Assessing and Managing Severe Accidents in Nuclear Power Plant

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Concept of severe accidents

• This presentation refers to severe accidents in power plants equipped with light water reactors (LWR)
• Definition: Nuclear power plant accidents are called severe accidents, when they lead to extensive degradation of fuel in the reactor core.
• Severe accidents can progress to partial or full melting of the whole reactor core.
• The core degradation resulting from reactivity initiated accidents can be very destructive - they are not treated in this presentation with the exception of the references made to the Chernobyl disaster
• Management of severe accidents are defined as Level 4 of the defense-in-depth concept
Progress of severe accidents

- Severe accidents initiate, when reactor core cooling can't be restored after a transient or accident.
- If reactor circuit is intact, operators try to restore core cooling by preventive SAM measures e.g. by initiating bleed and feed action in the secondary circuit, and if not successful then in the reactor circuit.
- If reactor circuit leaks, operators try to inject coolant to primary circuit by any available means (in case of PWR, however, borated water is needed).
- If bleed and feed actions are not successful, such sequences lead to uncovering and overcooling of the reactor core.
- In case of no cooling, reactor core eventually degrades and melts and relocates on the reactor vessel lower head (molten core materials are referred as 'corium').
Progress of severe accidents

- If the core melt progression can be stabilized on the lower head (e.g. by external cooling of the vessel), the ex-vessel (=in-containment) consequences are less severe.
- However, fission products, hydrogen and decay heat are released in large amounts to the containment atmosphere.
- If corium melts through the vessel, there are various energetic consequences caused by ejected high-temperature molten corium.
- Molten corium slumping to water pools (either in-vessel or ex-vessel), or pouring water on the molten material surface, may cause energetic steam explosions.
- Molten corium on the containment basemat initiates core-concrete interaction that releases aerosols and non-condensible gases to containment atmosphere and erodes the concrete ('China syndrome').
- Overpressure formation in the containment.
In-vessel retention of corium on the reactor vessel lower head by external cooling

molten metal layer

molten oxides

crust
Core-concrete interaction
Core melt stabilization of the EPR reactor
Core catcher of VVER reactor

- Reactor vessel
- Core catcher device filled with sacrificial material
- Cavity filled with water
Severe accident vulnerabilities

- There are various challenges to the containment integrity, often referred to as vulnerabilities
  - Isolation failure, bypass leakage, pre-existing opening ...
  - Energetic phenomena
    - Hydrogen combustion: large-scale deflagration, accelerated flames, detonation
    - In-vessel steam explosions (α-mode failure)
    - Ex-vessel steam explosions
  - Attack of containment liner by corium
  - Heat loads to containment penetrations
  - Overheating and failure of steam generator tubing (PWR)
  - Overpressure due to decay heat and
  - Overpressure due to release of noncondensible gases into containment atmosphere
Containments:
- large dry containment of EPR
- Mark-I, II, III of BWRs
Mark-I Containment as in Fukushima

- Spent fuel pool
- Reactor service floor
- Concrete reactor building
- Reactor pressure vessel
- Primary containment drywell
- Suppression pond wetwell
The key elements to be considered in mitigatory SAM

- Containment isolation and leak-tightness
- Primary circuit depressurization
- Core melt stabilization
  - in-vessel retention
  - ex-vessel corium stabilization
- Energetic events challenging containment integrity
  - hydrogen combustion
  - in-vessel and ex-vessel steam explosions
- Long-term heat removal from the containment
Consistent approach to Severe Accident Management

I Level 1 PSA: prevention goal (e.g. core damage frequency <10^{-4} /r-yr)
II System reliability: low fraction of sequences that can't be mitigated (e.g.<10^{-2})
   – sequences with impaired containment function (bypasses, pre-existing openings, etc)
   – high-pressure sequences
   – reactivity initiated sequences
III System reliability: containment leakages are low
IV Absence of containment failure due to physical phenomena
V Long-term coolability

Implementation of the SAM strategy
Hazards to be practically eliminated

Sequences to be prevented at PSA level 1
- sequences with impaired containment function (bypass sequences, pre-existing openings)
- high-pressure sequences (high-pressure ejection of molten core from the reactor vessel to the containment)
- reactivity initiated core melt sequences
Role of probabilistic risk assessments

• Setting priorities to SAM
• Bringing completeness to the assessment
• Consideration of all plant conditions: full-power operation, other operational conditions, and particularly outages
• Consideration of practically all initiating events:
  – Internal events:
  – Internal hazards (often referred as external events): fires, floods
  – External natural hazards: severe weather condition’s (wind, frost, heat, ...), earthquakes, floods, tsunami, cooling water clogging by algae or frazil ice, meteors, solar winds
  – External man-made hazards: gas clouds, oil spills, .
• Malvolent actions not included: not prone to probabilistic quantification
Severe accidents at commercial nuclear stations

- TMI (Three Mile Island Unit 2) March 1979
- Chernobyl Unit 4 April 1986
- Fukushima Dai-ichi, Units 1, 3 and 4 March 2011
What are the lessons learned from accidents?

By courtesy of Nigel Buttery/EdF Energy

• TMI-2 highlighted the need for
  – Symptom-based procedures
  – Severe accident management (SAM) guidelines
  – Led to the formation of **INPO** (Institute of Nuclear Power Operators, USA)

• Chernobyl highlighted the potential impact of severe accidents
  – Led to the formation of **WANO** (World Association of Nuclear Operators)

• What new aspects does Fukushima highlight?
  – Reinforces some of the previous lessons
  – External hazard initiator – need to get design basis right
  – First time SAM procedures have been used
  – Accident at a site involving multiple units and widespread disruption of infrastructure
  – Communications with the public
    • Perception vs reality; psychological trauma
    • Health effects “very small” but significant disruption
Additional features caused by Fukushima

- More explicit consideration of external hazards as a severe accident initiator
- Impact of simultaneous severe accidents in multiple units
- Spent fuel pool safety against external hazards
- More attention to proper application of PSA: coverage of all known initiators, respect of historical data
- New discussion of the meaning and acceptability of residual risks
- Exaggerated emphasis on the short-term and limited range conclusions of Fukushima-specific accident progressions
- Stress tests started with inadequate understanding of the contributing issues: limited emphasis on such issues as 'fail safe' definitions of valves, unavailability of battery power, loss of internal power distribution)
Future severe accidents: Are they still unexpected?

- The possibility of severe accidents and even associated large releases remains, whatever is done (concept of residual risks)
- Further reduction of the risks is supported by all stakeholders
- More profound application of both deterministic and probabilistic methods should be reinforced to improve the effectiveness of the defense in depth concept further (there was an IAEA/NEA Technical Meeting of such reinforcement two weeks ago in Pisa, Italy)
- Are there still initiators, conditions or their combinations left unattended in sense that their significance in terms of risk (frequency multiplied with consequences) is not properly appreciated?
- Contributions that are not prone to quantification: How to bring human actions (even malvolent ones) and organisational matters into assessments of residual risks?
What can we achieve in this meeting?

- Define the role and significance of various ITO aspects to reinforce our approach to nuclear safety (defense in depth concept)
- Discuss the quantification of ITO aspects in order to understand their contribution to the residual risks
- Define the ITO aspects and the way to implement them for the above purpose
- Benefit of the information provided by the other safety-critical activities