature and pressure version of the recently developed AP1000 CRDM, which has already been tested to eight million steps, to be used within the pressure boundary of the SMR integral reactor. Elimination of control rod penetrations through the reactor pressure boundary has resulted in reduced cost of manufacture and the elimination of the normally-postulated rod ejection event.

Illustration removed because of copyright Please look at Fig. 3 on hyperlink below

Source: Nuclear Engineering International

Safety issues

- Smaller reactors are easier to cool passively
- Some designs are very conventional in their approach to safety systems, but others, notably NuScale, take the opportunity to completely rethink heat transfer in accidents.
- The use of tight low volume containments.
- Sitting the containment in a large volume fuel-handling water pool.
- The use of multiple cooling routes and with low power cores the possibility of dry cooling by air convection without the melting of the reactor.

SMR Containment

Containment

NuScale

Reactor vessel

Illustration removed because of copyright Please look at Slide 6 on hyperlink below

Modules with own containment in water pond in concrete cells

Source: NuScale

- One of the opportunities for SMR safety design is to choose a small-volume pressure suppression containment more usually found with BWR systems.
- The NuScale, Westinghouse and ACP-100+ designs have below ground tight steel high pressure containments.
- Westinghouse and NuScale can operate with the containment under vacuum, so that the reactor has no insulation and is easier to cool by flooding the containment in a loss of cooling accident.
- The Westinghouse and ACP-100+ containments have internal water reservoirs for pressure suppression.
- The NuScale design has up to 12 reactors sitting in a large fuel handling pool.

Primary containment of Westinghouse SMR

Illustration removed because of copyright Please look at Slide 4 on hyperlink below

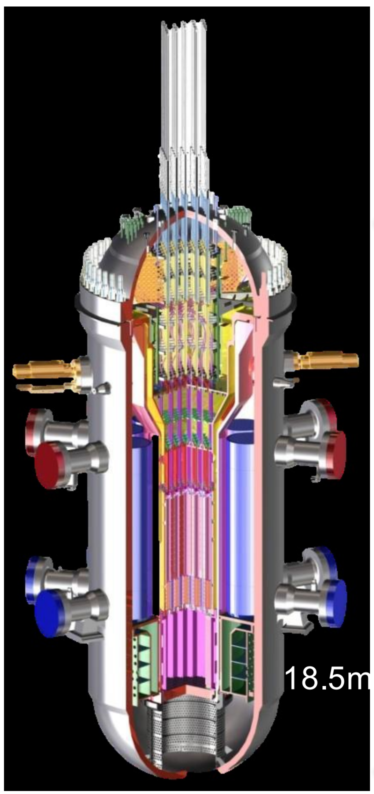
Source: Westinghouse

Manufacturing issues

- The only way the overnight costs for SMRs can compete with larger reactors is to have simple completely modular designs that can be made efficiently in factory conditions and quickly assembled on site.
- If SMR are successful then the number of systems built could be hundreds and experience from the aircraft and automotive industry might be useful.
- It would be worth making the investment in tooling for automated fabrication

Comparison of size of NSSS of an SMR to a regular PWR

SMART
NSSS
Net power 100 MWe



18.5m

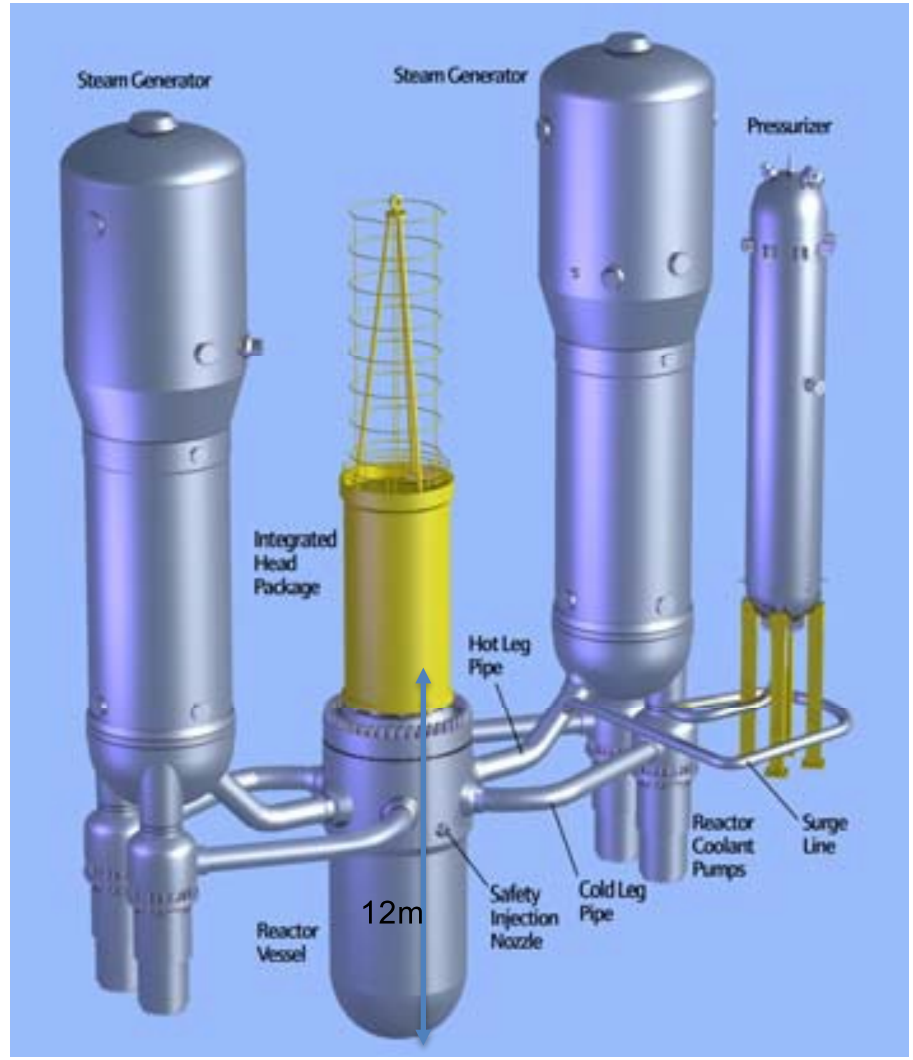
6.5m OD

mPower
NSSS
Net power 180 MWe

27m

4m OD

AP 1000 NSSS net power 1117 MWe



4.4m OD

Source: [IAEA ARIS data and images]

Footprint of SMRs – are they smaller?

Reactor	Nuclear island area		Nuclear and non-nuclear Island area		Total area	
	m^2	m^2/MWe	m^2	m^2/MWe	Hectares	m^2/MWe
Current designs relevant to UK						
EPR	~10000	6	~25000	15	Twin 170	~500
AP1000	~5000	4.5	~10000	9	Twin 125	~560
ABWR	~3250	2.5	~7500	5.5	Twin 50	~185
SMR designs						
mPower	~1225	7	~3675	20	Twin 16	~450
Westinghouse SMR	~1124	5	~4500	20	Single 6.5	~290
NuScale	~1458	32	~6561	146	x12 18	~333
SMART	~3600	36	~7200	72	Single ~9	~900
HTR-PM	~1300	12.5	~3000	29	Twin ~2	~100

SMRs occupy less land in absolute terms but are comparable relatively

What can we conclude about SMR costs?

- SMRs should be built in substantially shorter times than larger reactors
- SMRs will occupy much less land than larger reactors but the area occupied per unit power is not very different.
- Overnight costs of SMRs are similar to those of larger reactors.
- Levelised costs of electricity from SMRs may be smaller than from larger stations, but there is a large uncertainty which can only be resolved when an SMR building program is started.
- The unit cost of capital for an SMR station is still large for a deregulated electricity industry at around £2 billion.

What is the UK looking for

- The UK has not had a civil nuclear vendor for over 40 years and even lost the capability of making large components for the nuclear island and the turbine generator after Sizewell B was completed.
- SMRs present an opportunity for the UK to have a stake in the construction of a system that may lead eventually to involvement in GEN IV reactor construction and to be global nuclear player again.
- The hope is to find a project partner that will make space for UK participation and IP generation – perhaps on the model of a how aircraft are currently built.
- There are currently too many SMRs designs. Inevitably most will fail but the winners could eventually pick up 100s of projects. The trick is to pick the winner.