Severe accidents: definitions, parameters calculations & equipment qualification

Miroslav Kotouč
Jiří Duspiva
Tomáš Janda
Dept. of Severe Accidents and Thermomechanics

Equipment Qualification in Nuclear Installations, 20-23 May 2019, UJV Rez, CZECH REPUBLIC
Outline

1. Definition of a severe accident (SA)
2. Processes in the course of a SA
3. Management & mitigation of SAs
4. Structures, systems & components (SSC) during a SA
5. Codes for SA analyses
6. Assessment of outcomes of SA analyses
7. Equipment qualification for SAs
SA definition

- **Severe accident**
  - “Accident with substantial core damage”

- **Former terminology**
  - Design basis accidents (DBAs)
  - Beyond design basis accidents (BDBAs)
    - incl. SAs

- **Actual terminology (IAEA, WENRA)**
  - Design basis conditions (DBCs)
  - Design extension conditions (DECs)
    - DEC-A – complex sequences (w/o core melt)
    - DEC-B – SAs (core melt)
Processes in the course of a SA (1)

• **Unmitigated SA**
  - Phase just after an initiating event (IE) – identical to DBAs
    - initiated by e.g. loss of cooling accident (LOCA), station black-out (SBO)...
  - Core degradation = consequence of the absence of core cooling
    - Cladding oxidation – exothermic process, \( \text{H}_2 \) production
    - Cladding rupture – release of gaseous and highly volatile fission products (FPs)
  - Loss of fuel geometry – release of moderately volatile FPs
  - Fuel relocation into the lower plenum (LP) \( \Rightarrow \) reactor pressure vessel (RPV) ablation \( \Rightarrow \) RPV integrity loss \( \Rightarrow \) debris/molten materials (corium) release into the reactor cavity
    - High-pressure melt ejection (HPME) – aerosols dispersion into the containment (CTMT) volume
    - Low-pressure melt ejection – “slow” release of debris/corium into the pit
  - Molten core-concrete interaction (MCCI) – release of non-volatile FPs, \( \text{H}_2 \) production
Processes in the course of a SA (2)

- **Challenges for the CTMT**
  - Pressurization – steam, H₂ and non-condensable gases
  - Over-heating
  - Radiation – gaseous FPs, aerosols & vapors
Management & mitigation of SAs

- **SA management (SAM)**
  - Coolant injection into the core
  - Corium confinement:
    - In-vessel melt retention (IVMR)
    - Ex-vessel corium cooling
  - Long-term CTMT heat removal
  - Over-pressurization mitigation measures
  - FPs confinement

- **SSCs intended for the above-mentioned functions:**
  - Need of qualification?
  - To which conditions?
SSCs during a SA

• **Question?** which SSCs are being used in the course of SAs? For:
  • Unmitigated SAs vs.
  • SAs with SAM application

• **Answer!** determined by the SA evolution
  • A bunch of scenarios must be analyzed

• **SSCs used in the course of SAs:**
  1. *Systems for physical parameters/plant state measurement*
  2. *Components for SA mitigation*
     • Primary circuit (PC) depressurization measures
     • Systems for in-core coolant injection
     • Passive autocatalytic recombiners (PARs)
     • Core-catcher
     • Valves
     • Mobile devices
1. **Systems for physical parameters/plant state measurement**
   - Core exit temperature (CET) – used for determination of the entrance into SA management guidelines (SAMGs)
     - Low range; will be destroyed after core degradation onset; no qualification
   - PC loops temperatures – used for determination of the entrance into SAMGs
     - Low range; will be destroyed after core degradation onset; no qualification
   - Liquid level in spent fuel pool (SFP), steam generators (SGs), CTMT – sump
     - Possibility of clogging ⇒ measurement devices need to be qualified
   - Pressure in the CTMT – qualified for DBCs, wider range in SAs
   - H₂ concentration in CTMT – qualified for DBCs, wider range in SAs; low O₂ conc.!!!
   - Dose rate in CTMT
     - Data acquired during normal operation, in SAs used alternatively if CET unavailable
     - Qualification to higher ranges of dose rates (to capture EOPs ⇒ SAMGs)
   - Radioactivity (RA) release into environment
     - Outside CTMT; no qualification
   - Generally: qualification needed for cables and those devices which help to identify whether a certain system’s operation is hampered by clogging
2. **Components for SA mitigation**
   - PC depressurization – PORV, SRV
   - Periodical operation, very hot gases carrying aerosols
   - Systems for in-core coolant injection
   - Localized outside the CTMT, however, water intake from the sump ⇒ liquid is likely to contain much aerosols
   - PARs
   - Designed for SAs
   - Core-catcher
   - Designed for SAs
   - Valves
   - Steam dump to atmosphere valve
   - Mobile devices
   - Located outside the CTMT

- Generally: qualification needed in order to be able to carry out the required functions during SAs
Codes for SA analyses

- Integral codes
  - IE $\Rightarrow$ SA progression $\Rightarrow$ FPs release into environment (source term; ST)
  - “Lumped parameter” approach
  - FPs behavior (release from fuel $\Rightarrow$ transport in circuits $\Rightarrow$ behavior in CTMT $\Rightarrow$ ST)
  - FPs grouping into “classes”
    - Similar chemical behavior

- Main integral codes:
  - MELCOR
  - Sandia National Laboratories
    - for US Nuclear Regulatory Commission
  - ASTEC
    - IRSN+GRS
  - MAAP5
    - for EPRI
  - SOCRAT
    - IBRAE

<table>
<thead>
<tr>
<th>Class</th>
<th>Class Name</th>
<th>Chemical Group</th>
<th>Representative</th>
<th>Member Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>XE</td>
<td>Noble Gas</td>
<td>Xe</td>
<td>He, Ne, Ar, Kr, Xe, Rn, H, N</td>
</tr>
<tr>
<td>2</td>
<td>CS</td>
<td>Alkali Metals</td>
<td>Cs</td>
<td>Li, Na, K, Rb, Cs, Fr, Cu</td>
</tr>
<tr>
<td>3</td>
<td>BA</td>
<td>Alkaline Earths</td>
<td>Ba</td>
<td>Be, Mg, Ca, Sr, Ba, Ra, Es, Fm</td>
</tr>
<tr>
<td>4</td>
<td>I2</td>
<td>Halogens</td>
<td>I$_2$</td>
<td>F, Cl, Br, I, At</td>
</tr>
<tr>
<td>5</td>
<td>TE</td>
<td>Chalcogens</td>
<td>Te</td>
<td>O, S, Se, Te, Po</td>
</tr>
<tr>
<td>6</td>
<td>RU</td>
<td>Platinoids</td>
<td>Ru</td>
<td>Ru, Rh, Pd, Re, Os, Ir, Pt, Au, Ni</td>
</tr>
<tr>
<td>7</td>
<td>MO</td>
<td>Early Transition Elements</td>
<td>Mo</td>
<td>V, Cr, Fe, Co, Mn, Nb, Mo, Tc, Ta, W</td>
</tr>
<tr>
<td>8</td>
<td>CE</td>
<td>Tetravalent</td>
<td>Ce</td>
<td>Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C</td>
</tr>
<tr>
<td>9</td>
<td>LA</td>
<td>Trivalents</td>
<td>La</td>
<td>Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf</td>
</tr>
<tr>
<td>10</td>
<td>UO2</td>
<td>Uranium</td>
<td>UO$_2$</td>
<td>U</td>
</tr>
<tr>
<td>11</td>
<td>CD</td>
<td>More Volatile Main Group</td>
<td>Cd</td>
<td>Cd, Hg, Zn, As, Sb, Pb, Tl, Bi</td>
</tr>
<tr>
<td>12</td>
<td>AG</td>
<td>Less Volatile Main Group</td>
<td>Ag</td>
<td>Ga, Ge, In, Sn, Ag</td>
</tr>
<tr>
<td>13</td>
<td>BO2</td>
<td>Boron</td>
<td>BO$_2$</td>
<td>B, Si, P</td>
</tr>
<tr>
<td>16</td>
<td>CSI</td>
<td>Cesium iodide</td>
<td>CsI</td>
<td>CsI</td>
</tr>
<tr>
<td>17</td>
<td>CSM</td>
<td>Cesium Molybdate</td>
<td>CsM$^1$</td>
<td>CsM$^1$</td>
</tr>
</tbody>
</table>
Codes for SA analyses

- Main output variables from SA computational analyses in relation with EQ – temporal evolution of:
  - $p$ in CTMT
  - $T$ in CTMT
  - Gas composition entering the CTMT or environment
  - Humidity in the CTMT
  - Surface $T$ of solid structures
  - Occurrence of deflagrations
  - FPs distribution

- Still missing as an outcome from integral SA analyses:
  - Dose rates acting on SSCs
  - Recent analyses at UJV Rez:
    - MELCOR analysis $\Rightarrow$ FPs distribution in the reactor hall of VVER-1000 reactor
      CTMT $\Rightarrow$ MCNP5 evaluation of dose rate at 2 spots (RA measurement probes)
    - for a SA in open reactor & SFP (no CET measurement): EOPs $\Rightarrow$ SAMGs
    - MELCOR analysis $\Rightarrow$ FPs distribution in the reactor hall of VVER-1000 reactor
      CTMT $\Rightarrow$ MAVRIC/ORIGEN-S evaluation
Assessment of outcomes of SA analyses

- Typical temporal evolution of crucial parameters for an unmitigated SA – example:
  - VVER-1000/320 (Temelin NPP)
  - IE: large break LOCA + SBO
  - CTMT failure by over-pressurization not considered
  - MCCI ongoing
  - PARs taken into account
Assessment of outcomes of SA analyses

- CTMT pressure

![Chart showing over-pressure vs time](chart.png)
Assessment of outcomes of SA analyses

- CTMT atmosphere temperature, dew point temperature
Assessment of outcomes of SA analyses

- Concentration of steam, H₂, O₂ and N₂ in the CTMT atmosphere
Assessment of outcomes of SA analyses

- Relative humidity in the CTMT atmosphere

![Graph showing relative humidity over time](image-url)
Assessment of outcomes of SA analyses

- Surface temperature of a solid structure in the reactor hall

![Temperature vs. Time Graph](image-url)
Equipment qualification for SAs

- 2014: project for EQ for both Czech NPPs
  - 4x VVER-440/213 – Dukovany NPP
  - 2x VVER-1000/320 – Temelin NPP
- Identified were:
  - Equipment to be qualified
  - Relevant SA scenarios
  - Readings of maxima of decisive parameters, such as:
    - Atmosphere & component surface temperature
    - Pressure
    - Humidity
    - Water level
    - Hydrogen deflagration identification
    - RNs distribution (vapors, aerosols and gases)
      - in the air
      - in sumps and
      - settled on structures
- For SAs, crucial is the dose rate evaluation
  - up to several days of duration
  - new methodology under development, using the code SCALE/MAVRIC seq.
Thank You for Your Attention!