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# System code improvements for modelling passive safety systems and their validation

*GRS has been developing the system code ATHLET over many years. Because ATHLET, among other codes, is widely used in nuclear licensing and supervisory procedures, it has to represent the current state of science and technology. New reactor concepts such as Generation III+ and IV reactors and SMR are using passive safety systems intensively. The simulation of passive safety systems with the GRS system code ATHLET is still a big challenge, because of non-defined operation points and self-setting operation conditions. Additionally, the driving forces of passive safety systems are smaller and uncertainties of parameters have a larger impact than for active systems. This paper addresses the code validation and qualification work of ATHLET on the example of slightly inclined horizontal heat exchangers, which are e. g. used as emergency condensers (e. g. in the KERENA and the CAREM) or as heat exchanger in the passive auxiliary feed water systems (PAFS) of the APR+.*

***Erweiterungen von Systemcodes zur Modellierung passiver Sicherheitssysteme und ihre Validierung.*** *Der Systemcode ATHLET wird seit vielen Jahren von der GRS entwickelt. Da ATHLET, wie auch andere Codes, in Aufsichts- und Genehmigungsverfahren eingesetzt wird, muss es dem aktuellen Stand von Wissenschaft und Technik genügen. Passive Sicherheitssysteme werden von neuen Reaktorkonzepten wie Generation III+ und IV Reaktoren sowie SMR verstärkt genutzt. Die Simulation solcher passiven Systeme mit dem GRS-Code ATHLET ist noch immer eine große Herausforderung, da sie keine fest definierten Arbeitspunkte besitzen. Zusätzlich sind ihre treibenden Kräfte kleiner und Unsicherheiten in ihnen fallen hier stärker ins Gewicht. Dieses Paper beschreibt Validierungs- und Qualifikationsarbeiten der GRS für den Systemcode ATHLET am Beispiel von Wärmeübertragern mit leicht geneigten horizontalen Rohren, wie sie z. B. als Notkondensatoren (z. B. im KERENA oder CAREM) oder als Wärmeübertrager für ein passives Hilfsspeisewassersystem (PAFS) im APR+ eingesetzt werden sollen.*

## 1 Introduction

The system code ATHLET has been developed at GRS for many years. The acronym ATHLET stands for Analysis of the Thermal-hydraulics of Leaks and Transients. It is used for best estimate analyses of normal operation, incidents and accidents of the existing nuclear power plants. ATHLET has a substantial validation basis (e. g. LOCAs, transients, etc.) based on OECD/CSNI validation matrices, start-up and operational transients of nuclear power plants, international standard problems (ISP) and benchmarks [1].

According to World Nuclear News (WNN), currently about 80 new reactors are being planned or under construction in Europe. Most of them are of innovative design (such as ABWR, EPR, AP1000, WWER AES2006 or TOI). These designs are characterized by new features (e. g. passive safety systems, new coolants, integral designs, new operation modes). Therefore, the GRS codes must be extended in such a way, that they can be applied for safety analyses for these innovative designs which means that further. So, further code improvement and validation is required.

The safety concept of currently operated reactors is based on active safety systems. The active safety systems operate under forced convection conditions with defined operation points (such as nominal flow rates), which are achieved immediately after switching on pumps. In contrast, passive safety systems utilize basic physical laws (such as gravity, free convection, boiling, evaporation) and operate under conditions which are set on their own. The driving forces for operation are significantly smaller and change continuously with the boundary conditions. To illustrate this issue, the control of a loss of heat sink due to penetration isolation with active and passive systems for a boiling water reactor is described. The control of the accident with active safety systems is described using the example of the BWR type 72 and the control of the accident solely with passive safety systems using the example KERENA (advanced mid-power (1250 $MW_e$) boiling water reactor especially designed for mid-power grids). Both reactors have been developed by AREVA.

In case of the BWR type 72, a loss of heat sink is controlled as follows: The loss of heat sink due to a penetration isolation of the main steam lines leads to a pressure increase in the reactor pressure vessel (RPV). Scram is initiated due to the reactor protection signal "cross section areas of two main steam line isolation valves less than 85 %". After reaching the set point, the safety and relieve valves (S/R) open and steam is blown off into the wetwell. Thus, the pressure decreases and the S/R valves close. This repeats several times. Each blowoff of steam leads to a decrease of the water level in the reactor pressure vessel. During this time, the wetwell reservoir heats up due to mass and energy input. When the wetwell reaches a temperature of 50 °C, it is cooled actively by the residual heat removal system until it reaches again 40 °C. Owing to steam blow off, the water inventory in the RPV decreases. This loss is compensated by pumping water from the water reservoir of the wetwell back into the RPV.

In the KERENA case the same transient can be mitigated by passive systems (namely emergency condenser (EC), flooding pool, containment cooling condenser and the shielding/storage pool) only. Scram is activated due to the reactor protection signal "cross section areas of two main steam line isolation valves less than 85 %". After reaching the pressure set point the S/R valves open and steam is blown into the flooding pool (see Fig. 1 top left). Because of this, the pressure decreases and the valves close. Then the pressure increases again to the setpoint of the S/R valves. This procedure repeats several times. The cyclic opening of the S/R valves leads to a decrease of the water level in the RPV and the laterally connected emergency condensers. When the steam reaches the emergency condenser pipes, heat is transferred from the RPV to the flooding pools and a natural circulation with the core as heat source and the ECs as heat sink is established (see Fig. 1 top right). With further decreasing water level, the heat transfer through the ECs increases. Once the heat removal through the ECs is larger than the heat production in the core, the S/R valves stay close (see Fig. 1 bottom left). In the EC system, natural convection establishes depending on the driving pressure difference and the temperatures in- and outside of the tubes. The temperature inside the tubes corresponds to the saturation temperature of the pressure in the RPV whereas the temperature outside the tube depends on the flow and temperature fields which establish during heat input. All aforementioned parameters change continuously in time.

After approximately 10 h, the flooding pool begins to vaporize and steam enters the inerted nitrogen atmosphere of the containment which here leads to a pressure increase. After the steam gets in contact with the pipes of the building condenser, heat removal in the building condensers is initiated. The water inside the building condenser tubes is heated up and evaporates. Because the outlet of theses tubes is connected directly with the shielding/storage pool, the water in this pool is heated up and used as ultimate heat sink (Fig. 1 bottom right).

The simulation of the above described operation of passive safety systems is still a big challenge, since these systems have – compared to active systems – no defined operation points

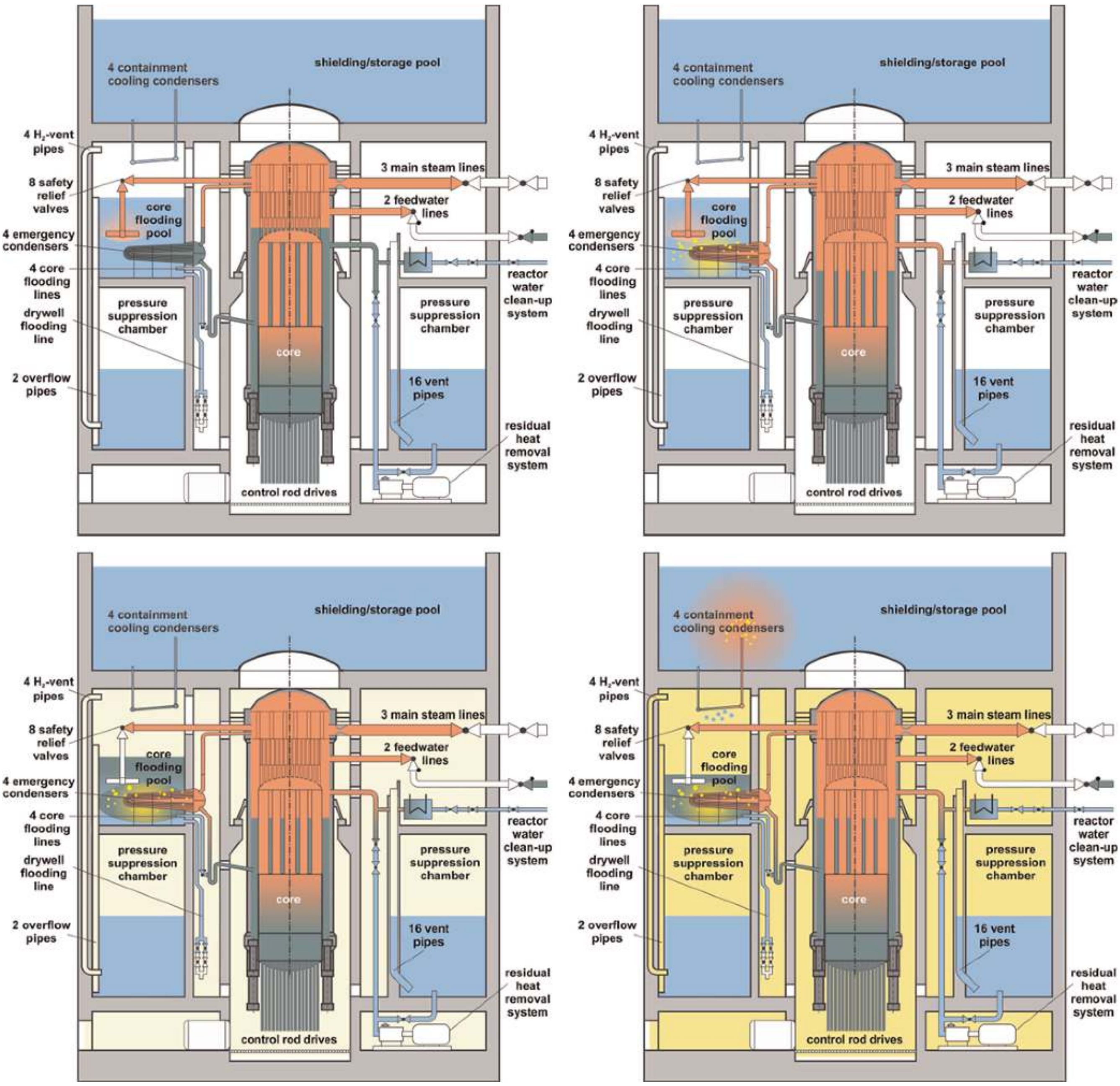


*Fig. 1. Loss of heat sink in the KERENA case, adapted from [14]*

and operate under conditions which are set on their own. Additionally, the driving forces of passive safety systems are smaller and uncertainties of parameters have a larger impact. This especially concerns the uncertainties of the initial and boundary conditions under which the passive safety systems operate. They increase with both the time period from the starting point of the event and the number of relevant phenomena or processes before a passive system starts operation.

This paper addresses the code validation and qualification work of ATHLET on the example of slightly inclined horizontal heat exchangers which are e.g. used as emergency condensers (e.g. in the KERENA and the CAREM) or as heat exchanger in the passive auxiliary feed water systems (PAFS) of the APR+. This work is presented in the following chapter.

## 2 ATHLET code validation and qualification for slightly inclined horizontal heat exchangers

During operation of the above mentioned KERENA emergency condensers, condensation of steam takes place inside the tubes and single phase natural convection or (subcooled) boiling takes place outside the tubes as sketched in Fig. 2. During condensation, different flow patterns can be observed. Figure 2 shows the flow patterns of a fluid flow through a slightly inclined horizontal heat exchanger. At the entry of the tubes, single phase vapour enters the heat exchanger. Due to condensation on the tube inner wall, annular flow establishes. In this flow region, only a thin water film occurs on the wall (see detail A-A in Fig. 2). Further condensation leads to a decrease of the steam velocity and a stratification of steam and water inside the tube (see detail B-B in Fig. 2). Further downstream slug flow, bubble flow and finally single phase water flow occur. The latter flow regime establishes only if the length of the pipe is sufficient. From these phenomenological considerations it is evident that the calculation of heat transfer coefficients in ATHLET have to consider all these phenomena/flow patterns at the in- and outside of the tubes.

Experimental investigations on the operation mode of the emergency condenser of the KERENA design and the predecessor design SWR600/1000 have been performed in Germany at the NOKO test facility in Jülich from 1994–2001 and at the INKA test facility in Karlstein since 2008 [2]. The research institutes Jülich and Rossendorf accompanied the NOKO experiments with analytical investigations using ATHLET [3, 4]. Within this work, the special package "Kondensation in waagerechten Rohren/condensation in horizontal tubes (KONWAR)" for determination of heat transfer coefficients during condensation in the tubes based on the flowmap of Tandon and during saturated and subcooled boiling on the outside based on a correlation of Stephan and Abdelsalam, was implemented into ATHLET version 1.2c in 1997 [3]. It was validated by the Forschungszentrum Jülich using the first NOKO experiments. The results were extremely promising. The only open point at that time was the experimental validation of the flow pattern map of Tandon. This should be done by using experimental data of a special instrumented single tube of the NOKO test bundle. Herein, non-condensables accumulated undesirably, due to a defective pump seal during the respective tests.

A few years later, GRS started own model improvements of ATHLET for consideration of condensation in and at horizontal heat exchanger bundles. This work focused first on horizontal heat exchanger bundles of VVER reactors [5]. The parameters differ in many relations from the emergency condenser test bundle (e.g. inner diameter, steam mass flow, flow pattern length, initial and boundary conditions, flow direction of steam and condensate). These differences lead to different phenomena to be considered in calculating the bundle behaviour.

After having prepared ATHLET for VVER-type bundles, GRS started work to empower ATHLET users to calculate condensation inside non-VVER-type horizontal tubes, too. In the following, the current model status for calculation of heat transfer in slightly inclined horizontal tube bundles like emergency condenser bundles of KERENA design is presented in chapter 2.1. Chapter 2.2 gives the results of the current validation steps for ATHLET version 3.0B.

### *2.1 Heat transfer model of ATHLET for slightly inclined horizontal heat exchanger bundles*

The standard ATHLET 3.0A heat transfer model considers [6]

- turbulent condensation in vertical pipes (correlation of Carpenter and Colburn),
- laminar condensation for vertical pipes (correlation of Nusselt),
- laminar condensation for horizontal pipes (correlation of Chato) and
- forced convection (modified Chen correlation).

First, the following four improvements were introduced into the ATHLET heat transfer package of ATHLET 3.0B:

- automatic check of the inclination of the pipe to decide if correlation for vertical or horizontal pipes are used for the calculation
- introduction of correlation of Dobson and Chato [7] for calculation of turbulent condensation in horizontal pipes
- modification of the correlation of Chen [6] in case of horizontal pipes for calculation of nucleate boiling on the outside of horizontal tubes. The correlation of Chen was developed for vertical pipes where the inner side is heated. In this case the total heat transfer coefficient $HTC_{TOT}$ is

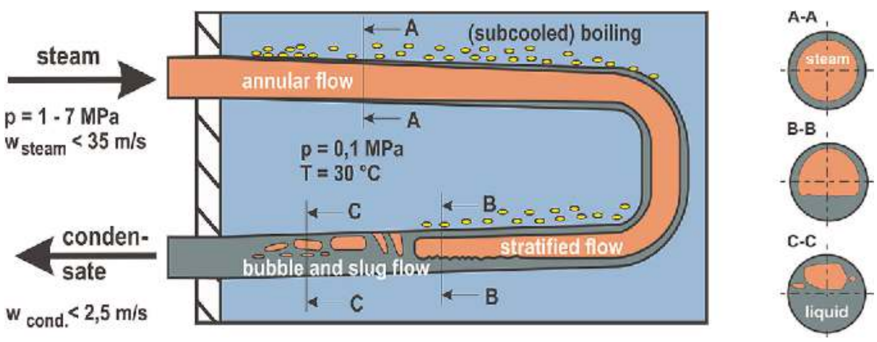


*Fig. 2. Flow patterns in a slightly inclined horizontal heat exchanger*

composed of a part for nucleate boiling $HTC_{NB}$ and a part for convective heat transfer $HTC_{CON}$ pursuant to the formula

$$HTC_{TOT} = S \cdot HTC_{NB} + F \cdot HTC_{CON} \quad (1)$$

Here, S is the suppression factor and F the enhancement factor. The higher the Reynolds number and the void fraction of the inner flow, the larger is the factor F, which is always larger than unity. Nucleate boiling enhances the convective heat transfer. On the contrary S, which is larger than 0, but smaller than unity, is small when the Reynolds number is high. A higher Reynolds number corresponds to a higher convective heat transfer which leads to a smaller thermal boundary layer with a higher spatial gradient. Thus, the mean temperature of the arising bubbles is smaller and so fewer bubbles are emerging. That means finally that less heat is transported from the wall to the fluid due to evaporation. For this reason, convection suppresses the heat transfer due to evaporation [8].

In case of horizontal pipes, the flow may not suppress the heat transfer due to evaporation [9]. Therefore, the ATHLET model was extended that in case of horizontal tubes, the factor S is assumed to unity.

- Finally the Thom equation used in ATHLET in order to estimate the temperature difference between wall and saturation temperature $\Delta T = T_{Wall} - T_{Sat}$ [6], was replaced by the current temperature difference of the last time step.

Next, two further improvements were introduced into the ATHLET heat transfer package of ATHLET 3.0B resulting in versions 3.0B mod 1 and 3.0B mod 2.

- ATHLET 3.0B mod 1: In case of nucleate boiling, the enhancement factor F in correlation of Chen is determined by using Lockhard-Martinelli-Parameter [6] as

$$F = 1 + 0.6 \cdot \left[\chi_{tt}^{-1}\right]^{0.8174} \quad (2)$$

where the Lockhard-Martinelli-Parameter is defined as:

$$\chi_{tt} = \left(\frac{\mu_L}{\mu_V}\right)^{\frac{n}{2}} \cdot \left(\frac{\varrho_V}{\varrho_L}\right)^{0.5} \cdot \left(\frac{1 - x_h}{x_h}\right)^{\frac{2-n}{2}} \quad (3)$$

In the equation, $\mu$ is the dynamic viscosity and $\varrho$ the density of liquid water (L) and vapour (V) and $x_h$ is the enthalpy based steam quality.

In general, the Lockhard-Martinelli-Parameter is defined as relation between the friction losses of a smooth pipe for liquid and vapour phase [8]:

$$\chi_{tt}^2 = \frac{(dp/dx)_l}{(dp/dx)_V} \quad (4)$$

The subscript tt means turbulent flow for both phases. Pressure losses are defined as

$$\Delta p = \frac{\varrho}{2} v^2 \lambda \frac{l}{d} \quad (5)$$

where the coefficient $\lambda$ may be defined as $\lambda = C \cdot Re^{-n}$ (e.g. Blasius: $\lambda = 0.316 \cdot Re^{-0.25}$) [6]) with the Reynolds number definition

$$Re = \frac{\varrho v d}{\eta} \quad (6)$$

Inserting the equations for pressure losses and the Reynolds number into the definition of the Lockhard-Martinelli-Parameter and simplifying the resulting formula, it is clear that not the enthalpy based steam quality but the flow based steam quality defined as

$$\dot{x} = \frac{\dot{m}_V}{\dot{m}_{tot}} \quad (7)$$

may lead to this suitable equation for the determination of the Lockhard-Martinelli-Parameter (in ATHLET models with n = 0.2):

$$\chi_{tt} = \left(\frac{\mu_L}{\mu_V}\right)^{0.1} \cdot \left(\frac{\varrho_V}{\varrho_L}\right)^{0.5} \cdot \left(\frac{1 - \dot{x}}{\dot{x}}\right)^{0.9} \quad (8)$$

Additionally, it impacts the used heat transfer correlation of Dobson and Chato, too.

- ATHLET 3.0B mod 2: In case of nucleate boiling, the macroscopic part of the Chen equation is determined by ESDU correlation [10] instead of correlation of Dittus-Boelter. In ESDU correlation, the Nusselt number is determined by:

$$Nu = a \cdot Re_c^m \cdot Pr^{0.34} \cdot F_N \quad (10)$$

The hydraulic diameter and velocity for the Reynold number is set to the outer diameter of the pipe and to:

$$u = \frac{W}{S_m \cdot \varrho} \quad (11)$$

respectively. In the last equation, W is the mass flow rate through the heat exchanger bundle and $S_m$ the minimal cross section of the bundle. $S_m$ is determined by the number, length, arrangement and pitch of the bundle pipes. $F_N$ is a coefficient determined by the number of pipes while a and m are fixed by the Reynolds number $Re_c$ and the arrangement of the pipes. A detailed description can be found in [10].

This means four different ATHLET versions were available for validation against experiments. The validation results are summarized in the following Chapter 2.2 and allow defining and focusing on a main improvement strategy for the calculation of typical phenomena during operation of slightly inclined horizontal heat exchanger bundles.

### 2.2 *Validation of current heat transfer model of ATHLET for slightly inclined horizontal heat exchanger bundles*

For validating the above described four different ATHLET versions (ATHLET 1.2c/KONWAR, ATHLET 3.0B, ATHLET 3.0B mod 1 and ATHLET 3.0B mod 2) together with experimental data of emergency condenser tests at NOKO test facility in Juelich [11] and at INKA test facility in Karlstein were used. Here, the main results which lead to the definition of the upcoming focusing improvement strategy are presented.

At the Forschungszentrum Jülich, the NOKO test facility was built in order to demonstrate the performance of the SWR1000 – which is the predecessor of the KERENA – emergency condenser. It comprises of a tube bundle section of 8 tubes, from which only 4 tubes were active in the considered experiments, a pressure vessel simulating the primary side and a condenser vessel simulating the flooding pool. The pipes inside the condenser vessel are surrounded by guide plates forming a chimney. The operational pressure of the facility is about 72 bars [11].

All in all 40 different NOKO experiments were simulated with ATHLET3.0B. They differed in the fill level of the primary side as well as in primary (10–70 bars) and secondary pressures (1–5 bars). Since on the primary and the secondary side saturation conditions prevailed, the temperatures in both pressure vessel and condenser vessel differed. In Fig. 3 a comparison of calculated and measured results is shown.

Figure 3 shows that ATHLET 3.0A significantly underestimates the transferred power of the tube bundle. ATHLET 3.0B, with the above mentioned improvements, provides better results. However, at higher primary pressures, deviations from the experimental data are still increasing. A reason could be uncertainties in the heat conductance of the used pipe material, since the main heat flow resistance of about 40 %–70 % is within the pipe wall.

Because the design of the tube bundle was adapted within the last decade, further emergency condenser tests were performed at the INKA test facility in Karlstein, Germany. The acronym INKA stands for Integral Teststand Karlstein. The INKA facility is a representation of the KERENA reactor with all its volumes and passive safety systems. The scaling in height is 1:1 while for its volumes the scaling is about 1:24. The passive safety systems are in full scale but the number is scaled down to 1:4 [12].

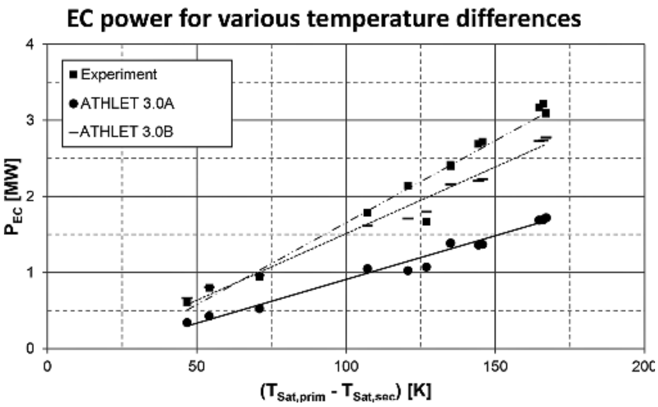


*Fig. 3. Comparison of emergency condenser experiments in NOKO facility with ATHLET 3.0B simulation*

The test data were used for additional validation work. Therefore the INKA test facility has to be mapped by ATHLET models. This so called nodalisation scheme is sketched in Fig. 4. It shows on the left a schematic picture of the components of the INKA facility needed for emergency condenser tests. On the right the appropriate representation of the facility in ATHLET is shown. The reactor pressure vessel is simulated by the GAP vessel and represented by the object GAP-RPV. The downcomer section is modelled by the objects DC-TOP, DC-MT, DC-M, DC-MB and DC-BOT. The emergency condenser is connected with the downcomer on the objects DC-MT and DC-MB by the steam pipe (STEAMP) and condensate pipe (CONDP). The flooding pool vessel on the secondary side is represented by the FPV-objects shown in Fig. 4. Similarly like in the NOKO-Jülich case, the emergency condenser in the INKA facility is emerged inside the flooding pool between two guide plates forming a chimney. Furthermore, the pipes of the condenser are fixed in their position by three support plates perpendicular to the guide plates which lead to four separated channels within the chimney section (FPVNOKO1–4). The outer chimney part is formed by the channel FPV-BP.

Altogether, four emergency condenser tests at the INKA test facility were simulated with all mentioned ATHLET versions and compared with experimental data, two stationary cases with different water levels in the RPV and different primary pressures and temperatures and two transient cases with different primary pressure gradients and secondary side temperatures (subcooled and saturated). The main validation results using one stationary and one transient experiment are presented in this paper. The boundary conditions are given in Tab. 1.

As a first result, the emergency condenser power transferred from inside the tubes to the outer water pool, is presented in Fig. 5 and Fig. 6 as time dependent lines for the above mentioned experiments. These experimental data are compared to the results of post test calculations performed with the four ATHLET versions ATHLET 1.2c KONWAR, ATHLET 3.0B, ATHLET 3.0B mod 1 and ATHLET 3.0B

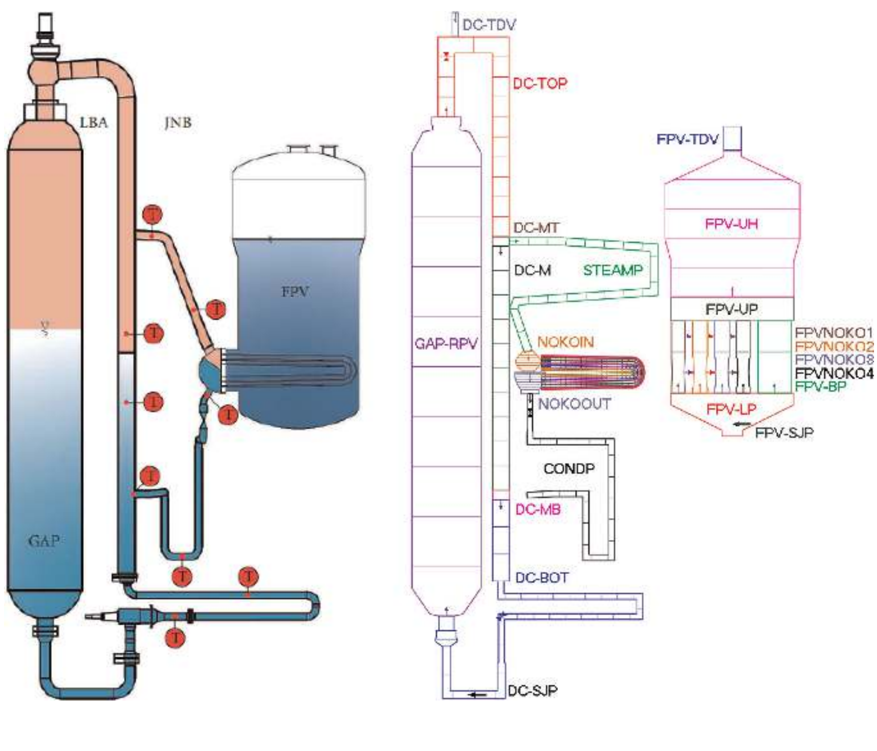


*Fig. 4. Scheme of INKA test facility for emergency condenser tests (left, [13]) and corresponding ATHLET nodalisation (right)*

mod 2. The power of the emergency condenser is calculated in both experiment and simulation with the mass flow rate through the emergency condenser and the enthalpy difference between its in- and outlet.

Figure 5 shows the comparison for the stationary experiment 2_12_1. After a starting transient the power stays constant from t = 240 s to t = 360 s, named "stationary phase" in Fig. 5. While ATHLET3.0B calculates a transferred power in this phase of about 16.9 MW, using ATHLET3.0B mod 1 leads to a slightly higher value of 17.7 MW and ATHLET3.0B mod 2 and ATHLET1.2c KONWAR to an additional slightly higher value of 18.35 MW. All four calculations underestimate the experimental value of 21.2 MW up to 20.3 %. The uncertainty of the experimental power measurement/determination is in the magnitude of 20 %. That means the analytical results are in good agreement with the experiments.

Figure 6 shows the comparison for the transient experiment 1_10_85_13_1. The comparison shows the same effects than for the stationary experiment: ATHLET underestimates the experimental data. ATHLET 3.0B mod 2 and ATHLET 1.2c KONWAR gave the best results, but all are within the uncertainty of the experimental power measurements. Otherwise, additional post test calculations for experiments with higher pressures show that with increasing pressure, the deviations increase up to 50 %. The reason for this must be determined and eliminated.

To allow a closer view of more expressive variables, the calculated heat transfer coefficients are plotted in Fig. 7 for the

*Table 1. Boundary conditions emergency condenser experiments at INKA test facility*

| Experiment | 2_12_1 (stationary phase) | 1_10_85_13_1 (transient) |
|---|---|---|
| **GAP Level** | 13.43 m | 11.04 m |
| $p_{GAP}/T_{GAP}$ | 10 bar/180 °C | 85 bar/300 °C → (400 s) → 20 bar/400 °C |
| $p_{FPV}/T_{FPV}$ | 1 bar/100 °C | 1 bar/30 °C |

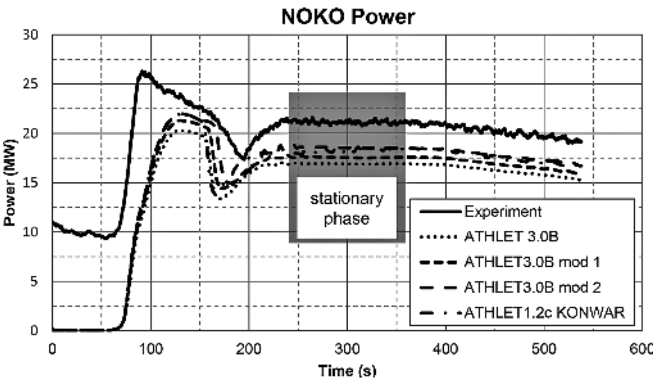


*Fig. 5. Transferred power of emergency condenser in INKA test facility during experiment NOKO_2_12_1 and during post test calculations with four different ATHLET versions (ATHLET1.2c KONWAR, ATHLET3.0B, ATHLET3.0B mod 1 and ATHLET3.0B mod 2)*

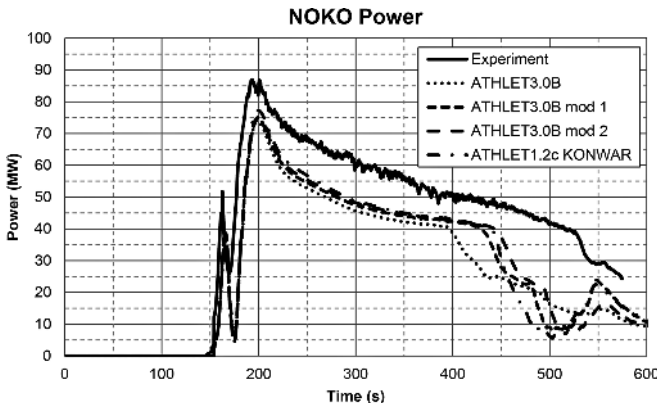


*Fig. 6. Transferred power of emergency condenser in INKA test facility during experiment NOKO_1_10_85_13_1 and during post test calculations with four different ATHLET versions (ATHLET1.2c KONWAR, ATHLET3.0B, ATHLET3.0B mod 1 and ATHLET3.0B mod 2)*

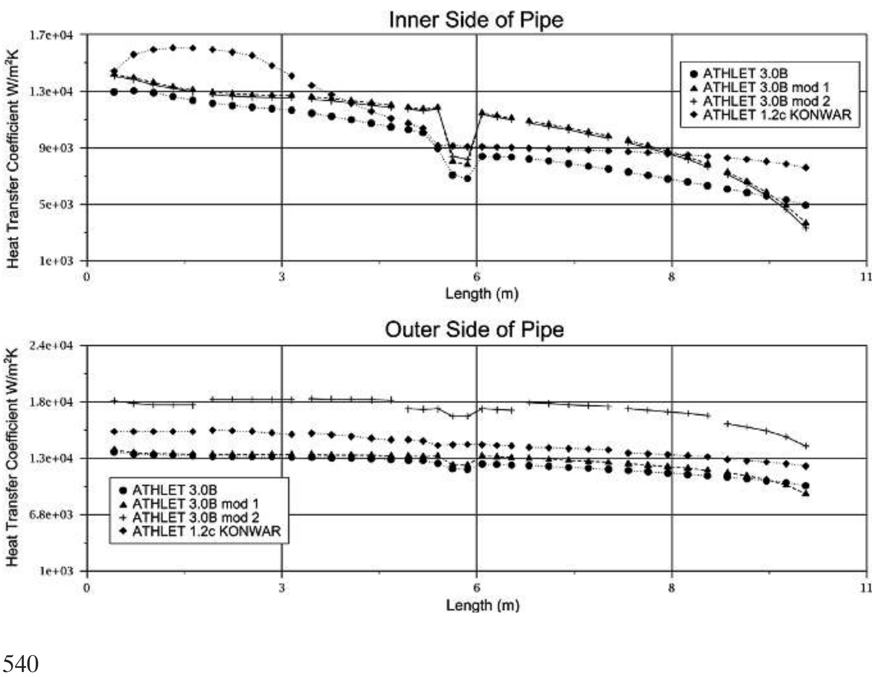


*Fig. 7. Heat transfer coefficients pipe inner side (top) and outer side (bottom) of calculation of experiment NOKO_2_12_1*

inner and the outer side of an emergency condenser pipe (row 2) with the mentioned four ATHLET versions as spatial plots.

Using the flow based steam quality instead of the enthalpy based one, the heat transfer coefficient on both sides is slightly increasing (ATHLET 3.0B → ATHLET 3.0B mod 1). In ATHLET 3.0B mod 2 the ESDU correlation for the macroscopic part of the Chen equation for nucleate boiling was implemented additionally. While in the upper picture of Fig. 7 almost no change is visible in the inner heat transfer coefficient, in the lower picture a large increase can be noticed. Using ATHLET 1.2c KONWAR, on the outside the value of the heat transfer coefficient is between ATHLET 3.0B mod 1 and mod 2. On the inside at the beginning of the pipe (annular flow) the heat transfer coefficient is larger than in the ATHLET 3.0B mod 2 but decreases towards the centre of the pipe and remains almost constant to the end. It should be noted that in the KONWAR case the elbow parts of the pipes were also impacted by the KONWAR module, although these parts are vertical, since no inclination check was performed by ATHLET 1.2c while this was done in the ATHLET 3.0B calculations. Thus, in the ATHLET 1.2c KONWAR case the heat transfer in the elbow parts may be overestimated.

In the NOKO_1_10_85_13_1 case flashing can be observed. In Fig. 8 the fluid temperature and the saturation temperature of the corresponding pressure in the lower part of the expansion bench of the downcomer line are shown. When starting the experiment, subcooled water flows out of the emergency condenser into the downcomer line indicated by the decreasing fluid temperature with its negative peak at t = 220 s. Hereafter, warmer water enters the section. Its temperature depends on the power of the emergency condenser. The larger the power, the smaller is the fluid temperature flowing into the downcomer section and thus the temperature gradient over time. Flashing occurs when the fluid temperature equals the saturation temperature. The larger the temperature gradient over time, the earlier flashing occurs. Due to the evaporation, the level inside the downcomer line increases and thus the power of the emergency condenser decreases. In Fig. 6 it can be seen that the lower the power of the emergency condenser is, the earlier the power decreases due to flashing.

In summary, ATHLET 3.0B here leads to quite good results similar to the NOKO Jülich case. Further modifications (using flow based quality instead of enthalpy based quality, ESDU correlation) give minor improvements. Due to code internal reasons they will not be included in the short-term into ATHLET. Although the results are better than before, they are not yet satisfying. Further development is needed.

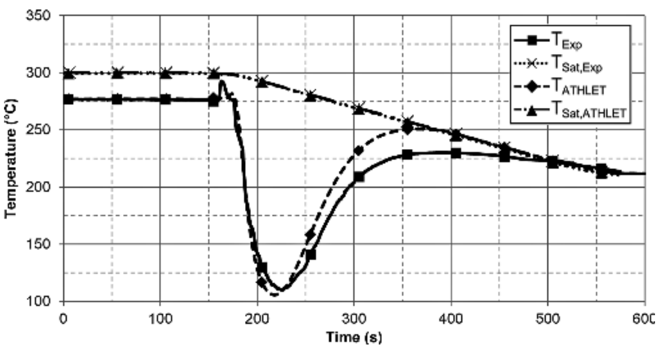


*Fig. 8. Temperature progression downcomer line*

## 3 Conclusions and outlook

First results of the simulation of the horizontal inclined emergency condenser of the KERENA concepts were shown. Although the code improvements for ATHLET done during the investigations lead to much better prediction of the emergency condenser power, the results are not yet satisfying and further investigations have to be done in order to simulate the heat transfer correctly. This work will be done in the framework of the PANAS project, sponsored by BMBF (02NUK041), in which GRS takes part. In this project, which started in July 2015, focus lies on heat transfer processes in passive residual heat removal systems. Various experiments with high time and spatial resolutions will be performed (GENEVA, TOPFLOW, etc.) with the aim to develop and validate evaporation and condensation models for ATHLET.

Beside the continuously running ATHLET development and validation projects, currently the so called EASY project has started, sponsored by the BMWi (RS1535A). Within the framework of EASY, the coupled code system ATHLET/COCOSYS is validated. For this validation work both already carried out and new performed INKA experiments will be used. The planned new experiments will be integral tests regarding design basis accidents (DBA), where the integral behaviour of the different passive safety systems (namely emergency condenser, containment cooling condenser, large water pools, overflow pipes and passive pressure pulse transmitter) used to cope with DBA is investigated.

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**INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Environmental Impact of Stressors.** IAEA Nuclear Energy Series No. NG-T-3.15. Published by the International Atomic Energy Agency, 2016, ISBN 978-92-0-101616-4, 94 pp., 38.00 EUR.

This volume of the updated INPRO Manual provides guidance to the assessor of an NES (or a facility thereof) that is planned to be installed, describing how to apply the INPRO methodology in the area of environmental impact of stressors. The INPRO assessment should either confirm the fulfilment of all INPRO methodology environmental CRs. or identify gaps (non-compliance with the INPRO methodology CRs) requiring corrective actions (including research, development and demonstration (RD&D)) to achieve long term sustainability of the NES assessed.

Die INPRO assessor (or team of assessors) is assumed to be knowledgeable hi the area of environmental impact of stressors and/or may be using the support of qualified national or international organizations (e.g. the IAEA) with relevant experience.

Two general types of INPRO assessor can be distinguished: a nuclear technology holder (i.e. designer, developer or supplier of nuclear technology) and a (potential) user of such technology. The role of the latter type of assessor, i.e. a technology user, is primarily to check, in a simplified manner, whether the designer (supplier) has appropriately taken into account the environmental aspects hi the design as defined by the INPRO methodology. A technology user is assumed to be primarily interested in proven technology to be installed hi his or her country in the near future. A designer (developer) performing an INPRO assessment can use this current publication to check whether the (innovative) design under development, which is expected to comply with the existing IAEA safety standards, meets the INPRO methodology environmental requirements for die assessment of sustainability of NES, and can additionally initiate modifications during early design stages, if necessary, to improve the environmental performance of the design.

Environmental impact from NES involves two large groups of factors. One group impacting the environment comprises the consumption of non-renewable resources including both fissile/fertile materials necessary to produce nuclear fuel and other materials (e.g. zirconium). All these factors and consumption of electricity necessary to construct, operate and occasionally decommission NES installations are considered in the INPRO methodology manual on environmental impact from depletion of resources.

Another group comprises radiological, chemical, thermal and other stressors which NESs release into environment. This group also includes water intake because this factor can be important for biota even when this water is returned to the environment in a clean form (e.g. as steam from nuclear power plant cooling towers). All these factors are considered in this INPRO methodology manual on environmental impact of stressors.

The INPRO methodology in the area of environmental impact of stressors covers only normal operation and anticipated operational occurrences of NES facilities. Consequences of potential accidents are discussed in die INPRO methodology manuals in the areas of safety of reactors and safety of the nuclear fuel cycle. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

In Section 2, general features of an environmental assessment are presented.

In Section 3, an overview of information that must be available to an INPRO assessor to perform the environmental assessment is provided.

In Section 4, the background of the INPRO methodology BP for environmental impact of stressors, and the corresponding URs and CRs, consisting of INs and ALs, are presented. At the CR level, guidance is provided on how to determine the values of the INs and ALs.

Appendix I provides general information on types of stressor and separate, illustrative lists of stressors (in the form of tables) for all facilities of an NES based on uranium and mixed oxide (MOX) fuel (as an example). This appendix could be used by an INPRO assessor as a starting point to generate input for the BP evaluation.

Appendix II presents simplified environmental analysis methods of how to calculate the impact of radiological stressors, i.e. the dose on humans and non-human biota (plants and animals). It also briefly discusses the calculation of the impacts of chemical stressors on humans and non-human biota.

Appendix III illustrates the concepts for optimization of the management options for reduction of the environmental impact of nuclear facilities.

Appendix IV provides basic information on the concept of collective dose, which is used in the INPRO assessment method described in this publication.