Design Extension Conditions and Severe Accidents in Light Water Reactors
Part 2: Analysis

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Analysis of design extension conditions

IAEA SSR-2/1 on analysis of design extension conditions (art. 5.27)

- An **analysis of design extension conditions for the plant shall be performed.**
- The main technical objective of considering the design extension conditions is to provide assurance that the design of the plant is such as to prevent accident conditions not considered design basis accident conditions, or to mitigate their consequences, as far as is reasonably practicable.
- This might require additional safety features for design extension conditions, or extension of the capability of safety systems to maintain the integrity of the containment. These additional safety features for design extension conditions, or this extension of the capability of safety systems, shall be such as to ensure the capability for managing accident conditions in which there is a significant amount of radioactive material in the containment (including radioactive material resulting from severe degradation of the reactor core).
- The plant shall be designed so that it can be brought into a controlled state and the containment function can be maintained, with the result that significant radioactive releases would be practically eliminated.
- The effectiveness of provisions to ensure the functionality of the containment could be analysed on the basis of the **best estimate approach**.

Various applications of severe accident analysis

- Analytical **support for design** of plant systems
- Demonstration of acceptability of the design in **licensing**
- Analytical support for **development of accident management programmes**
- Determination of **source terms for emergency planning**
- Support for **Level 2 PSA**
- Resolution of **severe accident issues**
- Development of **training programmes**

Objectives of severe accident analysis for design

- Verification of **compliance with the acceptance criteria**, in particular with the radioactive release targets
- Evaluation of **ability of design (in particular containment) to withstand severe accidents** and to identify particular vulnerabilities
- Demonstration of **capability of equipment** including instrumentation **to survive severe accident conditions** and be used in accident management
- Assessment of **doses to the control room operators** and in all other locations where operator activities may be required
- Determination of the **source term** - an input for off-site emergency planning
- Identification of **accident management measures** that could be carried out to mitigate the effects, but specific supporting calculations are needed

Specific tasks for analysis supporting accident management

- Selection of key symptoms
- Selection of mitigation strategies
- Determination of expected positive effects and possible negative effects of the strategy
- Specification of set-points to initiate and to exit a strategy
- Confirmation of choice of symptoms for long-term processes
- Prioritisation and optimisation of strategies
- Evaluation of effectiveness of systems to perform intended functions
- Specifications of environmental conditions for operation of instrumentation and NPP systems
- Recommendations for equipment or instrumentation upgrades
- Computational aid development (simplified diagrams for assessment

SR No. 56 (2008) Approaches and tools for severe accident analysis for NPPs - Contents

Characteristics of computer codes for severe accident analysis

- **Wide range of processes to be covered (thermal-hydraulics, chemistry, metallurgy, FP transport)**
- **Phenomena to be modelled**
  - **Core degradation and fuel melting, vessel melt through**
  - **In-vessel and ex-vessel cooling of core melt**
  - **In-vessel melt retention**
  - **Fuel-coolant interaction, steam explosions**
  - **Distribution of heat inside the RCS**
  - **High-pressure melt ejection/direct containment heating**
  - **Hydrogen generation, distribution and combustion**
  - **Failure or by-pass of the containment**
  - **Release and transport of fission products**
  - **Core-concrete interaction, basemat melt through**
- **Knowledge of phenomena and validation of codes limited (large uncertainties in calculations to be considered)**

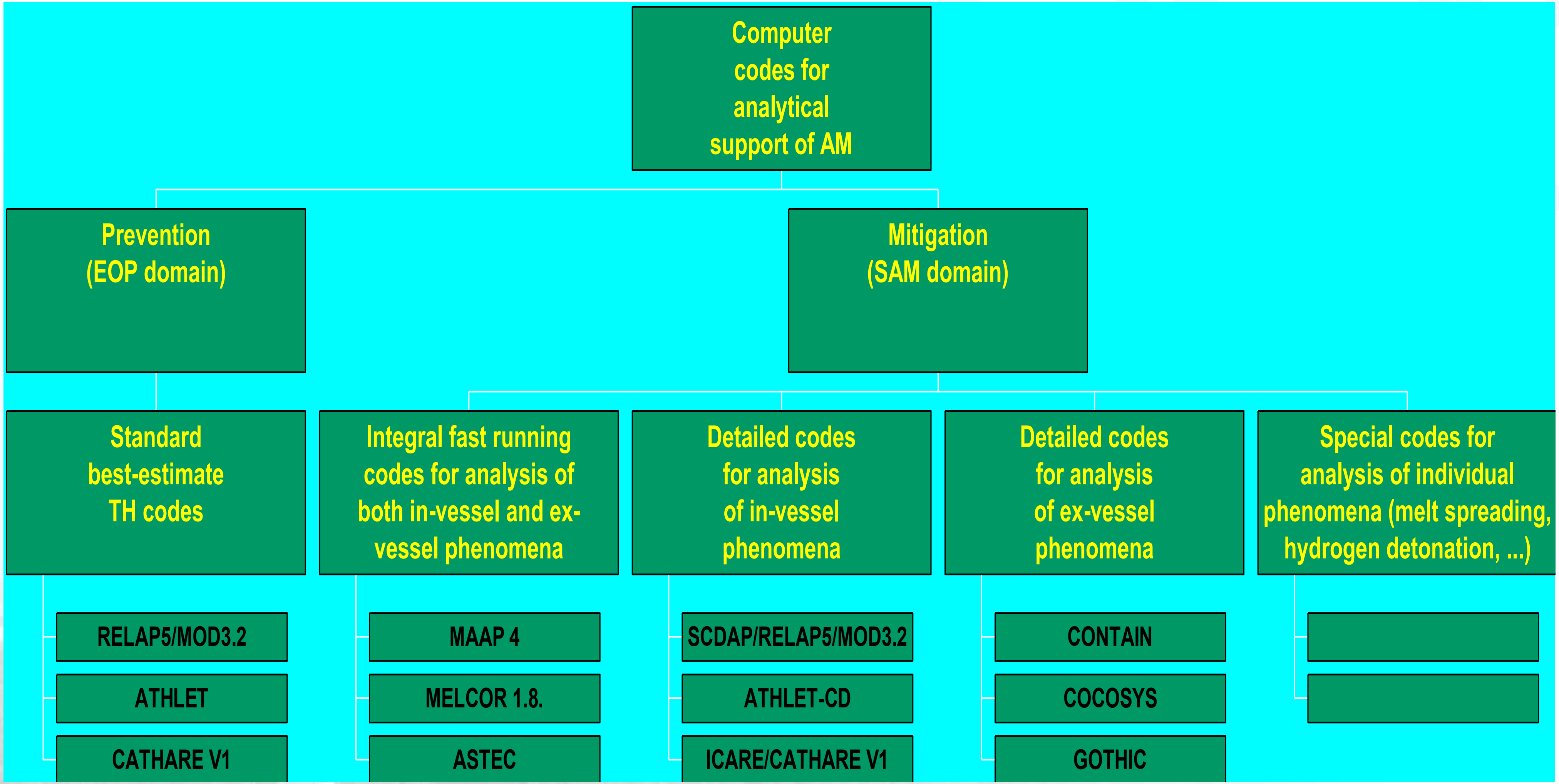
Level of understanding of phenomena for in-vessel analysis

- **Well understood phenomena**
  - Majority of phenomena in early phase of core degradation (boil-off, recriticality, reflooding before significant oxidation, cladding balooning, dissolution of fuel and other materials, …)
- **Low level of knowledge of phenomena**
  - Hydrogen production during flooding of degraded core
  - Recriticality of degraded core
  - Steam flow through the degraded core
  - Formation of debris
  - Formation of molten pool, formation of crust, its stability, break-through
  - Molten core relocation

Level of understanding of phenomena for ex-vessel analysis

- **Well understood phenomena**
  - **Both local and global containment pressurization**
- **Low level of knowledge of phenomena**
  - **Long lasting processes, including late phase of in-vessel phenomena as a boundary condition**
  - **Natural convention in the containment**
  - **Heat exchange with structures**
  - **Temperature stratification (typically underpredicted by integral codes)**
  - **Hydrogen distribution**
  - **Material interactions, mainly molten corium concrete interaction**

Examples of computer codes used for severe accident analysis



Phenomenon	ASTEC V0.3	MAAP 4.0.3	MELCOR 1.8.4	ATHLET-CD	ICARE/ CATHARE V1	SCDAP/ RELAP5 3.2
Fission and decay						
· Recriticality	-	-	-	✓	-	-
· Boron dilution effects	-	-	-	✓	-	-
· Absorber/fuel separation	✓	✓	✓	✓	✓	✓
Thermal-hydraulic						
· 2-phase	-	✓	✓	✓	✓	✓
Thermal non-equilibrium	-	-	-	✓	✓	✓
Momentum equation	-	-	✓	✓	✓	✓
Flexible nodalisation RCS	✓	-	✓	✓	✓	✓
Core reflood	-	-	-	✓	✓	✓
Non-condensibles	✓	✓	✓	✓	✓	✓
Impact of core degradation on flow paths	✓	✓	-	✓	✓	✓
Impact of blockage formation	✓	✓	-	✓	✓	✓
Core bypass	✓	User input	-	✓	✓	✓
Reflux condenser mode	-	✓	✓	✓	✓	✓
Natural gas convection within RPV	✓	✓	-	✓	✓	✓
Natural gas convection within RCS	-	✓	-	✓	✓	✓

Table A2-1 : Main features of severe accident codes (1)

Phenomenon	ASTEC V0.3	MAAP 4.0.3	MELCOR 1.8.4	ATHLET-CD	ICARE/ CATHARE V1	SCDAP/ RELAP5 3.2
Core heat transfer						
Radiation radial	✓	✓	✓	✓	✓	✓
Radiation axial	✓	?	✓	✓	✓	-
Radiation from molten pool	✓	✓	✓	-	✓	-
Initial core damage						
Fuel/cladding contact	✓	?	-	✓	✓	? ✓
Ballooning	✓	✓	-	✓	✓	? ✓
Oxide flowering	-	-	-	-	✓	? -
Oxide shattering	-	User input	-	-	-	? ✓
Irradiated fuel effects	-	-	-	-	-	? ✓
Non-fuel dissolution	-	✓	✓	-	✓	? ✓
Fuel dissolution	✓	✓	✓	✓	✓	✓
Oxide shell failure	-	P	P	P	✓	✓
Absorber models	AIC and B_4C	AIC or B_4C	AIC and B_4C	AIC or B_4C	AIC and B_4C	AIC or B_4C
Spacer grid	-	-	-	-	✓	✓
Canister wall	-	✓	-	✓	-	✓
Lower core support plate model	✓	✓	-	-	✓	-
Upper plenum structure model						✓

Table A2-1 : Main features of severe accident codes (2)

Phenomenon	ASTEC V0.3	MAAP 4.0.3	MELCOR 1.8.4	ATHLET-CD	ICARE/ CATHARE V1	SCDAP/ RELAP5 3.2
Oxidation and hydrogen						
Zirconium	✓	✓	✓	✓	✓	✓
During quenching	No model	No model	No model	✓	No model	✓
Double-sided oxidation	✓	User input	-	✓	✓	✓
U-Zr-O	✓	✓	-	-	✓	✓
During fuel/coolant interaction	No model	No model	No model	No model	-	No model
Particulate debris	-	✓	✓	-	✓	✓
Stainless steel	-	✓	✓	-	✓	✓
B_4C	-	-	✓	-	✓	✓
Impact of air	-	-	✓	-	✓	-
Relocation and pool formation						
Relocation velocity	-	User input	User input	User input	✓	✓
Heat transfer to cladding	✓	User input	User input	✓	✓	✓
Formation particulate debris	✓				✓	✓
Coolability model for particulate debris	-	✓	✓	-	✓	No model
Formation of metallic blockages	✓	-	✓	✓	✓	✓
Radial spreading	-	User input	?	-	✓	✓
Molten pool behaviour in core						
Stratification (metallic/oxidic)	-	-	-	-	-	✓
Heat transfer (transient / steady	-/✓	-/✓	-	-	✓	✓✓
Interaction with supporting	✓	✓	✓	-	✓	✓
Melting of structures above the	-	✓	✓	-	✓	✓
Failure criteria for	-	✓	-	-	-	✓
Relocation of non-molten	✓	-	-	-	-	✓

Table A2-1 : Main features of severe accident codes (3)

Phenomenon	ASTEC V0.2	MAAP 4.0.3	MELCOR 1.8.4	ATHLET-CD	CATHARE/ ICARE-2	SCDAP/ RELAP5 3.2
Fuel coolant interaction						
Melt fragmentation	✓	✓	User input	-	-	User input
Melt dispersal	-	-	-	-	-	-
RCS pressurisation	✓	✓	✓	✓	✓	✓
Steam explosion	-	-	-	-	-	-
Lower head behaviour						
State of the metallic and oxidic melt	Mixed	User input	Mixed	-	Mixed	Mixed
Debris coolability model	-	✓	✓	-	✓	✓
Pool coolability model	-	Optional	-	-	✓	
Detailed lower head failure model	-	✓	✓	-	✓	
Fission product release from fuel						
High volatile fission products	✓	✓	✓	✓	✓	✓
Medium and low volatile	✓	✓	?	✓	-	?
Release from molten pool	-	User input	-	-	-	-
FP transport in RCS & conn. lines						
Deposition in main coolant lines	✓	✓	✓	✓	-	
Revolatilization in main coolant lines	✓	✓	✓	✓	-	
Deposition in connecting lines	-	-	✓	✓	-	
Revolatilization in connecting lines	-	-	✓	✓	-	
Pool scrubbing	-	✓	✓	-	-	
Deposition in dry steam generator	✓	✓	✓	✓	-	
Chemistry						
Iodine	-	-	-	-	-	-
B_4C	-	-	✓	-	✓	✓

Table A2-1 : Main features of severe accident codes (4)

Difficulties in performing deterministic safety analysis of design extension conditions/severe accidents

- **Worldwide, there is no widespread agreement on the best approach to severe accident analysis**. The approach varies from predominantly probabilistic approach used in USA to the concept of address severe accidents with deterministic criteria typical for Europe.
- Although it is well established including IAEA Standards that analysis of severe accidents is performed with **best estimate approach (to the extent possible), [GSR-4] requires that the analysis still shall be conservative**. This can be ensured considering sufficiently large margins (significantly larger than in case of design basis accidents) in interpretation of the results in terms of predicted timing and severity of phenomena.

Difficulties in performing deterministic safety analysis of design extension conditions/severe accidents

- Another issue is connected with assumptions regarding **operability of plant systems in case of severe accidents.** Consideration of all plant systems even beyond their normal operating range is usually recommended and acceptable for development of severe accident management guidelines, but is very complicated to rely on survivability of systems in demonstrating acceptability of the plant design.
- In addition, majority of systems would not be available due to complete lack of normal and emergency power supply. **It is therefore advisable to demonstrate acceptability of the design using only systems dedicated to severe accident mitigation.** It is also in accordance with the requirement on independence of provisions at different levels of defence.

PIEs leading to BDBA or severe accidents (IAEA)

- The severe accidents result from sequences in which the safety systems have malfunctioned and some of the barriers to the release of radioactive material have failed or have been bypassed. **These sequences should be selected by adding additional failures or incorrect operator responses to the DBA sequences (to include safety system failure).**
- The most rigorous way of identifying severe accident sequences is to use the results of the Level 1 PSA. However, it might also be possible to identify representative or bounding sequences from an understanding of the physical phenomena involved in severe accident sequences, the margin existing in the design, and the amount of system redundancy remaining in the DBAs.
- Examples of severe accident initiators include the following:
  - Complete loss of the residual heat removal from the reactor core
  - LOCA with a complete loss of the emergency core cooling
  - Complete loss of electrical power for an extended period

Advisable assumptions for deterministic analysis of severe accidents for licensing of new reactors

- Best estimate computer codes to be used to the extent possible
- Best estimate of plant parameters and performance of the systems may apply
- Conservative assumptions may be relaxed, e.g. SFC does not typically apply
- Operator actions from MCR should not be credited before 30 minutes from the accident initiation (1 hour outside MCR)
- Demonstration of capability to perform required actions and survivability should be provided
- Use of systems whose failure led to the given severe accident should not be credited
- Preferably, analysis should consider only use of the systems dedicated for mitigation of severe accidents
- Large uncertainties in predictions (timing and severity) should be taken into account in interpretation of results

Adopted deterministic acceptance criteria for severe accidents

- Molten corium shall be coolable inside the RPV (in-vessel corium retention strategy)
- Reactor coolant system pressure should be reduced below 2 MPa at the time of molten corium relocation to the reactor bottom head
- Containment design pressure and temperature shall not be exceeded (500 kPa, 150 ^{O}C)
- Global hydrogen deflagration shall be avoided (average hydrogen concentration below 10 %)
- Survivability of the equipment important for the containment performance, including penetrations, isolation devices, hatches shall be ensured
- Radiological (EUR) criteria
  - **Atmospheric release of caesium-137 below 30 TBq**
  - **No Emergency Protection Action beyond 800 m**
  - **No Delayed Action beyond 3 km**
  - **No Long Term Action beyond 800 m**
  - **Limited economic impact**

CONCLUDING SUMMARY

Threats considered

Threats to early failure of containment integrity – to be practically eliminated

- High pressure melt ejection
- In-vessel steam explosion
- Hydrogen detonation or large scale combustion
- Direct containment heating
- Ex-vessel steam explosion

Threats to late failure of containment integrity – to be mitigated

- Molten Corium Concrete Interactions (MCCI) with potential containment melting through
- Hydrogen production and potentially local combustion
- Containment overpressurization (filtered-venting, if necessary)
- Significant fission product release through the containment leakages
- Containment bypass

Measures for ensuring containment integrity in case of severe accidents

- Fast RCS depressurization in the case of the core damage
- In-vessel corium retention by flooding the reactor cavity in combination with injection into RPV, using a baffle for streamline coolant flow around the vessel
- Installation of passive autocatalytic recombiners for severe accidents
- Containment filtered venting (not necessary, just as an additional protection)
- Ventilation of the surrounding structure of the primary containment, operable in severe accident conditions
- Instrumentation provided to allow the necessary actions to be carried out and the response monitored
- Ensuring habitability of the main control room
- Implementation of the plant specific Severe Accident Management Guidelines (SAMG)

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Common Acronyms

- ADS Automatic Depressurization System
- ADV Atmospheric Dump Valve
- AFW Auxiliary Feedwater System
- AM Accident Management
- APET Accident Progression Event Tree
- ATWS Anticipated Transient Without SCRAM
- B&W Babcock & Wilcox
- BWR Boiling Water Reactor
- CCFP Conditional Containment Failure Probability
- CCI Core Concrete Interaction
- CD Core Damage
- CDF Core Damage Frequency
- CE Combustion Engineering
- CET Containment Event Tree
- CFF Containment Failure Frequency
- CHR Containment Heat Removal
- CRD(HS) Control Rod Drive (Hydraulic System)
- CS Containment Spray
- DBA Design Basis Accident
- DCH Direct Containment Heating
- DW Drywell (BWR)
- ECCS Emergency Core Cooling System
- ERVC External Reactor Vessel Cooling
- FSAR Final Safety Analysis Report
- FCI Fuel-Coolant Interaction
- FEM Finite Element Method
- HPCS High Pressure Core Spray
- HPI High Pressure Injection
- HPME High Pressure Melt Ejection
- IPE Individual Plant Examination
- ISLOCA Interfacing System Loss of Coolant Accident
- IVR In-Vessel Recovery or Retention
  [different subjects, same acronym]

Common Acronyms (cont'd)

- LERF Large Early Release Frequency
- LHF Lower Head Failure
- LOCA Loss of Coolant Accident
- LPI Low Pressure Injection
- LPCS Low-pressure Core Spray
- LWR Light Water Reactor
- MAAP Modular Accident Analysis Program
- MACCS MELCOR Accident Consequence Code System
- MCCI Molten Core Concrete Interaction
- MSIV Main Steam Isolation Valve
- OTSG Once-Through Steam Generator
- PCS Power Conversion System
- PDF Probability Density Function
- PDS Plant Damage State
- PORV Power (or Pilot) Operated Relief Valves
- PWR Pressurized Water Reactor
- QHO Quantitative Health Objective
- RCP Reactor Coolant Pump
- RCS Reactor Coolant system
- ROAAM Risk Oriented Accident Analysis Methodology
- RPS Reactor Protection System
- RPV Reactor Pressure Vessel
- RST Revised Source Term
- RWST Refueling Water Storage Tank
- SAMG Severe Accident Management Guidelines
- SBLOCA Small Break LOCA
- SBO Station Blackout
- SERG Steam Explosion Review Group
- SG Steam Generator
- SGTR Steam Generator Tube Rupture
- SRV Safety Relief Valve
- STCP Source Term Code Package
- SV Safety Valve
- TAF Top of Active Fuel (in reactor core)
- TMI-2 Three Mile Island Unit 2
- UHI Upper Head Injection
- VB (Reactor Pressure) Vessel Breach
- WW Wetwell (BWR)

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…Thank you for your attention