Simulation of asymmetric phenomena during core degradation with the code system AC^2

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Introduction

The development of code systems, which are capable of simulating design basis and beyond design basis accidents, is a still an ongoing progress. The nuclear accident in Fukushima showed for the nuclear community, and for the world, that such unfortunate events can occur. Further improvement of these codes is important to develop more effective accident mitigation methods.

Currently, all of the relevant [1] code systems, which can simulate core degradation effects, have the assumption that the simulated and analyzed accident progression in the core is symmetric. That is why it is commonly accepted that for the calculations the core is divided radially into concentric rings and axially into segments. In each ring there is a representative fuel rod, and it is assumed that this representative fuel rod behaves exactly as all the fuel rods in that ring. This means that different parameters (temperature, power, material properties, etc.) differ only axially from segment to segment and radially from ring to ring. If there is a radially asymmetric phenomenon occurring in a ring, its asymmetrical property is averaged through the whole ring.

That is why asymmetric events can not be simulated yet with the existing, most relevant code systems, however these events can occur: control rod ejection, asymmetric power distribution due fuel change or asymmetric burnout, positive feedback of small temperature differences due to local oxidation peaks or asymmetric cold water injection.

The aim of this paper is to present the new methodology already implemented into the developer version of AC^2, which is capable of taking asymmetric, local effects into account, during an accident with core degradation. The focus of this paper is to introduce the new model itself with the help of some verification calculations. Extended and detailed reactor case scenarios are going to be analyzed in the future.

The code system AC^2

The code system AC^2 [2] is developed by GRS and consists of three main modules: **A**THLET, ATHLET-**C**D and **C**OCOSYS.

ATHLET is a thermal-hydraulic system code (Analysis of THermal-hydraulics of LEaks and Transients) and can be used for the analyses of the whole spectrum of leaks and transients in PWRs and BWRs. The code is applicable for western reactor designs as well as for Russian VVER and RBMK reactors. ATHLET is composed of several basic submodules for the simulation of the different phenomena involved in the operation of a light water reactor:

- thermo-fluid dynamics (TFD)
- heat transfer and heat conduction (HECU)
- neutron kinetics (NEUKIN)
- and control and balance-of-plant (GCSM)

The input dataset of ATHLET provides the basis for the ATHLET-CD input.

The **ATHLET-CD** (ATHLET Core Degradation) module is the extension of ATHLET and contains additional models for core degradation, late phase phenomena and source term calculations. ATHLET-CD is able to simulate the formation and movement of metallic and ceramic melts in the core and the thermal behavior of particle beds and molten pools. Furthermore, the release of fission products as well as their transport and deposition in the primary circuit can be simulated, which provides input for the containment calculations in the module COCOSYS.

The **COCOSYS** module contains mechanistic models for the comprehensive simulation of all crucial processes and conditions during severe accidents in containments of light water reactors. COCOSYS is not limited to relevant severe accident phenomena, but will also be able to demonstrate the interactions between these phenomena as well as the overall behavior of the containment.

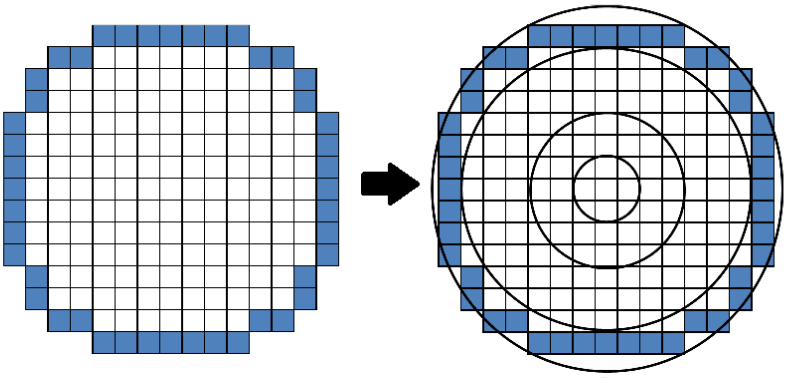
Full plant simulations can be performed by coupling ATHLET or ATHLET-CD with COCOSYS.

Simulating local effects during core degradation

Currently in ATHLET-CD, similarly to the other relevant severe accident codes, the core is divided radially into concentric rings. This approximation makes it possible to make fast and accurate calculations, if the analyzed scenario is symmetric. A typical example is shown in Figure 1. The colors of the figure depict the power distributed radially along the core. The inside of the core consists of fuel elements with same power, the outer side of the reactor is made out of low power elements. In this case, concentric ring nodalization is a valid approximation.

However, if the core has a partly asymmetrical power distribution (or any asymmetrical property) like shown in Figure 2, than using the same concentric ring-type nodalization influences the accident scenario. In this example, hot (red) and cold (white/blue) regions are next to each other. Using a ring-type nodalization means that the user has to make an average of the hot and cold regions, making the cold regions hotter and the hot regions colder.

To conclude, in order to take local effects into consideration during core degradation the commonly used concentric ring-type nodalization of the core should be changed to get realistic results. Local ring segments have to be created, like shown in Figure 2c. This modification can influence the validity of the existing models:



a, b,

Figure 1, Nodalization of the core, current method. Symmetric case

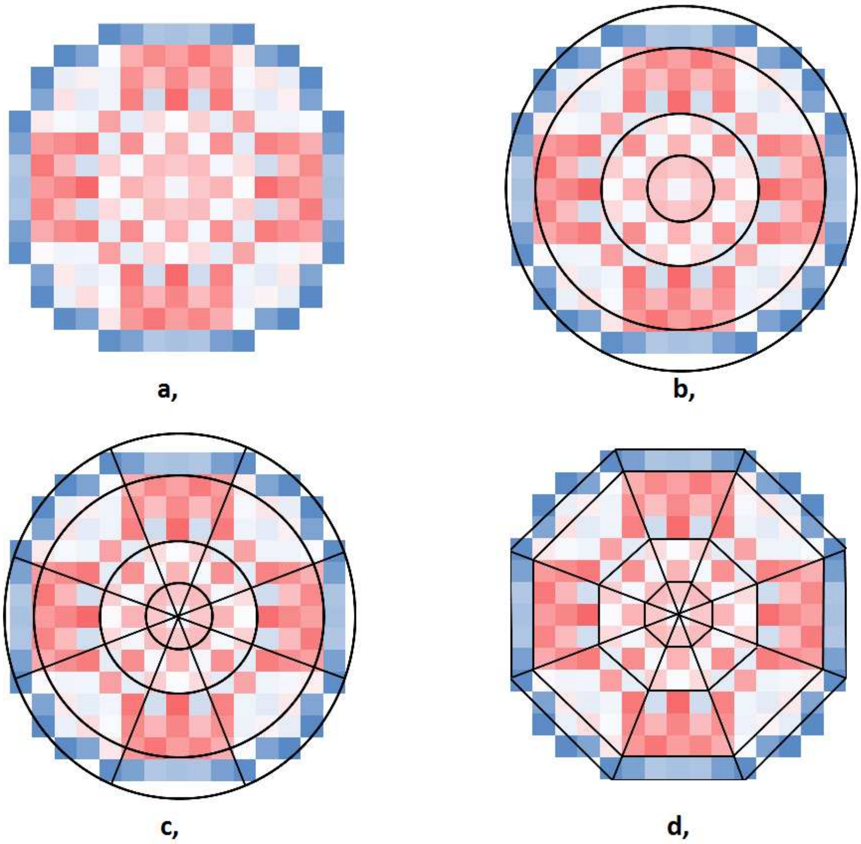


Figure 2, Nodalization of the core, asymmetric case. Current and new method
(colors indicate the power distribution compared to the average power of a fuel element)

- Conductive and convective heat transfer, power, axial melt relocation, oxidation and fission product release: calculated for one rod pin, multiplied by the amount of fuel rods in the node → new nodalization has low impact, the user has to change only the amount of fuel rods in the modelled node. ✓
- Fluid pathes are flexible and can be defined by the user → user can change the geometry according to the new nodalization. ✓
- Radiative heat transfer between nodes: core degradation with the new nodalization can create complex geometries → new radiative heat transfer model is needed: Identification of radiation blockages, free sides and new determination of view factors are necessary.
- Horizontal movement of molten material → two new directions possible, model extension needed (not described in this paper)

New heat radiation model

To determine the radiative heat transfer between the sides of the new ring segments it is necessary to be able to calculate the view factors between each surface. The view factor between surfaces X and Y is the proportion of the radiation which leaves surface X and strikes surface Y. Its value is only geometry dependent. In a ring-like geometry it was possible to obtain the view factors by using analytic equations, using the new nodalization the core geometry after a meltdown can be very complex, for which those equations are no longer valid. View factors have to be determined using a numerical solution:

$$VF_{X-Y} = \frac{1}{\pi * A_X} * \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\cos(\theta_X) * \cos(\theta_Y) * block}{S^2} * dA_j * dA_i \quad (1)$$

Where:

- A_X is the side area [m^2],

- dA_i,dA_j is the area of the subsurface [m^2],
- Θ_X, Θ_Y is the angle of the line connecting the two subsurfaces to the normal vector of the surface [°],
- S is the distance of the two subsurfaces [m],
- N is the amount of subsurfaces [-],
- block is the blockage indicator; its value is 1 or 0 [-],
- VF_{X-Y} is the view factor from surface X to surface Y [-].

The equation is visualized in the Figure 3. To take shadowing effects into account, for each pair of subsurfaces it is checked, whether the line between them hits another surface or not. If it hits another surface then the blockage factor is set to 0. Curved surfaces (Figure 2c) require a very detailed subdivision of the surfaces, which makes the determination of the view factors slow. Dividing the core into nodes with flat surfaces, like shown in Figure 2d, makes the numerical calculations faster. Neighbouring intact sides see each other totally that means the view factor between them is 1. If a node melts, view factors have to be calculated horizontally, axially and transversely. The model uses the assumption that all surfaces are flat. This is a valid assumption until the nodes are high enough and contain enough fuel rods, so that the radiation can not get through the node without hitting a fuel rod.

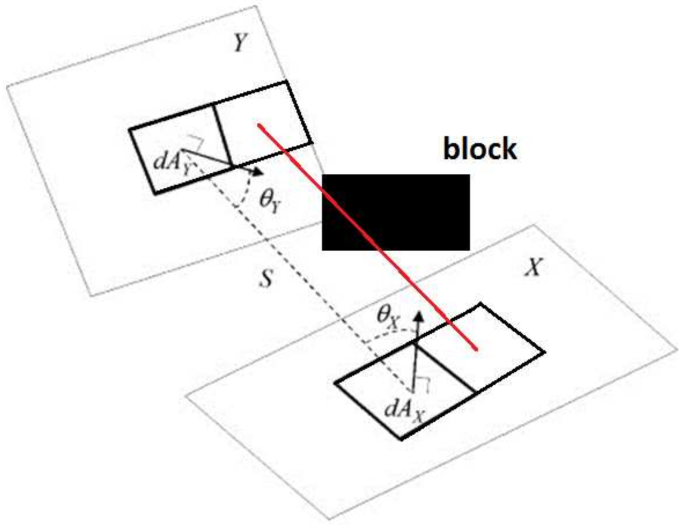


Figure 3, visualization of equation 1

In order to check whether the view factors are determined correctly, view factors from each side are summed up. If their sum is 1, then the view factors are calculated correctly. This check was performed many times using an external self-written program, which randomly tested thousands of possible geometry combinations. The new model delivered very good results.

In AC^2 the view factors are only recalculated when a node melts, and only those view factors are recalculated that are influenced by the geometry change. The amount of transferred radiative heat is calculated in each timestep for each node, using the determined view factors.

$$\frac{Q_{node}}{dt} = \sum_{i}^{\substack{source\\sides}} \sum_{j}^{\substack{target\\sides}} VF_{i-j} * \sigma * \varepsilon_i * \varepsilon_j * A_i * \left(T_i^4 - T_j^4\right) \quad (2)$$

Where:

- A_i is the area of the side [m^2],
- σ is the Boltzmann constant [J/K],
- ε_i, ε_j is the emissivity of source/target [-],
- T_i, T_j is the temperature of source/target [K],
- Q_{node} is the energy transferred from/to source [J],
- dt is the time step [s].

The net radiative power for each node is added as a term to the energy balance equation.

Example for asymmetry

The extent of this paper does not allow a detailed analysis of an asymmetric scenario. The aim of the presented example is to show the potential of the new nodalization, compared to the ring-like nodalization.

Two simulations were performed on a core with a power distribution shown in Figure 2, using nodalization b and d. A generic PWR sample was used, with an initial power of 2,6 GW. The evolutions of two SBO accident simulations were compared, which are depicted in Figure 4 and Figure 5. The figures show the cross section of the reactor core at the hottest level. The small colorful circles represent the fuel rods; they disappear if the node is molten. For visualization purposes in Figure 4 each ring has four rods depicted, but they are all calculated together, they behave identically. In Figure 5 all the depicted fuel rods can behave differently, each of them is in a separate node.

The difference between the two simulations is mainly caused by the modeling of the power distribution. In a ring-like nodalization, the power distribution in a ring has to be averaged, which can make a big difference, especially in the third and fourth "ring", like shown in Table 1.

Table 1, relative power distribution

	"Ring1"	"Ring2"	"Ring3"	"Ring4"
Ring nodalization	1,2	1,16	1,135	0,44
Asym. Nodalization (hot/cold)	1,2/1,2	1,18/1,14	1,21/1,06	0,55/0,33

Using the ring-like nodalization (Figure 4) first the inner rods melt, then all the other rods, except the cold, outer rods. Melting is different when the new nodalization is used (Figure 5), with asymmetric power distribution. Still, first the inner rods melt, but those inner rods that are closer to the "hot" zones in the ring 3. Later, all other inner rods melt. After a while, other rods melt also, but first always those that are closer to the "hot" zones. At the end of the simulation the rods in the cold nodes of "ring" 3 are still intact and their temperature is sinking. Each node radiates heat axially, horizontally and diagonally in the whole cavity, which was created during the core degradation.

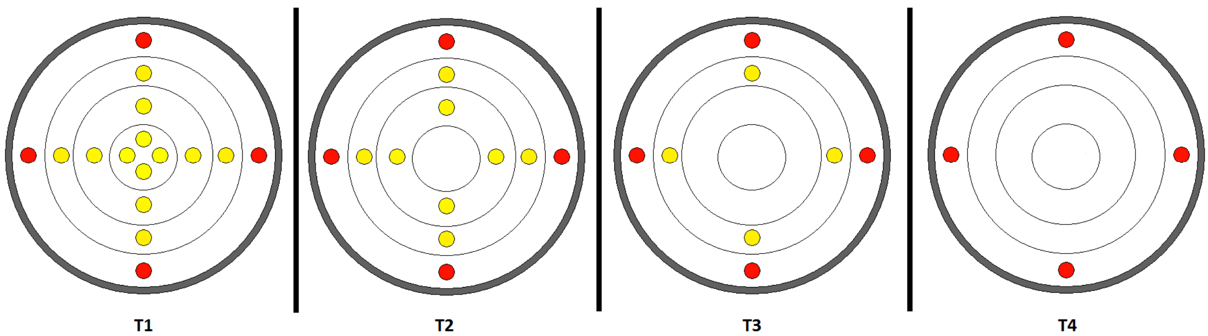


Figure 4, Test case accident evolution, using ring-like nodalization. Top view of the core, at the hottest level

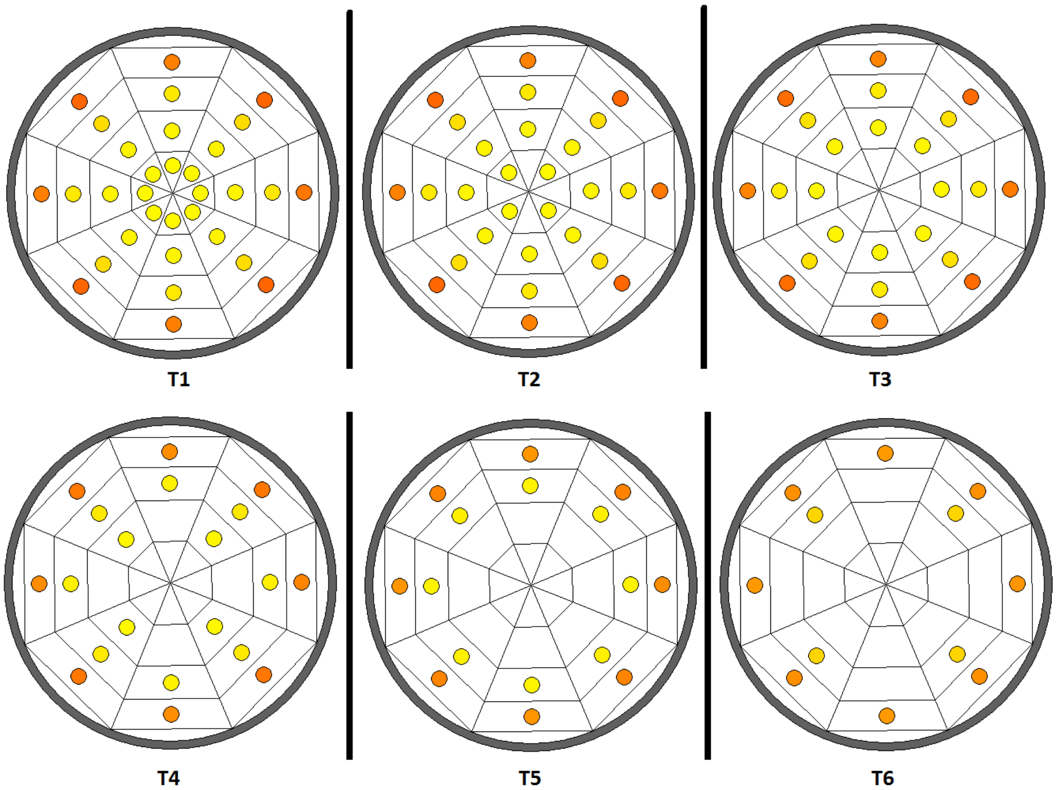


Figure 5, Test case accident evolution, using the new nodalization. Top view of the core, at the hottest level

This simple example showed that a new nodalization can have an effect on the accident evolution, even on a fairly symmetric scenario, with only some asymmetric properties. Of course, operator actions can increase or decrease the asymmetry in the system. Many other asymmetric scenarios can be analyzed with the help of this new model.

It is planned to make more asymmetric accident analysis in the future, to test the plausibility of the new calculations and the stability of the new model.

Conclusion

This paper presents the current status of the development made in AC^2 taking asymmetric core degradation into account. Using a new nodalization and a new heat radiation model it is possible to simulate radially asymmetric accident scenarios. A simple, but realistic accident scenario was analyzed to verify the developed model and to show the importance of the not ring-like nodalization. In the future other asymmetric accident scenarios are going to be analyzed.

Literature

[1] Nuclear Energy Agency, Committee on the safety of nuclear installations: Status Report on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions, Appendix-D. Nuclear Safety NEA/CSNI/R(2015)2, May 2015.

[2] A. Schaffrath, M. Sonnenkalb, J. Sievers, W. Luther, K. Velkov: Scientific codes developed and used at GRS-Nuclear simulation chain; Kerntechnik, 2016, Volume 81.