Generic Design Issues for 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
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
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

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
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
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

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?
UK requirements

- 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
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.
- This is the main challenge for successful deployment of SMRs.