Good Practices for Analyzing DEC-A (Design Extension Condition without Significant Fuel Degradation for Operating Nuclear Power Plants)

R2CA Summer School on DBA and DEC-A for Light Water Reactors, Bologna, Italy, July 4-6, 2023

Presented by Simon Verdebout
Prepared by Jinzhao Zhang (NEA DEC-A Project Task Leader)

PUBLIC | INTERNAL | RESTRICTED | CONFIDENTIAL

Introduction

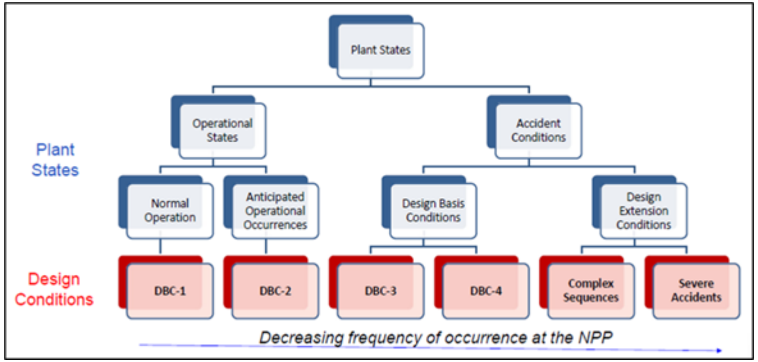
- The concept of “design extension conditions (DECs)” was first introduced in EUR in 1994 to define some selected sequences due to “multiple failures”:
  - Complex Sequences involve failures beyond those considered in the deterministic design basis but do not involve core melt;
  - Severe Accidents considered in the design, both to prevent early and delayed containment failure and to minimize radioactive releases for the remaining conditions.
- The DECs were adopted in the IAEA Safety Standards since 2012 and in the WENRA Safety Reference Levels in 2014 after the Fukushima Daiichi accident, comprising:
  - DEC A for which prevention of severe fuel damage in the core or in the spent fuel storage can be achieved (i.e., DECs without significant fuel degradation);
  - DEC B with postulated severe fuel damage (i.e., DECs without core melting).
- Objective: to further improve the safety of the nuclear power plant by:
  - enhancing the plant’s capability to withstand more challenging events or conditions than those considered in the design basis
  - minimising radioactive releases harmful to the public and the environment as far as reasonably practicable, in such events and conditions.

Introduction

- From IAEA: DEC-A are requested to be analyzed to ensure that “core melt can be prevented with an adequate level of confidence and that there is an adequate margin to avoid any cliff edge effects”.
- The DEC-A safety analyses have been implemented in many NEA member countries, but:
  - significant differences regarding the selection of the DEC-A scenarios, definition or justification of the acceptance criteria, validation and application of the computer codes, as well as the development and application of the methods to safety analyses of the DEC-A scenarios.
  - lack of internationally shared experience and methodologies between different stakeholders and organizations
- Objective of the OECD/NEA WGAMA/WGFS joint project on DEC-A (2021-2024):
  - Review of the definitions and requirements
  - Review of current status of knowledge
  - Review of the “good practices”

Review of Definitions and Requirements

- The European Utility Requirements (EUR) first introduced the DECs in 1994 to define some selected sequences due to “multiple failures”:
  - Complex Sequences involve failures beyond those considered in the deterministic design basis but do not involve core melt;
  - Severe Accidents considered in the design, both to prevent early and delayed containment failure and to minimize radioactive releases for the remaining conditions.
- Objective: to improve the safety of the plant extending the design basis
- Selection of DECs: should be done by plant designer and by use of probabilistic methods.
- Assessment of DECs: using best estimate (BE) methods (no need for application of single failure, etc.).



INTERNAL

Review of Definitions and Requirements

- The DECs were first introduced in the IAEA safety standards SSR-2/1 in 2012 and revised in 2016 to define postulated accident conditions that are not considered for design basis accidents, comprising:
  - conditions in events without significant fuel degradation (=DEC A);
  - conditions in events with melting of the reactor core (=DEC B).
- Objective: to provide assurance that the design of the plant is such as to prevent accident conditions that are not considered design basis accident conditions, or to mitigate their consequences, as far as is reasonably practicable.
- The objective of the safety analysis of DEC A is to demonstrate that core melt can be prevented with an adequate level of confidence and that there is an adequate margin to avoid any cliff edge effects.
- Selection of DECs: should use deterministic and probabilistic analysis and engineering judgement.
- Assessment of DECs: should use best estimate methodology. Sensitivity analysis should be performed to avoid any cliff edge effects.

Review of Definitions and Requirements

- The Western Europe Nuclear Regulators Association (WENRA) Safety Reference Levels (RLs) 2014 adopted DECs definitions similar to IAEA SSR-2/1:
  - DEC A for which prevention of severe fuel damage in the core or in the spent fuel storage can be achieved;
  - DEC B with postulated severe fuel damage.
- Objective: to further improve the safety of the nuclear power plant.
- Selection of DECs: consider those events and combinations of events, which cannot be considered with a high degree of confidence to be extremely unlikely to occur and which may lead to severe fuel damage in the core or in the spent fuel storage.
- Assessment of DECs: should rely on best estimate assumptions, all available devices can be used in the mitigation.
  - The consideration of uncertainties is useful to ensure that the best estimate results constitute a meaningful basis for the mitigation strategy.

Review of Definitions and Requirements

- The definitions of DEC-A in EUR, WENRA and IAEA documents are similar, with minor differences in sub-divisions and terminologies.
- The EUR requirements are applicable to new plants, the WENRA requirements are applicable to operating plants, while IAEA requirements are applicable to both (albeit more for new plants). → more detailed IAEA recommendations.
- The common objective is to improve safety in plant states not considered in traditional DBA events.
- The common recommendation is to use best-estimate methods for DEC-A analysis to avoid undue conservatisms.
- IAEA recommends sensitivity analysis to avoid cliff edge effects, WENRA suggests consideration of uncertainties.
- There may exist significant differences in the terminologies, interpretation and implementation by different countries and/or organizations. → need to be clarified.

Review of Current Status of Knowledge

- For certain DEC-A scenarios, complex physical phenomena could take place and may lead to the occurrence of nonlinear evolution behaviors like the cliff-edge effects.
  - For some phenomena, the current level of knowledge and modeling capabilities are limited and requires additional experimental investigations and code validation efforts.
  - Some of these topics are addressed within the OECD/NEA experimental projects like the ATLAS and ETHARINUS and in other dedicated facilities like the IRSN MIDI facility.
  - Phenomena like natural circulation flow, reversal and stability, heat and mass transfer at free boiling pool surface still require advanced experimental and analytical efforts.

DEC-A Scenario	ATLAS	PKL
Small-Break LOCA (SB-LOCA) with additional safety system failures		PKLIII H1 test
Station Blackout (SBO) transients	ATLAS A1 & A2 tests ATLAS3 C4.1 test	PKLIII H2 test
Extended loss of alternating current power (ELAP)		PKLIII I4.2 test
IBLOCA with additional safety system failures		PKLIIIi 2.2 test PKLIII J2 test
Cool-down after multiple steam generator tube rupture (SGTR)		PKLIIIi 6.1 test PKLIII J5 test
Steam Line Break (SLB) with SGTR	ATLAS2 B4.1 test	
Shutdown Coolability without residual heat removal system (RHRS)	ATLAS2 B4.2 test	PKLIII H3 test
Total loss of heat sink	ATLAS3 C4.2 test	

Review of Current Status of Knowledge

- The current DBA design/safety limits can be used for DEC-A analysis, but alternative criteria may be proposed to simplify the analysis or be consistent with the best estimate analysis methods.
- The existing DBA analysis codes can be used for DEC-A analysis, provided extended validation for DEC-A scenarios are made.
- Best estimate (or realistic) analysis method can be used, but conservative assumptions can be used in situations where knowledge is poor.
- Consideration of uncertainties and sensitivity analysis are useful and recommended.
- The integrated DSA/PSA methods are very promising to be applied to DEC-A analysis:
  - Extended best estimate plus uncertainty (EBEPU) methodology or Integrated Probabilistic DSA (IPDSA) by adding probabilistic information on the availability of the safety functions (either systems or manual actions);
  - Integrated Dynamic PSA (IDPSA) methods by adding the influence of the dynamics onto the probabilistic modeling.

Review of Current Practices

- A questionnaire with 36 questions was prepared to collect feedback from participating organizations/countries
- A review of the 25 answers from 30 participating organizations and 20 countries was made on:
  - Scenarios selection
  - Phenomenology identification and ranking
  - Acceptance Criteria Definition
  - Code selection and applicability assessment
  - Analysis methods
  - Treatment of cliff edge effects
  - Typical plant safety improvements
  - Documentation
- The key issues and challenges were identified
- Good practices were recommended for any future DEC-A analysis.

Key Issues and Challenges

- Definition of “Significant fuel degradation” or “Core melt” for DEC-A scenarios
  - The definition of DEC without “Significant fuel degradation” or “Core melt” is fuzzy in different documents (IAEA, WENRA, EUR)
  - The boundary between DEC-A and DEC-B is subject to interpretations (by occurrence frequency, consequence?) → clarifications needed
  - Use of PSA in selection and grouping of DEC-A scenarios is not a common practice → Combined with engineering judgement
- Objective of DEC-A analysis
  - The objective of DEC-A analysis is subject to interpretations (safety improvements to prevent or avoid “Significant fuel degradation” or “Core melt”, or compliance with criteria) → clarifications needed
- Criteria for DEC-A analysis
  - The DBA design or safety criteria are commonly used for DEC-A → consistency with the realistic method?
  - Conservative surrogate design or safety criteria are sometimes defined to accommodate the realistic (or best estimate) analysis method → to compensate the unquantified uncertainties or “cliff edge effect”?
  - Alternative criteria may be defined (e.g., Beta layer oxidation thickness, number of burst rods…)?

INTERNAL

Key Issues and Challenges

- Codes for DEC-A analysis
  - In addition to the thermal hydraulics, neutron physics and fuel rod thermal mechanical codes as used for the DBA analysis, multi-physics codes, severe accident codes and computational fluids dynamics codes are also used for DEC-A analysis
  - Extended validation of these codes under DEC-A conditions are needed → validation database sufficient?
- Methods for DEC-A analysis
  - Conservative, combined, best estimate plus uncertainty (BEPU) and realistic methods are used in a hybrid manner
  - Use of the recommended realistic method may not be enough (e.g., in case of insufficient margins or lack of knowledge) → BEPU method is recommended for limiting DEC-A scenarios with insufficient margins
  - Integrated DSA and PSA (IDPSA) would be a promising method, but practical tools are needed
- Assumptions for DEC-A analysis
  - No single failure, but only qualified safety features are credited
  - Operator actions are considered, but how to account for the (large) uncertainties?

Good Practices

- Definition of DEC-A scenarios
  - Use PSA, and use time-dependent CDF
  - Reduce engineering judgement
  - Group DEC-A scenarios as per functional challenge and identify enveloping scenario
  - Focus on most penalizing sequences and scenarios
  - Have a common list of DEC-A scenarios (design specific)
  - Merge DEC-A and DEC-B events?
- Definition of criteria for DEC-A
  - Use of DBA criteria as practical as possible
  - Justify alternative criteria
- Code and model development:
  - Use latest and validated code version
  - Use detailed thermal-hydraulics and multi-physics codes
  - Extended validation of codes for covering DEC-A conditions

INTERNAL

Good Practices

- Methods for DEC A analysis:
  - Adopt a commensurate approach with the main objective to improve the safety of the NPPs.
  - Use realistic method: BE assumptions for initial and boundary conditions should be used if necessary and possible, conservative assumptions must be avoided or minimized.
  - Use BEPU method to consider uncertainties for limiting DEC-A scenarios with insufficient margins
  - Use PSA to evaluate proposed changes in SSCs or accident procedures, by ensuring a good cooperation between DSA and PSA specialists.
  - Justify the timings for operator actions.
- Others:
  - Extend scope to DEC-B for operating NPPs.
  - Extend scope to non-water cooled NPPs.

Conclusions

- Although there are certain small differences in the EUR, WENRA, and IAEA definitions and requirements of the DEC-A analysis, the common objective is to improve safety in plant states not considered in traditional DBA events.
  - There may exist significant differences in the interpretation and the implementation by different countries and/or organizations, which need to be clarified.
  - The current level of knowledge and modeling capabilities for some DEC-A relevant phenomena are still limited and require advanced experimental and analytical efforts.
- Good practices in the general approach to DEC-A analysis, the code and model development, and sensitivity analysis and use of PSA were identified.
- The outcomes of the review as well as the recommendations will be documented in a NEA status report to be published in 2024.

Further Reading

1. EUR, “European Utility Requirements for LWR Nuclear Power Plants,” Revision E (2017).
2. EUR Training Course 2022, Budapest, October 19-20 (2022).
3. WENRA, “WENRA Safety Reference Levels for Existing Reactors”, Revision 2008 (2008); Revision 2014 (2014); Revision 2020 (2021).
4. WENRA-RHWG, “Issue F: Design Extension of Existing Reactors”, Guidance Document, October (2014).
5. International Atomic Energy Agency, “Safety of Nuclear Power Plants: Design”, Specific Safety Requirements SSR-2/1, Revision 1, IAEA (2016).
6. International Atomic Energy Agency, “Safety Assessment for Facilities and Activities”, General Safety Requirements GSR Part 4, Revision 1, IAEA (2016).
7. International Atomic Energy Agency, “IAEA Safety Glossary. Terminology Used in Nuclear Safety and Radiation Protection - 2018 Edition”, IAEA (2018).
8. International Atomic Energy Agency, “Fundamental Safety Principles", IAEA Safety Standards Series No. SF-1, IAEA (2006).
9. International Atomic Energy Agency, “Deterministic Safety Analysis for Nuclear Power Plants,” Safety Standards Series, Specific Safety Guide SSG-2 (Rev. 1), IAEA (2019).
10. International Atomic Energy Agency, “Design of the Reactor Core for Nuclear Power Plants”, Safety Standards Series, Specific Safety Guide SSG-52, IAEA (2019).
11. International Atomic Energy Agency, “Considerations on the Application of the IAEA Safety Requirements for the Design of Nuclear Power Plants”, IAEA-TECDOC-1791, IAEA (2016).
12. J. Zhang, et al., “Good Practices for Analyses of Design Extension Condition without Significant Fuel Degradation for Operating Nuclear Power Plants,” The 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20), Washington D.C., USA, August 20–25, 2023.