Small Modular Reactors

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Scope

- To highlight generic design issues from SMRs
  - But not to judge SMR performance against them
  - Aim is to point out the hurdles only
- Focus on small modular Pressurised Water Reactors (PWRs)
  - Highest Technology Readiness
  - Firmly rooted in existing LWR technology
  - But generic design issues mostly apply to other types
- No answers, only questions

SMR definition

- Various definitions apply
  - IAEA stipulate output < 300 MW electrical (MWe) unit size
  - But IAEA also consider < 500 MWe as small
  - Designs range from 10 MWe to 600 MWe
    - Lower end range a bit higher than large wind turbines
    - Upper end comparable with existing UK reactors (MAGNOX & AGR)
- Modular implies multiple units grouped together sharing common facilities and staff
  - Potential applications as single units
  - Or as multiple units making up a large power station
  - Implied assumption that there will be significant savings from multiple units

Plant size evolution

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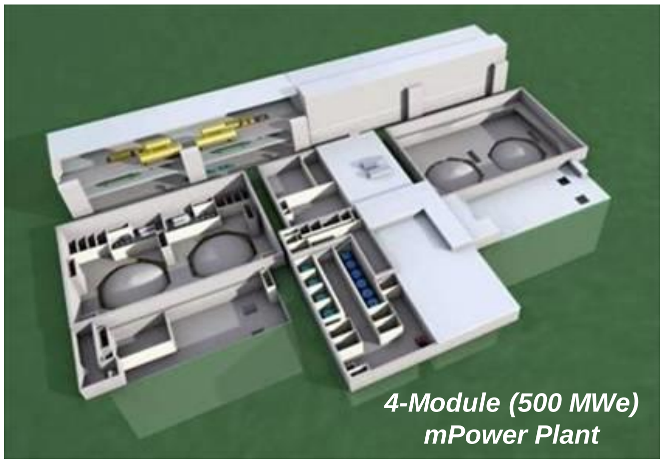
- Nuclear units sizes have historically increased eg French PWR fleet:
  - 1st generation 900 MWe
  - 2nd generation 1300-1500 MWe
  - 3rd generation 1650 MWe
- Large plants benefit from scaling factors:
  - Construction costs per MWe lower for large plants
  - Similar workforce need independent of plant size
- In developing countries plants > 600 MWe may be too large for the grid and the cash flow too onerous to finance
  - Challenge will be to make the smaller plants cost effective in this market
- In developed countries SMRs may need to be grouped into large power stations to be competitive
  - Challenge will be to demonstrate economic parity or near parity for a multiple unit power station compared with a single or twin-unit conventional power station
- Small module sizes may make additional sites viable
  - Siting near cities may be possible if no requirement for offsite evacuation

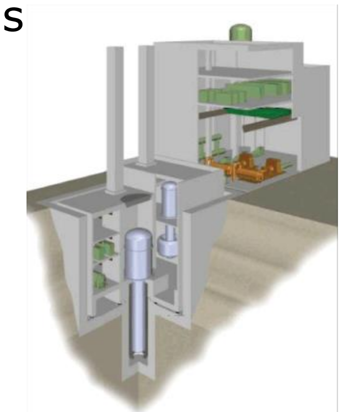
SMR niches

- Multiple unit modular power plants

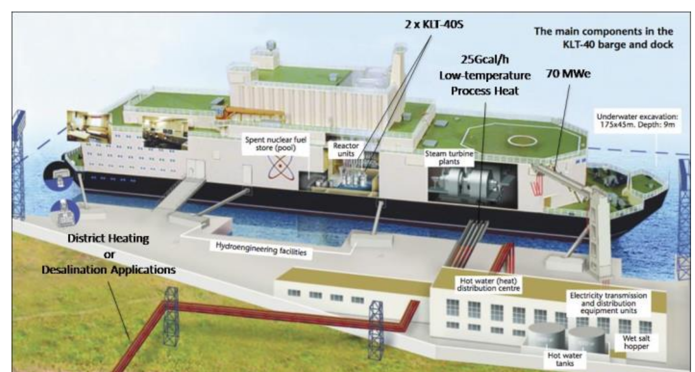


4-Module (500 MWe) mPower Plant

- Small plants suited to developing countries
  - Energy decarbonisation is a global issue and every available option will be required
- Desalination
- Small autonomous power sources for remote locations



- Barge mounted units



SMR survey

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- Many SMR designs are under development world-wide
  - Dominated by Light Water Reactors (LWRs)
  - LWR designs heavily based on existing design experience and therefore closest to potential deployment
- Furthest developed designs are probably at least 10 years from commercial deployment
  - US Department of Energy helping to finance design of two prototypes
  - Less developed designs at least 15 to 20 years from deployment
- Difficult to compare the pros and cons of the different designs because they are at different stages of development
  - In the end, utilities will decide which are deployed and they will be focusing on economics and financing considerations
  - Only a few of the many proposed designs will ever make it to commercial deployment

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	CNNC, operational in Pakistan
PHWR-220	220 MWe	PHWR	NPCIL, India
KLT-40S	35 MWe	PWR	OKBM, Russia
CAREM	27 MWe	PWR	CNEA & INVAP, Argentina
HTR-PM	2x105 MWe	HTR	INET & Huaneng, China
VBER-300	300 MWe	PWR	OKBM, Russia
IRIS	100-335 MWe	PWR	Westinghouse-led, international
Westinghouse SMR	225 MWe	PWR	Westinghouse, USA
mPower	180 MWe	PWR	Babcock & Wilcox + Bechtel, USA
SMR-160	160 MWe	PWR	Holtec, USA
ACP100	100 MWe	PWR	CNNC & Guodian, China
SMART	100 MWe	PWR	KAERI, South Korea
NuScale	45 MWe	PWR	NuScale Power + Fluor, USA
PBMR	165 MWe	HTR	PBMR, South Africa; NPMC, USA
Prism	311 MWe	FNR	GE-Hitachi, USA
BREST	300 MWe	FNR	RDIPE, Russia
SVBR-100	100 MWe	FNR	AKME-engineering, Russia
EM2	240 MWe	HTR, FNR	General Atomics (USA)
VK-300	300 MWe	BWR	RDIPE, Russia
AHWR-300 LEU	300 MWe	PHWR	BARC, India
CAP150	150 MWe	PWR	SNERDI, China
SC-HTGR (Antares)	250 MWe	HTR	Areva
Gen4 module	25 MWe	FNR	Gen4 (Hyperion), USA
IMR	350 MWe	PWR	Mitsubishi, Japan
Fuji MSR	100-200 MWe	MSR	ITHMSI, Japan-Russia-USA

Source: World Nuclear Association

NUSCALE & HOLTEC (USA)

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NUSCALE

45 MWe

Integral PWR

Reactor vessel submerged in water pool

Natural circulation

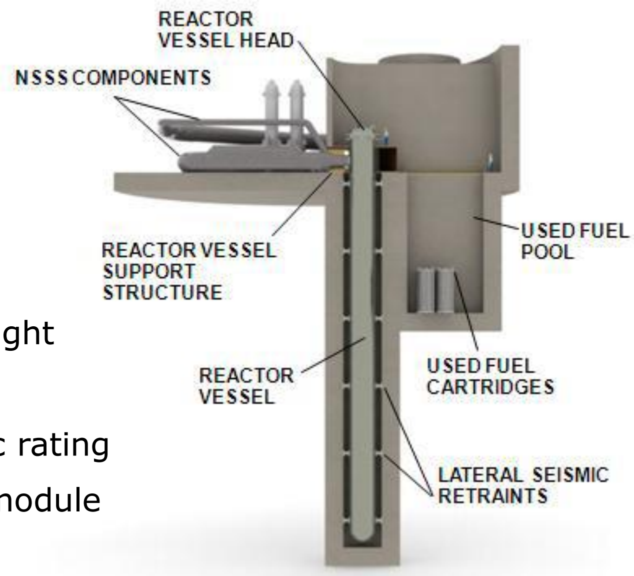
17x17 fuel assembly

1.8 m core active height

3.5 year refuelling cycle

HOLTEC

- 145 MWe
- Integral PWR
- Natural circulation
- 17x17 fuel assembly
- 3.6 m active core height
- 5.2 m^3 core volume
- ~30 MW/tHM specific rating
- Cartridge refuelling module



B&W mPower B&W & WESTINGHOUSE SMR (USA)

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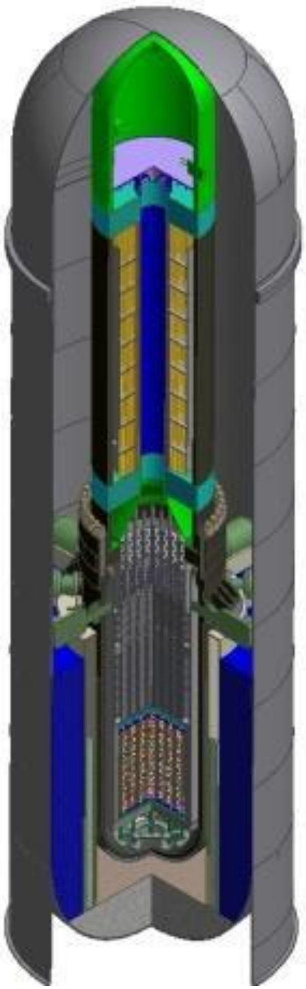
- mPower
  - 180 MWe
  - Integral PWR
  - Forced circulation
  - 69 17x17 fuel assemblies
  - 4.5 year refuelling cycle (single batch core)
  - ~35 GWd/t burnup
  - No soluble boron reactivity control

- Westinghouse SMR
  - 225 MWe
  - Integral PWR
  - Forced circulation (external coolant pump motors)
  - 89 17x17 fuel assemblies
  - 2.44 m active core height
  - 9.6 m^3 core volume
  - ~30 MW/tHM specific rating
  - Soluble boron reactivity control



General Atomics GT-MHR & GE-Hitachi PRISM (USA)

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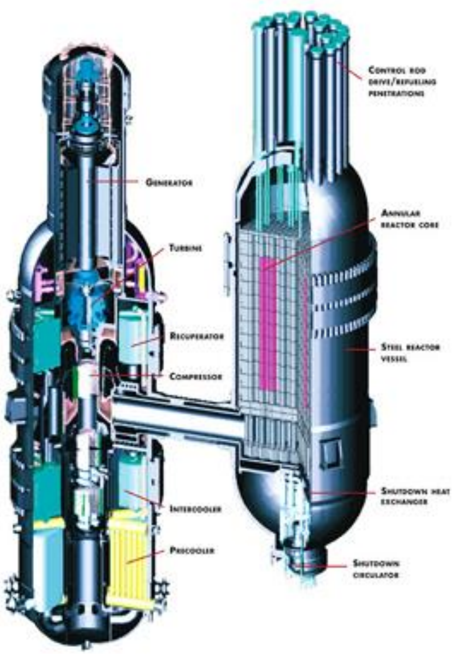
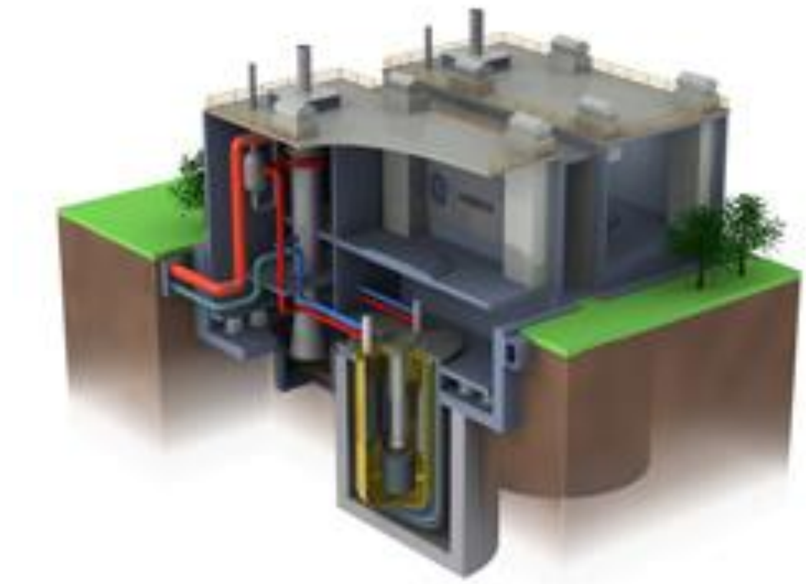
- GT-MHR
  - 285 MWe
  - High Temperature Reactor (HTR)
  - Ceramic TRISO fuel
  - Helium coolant
  - Graphite moderator
  - Fuel compact in prismatic fuel blocks
  - Core can dissipate decay heat without active systems



- PRISM
  - 622 MWe
  - Sodium cooled fast spectrum reactor
  - Metal fuel
  - Passive safety
  - Passive safety



Commonly occurring features of SMRs

- Simplified or passive safety
  - Integral pressure vessel
  - Large coolant masses for high thermal inertia
  - Low specific ratings
  - High vertical heights to enhance natural convection
  - Natural convection to manage decay heat
  - Small size does not necessarily improve safety
  - Multiple units in close proximity
- Underground siting of cores
  - Underground siting may improve protection in some scenarios, but not necessarily all scenarios
- Long refuelling cycles
  - Autonomous power sources have very long life cartridge cores (15 to 30 years)
  - Facilitated by low specific ratings

Integral PWR

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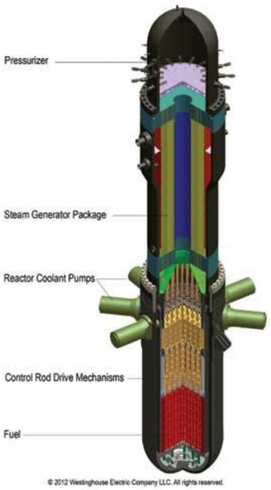
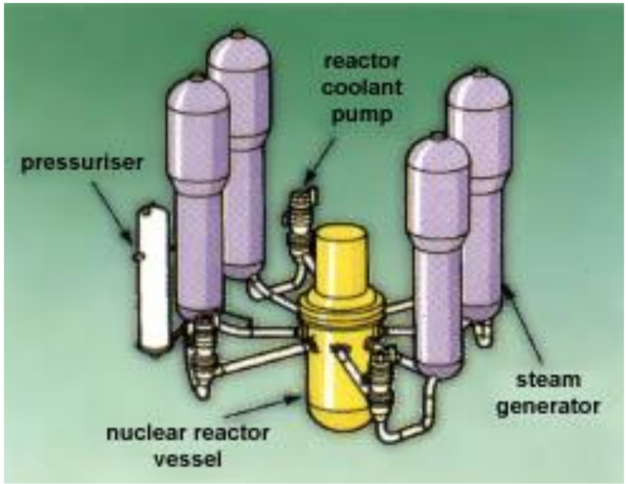
WHAT'S DIFFERENT?

- Core, steam generators, pressuriser, pumps and control rod drives all integrated within a single pressure vessel
- Contrasts with conventional PWR layout, with separate components
- Pressure vessel in some designs is very large



DESIGN ISSUES

- Response of components may not be the same in the integral system as in isolation
- Integrated response will need careful validation testing
- Maintenance procedures affected
- Large pressure vessel manufacture
- Control Rod Drive Mechanism (CRDM) design
- Canned pump design



Core design

WHAT'S DIFFERENT?

- Some SMRs use a single-batch fuel loading strategy
- Some SMRs have natural circulation
- Some low power SMRs have a lifetime core
- Some small modular PWR designs have no burnable poison reactivity control
- Small modular PWR fuel assembly design cut-down versions of existing designs and usually down-rated

DESIGN ISSUES

- Single-batch cores are less fuel efficient, with lower discharge burnup for a given initial enrichment
  - Adverse effect on economics
  - Increased spent fuel mass, though decay heat and neutron source less onerous
- Lifetime core source term higher than multi-batch core
- PWR reactivity control complicated with no soluble boron system
- PWR with natural circulation introduces strong coupling between thermal-hydraulics and neutronics, with potentially complex core response

Multi-module Design Basis/ interactions between modules

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WHAT'S DIFFERENT?

- Multiple modules (sometimes 10 or more) for competitive station output
- If module independence can be demonstrated then the accident sequence frequencies for each module multiplied by number of modules
  - Interactions between modules could have a non-linear effect on accident sequences
- Small modules have smaller volatile fission product inventories

DESIGN ISSUES

- What would be an appropriate design basis for individual modules to satisfy ONR Basic Safety Level (BSL) and Basic Safety Objective (BSO) requirements for the entire station?
- Consequences of accidental release of volatile fission products from a small module may not scale with module size

Containment

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WHAT'S DIFFERENT?

- Some LWR designs have compact containments with pressure suppression or external condensation

DESIGN ISSUES

- Management of containment pressure
- Management of severe accidents with multiple units in close proximity

Footprints

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WHAT'S DIFFERENT?

- Individual modules have small footprints compared with large LWRs
- But if grouped together into GWe power stations, the overall footprint may be comparable to that of a large LWR

DESIGN ISSUES

- Need to assess footprints in relation to actual sites
  - Plant layout and access
  - Cooling water
  - Grid access
  - Visual impact
  - Evacuation zones

Economics

WHAT'S DIFFERENT?

- Economics of scale
- Economics of factory replication
- Possibility of phased construction with an element of self-finance
- Operating and maintenance (O&M) costs
- New and spent fuel costs
- Decommissioning costs

DESIGN ISSUES

- Mitigation of unfavourable scaling trend with simplified design and shorter build times
- Viability of reducing unit costs through replication with realistic market demand
- Need to establish the principle of self-financing with potential investors as a valid means of financial risk mitigation
- Mitigation of unfavourable O&M cost scaling trend
- Adverse fuel route costs scaling for single-batch refuelling strategies
- Mitigation of possible adverse decommissioning cost trends?

Factory build

- Large emphasis on achieving cost reductions through high volume factory production
  - But are the required production volumes realistic, especially if there are multiple competing designs?

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Construction cost

- The costs of construction and financing construction is the largest contributors to the levelised generating cost
  - The key to making SMRs viable will be to reduce both these costs to overcome the various other unfavourable scaling effects
  - Other components such as operating and maintenance and fuel cycle costs are relatively minor and realistically could only make small contributions to reducing the levelised generating cost

UK requirements

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- Need to satisfy statutory requirements for safety & radiological doses (Office of Nuclear Regulation) and environmental discharges (Environment Agency)
  - Statutory requirements are agnostic about approaches used (eg active versus passive safety)
- Systems will need to go through consent processes:
  - Justification
  - Generic Design Assessment (GDA)
    - Estimated cost £100m – large overhead for a first of a kind SMR
  - Site planning application
  - Pre-Construction Safety Report (PCSR)
  - Pre-Operation Safety Report (POSR)
  - Continued Operation Safety Report (COSR)
- Staffing levels
  - A case will need to be made to ONR that the overall staff requirement for a power station containing multiple SMR units could be no more onerous

Design maturity

- Many SMR designs are at an immature stage of development
  - Far short of level needed for GDA
- The detailed design data needed to assess safety, performance and economics have not been produced in many cases
  - Difficult to make assessments that are truly meaningful until the design has reached a late stage of maturity
  - Tendency for claimed performance being driven by wishful thinking?

Conclusions

- Small modular reactors, especially small modular LWRs are no doubt technically viable and could be successfully licensed for operation if there is sufficient commitment
- But need to recognise that there are multiple design hurdles that will need significant investment
- However, the most difficult aspect will be to strengthen the business case for SMRs to the point where the necessary technical investment will be available
  - It is important to recognise that the theoretical advantages of SMRs with respect to financing and affordability need to be balanced against multiple adverse scaling trends and other adverse design trends
- Reducing capital cost and finance cost are the key to SMR viability
  - This is the main challenge for successful deployment of SMRs