OECD NEA
Halden HTO
Project

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Andreas.Bye@ife.no

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Small Modular Reactors, SMRs – Energy source for the future?

Andreas Bye

ESRA seminar

Fremtidens energikilder -
Sikkerhetsutfordringer med fornybar energi

Me and the Halden HTO Project

- Andreas Bye, Chief Scientist, IFE
- Programme Manager OECD Nuclear Energy Agency Halden Human-Technology-Organisation (HTO) Project, from 1/1 2021
  - 12 member countries, 20 organisations
- OECD NEA Halden HTO Project is a direct continuation of the Halden Reactor Project
  - Formed in 1958
  - Fuels and Materials research in the Halden Reactor
  - Late 1960s first process control work
  - 1972 Computerized process control for surveillance of nuclear power, OPCOM and DEMP
    - First in the world
  - Separate research line in the Halden Project: Process control -> Man-Machine research -> Man-technology-organization, now HTO
  - The Halden Reactor closed in 2018

Why nuclear?

- Carbon free

Outline

- What is an SMR, Small Modular Reactor
- A brief history of nuclear power
- Examples of some SMR technologies, Gen IV
- Safety challenges
  - The main nuclear accidents: Can they happen in an SMR?
  - New safety challenges?
- IFE HTO applied research on the topic

What is an SMR?

- OECD Nuclear Energy Agency*:
  - “Small modular reactors (SMRs) are nuclear reactors with power outputs between 10 MWe and 300 MWe.

* https://www.oecd-nea.org/jcms/pl_26297/small-modular-reactors

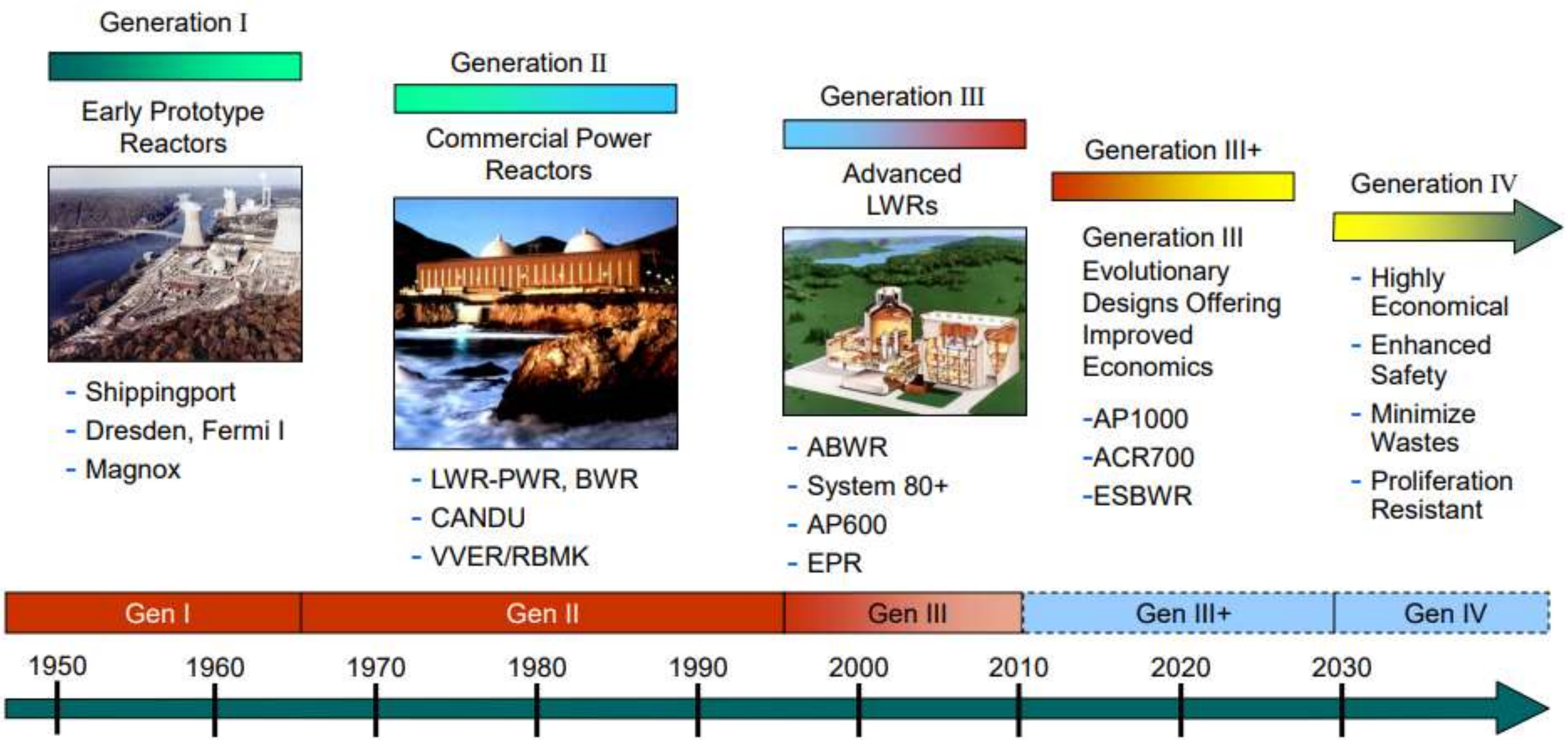
Why SMR?

From the U.S. Department of Energy*:

- Modularity
- Lower capital investment
- Siting flexibility
- Enhanced safety and security
- Greater efficiency
  - And other industrial applications such as hydrogen production, desalination plants, district heating
- Safeguards & security / nonproliferation

* https://www.energy.gov/ne/benefits-small-modular-reactors-smrs

Nuclear history at a glance (U.S. DoE)



Gen IV reactors

- In September 2002, the Generation IV International Forum* selected six system concepts for further development:
  - Very High Temperature Reactor
  - Supercritical Water Cooled Reactor
  - Gas Cooled Fast Reactor
  - Lead Cooled Fast Reactor
  - Sodium Cooled Fast Reactor
  - Molten Salt ReactorGen IV
- Thorium can be used as fuel in fast breeder reactors, a number of solutions for thorium based reactors have been proposed and some are in operation.

* https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

Gen IV

- Advantages (different advantages for different types)
  - Much better exploitation of the fuel, waste problem reduced (not so long-lived)
  - Fast breeders can burn their own and other plants' waste
  - High temperature facilitates hydrogen production
  - Can be used for water desalination
  - Some operated on low pressures (atmospheric), better safety
  - Good safeguardability (non-proliferation)

- Some, e.g., gas-cooled reactors, have been in operation for years
- Some drawbacks
  - Uncertainty about safety, especially related to the materials
  - Economy of other normal reactors

Nonproliferation

- Establishment of FFI (1946) and IFA (1948)
  - (Olav Njølstad: “Strålende forskning, Institutt for energiteknikk 1948-98”)
- History of civilian and military nuclear power split from the 50s and 60s
  - in Norway already in 1947 when they decided to establish Institutt for Atomenergi (IFA) to run the nuclear projects
  - An industry (enrichment plants, etc) is required to make atomic bombs, however nuclear material may still be used for “dirty bombs”
- Nonproliferation are these days supervised by international organizations and treaties
  - Safeguards
- Possibilities are reduced by inherent design in many new reactors and SMRs
  - Thorium (linked to enrichment degree)
  - Molten salt (fuel embedded in the salt)

SMRs soon to be in operation

- Based on proven technology, typically light water
  - NuScale, many other developers
  - Small PWRs (pressurized water reactor)

Brief history of accidents in the nuclear industry

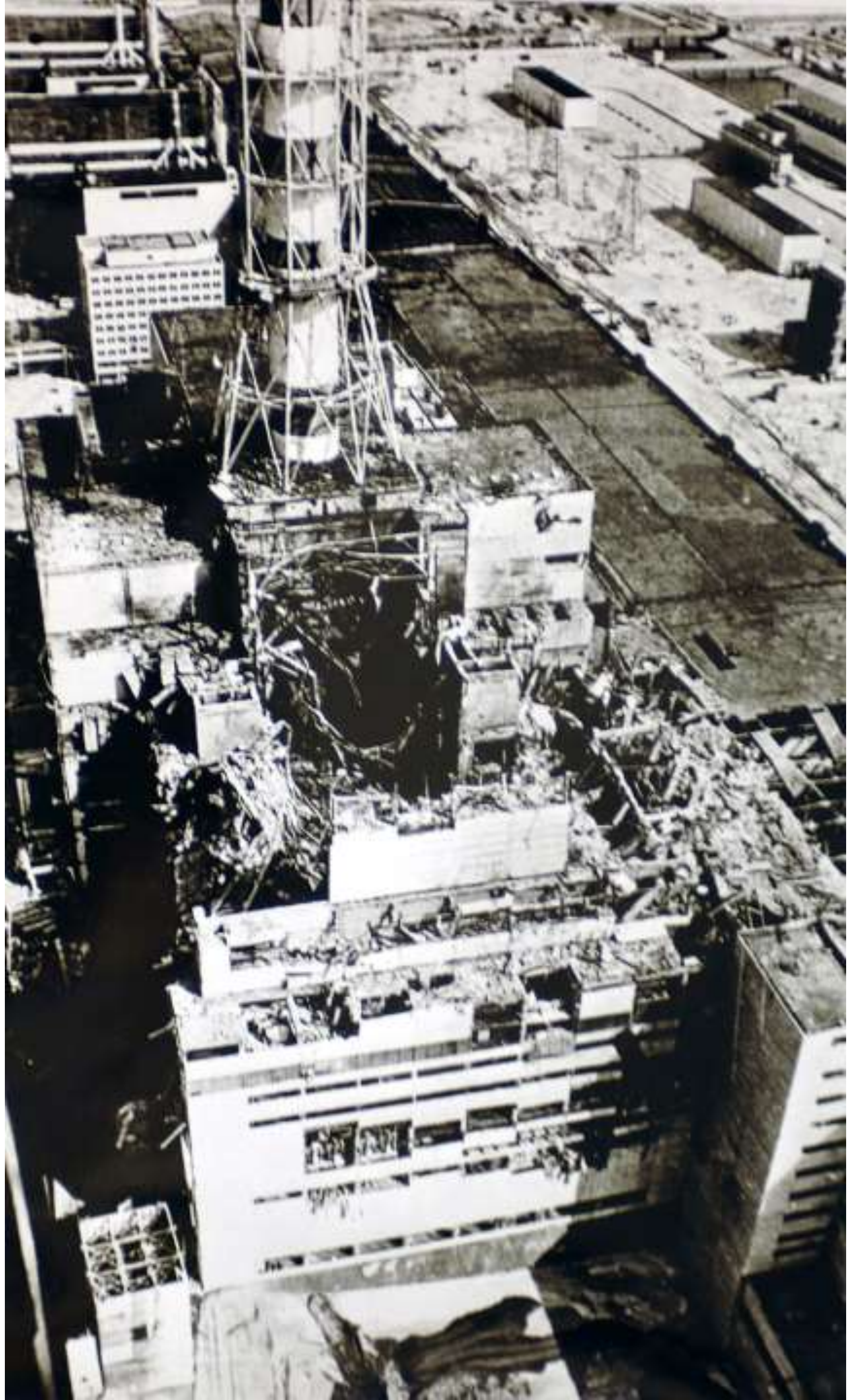
- Chernobyl
- Three Mile Island, Fukushima

- Can these accidents happen in SMRs or in modern reactors?

Chernobyl 1986

Core meltdown and explosion during a safety test

(Picture: Wikipedia)



Causes of the Chernobyl accident

Many causes: Politics, safety culture

Underlying design:

- Positive void coefficient of reactivity
  - Moderator: graphite
  - Coolant: water
  - If cooling is lost by water heating up and evaporating, neutrons will still be moderated, and the chain reaction continues
  - This is improved in operating RBMKs after the Chernobyl accident
- A standard western plant has negative void coefficient
  - Uses water (liquid) both as coolant and moderator
  - If water evaporates, neutrons will not be moderated, and the chain reaction slows down

Three Mile Island 1979

Partial meltdown and release of radioactivity

(Picture: Wikipedia)

Causes of the TMI-2 (Harrisburg) accident

- Mechanical failures in the secondary system and a stuck relief valve
- Poorly designed Human-System-Interface, training, and procedures
  - “Human error”, thought the situation was different from the actual situation
  - Teamwork: New eyes from a new crew found the cause and solution
  - Starting point for increased efforts in Human-Technology-Organisation research
- Underlying design:
  - Decay heat removal in big nuclear power plants (the reactor automatically tripped, stopping the nuclear chain reaction as supposed, but the accident developed in the hours afterwards)

Fukushima Daiichi 2011

- Earthquake -> shutdown ok
- Tsunami -> cut the external power and flooded the emergency diesel generators
- No power to circulation pumps for cooling
- 3 nuclear meltdowns, 3 hydrogen explosions and release of radioactivity

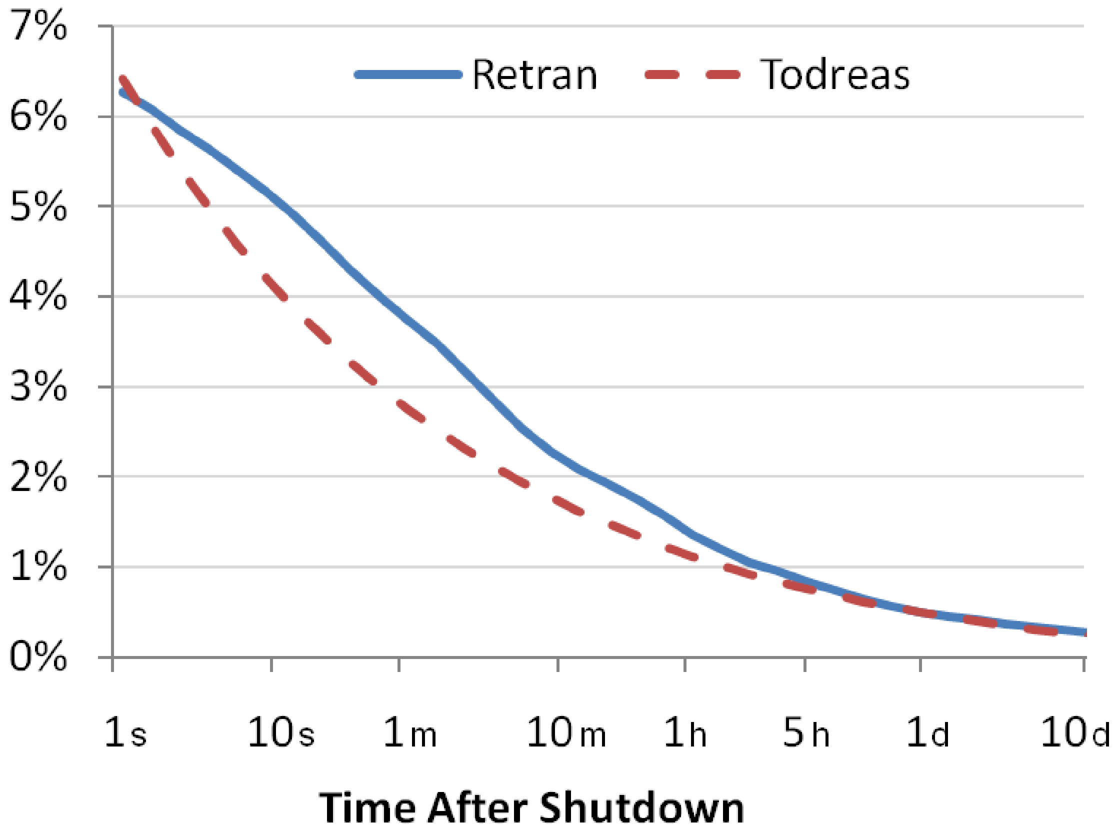
(Picture: Wikipedia)

Causes of the Fukushima Daiichi NPP accident

- Many causes: lack of risk assessment for flooding, etc. Safety culture?
- Some of the on-line accident handling was good, under extreme conditions
- Underlying design:
  - Decay heat removal in big nuclear power plants
  - Old design of core cooling after shutdown: active pumps, amounts of water etc

Decay heat

- The core needs cooling for a long time after shutdown
- Old plants: Active water pumps, need power
  - From the external electricity net
  - Emergency diesel generators
- Defense-in-depth (several layers of barriers)
- Beyond design basis (BDB)
  - Fukushima: 15 meter high tsunami was defined as BDB



From Wikipedia:

"Decay heat as fraction of full power for a reactor SCRAMed from full power at time 0, using two different correlations"

Decay heat removal, new solutions?

- Natural circulation
- Other passive systems, including large amounts of water available (sink core into water basins, etc)

SMRs: remove the decay heat problem by design

- Some of the new designs:
  - The shape and size of the reactor designed by worst case calculations of needed water and air for cooling all decay heat, without any power available
  - -> 50-70 MW per unit

Advanced reactors, safety considerations

- U.S. NRC: "Risk-Informed and Performance-Based Human-System Considerations for Advanced Reactors" (March 2021):
  - Advanced reactors: including all non light water reactors (LWRs), SMRs, microreactors, fusion reactors
  - Safety attributes:
    - Inherent safety characteristics
    - Passive safety features
    - Automated safety systems
    - Manual operator actions

Challenges in the future

- More automation
  - Marketed as a safety feature
  - Is it really? How is the human-automation collaboration?
- Multi-unit
- Remote operation
- Unforeseen stuff, the black swan

SMR research questions (courtesy IFE team: Rob McDonald, Claire Blackett, Maren Eitrheim, Stine Strand)

Multi-user/multi-unit issues

- Unit confusion
- Variability and differences between units (similar or different)
- “Carry over” effects between units
- Multi unit disturbances (Situation Awareness and workload issues)
- Staffing

Remote operation issues

- Aspects of Latency
- Degrees of automated operation
- HMI presentation “local vs. remote”
- Psychological detachment, local vs remote
- Operators' familiarization and competence with differences between units

The Halden HTO Project and safety in SMRs

- Human Performance
  - Crew roles, teamwork, decision making under uncertainty
- Digital I&C - Safety Assurance
  - How to license digital systems
- Control Room Design & Evaluation
  - CR validation and Human-system interfaces
- Human-Automation Collaboration
  - Higher degree of automation on SMRs, basic multi-unit questions
- Digital Systems for Maintenance and Operations
  - Condition monitoring and outage
- Digital Transformation of Decommissioning
  - Plans for decommissioning must be made at time of design
- Cyber Security for Main Control Rooms
  - Threats, detection and response, human behaviour during incident response

The Halden HTO Project and safety in SMRs

- Supported by experimental labs, HAMMLAB, VR-lab, robot lab, cyber lab
- SMR simulator

Halden Man-Machine Laboratory

Conclusions

- SMRs have inherent safety characteristics and passive safety features that makes them safer by design than traditional nuclear power plants
- There are still challenges to safety and operations

- IFE and the Halden HTO Project work on many of these challenges.

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Thanks!

Contact: Andreas.Bye@ife.no