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Towards European Licensing of Small Modular Reactors

ELSMOR Summer School SMR specific safety issues

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SMR specific safety issues

- LW SMR Design Specificities
  - LW-SMR are mainly designed in order to reach power levels in which natural behaviour and passivity are efficient enough to ensure safety functions
  - The main goal is to improve safety:
    - by limiting the needs for support function (passivity)
    - by limiting or supressing some initiator events (LOCA with integrated primary system, dilution with boron free reactors...)
    - by simplifying the general design of the reactor

Points of interest found in LW-SMR main safety goals

Defense in Depth: Passive systems are “always on”, and potentially affect the system at different situations

- The possibility to use a passive system in different level of defense in depth would require a strong increase of the reliability of the system, and a robust demonstration of this reliability including uncertainties, while passive systems bring designer new challenges, due to:
  - Innovative technologies without sufficient operational experiences
  - Uncertainties related to qualification and reliability assessments
  - Operational aspects as periodic testing, maintenance and in-service inspection

Multi-module units: the impact on safety of the increase of shared systems in a multi-module units will require specific studies

Waste creation and handling

Start with Defence-in-Depth

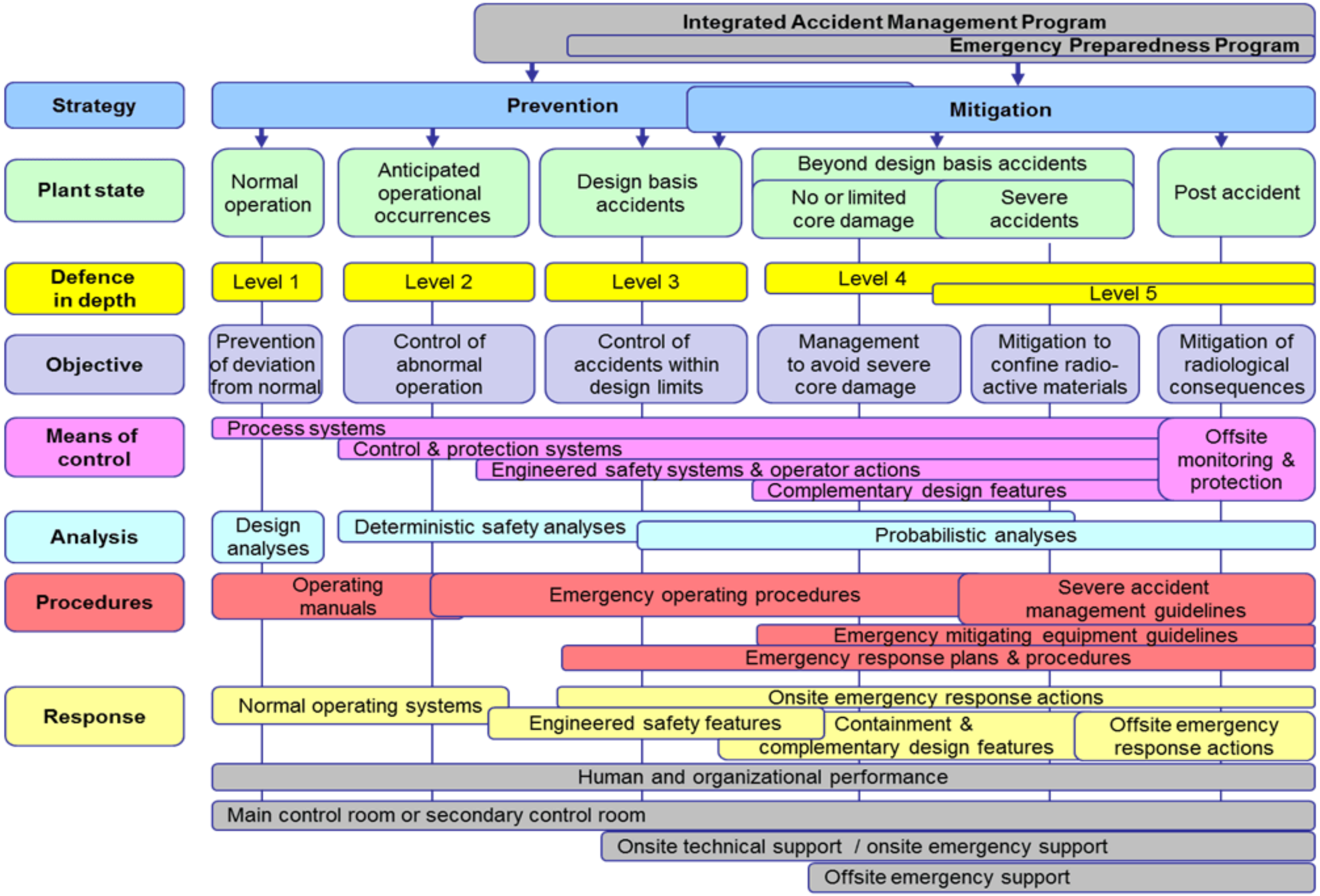
- Concept
- Levels

- Remember also three high level objectives
  - Core cooling, criticality control, barriers to release

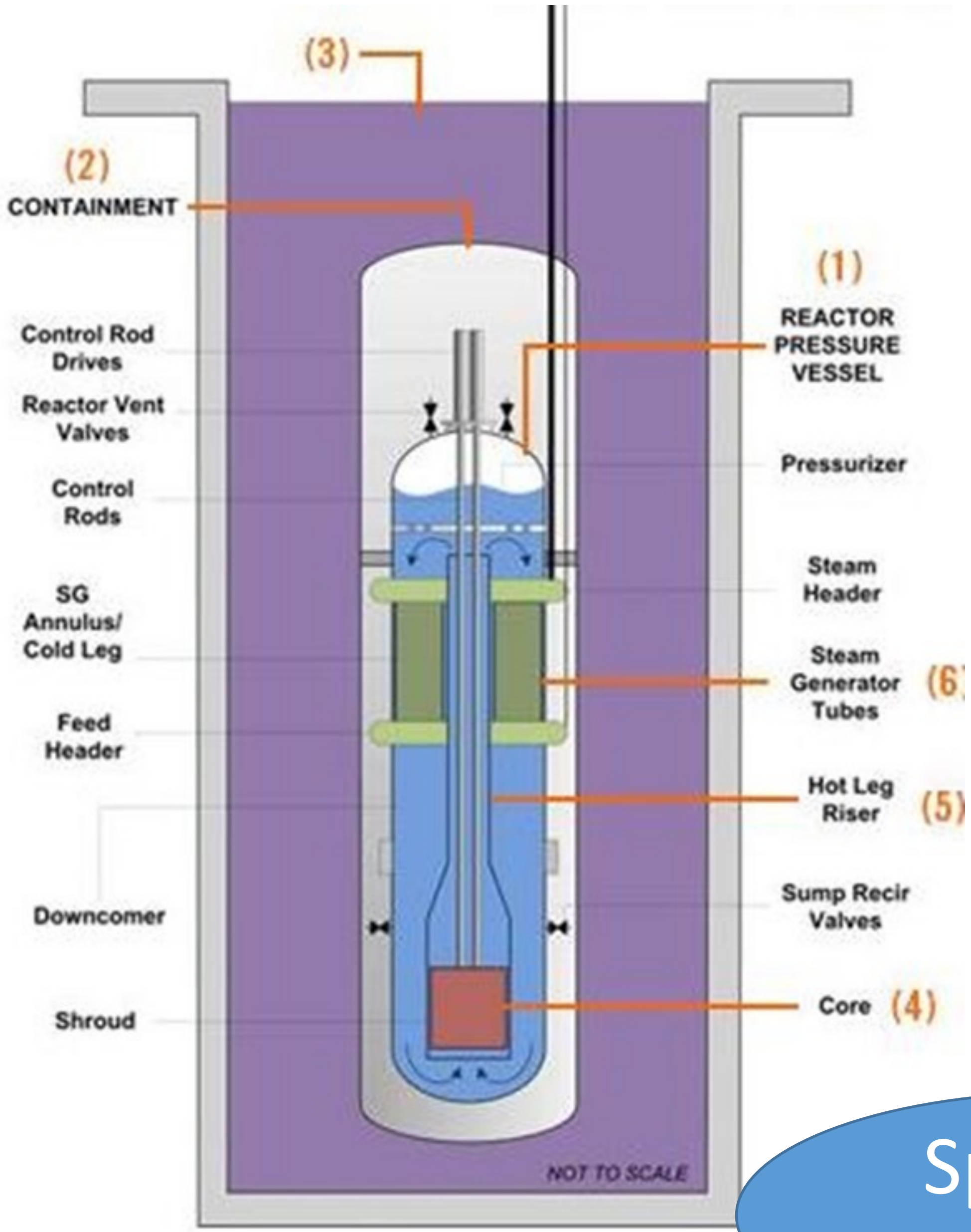
TABLE I. LEVELS OF DEFENCE IN DEPTH

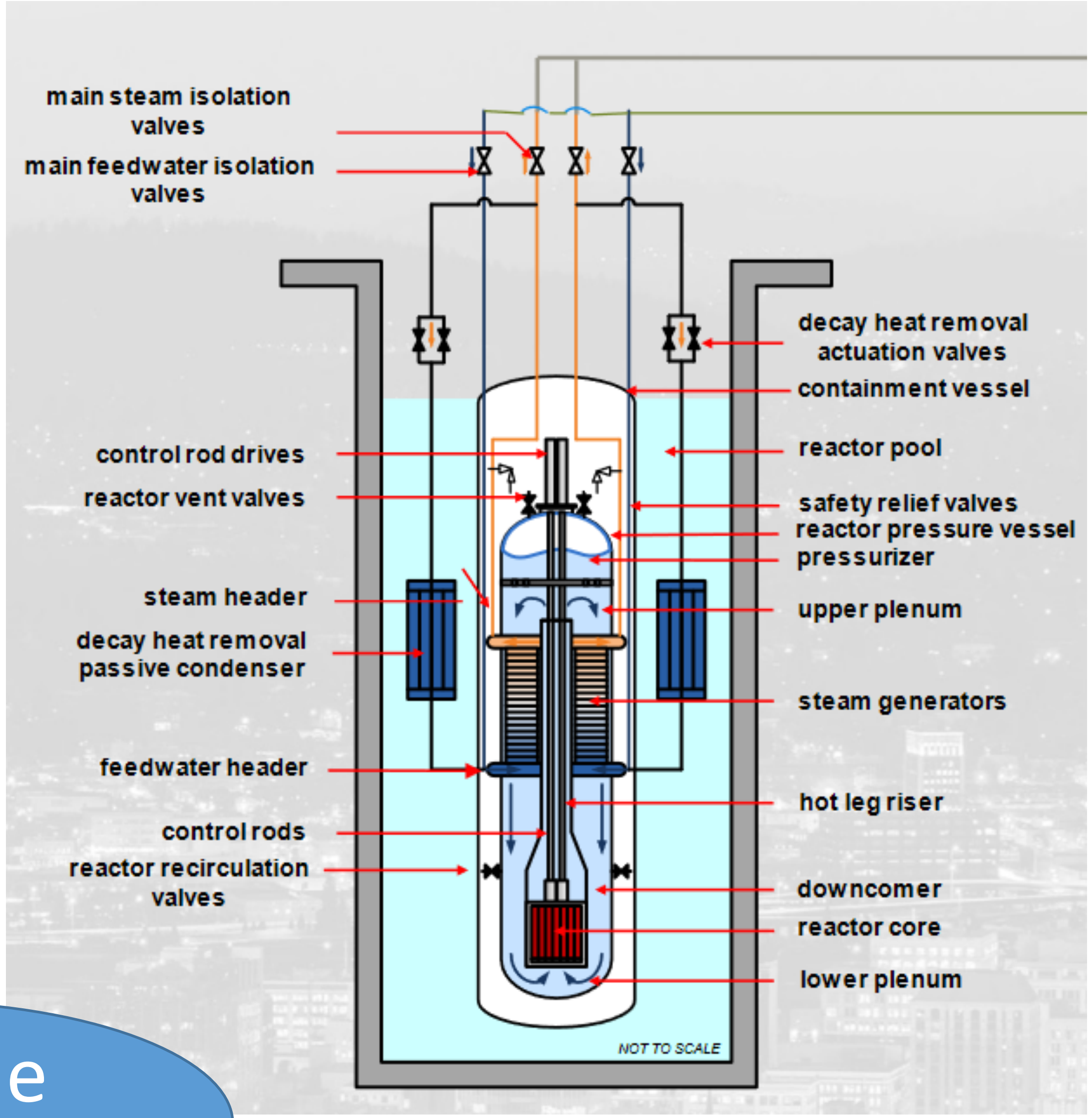
Levels of defence in depth	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

A 5-layer defense-in-depth in nuclear power plant	
Layer 1	The uranium oxide fuel rods with inert, ceramic quality
Layer 2	The fuel pellets of airtight zirconium alloy
Layer 3	The steel pressure vessel
Layer 4	The pressure resistant and airtight steel containment
Layer 5	The steel-reinforced concrete reacting building



DIS-16-04, Small Modular Reactors: Regulatory Strategy, Approaches and Challenges - Canadian Nuclear Safety Commission





Spot the differences

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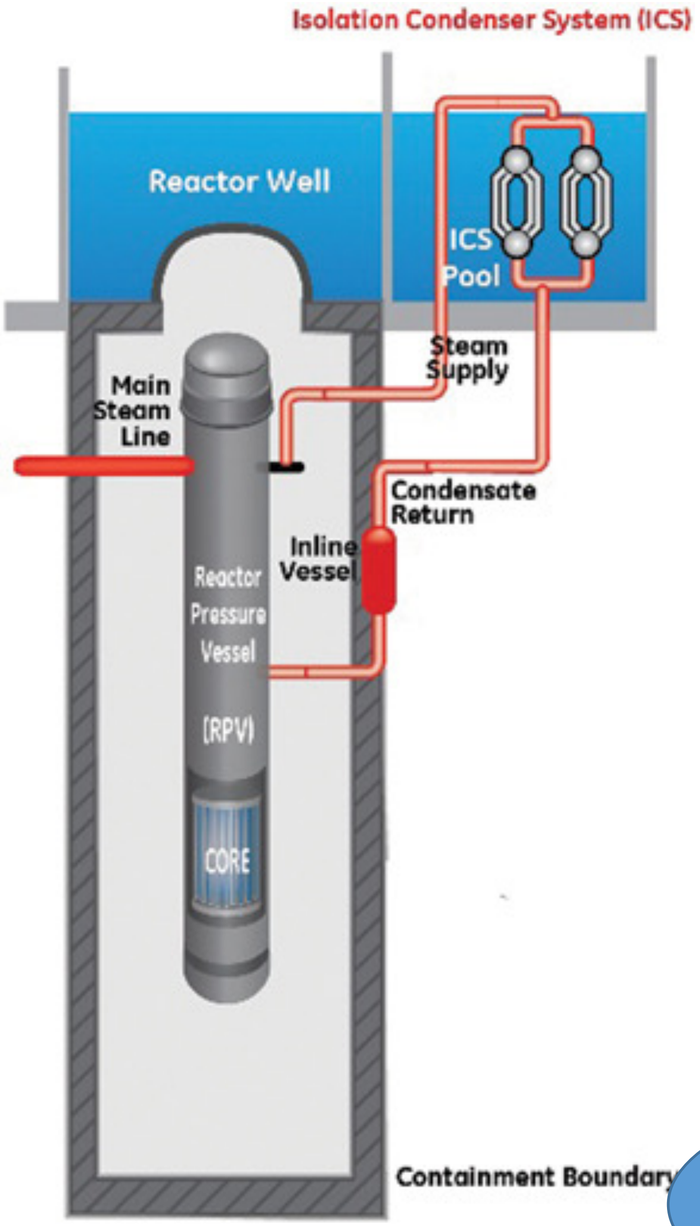

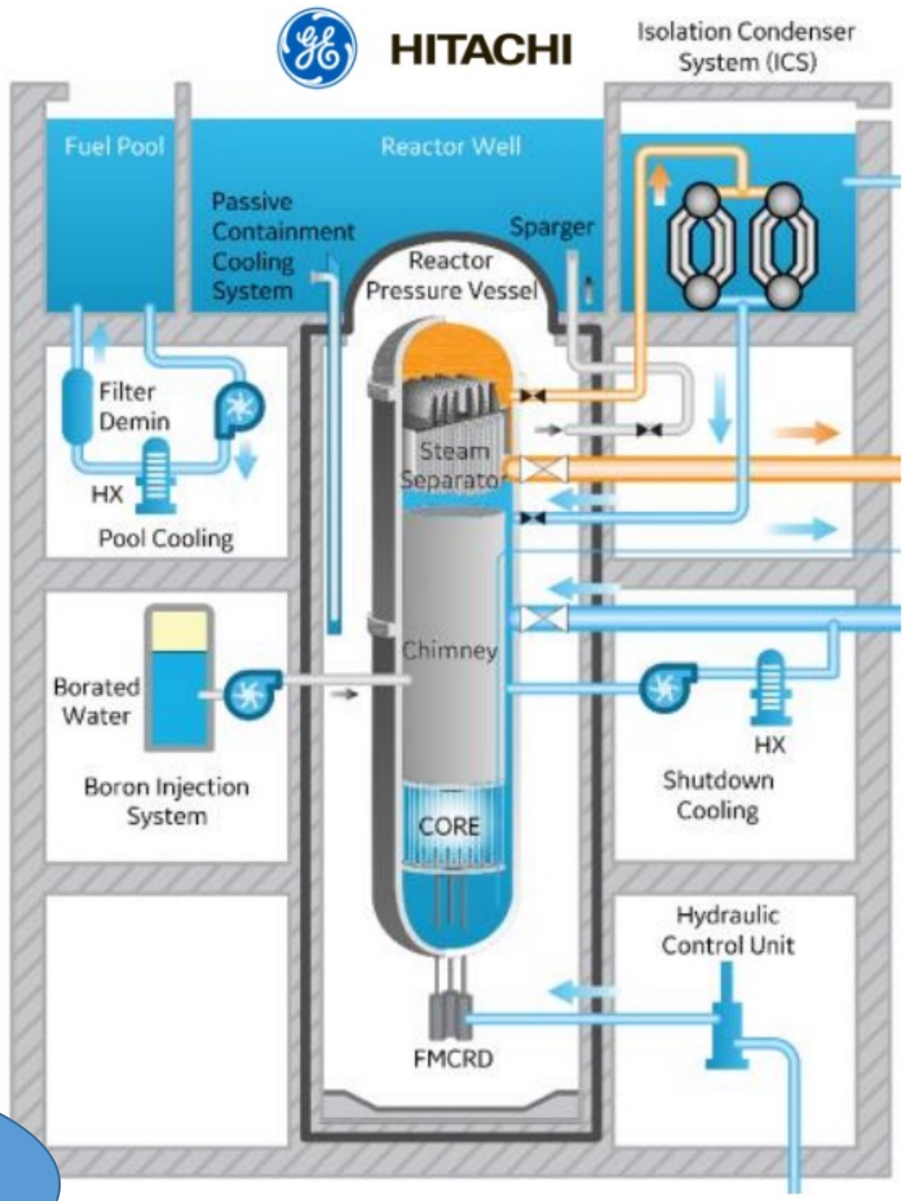

Spot the differences

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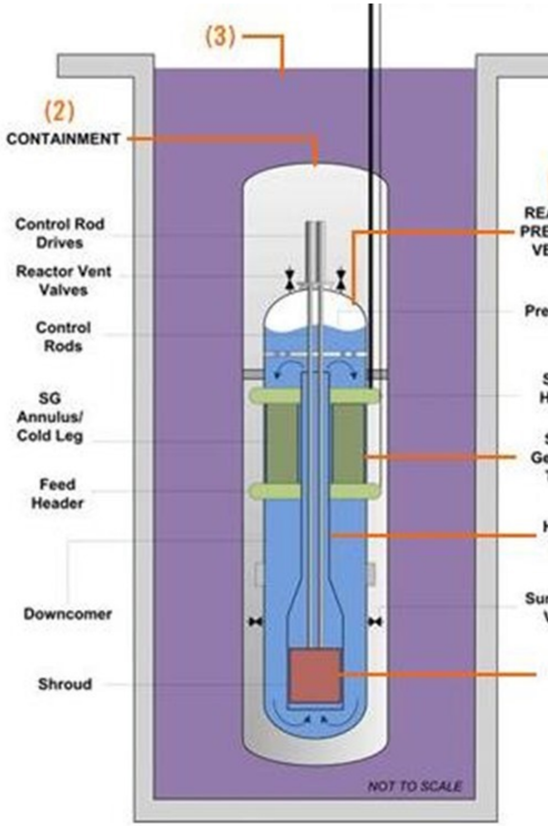
Assessing plants with high use of passive systems

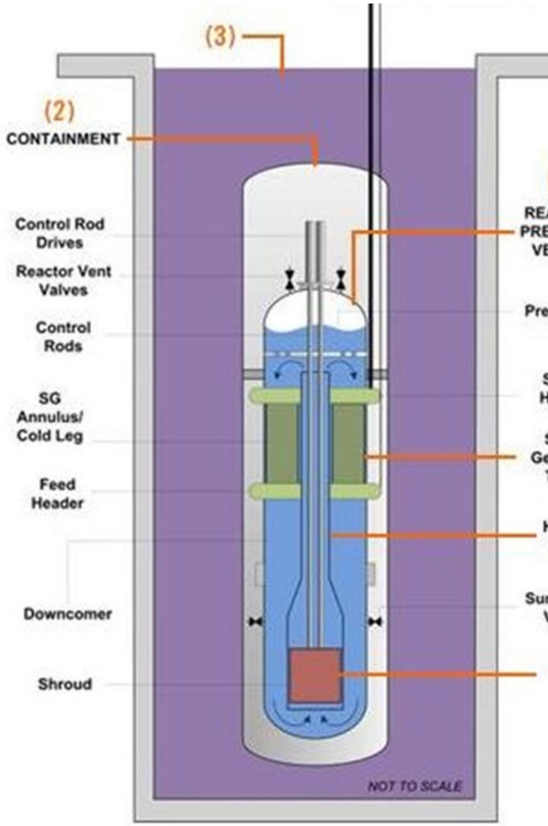
- The objective of safety assessments is to verify the safety requirements by analysis, simulations and other means
- The assessment should identify uncertainties and analyse their impacts and to verify the DiD level strengths and independence of individual DiD levels – This is especially important for SMR relying heavily on passive safety systems
- For example, the uncertainty analysis of thermo-hydraulic phenomena in passive systems can be divided to the following classes:
  - Uncertainties related to T-H analysis (-> Phenomena level)
  - Uncertainties related to T-H performance (-> System level)
  - Uncertainties related to the probabilistic analysis (-> System architecture / Plant level)



Development of requirement management approach for safety analysis methodology

Requirements elaboration example:

- Starting point the high-level DiD requirement
  - DID-04: ”The implementation of Defence-in-Depth in LW-SMRs must be tolerant.”
- Level 1 requirements reflect the demonstration of safety at the level of specific subsets of the system architecture
  - DID-04-L1: ”Tolerance for deviations in actuation and operating parameters of the passive safety systems shall be demonstrated.”
- Level 2 requirements reflect the need to analyse behaviour of specific systems
  - DID-04-L2-01: ”Effects of deviations from pre-defined system configurations for the actuation and performance of passive safety systems shall be analysed.”
  - DID-04-L2-02: ”Effects of deviations from designed actuation parameters for the actuation and performance of passive safety systems shall be analysed.”
  - DID-04-L2-03: ”Effects of deviations of operating conditions during the performance of passive safety systems shall be analysed.”
- Level 3 requirements reflect the need to analyse the behaviour of specific components of specific system or phenomena
  - DID-04-L3-01: ”Effects of system valve closing fully or partially during the performance of a passive safety system shall be analysed.” Etc…



Multi-module units

- Some SMR designs have several reactors operated in the same plant
  - NuScale: 4 – 12 reactors
  - Nuward: n*2 reactors

- Where would there be issues?

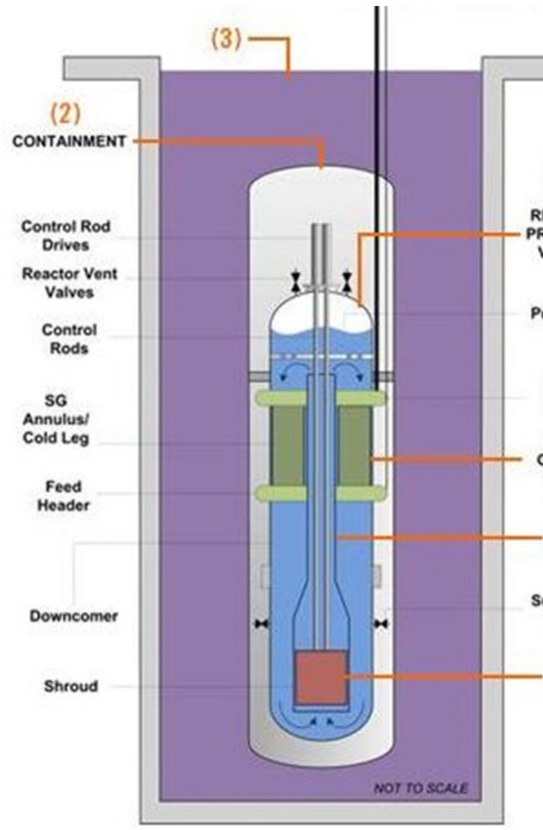
Safety for Multi-Units & sharing of system

- The implementation of several modules on the same site leads to safety issues in addition to the basic safety demonstration associated with each module, e.g.:
  - Potential impact of module accident/hazards occurring in one module on the neighbouring modules
  - The sharing of equipment and the consideration of external hazard can lead to simultaneous initiating events (LOOP, common turbine….), then possibly lead to DEC-A and DEC-B on several modules
  - New requirements can be discussed with regard to these potential concommitant accidents and the sharing of common safety equipment.

- PSA : identification of the key technical issues related to Multi-units PSA
  - Muti-Units Risk metrics definition (Core Damage Frequency and Large early release frequency) for a multi-units site
  - Identification of Initiating event with the potential to affect several modules
  - Inter-Unit Common cause failure and CCF parameters for large group
  - Numerous combination of plant operating states of each unit
  - Human reliability assesment
  - Complexe multi-unit accident sequence modeling

Safety of Operation and human factors issues

- **Operations and Human Factors regarding SMR specificities:**
  - **Modular Design: off-site module construction + operation of multi-unit plants**
    - **According to the systems integration level of the module (complexity) more than unitary system tests could be necessary to be conducted on fabrication site by the supplier**
    - **As modules integrate different systems, on the fabrication site the supplier must be able to test systems one by one and by modules**
    - ➢ ***Operation of multi-unit plants : qualifying plant personnel, specific training requirement for plant personnel (supervision and maintenance)***
  - **Impact of passive safety systems on human supervision:**
    - **different Passive Safety Systems in terms of level of passiveness (IAEA definitions related to "intelligence", mobile mechanical part, fluid motion)**
    - **System dependency could be more complex than with active systems**
    - **If the plant safety systems are not so passive, HOF issues are linked to automation issues (supervision of safety system status and ability of the team to intervene)**
    - ➢ ***Human-Machine Interface design and procedure design for monitoring and securing passive systems is a potential issue***



Safety for Operation and human factors issues

- **Impact of multi-unit plant operation on supervision:**
  - **Every Unit**
    - might be **in different operational state**
    - might **share support systems**
    - might be **concerned by the same aggression** /crisis /extreme situation (or cascade effect)
    - might be **with different design/technology** due to cost effect over time

➢ **The control room layout and the HMI design must prevent**

- the risk of **unit confusion/mixing**
- the risk of **missing an accurate understanding of every unit's actual state and evolution**
- the risk of **operator overload**, and delayed or erroneous operation actions

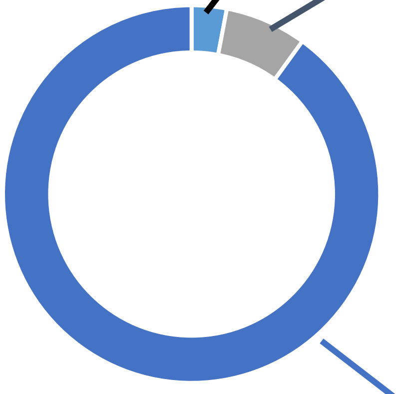
➢ **The supervision team organisation, role and staffing, must prevent**

- risks linked to **co-activity** (miss-allocation of equipment and staff, priority on production vs safety)
- risk of **overload** notably in abnormal situations
- Insufficient Defence in Depth on global team staffing and organisation

Waste and decommissioning

- Radiological waste must be handled responsibly
- Waste streams for small and large nuclear power plants using same technology are relatively similar, but may have some quantitative differences
- Waste management and decommissioning something that needs to be planned from the beginning

Nuclear waste



3% of volume: high level waste

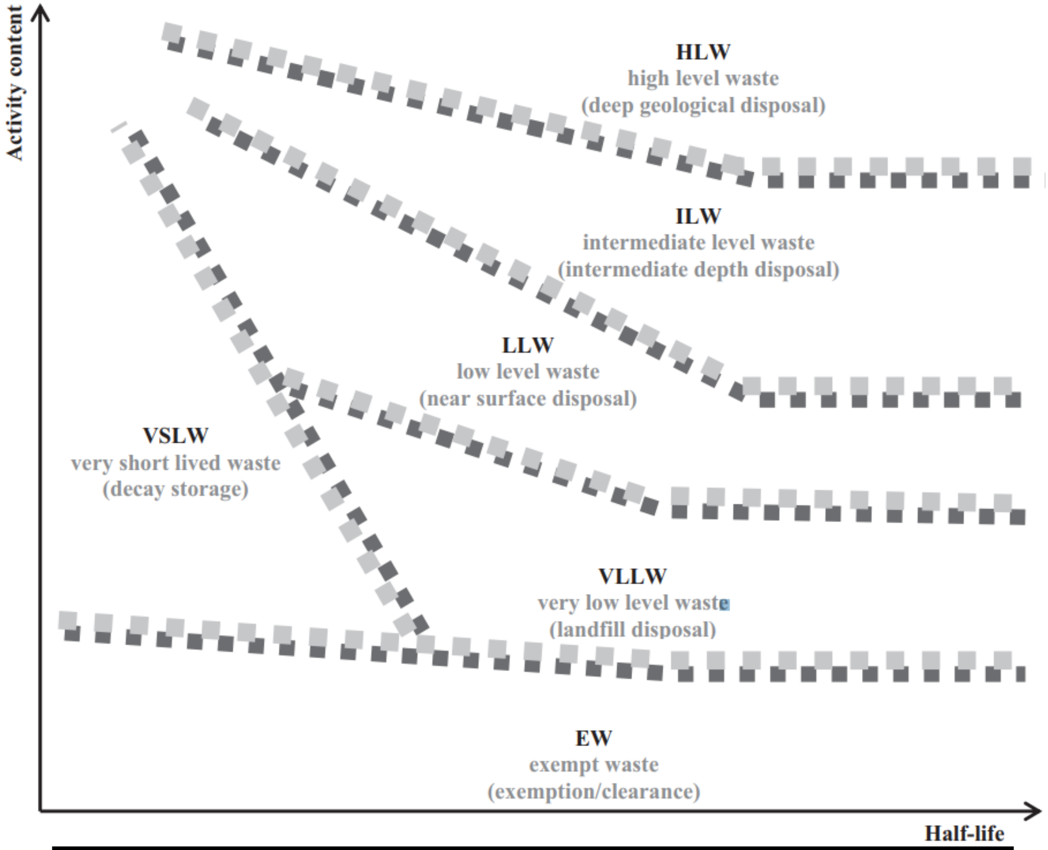
- Spent nuclear fuel, usually what is thought of as ”nuclear waste”

7% of volume: intermediate level waste

- Process cleaning resins, irradiated structural components, etc…
- Similar radioactive waste in medical, industrial fields

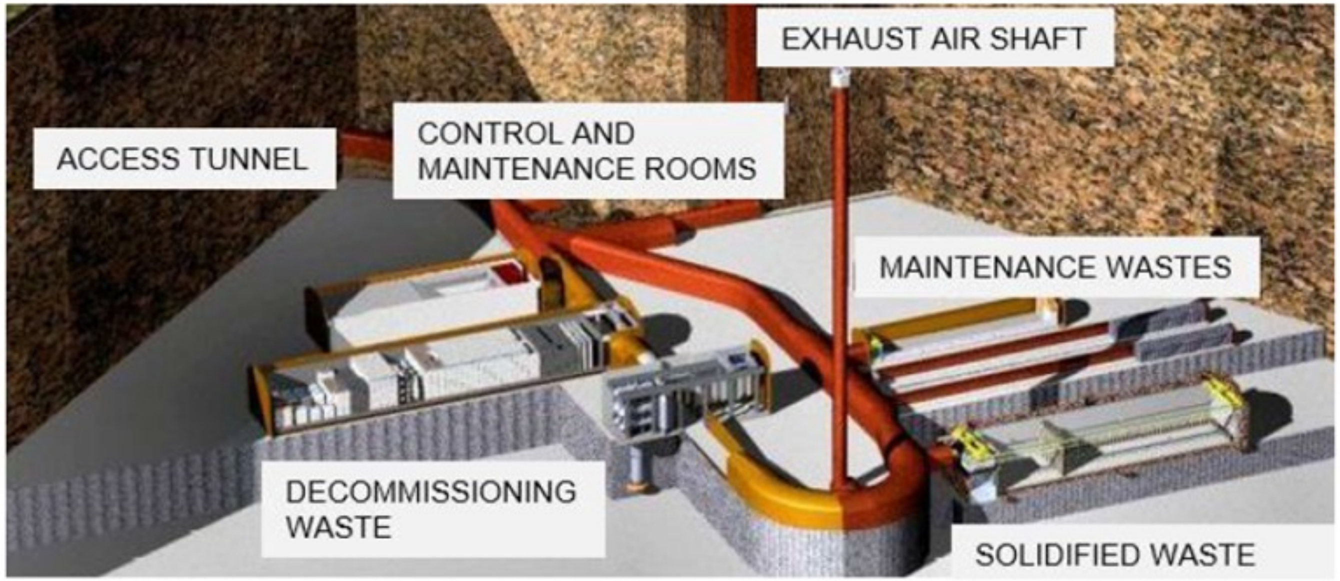
90% of volume:low level waste

- Used clothes, contaminated tools etc

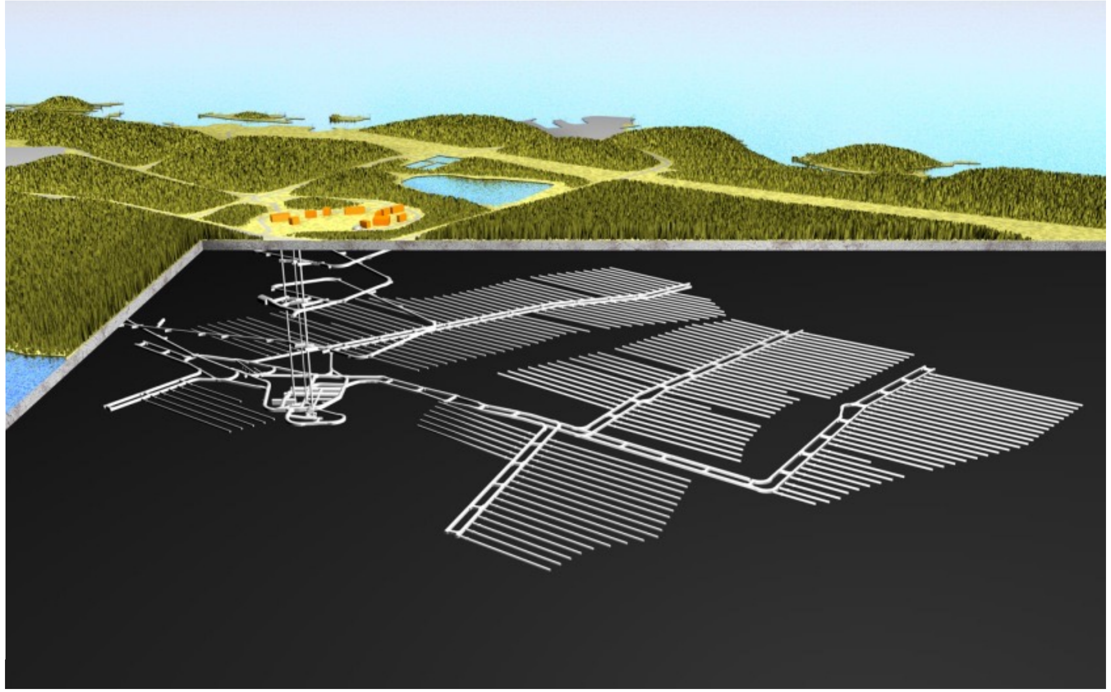


Annual production of high level waste in one GW-scale reactor is in the order of 50 tons.

Geological disposal a standard way for ensuring separation from environment



Loviisa low and intermediate waste repository at 100 m below ground, currently operational.
Figure from AINS Group



Posiva spent fuel final repository at 400 m below ground, currently under construction with operations permit applied for. Figure from Posiva

SMR specific issues for Refueling, spent fuel management, transport and disposal as well as decomisionning

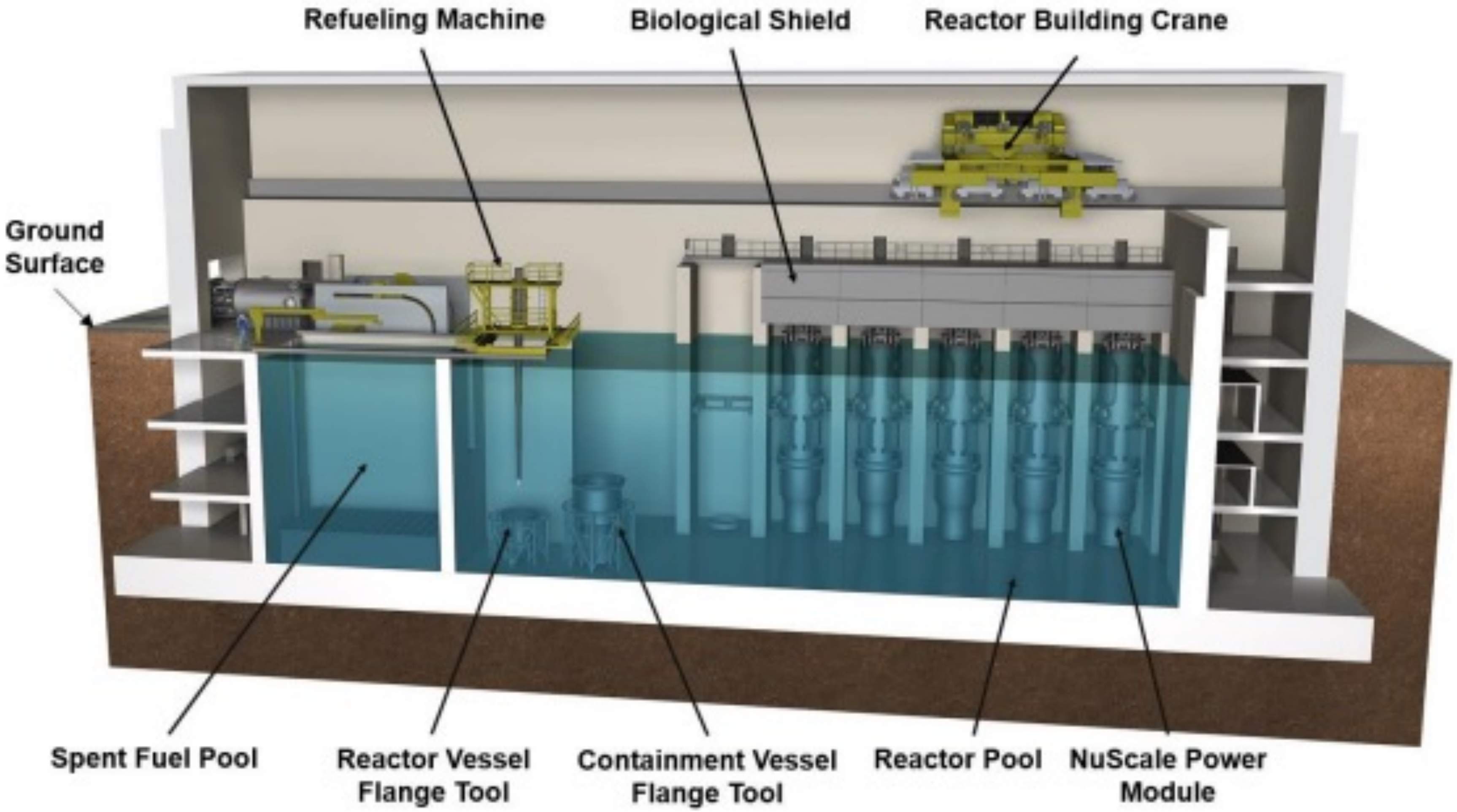


Figure 5. Reactor building cut-away view

Safety for Refueling, spent fuel management, transport and disposal as well as decomisionning assessment

- Smaller cores inherently waste neutrons due to neutron leakage, either resulting in lower burnup or need for additional reactivity
  - If smaller burnup, higher amount of actinides in fuel compared to large LWR fuel
  - Increase the remaining reactivity of the assembly and then the risk of criticality outside of the core
  - If higher initial criticality of fuel assembly, increase of the impact of a core loading error
- Boron-free core
  - Potential issue with mishandling of the fuel assembly during loading
- Reactor/Spent Fuel Pool independency: If the Spent Fuel Pool is the heat think of the reactor it should be shown that:
  - An accident in one module should not induce an accident to the SFP
  - An accident to the SFP should not induce an accident to the modules and especially not deteriorate the performances of the heat sink for the module(s)
  - The external situations like LOOP or hazard impacting all the installation (in particular extrem earthquake) has to be taken into account. In such situation the sizing of the pool should allow to ensure all the safety function for SFP and module(s)

What is essential for the final disposal safety case?

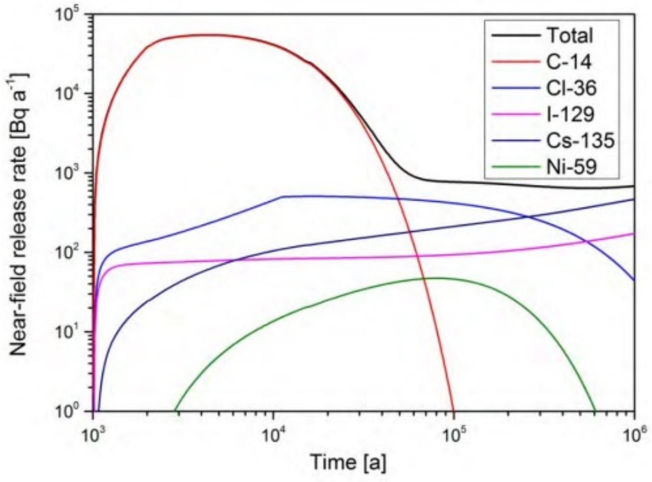
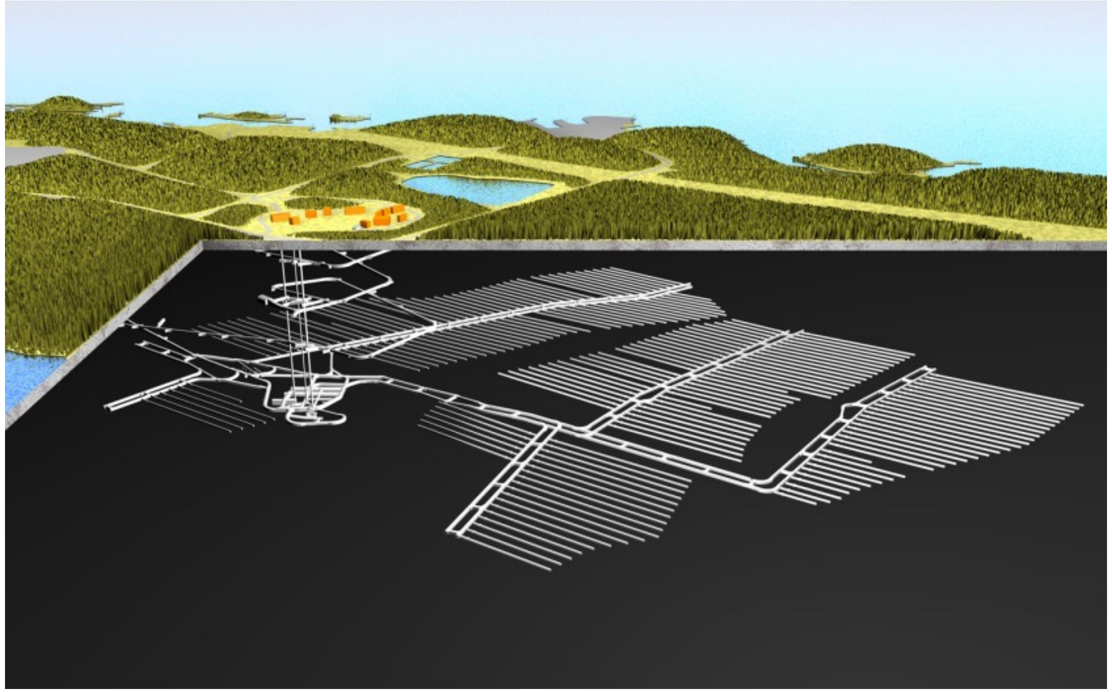


Figure 8-1. *Evolution of the total radionuclide release rate from the repository near field to the geosphere in the reference case of the base scenario, summed over the F-, DZ- and TDZ-paths, and the evolution of release rates of C-14, Cl-36, Ni-59, I-129 and Cs-135, which are the radionuclides that make the largest contributions to the total.*



Posiva spent fuel final repository at 400 m below ground, currently under construction with operations permit applied for. Figure from Posiva

Safety of Refueling, spent fuel management, transport and disposal as well as decomisionning assessment

- Decommissioning
  - Compact reactor: The compact design of modules could bring difficulties for decommissioning operations, and decommissioning as to be taken into account at the early phase of the design
  - Sealed Module(s): Offsite decommissioning (at dedicated offsite facility) would be easily performed, economically competitive and likely be more controlled by regulatory authority than traditional onsite decommissioning activities. However, importance of transportation safety/security is to be increased.
  - Multi-modules aspects: decommissioning for multi-unit plants may be sequenced (decommissioning of modules while some modules are operating) and thus would require resolution of security and safety issues (e.g., removal routes, works close to operating modules, potential induced hazard on operating modules etc.). That is why decommissioning aspects should be considered early at the design stage
  - Non-electric uses: often located near use, so on valuable land, and therefore decommissioning should be swift

SMR specific safety issues

- SMRs are nuclear reactors, and share similar issues with large power plants
- Some special issues stemming from e.g.
  - High use of passive safety features
  - Use of multiple reactor modules
  - Small cores

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