Severe Accidents & Level 2 PSA

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Outline

- General analysis process and scope
- Severe accident phenomena
- Analysis steps/ important considerations
- Applications
Main nuclear accidents and reactor years of operation worldwide
General PSA Process

INITIATING EVENTS

SAFETY SYSTEM FAILURE

CORE DAMAGE

SEVERE ACCIDENT PROGRESSION

CHALLENGE TO CONTAINMENT

RELEASE OF RADIOACTIVITY

DISPERSION IN THE ENVIRONMENT

HEALTH/ FINANCIAL CONSEQUENCES

LEVEL 1 PSA
Core damage frequency

LEVEL 2 PSA
Large release frequency

LEVEL 3 PSA
Societal risk
Levels of PSA and Interfaces

**Level-1 PSA**

**INTERFACE – Plant Damage States**

**Level-2 PSA** models: phenomena that could occur following core damage; challenges to the containment integrity; transport of radioactive material in the containment
- considers the effectiveness of the design/ severe accident management measures to mitigate the effects of core damage
- estimates the frequency/ magnitude of a release of radioactive material to the environment

**INTERFACE – Source Term Categories/ Release Categories**

**Level-3 PSA**
Phenomena of Severe Accidents – Details of In & Ex-vessel Phase

- insufficient core cooling ⇒ begin of core dry-out / heat-up
- ballooning and bursting of FE cladding ⇒ begin of FP release from FE gap
- begin of Zr-oxidation of FE cladding ⇒ exothermic reaction with H₂ release ⇒ acceleration of core heat-up
- degradation of control rods and material relocation
- escalation of Zr-oxidation of FE cladding and H₂-generation and core heat-up
- degradation of FE and extended FP release ⇒ molten pool generation inside the core
- core material slumping into lower plenum and RPV heat-up
- RPV failure and melt release into reactor cavity

⇒ ex-vessel phase
  * High Pressure melt ejection, Direct Containment heating
  * Molten Core Concrete Interaction ⇒ FP-release, long term H₂-, CO-, CO₂- and steam release
  * water ingestion into cavity ⇒ long term containment pressure increase ⇒ filtered venting
  * basemat penetration due to MCCI
Phenomena of Severe Accidents –
Formation of liquid phases and core melt in the reactor

Absorber Materials

- 1400: $\text{UO}_2/\text{Zr}$
- 1200: $\text{Fe}/\text{Zr}, \text{Ni}/\text{Zr}$
- 1070: Melt of Ag, In, Cd

Cladding and Assembly

- 2300: Eutectic Interaction $(\text{Fe, Ni, Zr})_O/(\text{ZrO}_2, \text{UO}_2)$
- 2000: Melt of Zr, $\alpha$-Zr($O$)

Degree of Degradation

- No Damage
- Local Clad Damage
- Local Assembly Damage
- Significant Degradation
- Total Core Degradation

Fuel

- 3000: Ceramic Melt $\text{UO}_2, \text{ZrO}_2$
- 2600: Oxide Mixture

Formation of liquid phases and core melt in the reactor

- Loss of Geometry, Formation of Melt Pool, Debris Bed and Cavity

Formation of metallic and ceramic melt and of blockages

- Clad oxidation and Hydrogen generation
- Clad degradation and Hydrogen generation
- Oxide Mixture

- Formation of liq. metallic Phases

- $1200 \degree C$
- $2000 \degree C$
- $2500 \degree C$
- $3000 \degree C$
Phenomena of Severe Accidents – Core Degradation

• Degradation of control rods > 1400 K
  ✓ eutectic reactions of different materials: AIC – steel – Zr
  ✓ degradation of control rods at lower temperatures than melting points of material
  ✓ material relocation within core (candling process)

⇒ freezing in lower position and formation of local blockages

⇒ recriticality during reflooding?

SIC-Tests des FzK, M. Steinbrück, CSARP 2007
End state resembles TMI–2 in-core configuration, i.e. cavity above re-solidified corium pool supported by almost intact fuel rods.
Phenomena of In-vessel Melt Retention

- Radiative Heat Transfer
- Liquid Metal Layer (Rayleigh-Benard Convection)
- Focussing effect of metallic layer
- Molten Debris
- Debris Crust
- Conduction Through the Wall
- Natural Convection with Internal Heating
- Nucleate Boiling
- Water
High Pressure Melt Ejection

- Containment
- Reactor vessel
- Reactor cavity
- Melt ejection
- Gas blowdown
- Hole ablation
- Deposition
- Trapping by structures
- Entrainment
Phenomena of Severe Accidents – Ex-vessel Phenomena Direct Containment

Heating

• Typical debris dispersal fractions in different reactor designs
## Example of Severe Accident Sequence

**Late overpressurisation sequence:**

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of core cooling</td>
<td>0</td>
</tr>
<tr>
<td>Core uncovery</td>
<td></td>
</tr>
<tr>
<td>Zr oxidation (H₂ production)</td>
<td>2</td>
</tr>
<tr>
<td>Loss of core geometry and meltdown</td>
<td></td>
</tr>
<tr>
<td>Fission product release</td>
<td></td>
</tr>
<tr>
<td>Molten core/debris relocation to lower plenum</td>
<td></td>
</tr>
<tr>
<td>Interactions with water (energetic/non-energetic)</td>
<td></td>
</tr>
<tr>
<td>Reactor vessel breach</td>
<td>4</td>
</tr>
<tr>
<td>Core relocation/ ejection into containment</td>
<td></td>
</tr>
<tr>
<td>Interactions with any water (energetic/non-energetic)</td>
<td></td>
</tr>
<tr>
<td>Core-concrete interaction</td>
<td></td>
</tr>
<tr>
<td>Additional combustible gas (H₂ and CO production)</td>
<td></td>
</tr>
<tr>
<td>Additional fission product release</td>
<td></td>
</tr>
<tr>
<td>Containment loading (over-pressure/ over-temperature)</td>
<td></td>
</tr>
<tr>
<td>Basemat penetration</td>
<td></td>
</tr>
<tr>
<td>Containment failure and release to environment</td>
<td>40</td>
</tr>
</tbody>
</table>
Containment Event Trees

- A CET is a logical framework for estimating the range of consequences associated with a given accident sequence.

- A CET is a time-line of accident progression:
  - It represents the sequence of events that could lead to failure of the containment pressure boundary and fission product release to the environment.
  - Model all the physical and chemical processes that could occur.

- Reflect the phases of severe accident progression:
  - In-vessel processes following onset of core damage
  - Ex-vessel processes following vessel breach
  - Long term processes in the containment
Severe Accident Analysis Codes

**Core & debris behaviour**
- Core heat-up and degradation
- Debris behaviour in bottom head
  - High pressure melt ejection
  - Debris behaviour in reactor cavity: interaction with water or concrete

**Thermal-hydraulics**
- Heat and mass flows in core region
- Heat and mass flows through RCS
  - Direct containment heating
  - Containment threats

**Fission product behaviour**
- In-vessel release from fuel
- Fission product transport in RCS
- Ex-vessel release from fuel
- Fission product transport in containment

**Containment threats**
- Source term
Quantification of CET

- CETs supported by severe accident analysis
  - Integral codes
  - Single effects codes/ specialised analysis
  - Research/ experimental results
  - Results from a reference plant

- Accident analysis codes
  - MAAP (Modular Accident Analysis Program); MELCOR
  - THALES, ASTEC

- Some events can be quantified using traditional systems analysis techniques
  - Probability containment sprays start/run on demand
  - Probability operators manually open containment filtered vent

- Some events using expert opinion, representing a degree of belief
  - The frequency of an external steam explosion after vessel breach
Uncertainties, Sensitivities

- Of the important parameter which affect the sequence of events and the progression of severe accidents. (e.g. parameters affecting timing of high pressure melt ejection, primary circuit depressurisation, hydrogen, ...)
Some Applications of Level 2 PSA
(Based on IAEA Safety Guide SSG-4: ‘Development and Application of Level 2 PSA’)

**Successful examples of applications of Level 2 PSA:**

- Comparison of results of the Level 2 PSA with probabilistic criteria
  - To determine if the overall level of safety of the plant is adequate
- Evaluation of plant design
  - To identify potential vulnerabilities in the mitigation of severe accidents
  - To compare design options
- Development of severe accident management guidelines
- Use of the source terms to provide an input into emergency planning
- Use of the source terms and frequencies to determine off-site consequences (Level 3 PSA)
- Prioritization of research relating to severe accident issues
- Use of a range of other PSA applications in combination with Level 1 PSA results
Severe Accident Management

- Use of Level 2 PSA results for the evaluation of the measures and actions that can be carried out to mitigate the effects of a severe accident
  - To determine the effectiveness of the severe accident management measures that are described in the SAM guidelines or procedures
  - To identify all interdependencies between the various phenomena that can occur during a severe accident to take them into account in the development of the severe accident management guidelines
  - Several examples illustrate the importance of consideration of interdependencies
    - depressurization of the primary circuit may prevent high pressure melt ejection but might increase the probability of an in-vessel steam explosion
    - introducing water into the containment may provide a cooling medium for molten core material after it has come out of the reactor pressure vessel but might increase the probability of an ex-vessel steam explosion; etc.
  - The updates of the Level 2 PSA and updates of the SAMGs guidelines should be performed in an iterative manner
    - to facilitate the progressive optimization of the severe accident management guidelines
AP1000 In-vessel Melt Retention

- In-vessel retention of molten core
- Reactor cavity flooded from IRWST at onset of core damage
- Aim to provide cooling to the outside of the reactor vessel to prevent failure
- Insulation designed to allow water to contact reactor vessel
  - Prevents ex-vessel steam explosion, HPME, core-concrete interaction
  - Needs research, demonstration
EPR Core Melt Retention

Diagram showing components such as Spreading Compartment, Sacrificial Material, Melt Discharge Channel, Protective Layer, and Melt Plug.
After collection of Corium in cavity release to dedicated spreading area and later flooding from above and intrusion from below with water.
Phenomena of Severe Accidents – Ex-vessel Phenomena Experiments on Melt Spreading
ECOKATS-1 (2003, FZK)

• Melt parameter
  ✓ $M_{\text{melt}}$ 786 kg
  ✓ $M_{\text{oxide}}$ 574 kg
  ✓ $T_{\text{ini}}$ 1600°C
  ✓ Flow Rate 2.48 l/s
  ✓ Time 89 s
Phenomena of Severe Accidents – Ex-vessel Phenomena Experiments on Melt

Spreading ECOKATS-1 (2003, FZK)

- Final state after cool down of melt

- Additional experiments with melt spreading under water available (melt flooding);
Core catcher provides corium confinement and exclude corium discharge outside the containment in any scenario.

- Protects the reactor cavity against thermal and mechanical impact of corium
  - Takes in and accommodates solid and liquid corium constituents
  - Ensures formation of optimal structure and properties of the melt pool and subsequent solidification of corium
  - Provides heat sink from corium to cooling water passively supplied min 24 h without any coolant makeup
  - Provides corium retention
  - Minimises hydrogen and radionuclide release into containment on ex-vessel phase of a core melt scenario
Decrease in reactor water level due to loss of cooling capability of emergency condenser, followed by uncovering the core

Function has not been correct

Decrease in reactor water level
- Uncovering the Core
  - Hydrogen Generation due to the Zirconium-Water reaction
  - Possible Fuel Rod damage
3-7. Major event progression at Unit 1 (3/4)

Hydrogen explosion in the operation floor
4-1. Summary of the status of damaged fuel in Unit 1

- All fuel melted through PCV from original position.
  [as per MAAP analysis]
- Further, it is likely that the PRV was damaged so that considerable amount of fuel was assumed to be melted down to the bottom of PCV.
  [Assumed from indicated level of water level gauge]
  [Assumed from heat balance based on the water injection record]
  [Assumed from gas concentration in PCV]
  [Assumed from Reactor Auxiliary Machine Cooling System]
  [Evaluation of indicated value of thermometer] etc.
- Currently, water injection is continued through Feed Water Line so that the temperature at the bottom of RPV and inside of PCV is stabilized below 100 °C.
- Therefore, it is evaluated that the fuel melted down to the PCV is substantially cooled down by injected water.
Phenomena of Severe Accidents – Core Degradation
Severe Accident at TMI-2

- stop of core degradation was in this situation by no means possible
- heat transfer from molten pool limited due to thick surrounding crust
- lateral crust failure and core slumping followed
- core degradation stopped after core slumping
- core material accumulated at lower plenum wall
- formation of a hot spot
- cooling by possible water penetration after re-establishing of water injection
- effective heat transfer avoided vessel failure, not fully understood
Conclusions

- The range of phenomena that could occur during a severe accident covers many technical areas with strong interactions and feedback.

- Research activities carried out over many years to understand severe accident phenomena and provide data.

- Structured approach has been developed for carrying out the analysis.

- Conditional probability of CET is supported by accident analysis.

- SAMGs is an important element of “Defence in Depth.”
THANK YOU FOR YOUR ATTENTION

Questions please?

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