Small Modular Reactors

Innovation in the Nuclear Industry

Prepared by

OSPE's Energy Task Force

with Graphical Support from

Market Intelligence & Data Analysis Corp. (MIDAC)

June 2019

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Presentation Outline

- References
- Challenges with the Current Large Nuclear Reactors
- Advantages of Small Modular Reactors (SMRs)
- SMR Technologies
- Challenges with SMR Technologies
- Role of SMRs in Climate Change Mitigation
- SMR Development in Canada
- Policy Implications for Governments

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

References

- For additional reading the following 3 references provide an excellent summary of International SMR technologies and Canada's SMR program:
  - IAEA – SMR Technology Developments
    https://aris.iaea.org/Publications/SMR-Book_2018.pdf
  - Canadian SMR Roadmap Report
    https://smrroadmap.ca
  - Canadian SMR Technology Working Group Report
    https://smrroadmap.ca/wp-content/uploads/2018/12/Technology-WG.pdf

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Abbreviations Used in These Slides

- CNL – Canadian Nuclear Laboratories
- CNSC – Canadian Nuclear Safety Commission (the nuclear regulator in Canada)
- GHG - Greenhouse Gas
- FOAK – First-of-A-Kind reactor
- MWt / MWe – Megawatt thermal / Megawatt electric
- SMR – Small Modular Reactor
- TRISO - Tristructural-isotropic fuel (U coated with carbon/silicon carbide/carbon)
- UFl – Uranium Floride, UN – Uranium Nitride, UO_2 – Uranium Dioxide
- UZr – Uranium Zirconium alloy
- Th232 - Thorium 232 atomic weight (a fertile isotope)
- U238 – Uranium 238 atomic weight (a fertile isotope)
- U235 – Uranium 235 atomic weight (a fissile isotope)

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Challenges with the Current Large Reactors

- Large financial commitment – typically >6 B$ ($6,000/kW)
- Large capacity commitment – typically >1,000 MW
- Long lead time – typically 6 years
- Cost over-runs - typically 100% ($12,000/kW for Vogtle)
- Schedule over-runs - typically 10-12 yrs instead of 5-6 yrs
- Radioactive waste lifetimes - typically 400,000 years
- Poor utilization of fuel supply - typically only 1% of mined U
- Proliferation concerns - especially with U235 enrichment
- Accident concerns – especially with high pressure reactors

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Advantages of SMRs

Each SMR technology will have most but not all of the characteristics in the following 3 slides:

- No GHG emissions during operation.
- Output not affected by weather.
- Passively safe (some types are walk-away safe).
- Can produce both electricity and high temperature heat.
- Can be distributed - located close to electric & thermal loads.

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Advantages of SMRs (cont'd)

- Can load follow to complement wind and solar generation.
- Can supply base-load (continuous demand).
- Can produce hydrogen gas – a clean energy carrier.
- Improved fuel utilization (up to 100% utilization of mined U).
- Reduced radioactive waste life-time (up to 1000x shorter).
- Can expand the fuel supply by converting existing supplies of fertile isotopes (U238 and Th232) into fissile isotopes.

Small Modular Reactors

Innovation in the Nuclear Industry

Advantages of SMRs (cont'd)

- Factory fabrication and testing, truck shipment to site
- Smaller financial (and size) commitment
- Short delivery time after FOAK licensing is completed
- Proliferation resistant
- Schedule and cost certain if standard modules are stocked
- Projected to cost less than a coal fired plant in $/kWh after SMRs are mass produced in volume (approx. $3,500/kW).

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Small Modular Reactor Technologies

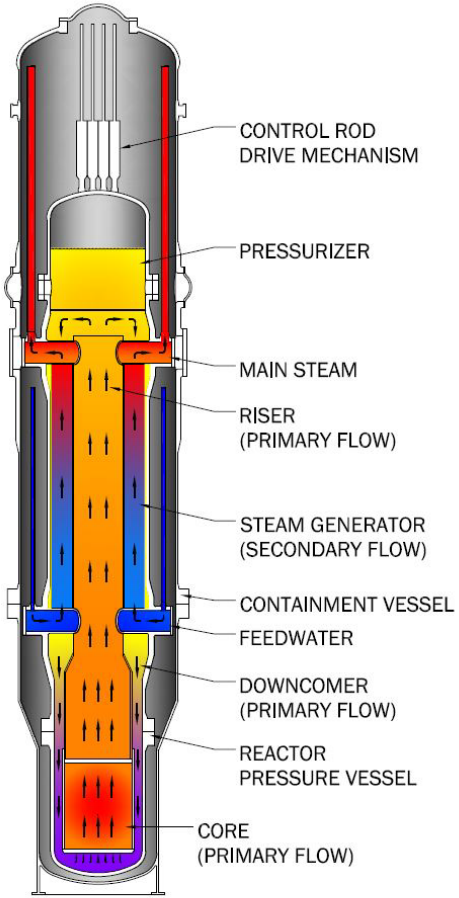
- Water cooled reactors
  (smaller advanced versions of existing large reactors)
- High temperature gas reactors
- Liquid metal cooled fast neutron reactors
- Molten salt reactors
- Heat pipe micro-reactors

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Technologies
Water Cooled Reactors
NuScale Power (USA)

- 200 MWt / 60 MWe
- 314 ^{0}C core temperature
- Light water coolant
- 5% enriched fuel, UO_2
- https://www.nuscalepower.com



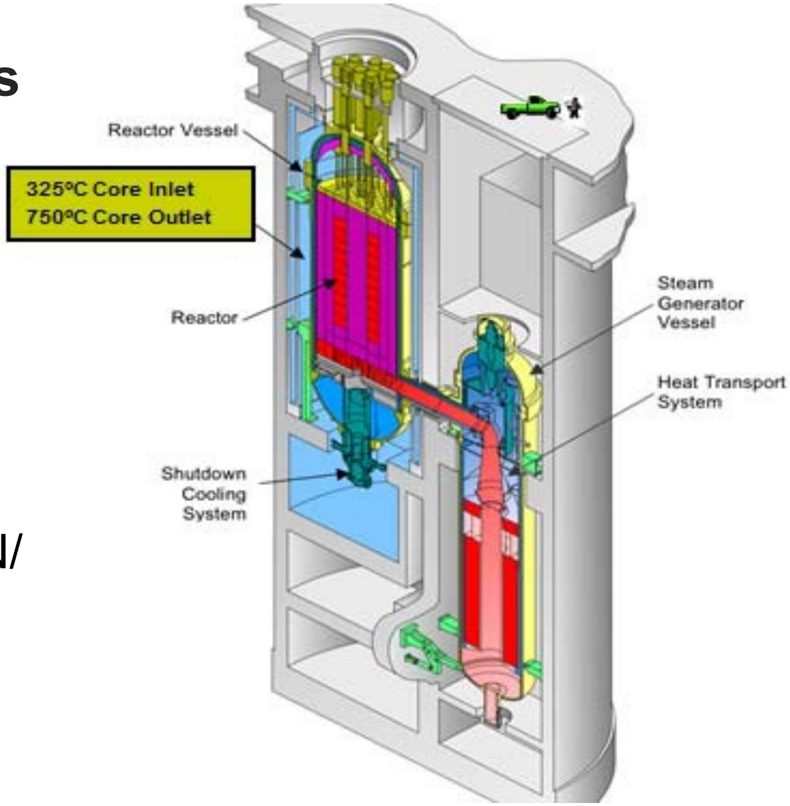
ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Technologies
High Temperature Gas Reactors
Framatome SC-HTGR (USA)

- 625 MWt / 272 MWe
- 750 ^{0}C core temperature
- Helium coolant
- 20% enriched fuel, TRISO
- http://www.framatome.com/EN/us_platform-3225/framatome-htgr.html



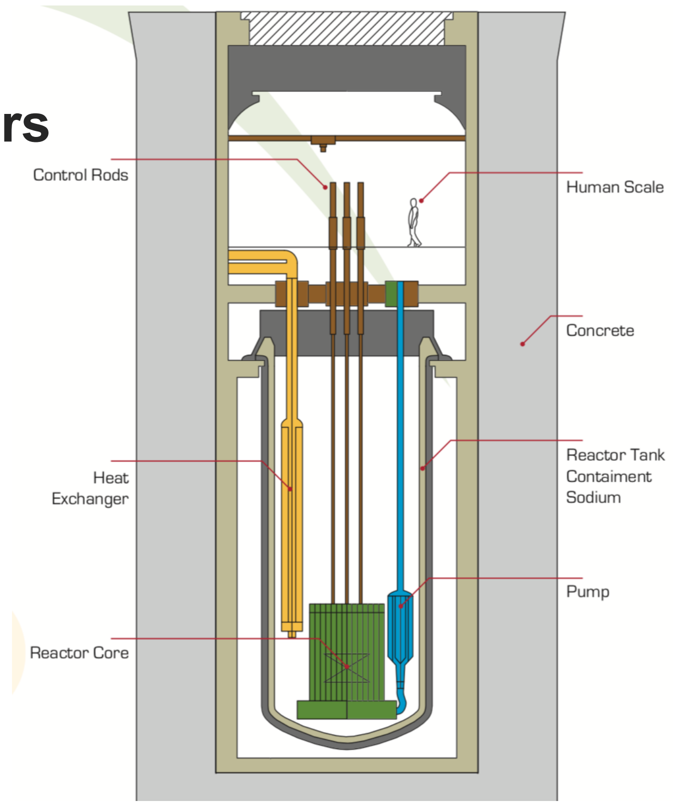
ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Technologies
Liquid Metal Fast Neutron Reactors
ACR-100 (USA)

- 260 MWt / 100 MWe
- 510 ^{0}C core temperature
- Sodium coolant
- 17% enriched fuel, U/Zr alloy
- https://www.arcnuclear.com/technology



ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Technologies
Molten Salt Reactor
Terrestrial Energy IMSR- 400 (CAN)

- 400 MWt / 190 MWe
- 700 ^{0}C core temperature
- Molten salt coolant & fuel
- 5% enriched fuel, UFI
- https://www.terrestrialenergy.com

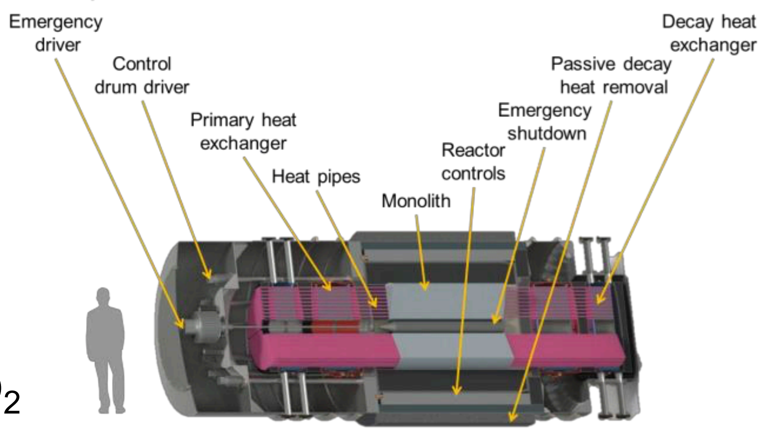
ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Technologies
Heat Pipe Micro-Reactors
Westinghouse eVinci (USA)

- Up to 20 MWt / 5 MWe
- 650 ^{0}C core temperature
- Heat pipe cooling
- 20% enriched fuel, UN or UO_2
- http://www.westinghousenuclear.com/new-plants/evinci-micro-reactor



ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Challenges with SMRs

- Reliability, safety, cost and schedule performance need to be proven at commercial scale.
- High temperature reactors need to overcome metallurgical and corrosion issues.
- Fast reactors need to prove their fuel breeding effectiveness.
- Need to prove new coolants (eg: liquid sodium and molten salts) can be handled safely at commercial scale.
- Fuel recycling has to be proven cost effective and environmentally benign.
- Factory mass production capability needs to be developed and demonstrate economies of standard modular design.

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Role of SMRs in Climate Change Mitigation

- Can provide emission-free electricity and heat.
- Can load cycle - can complement variable renewables (wind and solar) and compensate for dry years (hydro).
- Not sensitive to extreme weather events.
- Can provide water desalination.
- Can provide hydrogen as a clean energy carrier and to produce clean synthetic fuels (with bio-mass feedstock).
- Ideal for base-load energy supply (90%+ capacity factor).

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

SMR Development in Canada

- Canadian SMR Roadmap in Nov. 2018 recommended:
  - Government funding for demonstration projects at CNL - cost sharing arrangement with the private sector.
  - Government risk-sharing with the private sector for the first commercial SMR.
  - Developing SMR policy, legislation and regulations.
  - Engaging and educating the public regarding SMRs.
  - Developing SMR international partnerships and markets.
  - Developing SMR deployment action plan.
- CNL & CNSC are reviewing several SMR designs.

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Policy Implications for Governments

- Need all 3 levels of government to develop policies, legislation and regulations that recognize SMRs as a viable low emission energy option for climate change mitigation.
  - Federal government has nuclear technology responsibility, owns CNL (nuclear laboratories) and has suitable SMR test sites and financial resources.
  - Provincial governments have energy sector responsibility including energy pricing policies and regulations.
  - Municipal governments control land use and zoning and utility rights of way for electricity and district heating systems.

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS

Small Modular Reactors

Innovation in the Nuclear Industry

Questions?

ONTARIO SOCIETY OF PROFESSIONAL ENGINEERS