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System codes improvements for modelling passive safety systems and their validation

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Motivation – Current Situation in Germany (1)

After the Fukushima nuclear disaster, the German Federal government decided to terminate the use of nuclear energy latest by 2022

- 8 NPP were permanently shut down in March 2011
- 9 NPP (7 PWR, 2 BWR) continued operation
- Permission for plant operation expires as follows:
  - 2015: Grafenrheinfeld (PWR) (currently shut down)
  - 2017: Gundremmingen B (BWR)
  - 2019: Philipsburg 2 (PWR)
  - 2021: Brokdorf, Grohnde (both PWR)
    Gundremmingen C (BWR)
  - 2022: Emsland, Isar 2, Neckarwestheim (all three PWR)

Motivation – Current Situation in Germany (2)

Why does Germany / GRS continue with reactor safety research in general?
Why does GRS continue with the ATHLET code development in particular?

- The German legislation demands a precaution against damage according to the **current state of science and technology (S&T)** for NPP approval and operation.
  - **Current**: The state of science and technology is continuously developing
  - **S&T**: Advanced methods, equipment and operating modes which leading experts (such as the German Reactor Safety Commission (RSK)) expect to be required
  - ➢ In this connection economic considerations play no role
- Common understanding is that in the remaining operating time of the German NPP (until 2022) the **high safety standard** shall be **maintained** and **further improved**.
- The **GRS codes** (such as ATHLET or COCOSYS) are applied in both, the **nuclear licensing** and **supervisory procedures**. Therefore, these codes must represent the current state of science and technology.
- In addition the German ministries request that GRS will be able to **assess** current **NPP concepts** and **new builds** abroad.

Motivation – Challenges (1)

Features of new reactor designs

- GRS reviews continuously these new builds and the reactor concepts
- Most of them are innovative designs with **new safety features** (such as **passive safety systems**)
  - Gen. III+: The safety concept is solely based on passive safety systems
  - SMR: Concepts with an infinite decay heat removal without any need for electricity or external input
    Integral designs
    Safety concepts based on exclusion of accidents
    Compact components (heat exchangers with a high heat flux density)
  - Gen IV: **New coolants** (gas, liquid metal, molten salt), fast neutron spectra
- **New operation modes** (load-following operation, longer fuel cycles, higher burn up)

➢ GRS tools shall be **extended** in such a way, that they can be applied for safety analyses for these innovative designs

Motivation – Challenges (2)

What are the challenges for system codes for simulation of passive safety systems?

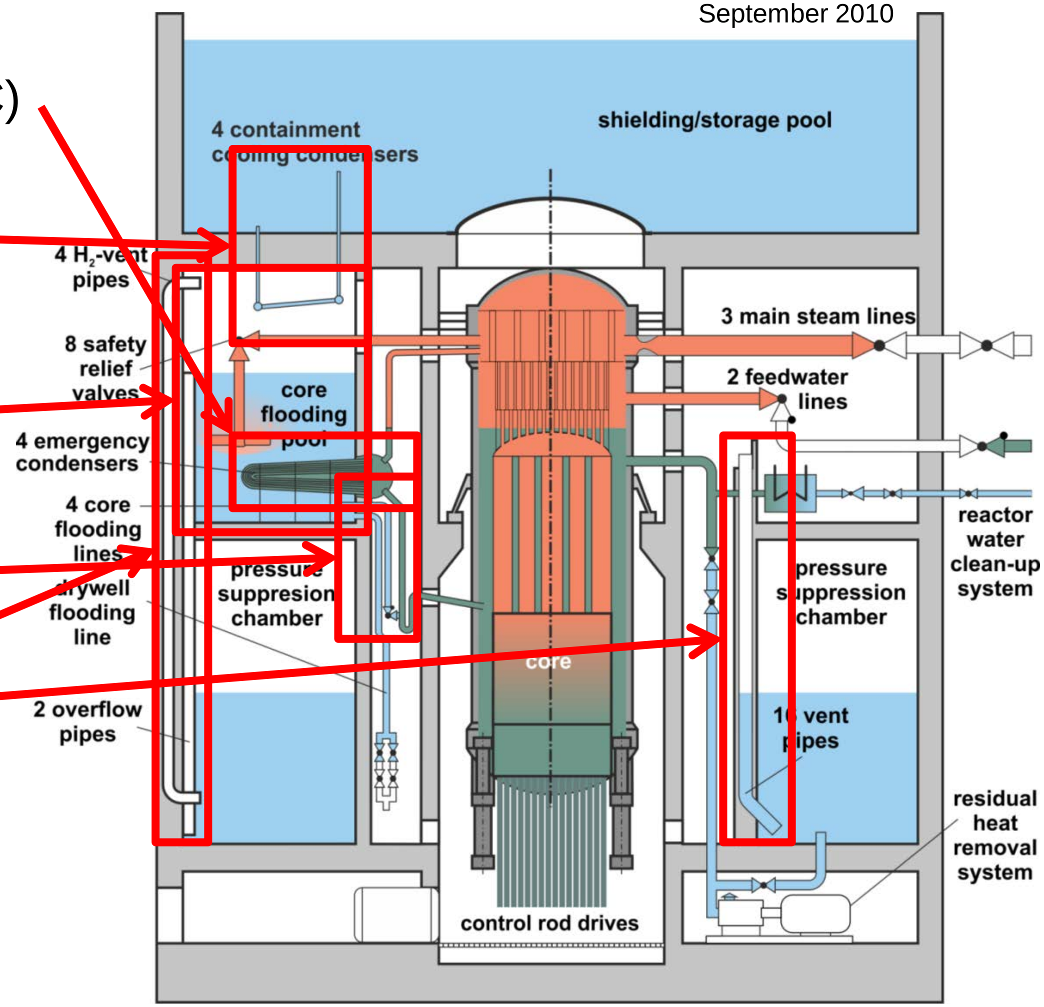
- Active safety systems operate under forced convection conditions with **defined operating points** (such as nominal flow rates), which are achieved immediately after switching on the pumps
- Passive safety systems utilize basic physical laws (such as gravity, free convection, boiling, evaporation) and **operate under conditions, which set on its own**, the driving forces and the (heat transfer) capacity change continuously
- For code validation & qualification we need:
  - component tests, important for understanding of operational behaviour of passive safety systems
  - integral tests to take interactions between different passive systems into account

Passive Safety Systems KERENA

KERENA Passive Core and Containment Cooling System

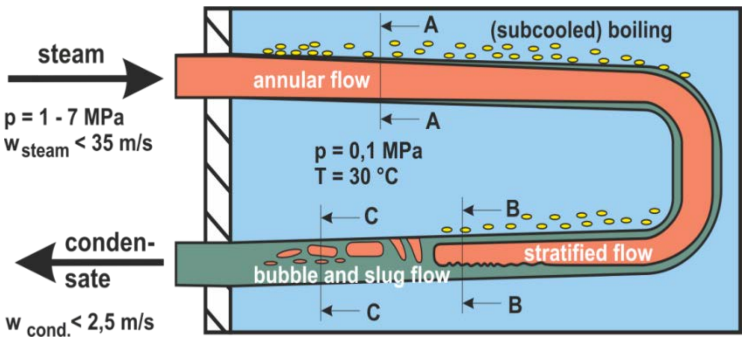
Adapted from:
AREVA Technical Brochure KERENA
The 1250 MWe Boiling Water Reactor
September 2010

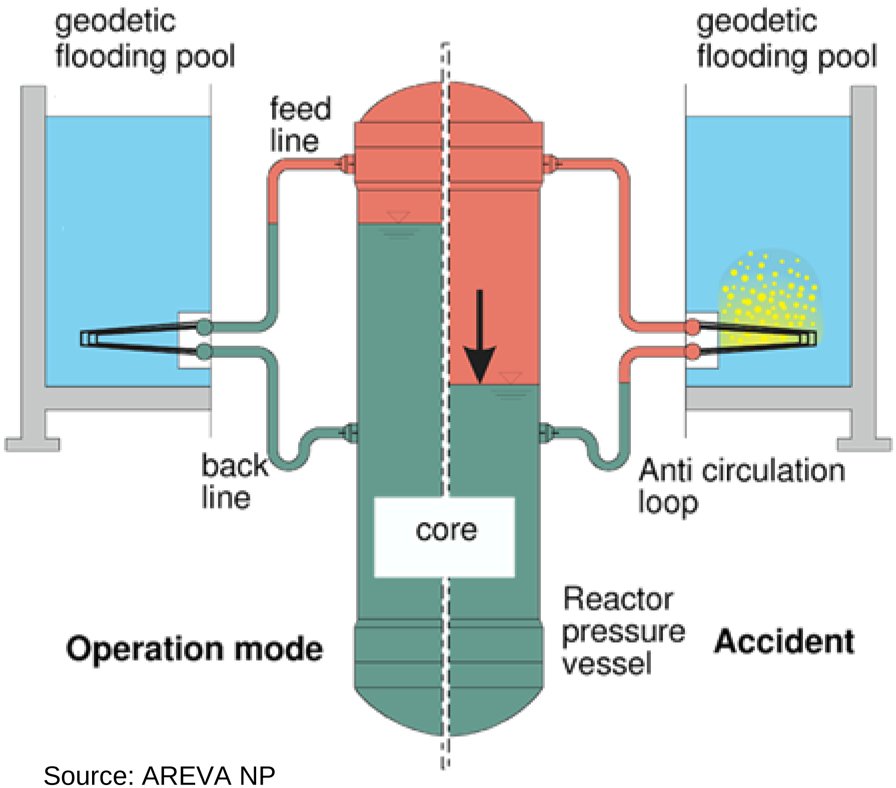
- Emergency Condenser (EC)
- Containment Cooling Condenser
- Flooding Pool
- Core Flooding Lines
- Overflow Pipes
- Passive Pressure Pulse Transmitter



EC Simulations

- Most important processes:
  - Condensation heat transfer inside tubes (depending on local flow pattern)
  - Convective boiling heat transfer at the outside of the tube bundle
  - Free convection in water pool
- Low operational pressure



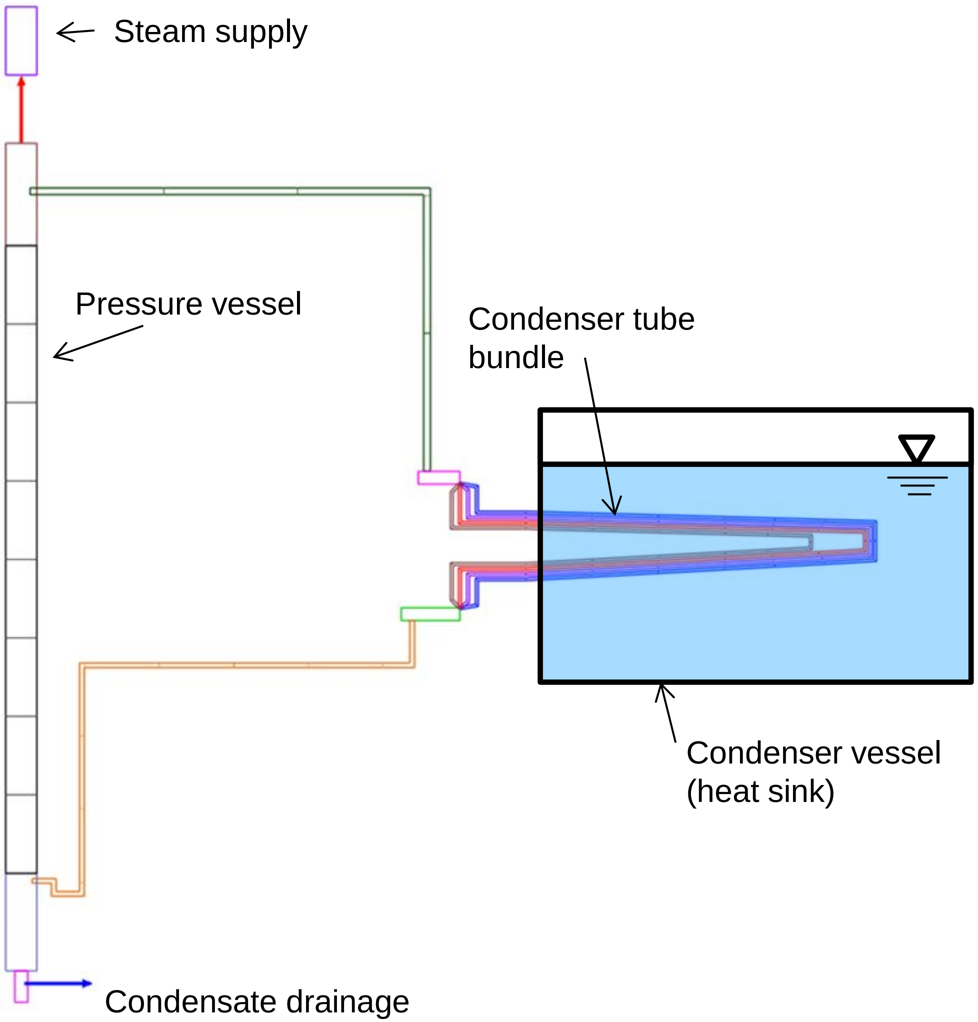


Source: AREVA NP

EC Simulations – NOKO (1)

NOKO Test Facility

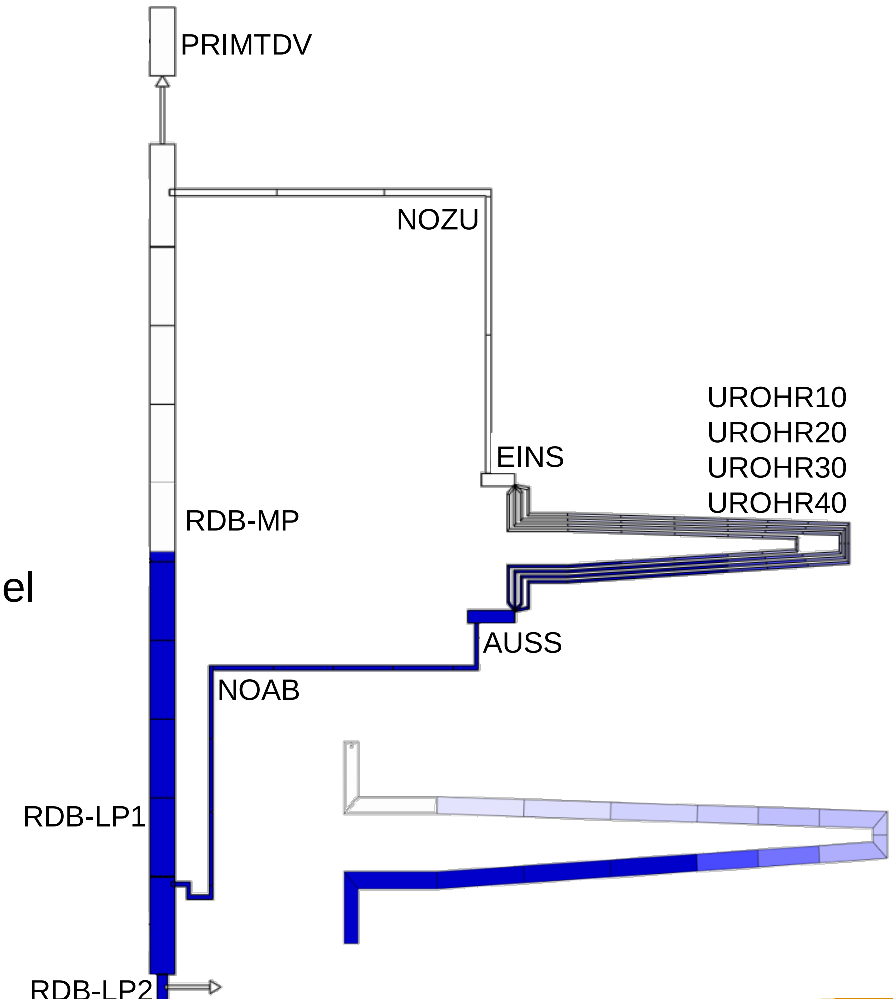
- Notkondensator (NOKO)
- Single component test rig, originally sized pipes with same material like in the NPP
- Max. power of electrical heater for steam supply: 4 MW
- Experiments carried out under quasistationary conditions



Nodalization scheme in ATHLET (condenser vessel only schematic)

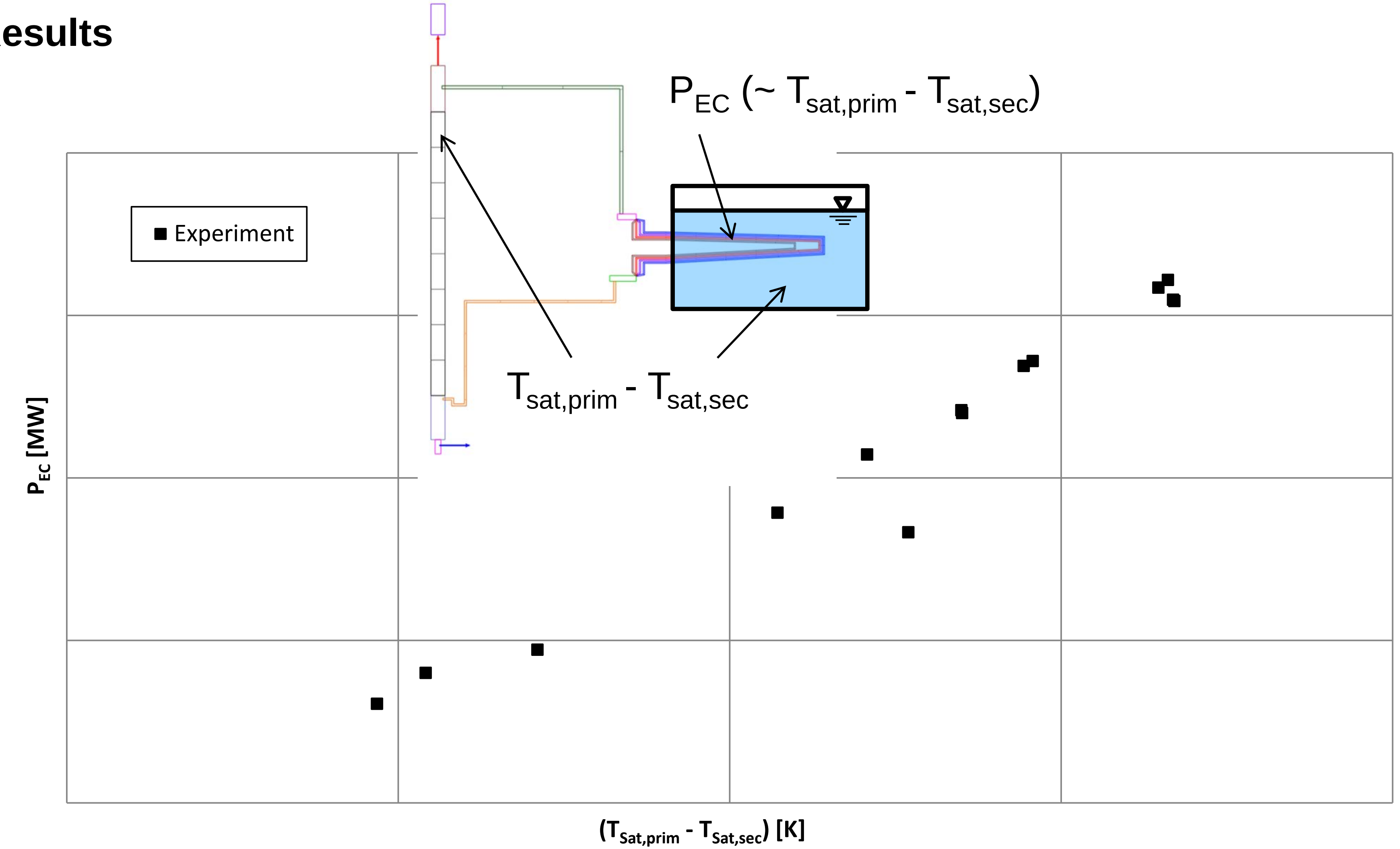
EC Simulations – NOKO (2)

- Objective of the experiments: Determination of the condenser power dependent on the following parameters:
  - Primary side pressure
  - Secondary side pressure
  - Secondary side temperature
  - Liquid level in pressure vessel
  - Liquid level in condenser vessel



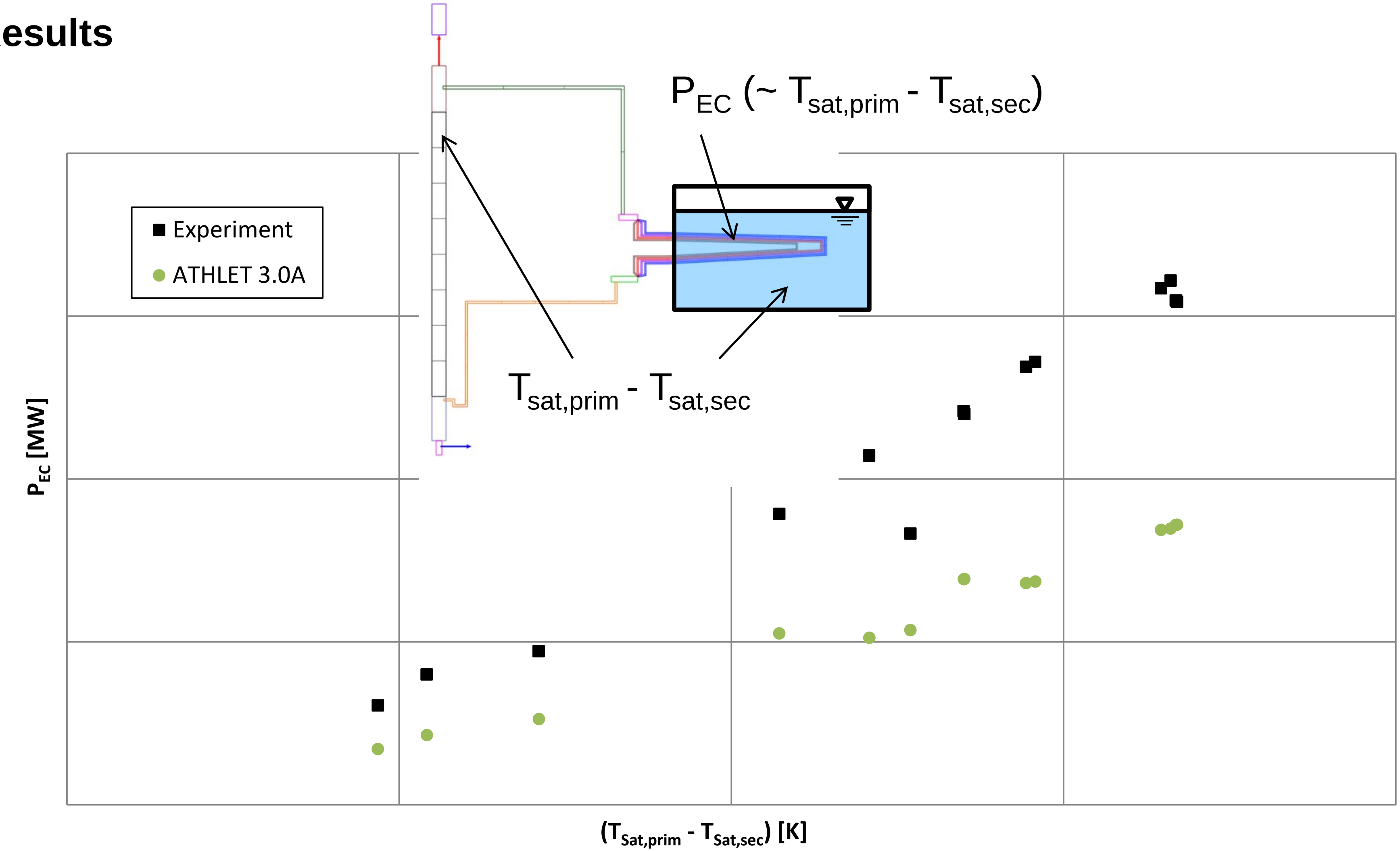
EC Simulations – NOKO (3)

Results



EC Simulations – NOKO (4)

Results

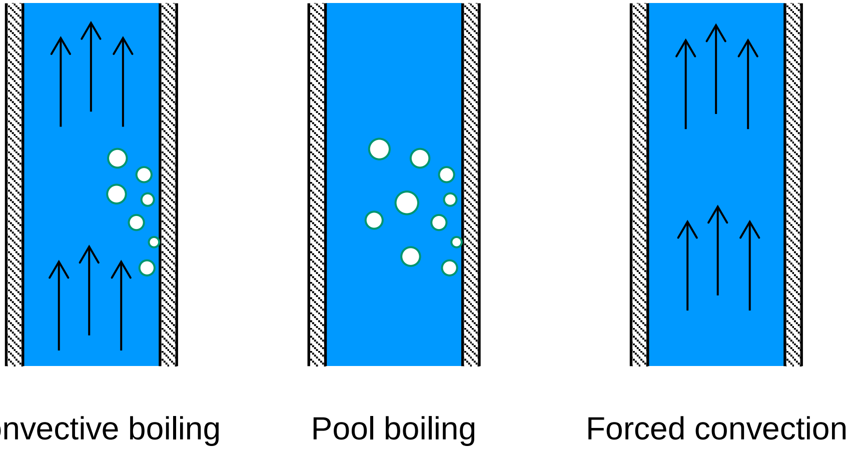


EC Simulations – NOKO (5)

Model Adaptations

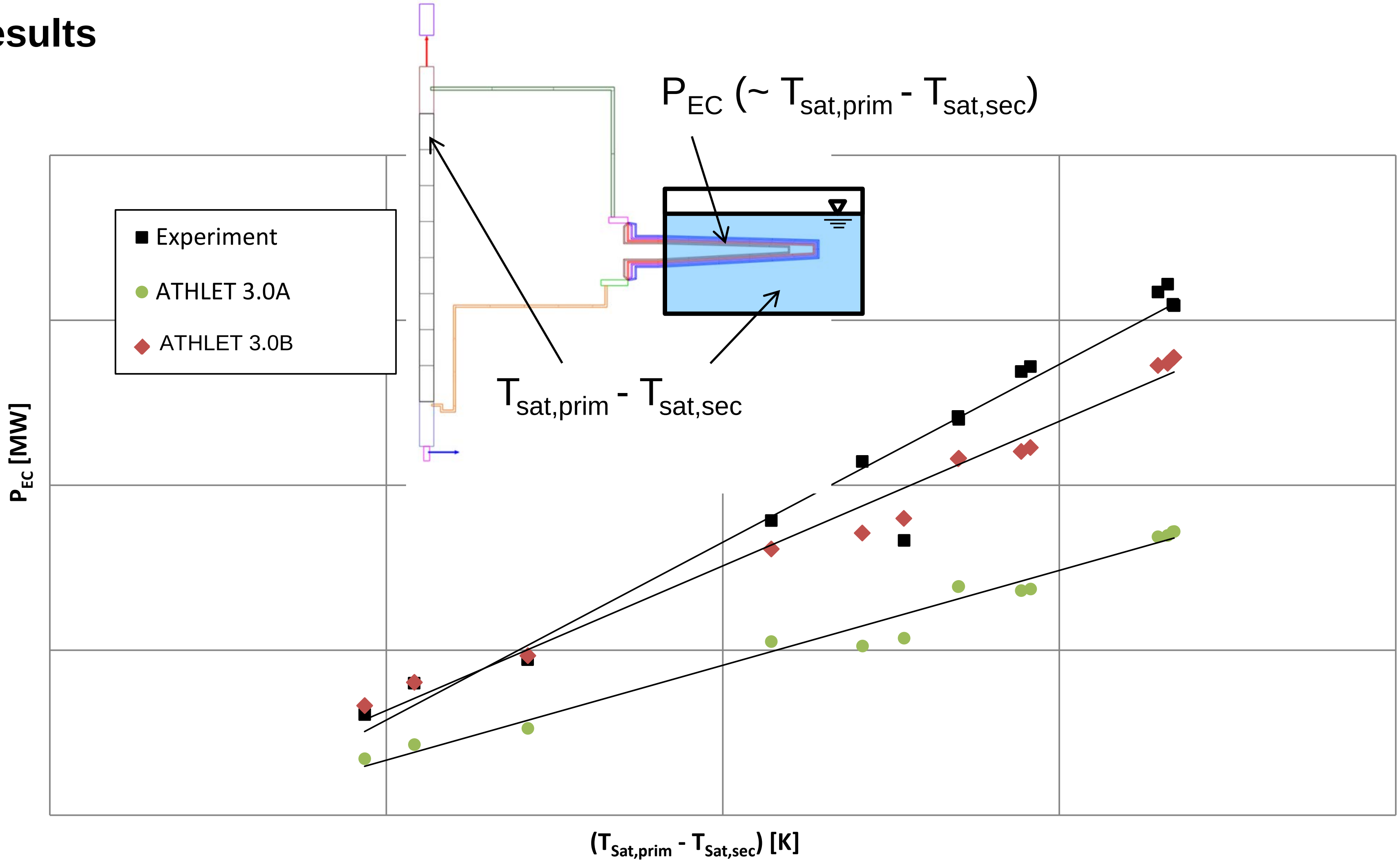
- ATHLET 3.0A underestimates the transferred heat approximately by the factor 2
  - ➢ Need for new/improved heat transfer models
- Implemented changes to the code:
  - – Secondary side (subcooled/saturated nucleate boiling):
    - Suppression factor in Chen-equation for convective boiling has been set to 1.0 for flow outside of horizontal tubes

$$htc_{CB} = S \cdot htc_{PB} + F \cdot htc_{FC}$$



EC Simulations – NOKO (6)

Results



EC Simulations – NOKO (7)

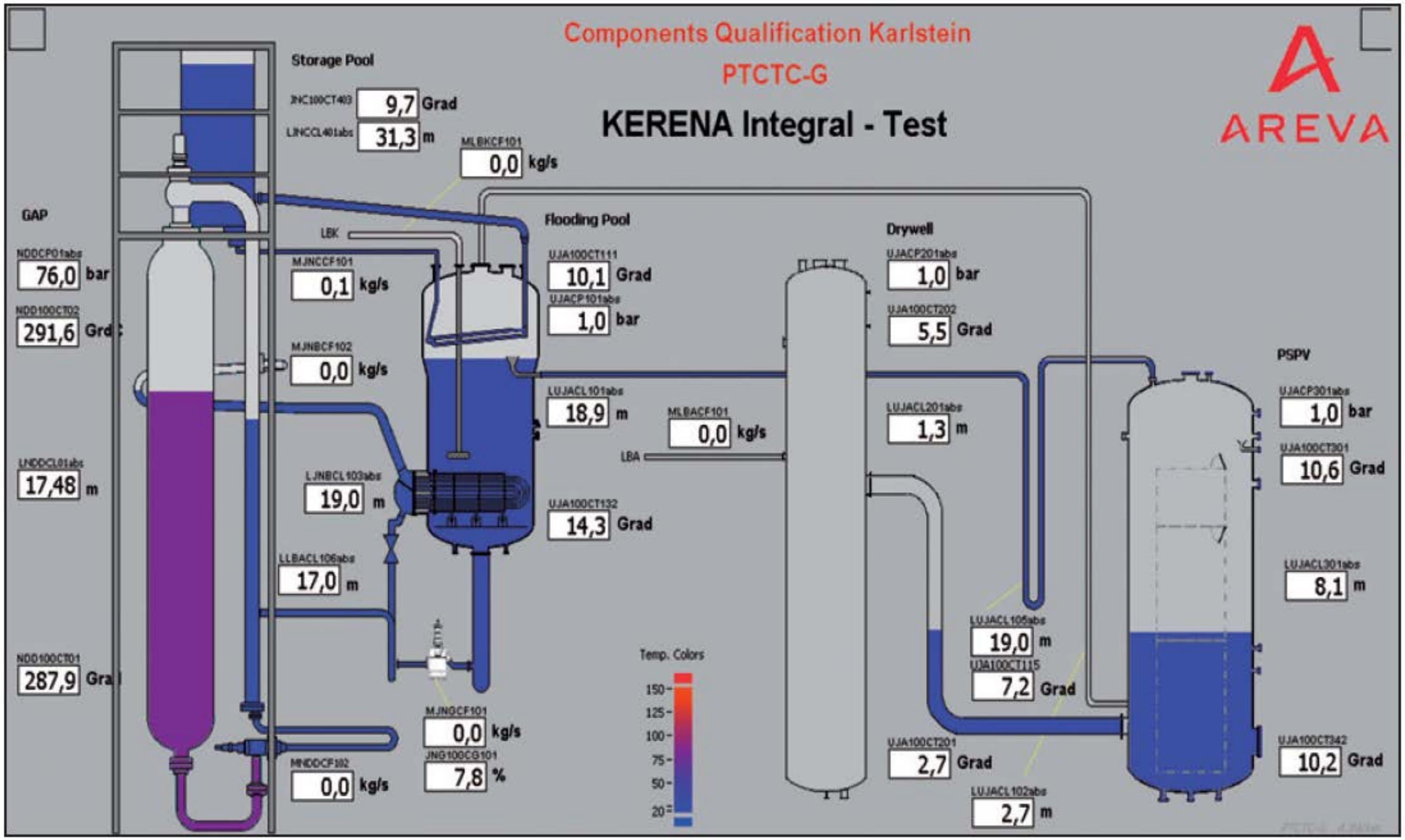
Conclusions

- Revision of models is reasonable and backed by empirical observations
- Calculated EC power considerably closer to experimental results than before
- At higher primary pressures apparently increasing deviations from the experimental data
- Thermal conductivity of the condenser pipe material not exactly known (main heat flow resistance: approximately 40% - 70% of total resistance)

EC Simulations – INKA NOKO (1)

INKA

- Integral Test Stand Karlstein (Integral test facility Karlstein)



Drescher et al.: Passive BWR Integral LOCA Testing at the Karlstein Test Facility INKA. atw Vol. 59 (2014)

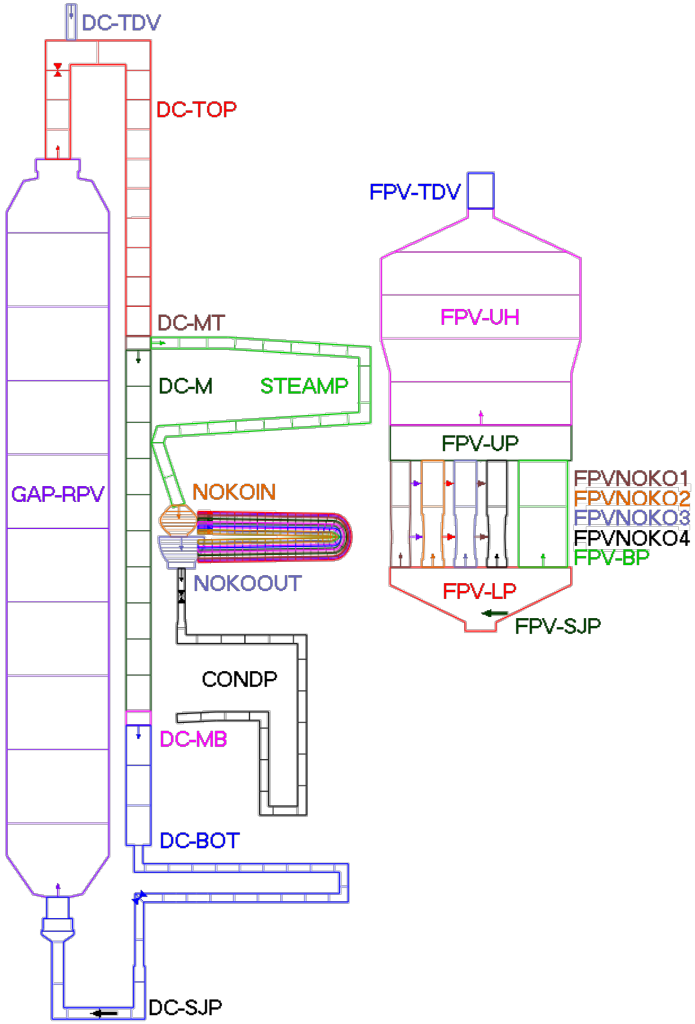
EC Simulations – INKA NOKO (2)

Scaling

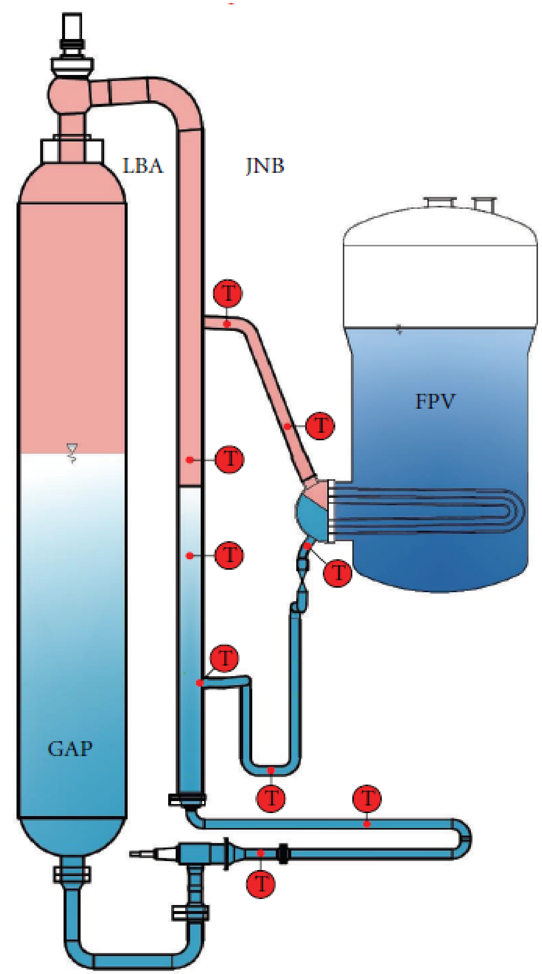
- 1:1 height scaling, 1:24 volume scaling
- 1:4 component scaling
- 22 MW Benson boiler for steam production (less than EC power)
  - No true steady state experiments at high pressures
- GRS simulated 5 experiments
  - 3 stationary cases with different
    - water levels
    - primary pressures and temperatures
  - 2 transient cases with different
    - primary pressure decreases
    - secondary temperatures (subcooled and saturated)

EC Simulations – INKA NOKO (3)

ATHLET Modelling



Leyer, Wich: The Integral Test Facility Karlstein. Hindawi Publishing Corporation. Science and Technology of Nuclear Installations. Volume 2012, Article ID 439374. 2012



Towards Convergence of Technical Nuclear Safety Practices in Europe

EC Simulations – INKA NOKO (4)

Used ATHLET Versions

- ATHLET 3.0B
  - Suppression factor outside horizontal bundles = 1
  - Substitution of Thom equation for ΔT calculation
  - HTC for condensation in horizontal tubes
- ATHLET 3.0B mod 1
  - In addition to that: $\dot{x}$ used instead of x_h
- ATHLET 3.0B mod 2
  - In addition to that: ESDU correlation
- ATHLET 1.2C KONWAR

EC Simulations – INKA NOKO (5)

Code modifications ATHLET 3.0B → 3.0B mod 1

- In ATHLET, $x_h = \frac{h - h'}{r}$ is frequently used instead of $x_m = \frac{m_D}{m_{ges}}$ or $\dot{x} = \frac{\dot{m}_D}{\dot{m}_{ges}}$
  - Error when not in thermal equilibrium
  - Error when steam and water have different flow velocities (relevant e.g. for heat transfer correlations)
- Therefore modification: Usage of $\dot{x} = \frac{\dot{m}_D}{\dot{m}_{ges}}$ instead of $x_h = \frac{h - h'}{r}$
- Has an effect on:
  - Reynolds number $Re = f(\dot{m})$ → Dittus-Boelter correlation → htc_{FC} in Chen equation
  - Lockhart-Martinelli-Parameter → Factors S and F in Chen equation

EC Simulations – INKA NOKO (6)

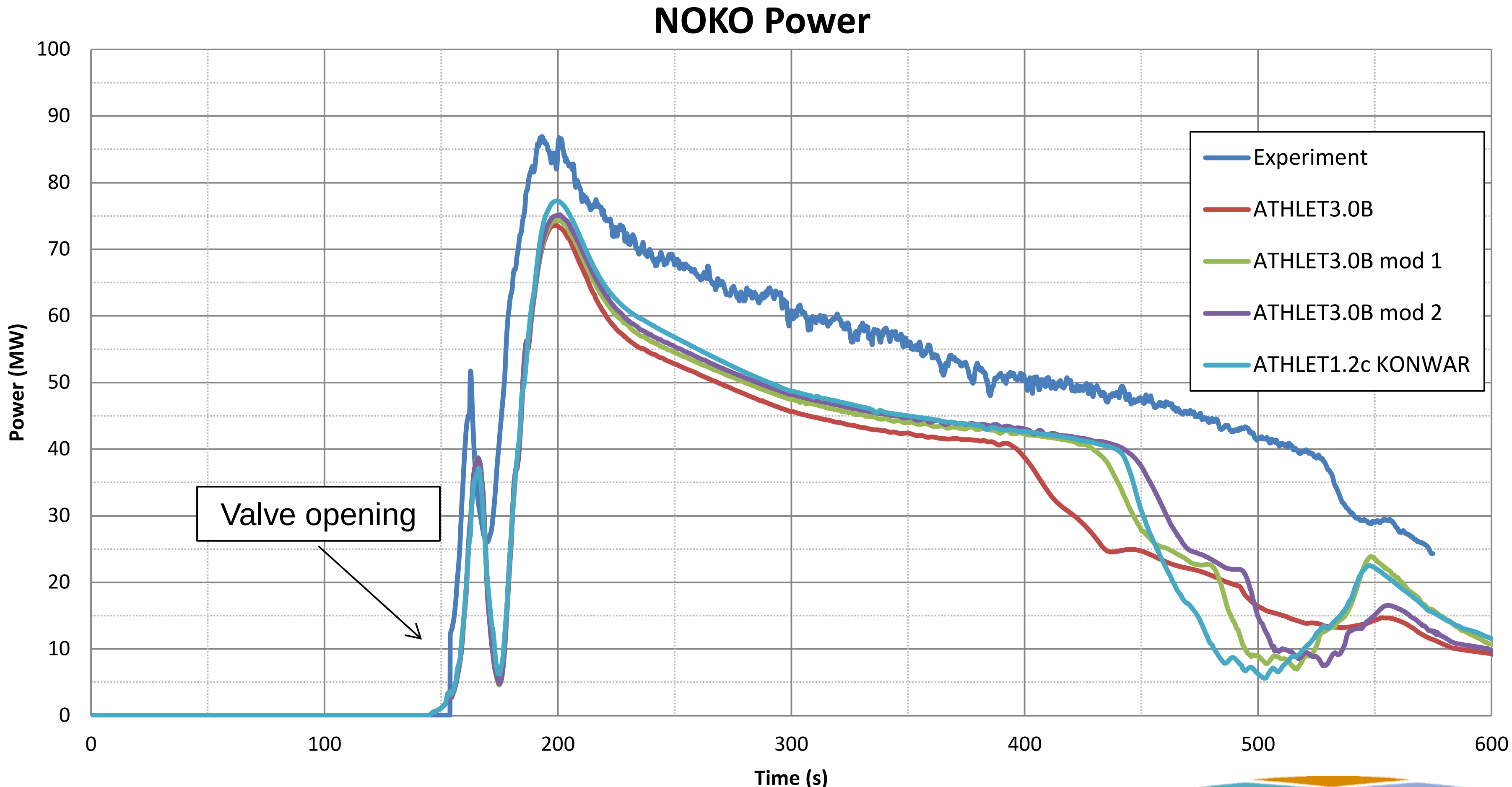
Code modifications ATHLET 3.0B mod 1 → 3.0B mod 2

- Usage of ESDU (Engineering Science Data Unit) correlation for tube bundles in cross flow instead of Dittus-Boelter correlation for convective heat transfer and thus for htc_{FC} in Chen equation
- Increased heat transfer coefficient at the outside of the emergency condenser
- RELAP5-3D uses ESDU correlation for the calculation of heat transfer in horizontal bundles in crossflow
- HZDR (Helmholtz-Zentrum Dresden-Rossendorf) applied ESDU correlation in own INKA simulations

EC Simulations – INKA NOKO (7)

Results

p_{prim} = 85 bar (300°C) ↘ 20 bar (212°C); p_{sec}= 1 bar (30°C)



EC Simulations – INKA NOKO (8)

Conclusions

- Further modifications (usage of $\dot{x}$ instead of x_h, ESDU correlation) give rise to minor improvements
  → They will not be included in ATHLET for code-internal reasons

- However, results are not yet satisfying
  → Need for further development

Current Projects, Future Tasks (1)

- German Research Project EASY (since March 2015):
  - Integral experimental and analytical investigations regarding the controllability of design accidents with passive systems
  - Simulation of integral tests regarding leakages and transients
  - Mainly INKA experiments are used for ATHLET validation
  - Components considered:
    - Containment Cooling Condenser
    - Passive Pressure Pulse Transmitter
    - Vent-Pipe and Overflow-Pipe
    - Etc.

Current Projects, Future Tasks (2)

- German Research Project PANAS (since July 2015):
  - Passive Nachzerfallswärme-Abfuhrsysteme (Passive decay heat removal systems)
  - Focus on heat transfer processes in passive residual heat removal systems
  - Various experiments with high time/spatial resolution (GENEVA, TOPFLOW,…)
  - Development and validation of evaporation/condensation models for ATHLET
  - Components considered:
    - Emergency Condenser
    - Containment Cooling Condenser

Current Projects, Future Tasks (3)

- EU Research Project NuSMoR
  - Preparation of consortium on first safety assessment of European reference SMR design for proposal participating in next EURATOM work programme
  - About 20 partners from 8 European countries, coordinated by GRS as TSO and including all leading European nuclear stakeholders
  - International industrial advisory board
  - Topics:
    - (Pre-normative) research on passive safety and their experimental validation
    - Code improvement, validation and benchmarking
    - Harmonisation of (European) codes and standards
    - Evaluation of the results with view to integration into European NPP sector
  - This project will
    - develop an advanced safety concept with (infinite/long) decay heat removal without any need for electricity of external input and
    - address and solve currently open regulatory issues of supervisory procedures by early involvement of regulators and TSO

Conclusions

- Although Germany terminates the use of nuclear energy it will continue to perform reactor safety research
  - National approach: to maintain and ensure the high safety standard for the remaining operation time
  - International approach: assess current NPP concepts and new builds abroad
- GRS nuclear simulation chain will be further improved and validated
- Important topics are innovative reactor concepts with passive safety systems
- Examples of model development were presented
- GRS tries to establish a further research project on this topic for SMR on a EU level

Acknowledgements

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Additional Slides