NuScale SMR 3-D modelling and analysis of boron dilution with the system code ATHLET in the framework of McSAFER

E. Diaz-Pescador
Helmholtz-Zentrum Dresden Rossendorf (HZDR)
01328 Dresden, Germany
e.diaz-pescador@hzdr.de

M. Jobst, S. Kliem
Helmholtz-Zentrum Dresden Rossendorf (HZDR)
01328 Dresden, Germany
m.jobst@hzdr.de, s.kliem@hzdr.de

ABSTRACT

The small modular reactor (SMR) NuScale is modelled by Helmholtz-Zentrum Dresden Rossendorf (HZDR) in the framework of the European McSAFER project. NuScale is a SMR of integral pressurized type operated with light water driven by natural circulation. This work summarizes the NuScale SMR modelling approach with the system code ATHLET and presents the results from an inadvertent boron dilution sequence, based on the Design Certification Application (DCA). Steady-state and transient results show agreement, thereby demonstrating ATHLET strong simulation capabilities on complex transients applied to SMR designs. The results show a decrease in core nominal boron concentration and subsequent reactivity insertion by boron feedback. The reactor is tripped upon "high pressurizer pressure" function and the actuation of the decay heat removal system provides long-term heat removal.

1. INTRODUCTION

Nuclear power constitutes one of the largest sources of low-carbon baseload electricity. It represents a reliable source for climate change mitigation and a viable solution to meet energy supply security. In the current worldwide decarbonization context, the development and deployment of SMRs is receiving increasing attention by several countries and organizations due to cost reduction, energy flexibility and advanced safety features. The deployment of SMRs in Europe is envisaged to be promoted following recent modifications in the European Union (EU) Taxonomy Regulation, which includes nuclear activities as part of the roadmap for the decarbonisation of the Union's economy by 2050. More concisely, the EU Taxonomy envisages the construction of new nuclear power plants (NPPs) using best available technologies, highlighting new generation of water cooled SMRs.

The NuScale Power Module (NPM) consists of a water cooled SMR, developed by NuScale Power LLC in the USA for electricity production and non-electrical process heat applications [1]. One of the unique features of NuScale consists of passive heat removal by natural convection in all operation modes. Natural convection is driven by differences in coolant densities, thereby reducing reactor size and components as well as eliminating pumps inside reactor coolant system (RCS). This leads to a higher reactor simplicity and reduction of core damage frequency compared to existing reactor designs [1].

The SMR NuScale design is modelled by HZDR in the framework of the European McSAFER project, which is devoted to high-fidelity calculations by state-of-the-art multiscale and multi-physics techniques applied to safety analyses in SMRs [2]. The work presented in this contribution highlights the development of a thermohydraulic model of NuScale SMR with the best estimate code ATHLET and includes discussion of results from applied safety analyses. The reference accident scenario is an inadvertent deboration through the make-up line of the chemical and volume control system (CVCS) at hot full power. This event is based on one of the accident scenarios from the DCA report [1].

The thermohydraulic model of NuScale SMR comprises a state-of-the-art 3-D integral reactor pressure vessel (RPV) and two helical coil steam generators (HCSG) with extended secondary-side piping beyond isolation valves. The 3-D RPV in ATHLET is built upon parallel multichannel approach. This approach is supported by ATHLET 3D-Module through rectangular and cylindrical grids and extension of momentum balance equation convective term in 2-D/3-D Cartesian and cylindrical coordinates [3].

This allows consideration of cross-flow momentum transport and simulation of 3-D phenomena such as coolant mixing. This modelling approach is intended to provide a more realistic representation of multidimensional flows, especially inside downcomer and riser regions. The presented NuScale 3-D RPV model benefits from the modelling experience gained by the authors in previous studies applied to other reactivity-initiated accidents [4,5]. The SMR features, ATHLET modelling as well as discussion and conclusions from simulation results are introduced in the following sections.

2. NUSCALE SMR AND ATHLET MODELLING

2.1. NUSCALE POWER MODULE

The NuScale Power Module (NPM) consists of a SMR of integral pressurized water reactor (PWR) type operated with light water driven by natural circulation with reactor core, HCSGs and pressurizer system located in a common reactor vessel enclosed in a cylindrical steel containment. The containment is submerged in a water pool, which constitutes the ultimate heat sink. The pressurizer is enclosed in the RPV upper head and provides pressure control by actuation of spray nozzles and two immersion heat bundles, each providing 400 kW during normal operation. The nominal core power accounts for 160 MW_{th} with an electrical output of 50 MW_{e}. The layout of NuScale Power Plant is depicted in Fig. 1.

The 2 HCSGs comprise 1380 tubes, arranged in several bundle sets connected to inlet and outlet plena. Subcooled water is injected by feedwater pumps and superheated steam is generated inside the tubes. Upon abnormal or accident conditions, two diverse and redundant passive safety systems bring decay heat from reactor core into containment pool. The decay heat removal system (DHRS) lines are connected to the secondary side piping and provide heat removal through two heat exchangers submerged in the water pool. The emergency core cooling system consists of a set of 3 reactor vent and 2 recirculation valves to provide core cooling in case of loss-of-coolant-accident events. Finally, the water pool provides containment passive cooling and reduction of containment pressure.

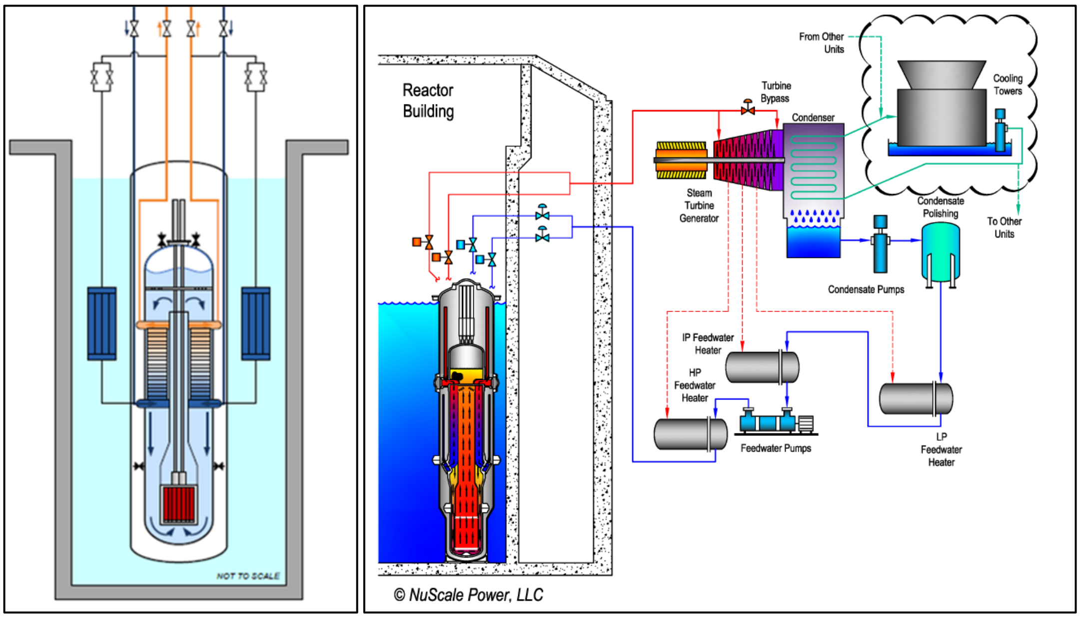

Fig. 1. NuScale Power Module layout [1]

2.2. ATHLET MODEL

The thermohydraulic model of NuScale Power Plant is developed with the best estimate system code ATHLET [3], based on available geometric data from the DCA report [1] and engineering judgement assumptions. The model layout is displayed in Fig. 2. The main systems and components are listed as:

1. 3-D reactor pressure vessel
2. Helical coil steam generators
3. Feedwater and steam lines
4. Decay heat removal system

5. Chemical and volume control system

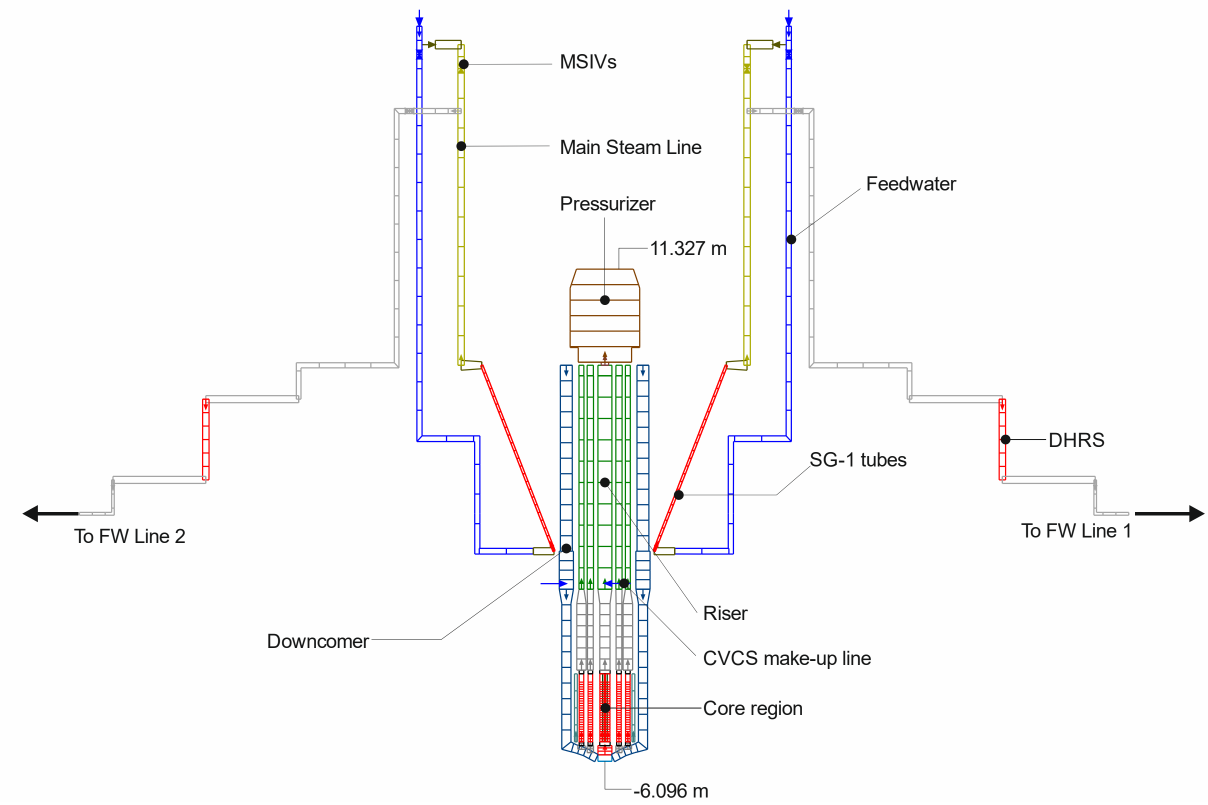

Fig. 2. ATHLET nodalization of NuScale SMR

The main component of the thermohydraulic model is the 3-D RPV, which is built upon cylindrical and rectangular grids based on the massive representation of vertical (1-D) parallel channels. Hydraulic channels are connected by cross-connection objects and single junction pipes. The RPV topology comprises three main regions; downcomer annulus, those regions inside the downcomer-to-riser walls and pressurizer vessel on top. The downcomer is discretized in a rectangular grid, whereas those regions inside downcomer-to-riser walls are discretized by two radial rings surrounding a central channel in a cylindrical grid. The core region comprises lower and upper support plates, radial reflector and fuel assemblies, arranged in a rectangular grid with individual representation of each channel.

The RPV and HCSG include heat structures for the simulation of heat transfer processes. The core comprises 37 fuel assemblies, each in a fuel matrix of 17x17-25. A dedicated fuel rod model provides simulation of nuclear heat generation. The 1380 HCSG tubes are modelled by inclined (straight) pipes to preserve overall heat transfer surface and design symmetry. Enhanced heat transfer [6] is achieved by implementation of a geometry multiplication factor in the heat conduction objects (HCOs). The pressurizer heaters are modelled by two separated HCOs integrated in the pressurizer vessel. The insulation losses are input by stationary heat flow controlled by a heat transfer coefficient.

The secondary side includes two feedwater and steam lines, which extend beyond the main isolation valves and are connected to inlet and outlet HCSG plena. Feedwater flow is provided by fill-objects (massflow/enthalpy boundary condition) at the inlet of feedwater piping, and the outlet of the steam lines is connected to time-dependent volume objects (pressure/enthalpy boundary condition). The DHRS consists of two lines connected to main steam and feedwater lines. The water pool outside containment vessel is modelled by a fixed temperature boundary condition of 37°C imposed over the DHRS heat exchanger. Finally, the CVCS is represented by make-up and letdown lines, which are modelled by fill-objects connected to riser and downcomer regions, respectively. The actuation of the several reactor systems follows the engineered safety features actuation system (ESFAS) and is controlled by the GCSM module. Those are introduced in Section 3 together with the analysis of the transient results.

2.3. BORON DILUTION SCENARIO

The scenario is started by an inadvertent deboration through the make-up line of the CVCS at a rate of 3.15 kg/s and 4.85°C. The transient calculation is started at hot full power and beginning of cycle with a nominal boron concentration of 1600 ppm. Deboration inside the vessel is calculated with the profile model boron tracking. Neutronic calculation is conducted with the point kinetics model and conservative boron (-10 pcm/ppm), moderator (0.0 pcm/K) and Doppler coefficients (-2.52 pcm/K). Decay heat generation is based on an ANS-94 time-dependent table. The model includes a hot pin fuel assembly with a hot channel factor of 2.0 for the evaluation of departure from nucleate boiling ratio (DNBR).

3. ANALYSIS OF THE RESULTS

Prior to the implementation of the boundary conditions over the simulation, a 6000 s zero-transient calculation is performed with ATHLET to reach stable conditions before the beginning of transient calculation. The results are gathered in Table 1 together with comparison to NuScale DCA report.

Parameter	Unit	DCA	HZDR	Error (%)
Primary pressure	bar	127.55	126.70	0.66
Core inlet temperature	degC	258.33	254.70	1.40
Core outlet temperature	degC	313.89	315.12	0.39
RCS mass flow rate	kg/s	535.24	531.31	0.73
Core mass flow rate	kg/s	496.17	490.49	1.14
Pressurizer level	%	60.00	59.59	0.68
Feed water mass flow rate	kg/s	67.07	67.07	0.00
HCSG inlet temperature	degC	148.72	148.30	0.28
HCSG outlet temperature	degC	306.89	311.64	1.54
Secondary pressure	bar	34.47	33.50	2.81

Table 1. Steady state parameters

Firstly, a transient calculation has been performed at constant power (without reactivity feedbacks) to assess the boron front propagation along the vessel and time for loss of shutdown margin (SDM) below 1388 ppm, which is reached at 1884 s in the DCA report. The results in ATHLET show agreement with a loss of SDM at 1879 s. The transient calculation with point kinetics is started with the injection of cold and non-borated water into the riser section through the make-up line at a rate of 3.15 kg/s. This leads to a continuous reduction in boron concentration at the core and to positive reactivity insertion by the boron feedback and a subsequent core power increase. This behaviour is observed in Fig. 3.

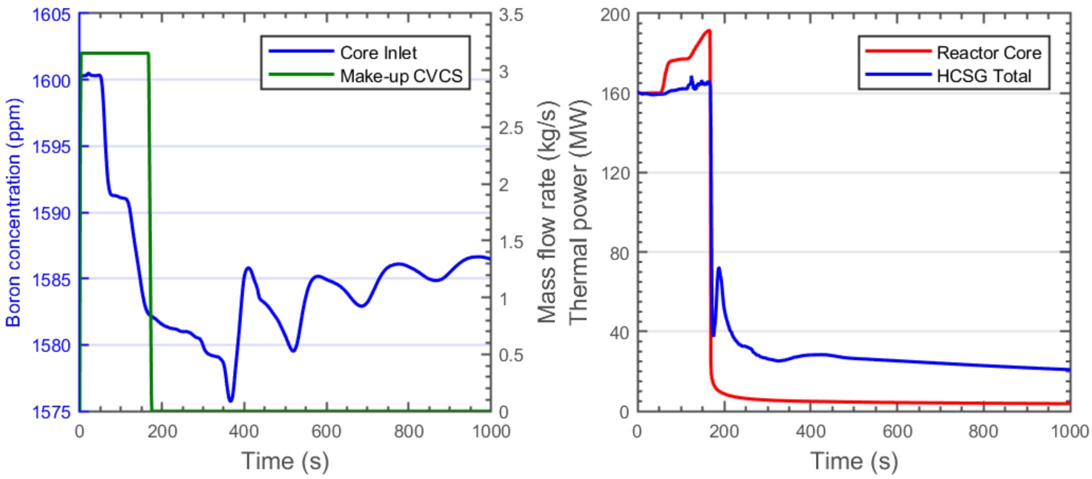

Fig. 3. Boron concentration and CVCS mass flow rate (left) and system powers (right)

The core power increase leads to a heat-up of the RCS with subsequent coolant thermal expansion, pressure and pressurizer level increase (see Fig. 4). At around 168 s, the reactor is tripped following “high pressurizer pressure” function at 137.89 bar. This setpoint also constitutes the ESFAS function for secondary side isolation (5 s closing time) and actuation of the DHRS isolation valves (30 s opening time). The control rods are fully inserted within 2 s, providing enough negative reactivity to shut down the reactor. The reactivity contribution is depicted in Fig. 5. Following reactor trip, the fission chain reaction is terminated and core outlet temperature decreases drastically leading to a rapid fall in natural circulation mass flow rates, as observed in Fig. 4. From then on, the core ΔT corresponds to the decay heat power generated by the decaying fission products.

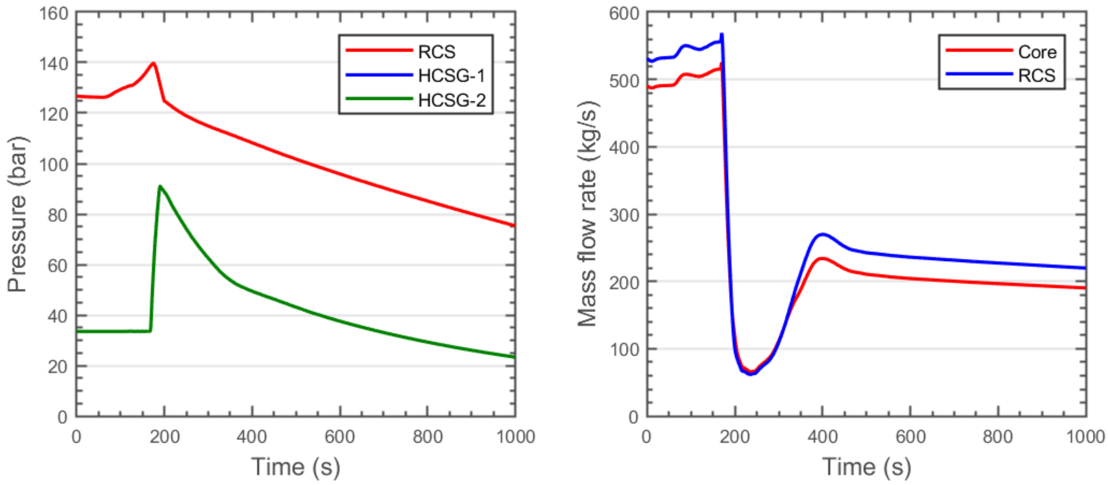

Fig. 4. System pressures (left) and mass flow rates (right)

After “high pressurizer pressure” setpoint is reached, the ESFAS leads to the closure of the main steam and feedwater isolation valves and the secondary side is isolated at 175 s. This leads to a rapid pressure increase inside both steam generators, as observed in Fig. 4. Likewise, the ESFAS actuates (opens) the DHRS isolation valves at 199 s. The DHRS actuation provides a reliable heat sink, which cools down the RCS by stable heat removal provided by the two lines connected to the steam generators. Fig. 6 shows the stable mass flow rates and heat removal through one of the DHRS lines. Due to reactor design symmetry, the behaviour of both lines is identical in this accident scenario. The effect of the DHRS can be seen in the stable heat removal through the steam generators (see Fig. 3) and the increase and stabilization in the RCS mass flow rates following reactor trip, as observed from Fig. 4.

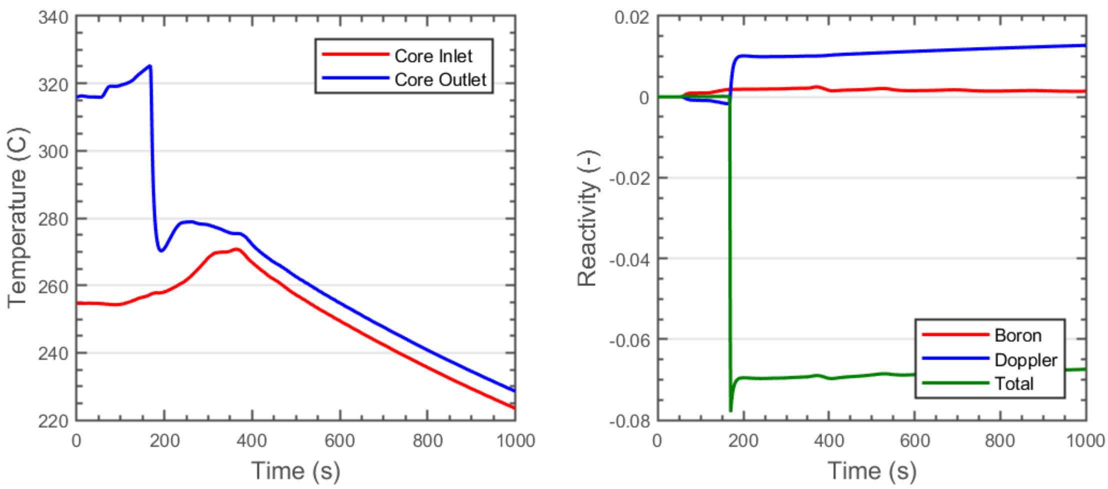

Fig. 5. Core temperatures (left) and reactivity evolution (right)

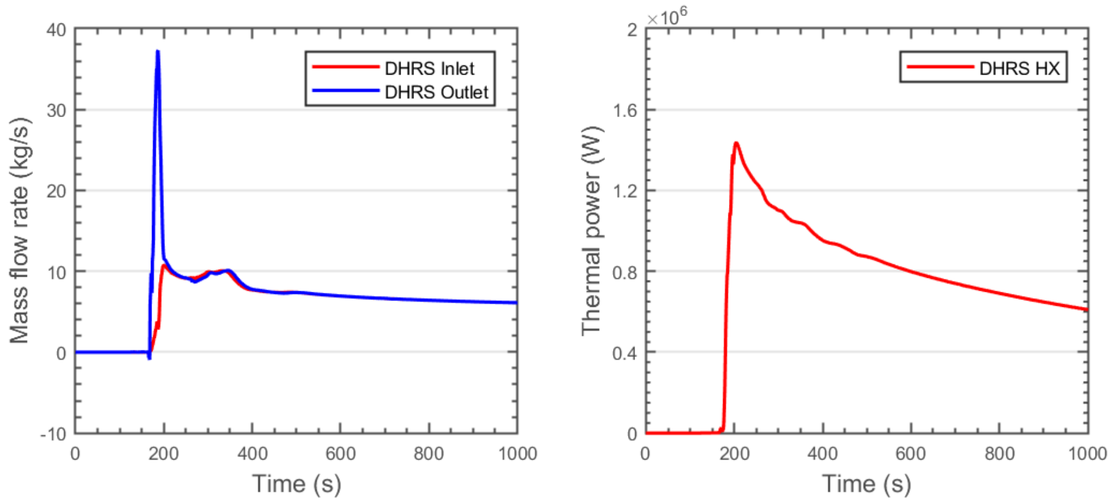

Fig. 6. DHRS line 1 mass flow rates (left) and heat removal (right)

4. CONCLUSIONS

In the framework of the McSAFER project, HZDR has developed a thermohydraulic model of NuScale SMR with the system code ATHLET. The model includes a state-of-the-art 3-D RPV, which has proven to be capable to accurately represent nominal operation conditions as well as boron transport and correct prediction of loss of SDM.The results from the inadvertent deboration show that the reactor is tripped by the “high pressurizer pressure” setpoint following an increase of core power by the positive reactivity insertion by the boron feedback. The ESFAS isolates the secondary side and activates the DHRS. The latter provides a reliable heat sink to cool down the RCS by maintaining stable natural circulation flow rates and is able to bring the reactor to a long-term safe and stable condition.

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