THE NUCLEAR SIMULATION CHAIN OF GRS

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Abstract

In order to simulate all relevant phenomena within a nuclear power plant during normal operation, incidents, accidents and severe accidents, GRS uses different largely self-developed and validated methods and computer codes. These codes are forming the so-called nuclear simulation chain covering phenomena of neutron kinetics, thermal hydraulics within the cooling circuit and containment as well as structural mechanics. By developing most of the codes by its own, GRS gets an enhanced understanding of the related physical phenomena and remains independent of other (commercial) organizations. In parallel, GRS also uses third party codes and develops interfaces to its own codes. Due to decreased funding, GRS co-operates also with other organizations when developing its codes. In order to stay and effect on the current state of science and technology, GRS takes part continuously in national and international projects, especially in experimental programs. The codes can be licenced by interested organizations in order to increase the worldwide nuclear safety standards. This paper shows first an overview about the whole simulation chain, while secondly the motivation of the further development of the nuclear simulation for advanced light water reactors (ALWR) is described.

1. INTRODUCTION

In Germany, the Atomic Energy Act (AtG) [1] is the legal basis for the construction, operation, modifications as well as decommissioning and dismantling of nuclear power plants (NPP) and other nuclear facilities. The required safety is regulated by laws, regulations, technical rules and policies. These safety requirements are adapted to the latest developments and insights; an important measure for this is the current state of science and technology [2]. In the nuclear licensing and supervisory procedures, the compliance with these requirements is assessed, confirmed and monitored during the entire life time. Safety assessments of NPP and other nuclear facilities are extremely complex. Technical, as well as organizational, issues have to be considered. The technical complexity comes up because the plants are very different themselves, built at sites with different conditions, and are equipped with various types of reactors and components.

The independent and nonprofit Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH is the main Technical Support Organisation (TSO) in nuclear safety for the German federal government and active in all of the above-mentioned activities. Additionally, GRS is a major research organization. Over 60 technical experts are developing and validating amongst others a nuclear simulation chain, which allows the simulation and assessment of all relevant phenomena for the analysis of operational states, incidents, accidents and severe accidents in NPP and in other nuclear facilities. The scientific basis for the code development and validation activities is built by new insights on physical phenomena, reliable plant and experimental data, as well as information gained from operational occurrences or accidents. Because GRS operates no test rigs, monitoring and evaluation of the results of national and international reactor safety research network projects, and especially the participation in experimental programs, are an essential part of the work. Through its national and international research and expert activities, GRS is able to consider, in this context, the current state of science and technology.
2. NUCLEAR SIMULATION CHAIN

Today, a comprehensive, historically grown scientific code system is available at GRS. In general, GRS develops, as far as possible, its own codes, because this approach leads to an improved understanding of the relevant physical phenomena. This approach allows GRS to be independent of the interests of commercial software developers and therefore to improve selected codes to respond faster and more flexible to current events.

![Nuclear Simulation Chain of GRS](image)

**FIG. 1 Nuclear Simulation Chain of GRS [3].**

The structure of this nuclear simulation chain is depicted in Fig. 1 [3]. It consists of GRS’ own developments (deep blue boxes) and third party codes (white boxes). Many codes can be coupled simply for data transfer (indicated by dotted lines in Fig. 1) or in a more complex way through interfaces (indicated by red lines in Fig. 1). The latter option requires the development of appropriate interfaces. The advantages of coupling will be discussed more detailed later in this section.

The codes are assigned to main research fields: reactor physics, thermal-hydraulics/severe core damage and structural mechanics (columns in Fig. 1). The systems/components: reactor core, reactor coolant system (RCS), containment which can be simulated with the codes are arranged in rows and correspond to the respective fundamental safety functions control of reactivity, core cooling and enclosure of radioactivity. In addition, there is a fourth row, which contains other codes (e.g. for visualization, sensitivity, uncertainty and probabilistic dynamic analysis). The purposes of the main codes developed and/or used by GRS and sorted by research fields are explained in the following:

- **reactor physics**
  - DORT/TORT: solution of time-dependent neutron transport equations for 2D/3D transients
  - QUABOX/CUBBOX: 3-D neutron kinetics core model
  - KENOREST: prediction of the characteristics of irradiated light water reactor fuels
  - VENTINA: calculation of burn-up nuclide inventories
  - KMacs: modular adaptable core simulator
- **thermal-hydraulics/severe core damage**
  - AC³: code system consisting of the codes ATHLET, ATHLET-CD and COCOSYS
  - ATHLET: lumped parameter code for analysis of leaks and transients in the RCS,
- ATHLET-CD: extension of ATHLET for severe accident analyses in the RCS including core meltdown and fission product release
- COCOSYS: detailed LP code for analysis of conditions within the containment and buildings of NPP in case of accidents and severe accidents
  - structural mechanics
  - PROST: probabilistic analysis of structural reliability of piping/vessels
  - WinLeck: analysis of leak areas and discharge flow rates based on geometry, material, medium
  - ASTOR: simplified procedures for the integrity assessment of reactor pressure vessels (RPVs) and piping loaded under internal pressure and high temperatures concerning failure times
  - TESPA-ROD: strain and burst behavior of a fuel rod under of a LOCA conditions
- others
  - ATLAS: analysis simulator for pre-processing, visualization of results and interactive control of the simulation of several computer codes
  - SUncISTT: determination of sensitivities/uncertainties in criticality, inventory, source term tool
  - SUSA: uncertainty/sensitivity analyses
  - XSUSA: nuclear cross section uncertainty/sensitivity analysis
  - MCDET: Monte Carlo event tree for probabilistic assessment of consequences of (severe) accident scenarios

The advantage of the nuclear simulation chain is that selected modules and/or codes can be coupled if necessary. Below considerations for couplings of codes within a research field or research field overarching are discussed. For example in Fig. 1 it can be seen that three different methodologies exist for the calculation of the thermal-hydraulics in the RCS. These are the system code approach (AC\(^2\)), the CFD code approach (ANSYS/CFX or OpenFOAM) or the coupled system and CFD code approach (AC\(^2\) and ANSYS/CFX or AC\(^2\) and OpenFOAM). The selection of the appropriate approach and code for the respective issue is based on the necessary spatial resolution. With the latter mentioned options, it is possible to determine the overall RCS behavior by the LP code while relevant parts being of special interest can be calculated in a detailed 3D solution. In general, the same considerations can be applied also for the containment. In this research field, work is ongoing to couple COCOSYS with a 3D water pool model CoPool [4].

The starting point of the research field overarching consideration is the simulation of a design basis accident (DBA) with the ATHLET code (now integrated in AC\(^2\)). Further codes can be coupled to consider detailed phenomena/processes such as QUABOX/QUBOX for the detailed simulation of 3D neutron kinetic in the core or CFD codes like ANSYS/CFX or OpenFOAM for the simulation of 2D/3D velocity, temperature and concentration fields in the RCS or the containment. If the DBA is progressing into a beyond design basis accident (BDA) or a severe accident, in which for example core melt and melt relocation occurs, the user can pass over to the ATHLET-CD (also included in AC\(^2\)). ATHLET-CD can be operated in coupled mode again with COCOSYS (also included in AC\(^2\)) for whole plant analysis including fission product behavior and release into the environment. In the near future, it is also intended to couple AC\(^2\) with ASTOR to consider structure mechanics aspects of RCS behavior under steady state and dynamic loads or fluid/structure interactions [5].

All applied codes are systematically validated, e.g. the thermal-hydraulic codes based on a well-balanced set of integral and separate effect tests e.g. derived from CSNI code validation matrices.

3. MOTIVATION FOR FURTHER DEVELOPMENT OF THE NUCLEAR SIMULATION CHAIN UNDER CONSIDERATION OF THE CURRENT GERMAN AND EUROPEAN ENERGY POLICY

After the Fukushima nuclear disaster the German federal government decided to terminate the use of nuclear energy latest in 2022 (13th amendment of the atomic energy law in March 2011) [6]. The government decided to shut down permanently 8 NPPs (GKN-1, KKB, KKK, KKP-1, KRU, KW-B, KW-2, KI). Nine NPPs have been continuing operation, but the time points when the operation permission of the respective NPP expires has been fixed (2015: KKG, 2017: KRB-B, 2019: KKP-2, 2021: KBR, KRB-C and KWG, 2022: GKN-2, KKE, KKI-2). Under these special political conditions it is important, to illustrate our numerous national and international partners, how the further development of the nuclear simulation chain of GRS continues.
The further development of the GRS nuclear simulation chain takes into account two (a national and an international) aspects. The national aspect is based on the common understanding of all German stakeholders, that in the remaining operating time of the German NPP, the high safety standard shall be maintained and further improved. During the structured phasing-out safety must be guaranteed in line with the latest developments in science and technology. This requires besides extensive training at universities and colleges, for the next generation of scientists and personal working in utilities, approval authorities and TSO also the further development and validation of the nuclear simulation tools.

In Europe, national government policies differ on the further use of nuclear energy for electricity generation. Many countries (e.g. Russia, UK, Finland, Hungary, Poland) are planning to build new NPPs or at least maintain and/or extend their operating time. Currently 27% of all electricity consumed in the European Union (EU) is generated by NPPs. All scenarios of the Energy roadmap 2050 of the European Commission (EC) include the reliance on nuclear power. This implies both an increasing role for long-term operation and the construction and grid connection of new builds [7]. The projection in the latest Nuclear Illustrative Programme (PINC) forecasts a stable nuclear capacity in Europe between 95 and 105 GW from 2030 onwards. At this time, roughly 80-90% of the installed capacity would be new builds [8], mainly Advanced Light Water Reactors (ALWR) considering important lessons learnt from the Fukushima event (such as the control of long term station blackouts) and the EU Stress Tests. For the reception of legitimate nuclear safety and/or security interests German authorities require in this context own and independent expertise for the safety assessments of NPPs and other nuclear facilities in our neighbourhood on an international level of science and technology.

Reactor technology has been developed and improved for almost five decades. The ALWR designs are now ready to solve the future EU energy supply shortfall problem. They incorporate passive safety features (PSFs) which do not require any active controls or operational intervention to manage accidents. The PSFs work according to basic laws of physics such as gravity and natural convection and are automatically initiated. By combining these PSFs with proven active safety features (ASFs), the ALWR can be considered to be amongst the safest equipment ever made [9]. In Gen III+ reactors, DBA can be solely controlled by PSF.

Current nuclear rules and regulation as well as evidence tools were largely developed for Gen II NPPs relying on an ASF. Although they are generic and reactor-design independent, it must be ensured whether they can treat all aspects of PSFs reasonably. This includes inter alia the mutual influence between ASFs and PSFs, of the PSFs with each other, of different trains of PSFs with each other and the application postulates (e.g. failure of trains of systems and the single failure concept). The widely different definitions for PSF currently used, cause difficulties in applying nuclear rules and regulations. The most common definitions originate e.g. from the IAEA, EPRI and the German Safety Requirements for Nuclear Power Plants. They differ e.g. concerning the degree of passivity, the supply of auxiliary energy to initiate the system start. Even today, numerous still open questions addressed in [10], have to be answered prior to the implementation of PSFs:

- Which initial and boundary conditions do PSFs require for their operation? Is it ensured that these conditions will be present in case of challenge?
- How to test PSFs? How to evaluate its reliability, if the PSF cannot be inspected or periodically tested after installation? Are damages leading to failure of a PSF detected reliably? How to evaluate ageing materials? How do PSFs behave under deviating conditions?
- Which redundancies do PSFs require? Must a single error be postulated? How to assess the elimination of human actions (human errors are excluded, but PSFs cannot be used for AM).

Current discussions on these topics, are taking place at the International Project on Innovative Nuclear Reactors and Fuel Cycles of the IAEA, the Working Group on the Regulation of New Reactors of the Western Nuclear Regulators Association (WENRA), the Committee on Nuclear Regulatory Activities (CNRA) of the Organisation for Economic Cooperation and Development / Nuclear Energy Agency (OECD / NEA), the Working Group Safety Fluid Systems of the European TSO Network (ETSON) and NUGENIA. The results of these discussions are continuously monitored by GRS and implemented in nuclear simulation chain. Selected examples will be presented in the following GRS contribution on the qualification of AC2 [11].

4. CONCLUSIONS AND OUTLOOK

Despite the termination of the use of nuclear energy, the German Federal government will support the further development and validation of the nuclear simulation chain consisting of methods and computer codes
covering all relevant phenomena of (neutron kinetics, thermal hydraulics within the cooling circuit and containment as well as structural mechanics) of NPPs and other nuclear facilities also in future. This is done basically for two reasons: first to guarantee the safe operation of the German NPPs during the structured phasing-out for the next 5 years which require the preservation of nuclear simulation tools with the latest developments in science and technology and second to support the German authorities at the reception of legitimate national nuclear safety and/or security interests (e.g. for the lifetime extension of existing NPPs and new builds) in our neighbourhood.

Even under the new German energy policy framework GRS remains a stable partner for all topics of code development, validation, application, code transfer and user support and training and will continue to participate in all relevant national and international projects. The (codes of the) GRS nuclear simulation chain, are being – even beyond 2022 – further developed and validated for (all already existing as well as existing then upcoming) issues and will thereby substantially contribute to increase the worldwide nuclear safety standards.

ACKNOWLEDGEMENTS

The development of the GRS nuclear simulation chain is currently funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) within several projects (essentially RS1507, RS1518, RS1520, RS1526, RS1532, RS1535, RS1540, RS 1538, RS1543, RS1546, RS1547).

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