Issues related to the safety assessment of the SMR concepts

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SMR development:

- Water cooled reactors:
  - Proven LWR technology reactors
  - Technology of heavy water reactors
- High temperature gas cooled reactors
- Liquid metals cooled fast reactors technology
Introduction

- In the post-Fukushima world, long term station blackouts have to be considered
- Simple, robust and efficient infinite passive cooling systems should be developed

Selected issues, related to the passive cooling systems:
1. Needs for the harmonisation of nuclear rules and regulations
2. Availability of computer codes and modelling gaps for the simulation of passive systems
3. Thermal hydraulic challenges, related to the availability of experiments for computer models validation
Needs for the harmonisation of nuclear rules and regulations, related to the passive cooling systems
Safety-related terms such as passive safety systems are widely used without consistent definitions in the documents of IAEA, Electric Power Research Institute and Nuclear Regulatory Authorities of different EU countries and others. The uniform definitions for passive safety systems and thereto making requirements are highly desirable throughout Europe and even worldwide. The development of a common harmonised understanding could significantly facilitate the processing of a future licensing application.
Harmonisation of definitions of passive safety systems

Types of Passive Safety Systems

Passive safety systems for removing the decay heat from the core after a reactor scram, are:

- Pre-pressurized core flooding tanks (accumulators)
- Elevated tank natural circulation loops (core make-up tanks)
- Gravity drain tanks
- Passively cooled steam generator natural circulation
- Passive residual heat removal heat exchangers
- Passively cooled core isolation condensers
- Sump natural circulation

IAEA. TECDOC 1624, 2009
Harmonisation of definitions of passive safety systems

Types of Passive Safety Systems

Passive safety systems for removing the heat from the containment and reducing pressure inside containment subsequent to a loss of coolant accident, are:

- Containment pressure suppression pools
- Containment passive heat removal/pressure suppression systems
- Passive containment spray

IAEA. TECDOC 1624, 2009
Passive safety system is:
• a system which is composed entirely of passive components and structures, or
• a system which uses active components in a very limited way to initiate subsequent passive operation

Harmonisation of definitions of passive safety systems


Categories to distinguish the different degrees of passivity

<table>
<thead>
<tr>
<th>Category A</th>
<th>Category B</th>
</tr>
</thead>
<tbody>
<tr>
<td>- no signal inputs of ‘intelligence’</td>
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</tr>
<tr>
<td>- no external power sources or forces</td>
<td>- no external power sources or forces</td>
</tr>
<tr>
<td>- no moving mechanical parts</td>
<td>- no moving mechanical parts; but</td>
</tr>
<tr>
<td></td>
<td>- moving working fluids.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Category C</th>
<th>Category D</th>
</tr>
</thead>
<tbody>
<tr>
<td>- no signal inputs of ‘intelligence’</td>
<td>- signal inputs of ‘intelligence’ to initiate the passive process</td>
</tr>
<tr>
<td>- no external power sources or forces; but</td>
<td>- energy to initiate the process must be from stored sources such as batteries or elevated fluids</td>
</tr>
<tr>
<td>- moving mechanical parts, whether or not moving working fluids are also present.</td>
<td>- active components are limited to controls, instrumentation and valves to initiate the passive system</td>
</tr>
<tr>
<td></td>
<td>- manual initiation is excluded.</td>
</tr>
</tbody>
</table>
Harmonisation of definitions of passive safety systems

Types of Passive Safety Systems

Passive safety systems for removing the decay heat from the core after a reactor scram

- Pre-pressurized core flooding tank (accumulator) **Category C** passive safety system
- Elevated gravity drain tank **Category D** passive safety system

*IAEA. TECDOC 1624, 2009*
Harmonisation of definitions of passive safety systems

Types of Passive Safety Systems

Passive safety systems for removing the heat from the containment and reducing pressure inside containment subsequent to a loss of coolant accident.

Containment pressure reduction and heat removal following a LOCA using a passive containment spray and natural draft air. The air flow for the cooling annulus, that is generated by a chimney-like type effect, is a Category B passive safety system. The containment vessel sprays are a Category D passive safety system.

IAEA. TECDOC 1624, 2009
Harmonisation of definitions of passive safety systems


The definition of Advance LWR Utility Requirements of EPRI is quite similar to IAEA Category D.

EPRI defines that a passive systems should rely primarily on passive principles. The use of active features should be limited to valves, monitoring and instrumentation.

The German Safety Requirements for Nuclear Power Plants use a much stricter definition (similar to IAEA Category A or Category B).

Components which require an active activation and or containing parts that change their position within the sequence (e.g. a flap that opens during an accident) will be regarded as active.

Harmonisation of definitions of passive safety systems


**Passive Device (Component):** A device (component) whose functioning is connected only with the event that triggers its operation and does not depend on the operation of another active device for example a control device, power source or the like.

*Note:* In design terms, passive devices are divided into components with mechanical moving parts (for example, non-return valves) and components without mechanical moving parts (for example, pipes and vessels).

(similar to IAEA **Categories A - C**)

**Conclusion**

The different definitions of **Functions of Passive Systems** show a great influence on the requirements to passive components.
Thermal hydraulic challenges, related to the simulation of passive systems

Vertical heater in glass tank

Velocity stream lines and contours by digital PIV
Thermal hydraulic challenges, related to the simulation of passive systems

SMART (System-Integrated Modular Advanced Reactor)

Passive Safety Systems:
- Passive Residual Heat Removal System
- Emergency Cool-Down Tank (ECT)
- Emergency Core Coolant Tank
- Emergency Boron Injection Tank

IAEA. TECDOC 1624, 2009
## SMART (System-Integrated Modular Advanced ReacTor) Passive Safety Systems

<table>
<thead>
<tr>
<th>Passive Safety Systems</th>
<th>Related Phenomena</th>
<th>Characterizing thermal-hydraulic aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Residual Heat Removal System (PRHRS)</td>
<td>Behaviour in large pools of liquid</td>
<td>• Thermal stratification&lt;br&gt;• Natural/forced convection and circulation&lt;br&gt;• Steam condensation (e.g. chugging, etc.)&lt;br&gt;• Heat and mass transfer at the upper interface (e.g. vaporization)&lt;br&gt;• Liquid draining from small openings (steam and gas transport)</td>
</tr>
<tr>
<td></td>
<td>Natural circulation</td>
<td>• Interaction among parallel circulation loops inside and outside the vessel&lt;br&gt;• Influence of non-condensable gases&lt;br&gt;• Stability&lt;br&gt;• Reflux condensation</td>
</tr>
<tr>
<td></td>
<td>Behaviour of emergency heat exchangers and isolation condensers</td>
<td>• Low pressure phenomena</td>
</tr>
<tr>
<td>Emergency Cool-Down Tank (ECT)</td>
<td>Core make-up tank behaviour</td>
<td>• Thermal stratification&lt;br&gt;• Natural Circulation</td>
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</tbody>
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### Thermal hydraulic challenges, related to the simulation of passive systems

SMART (System-Integrated Modular Advanced Reactor)

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<td>Emergency Core Coolant Tank</td>
<td>Effects of non-condensable gases on condensation heat transfer</td>
<td>• Effect on mixture to wall heat transfer coefficient&lt;br&gt;• Mixing with liquid phase&lt;br&gt;• Mixing with steam phase&lt;br&gt;• Stratification in large volumes at very low velocities</td>
</tr>
<tr>
<td></td>
<td>Thermo-fluid dynamics and pressure drops in various geometrical configurations</td>
<td>• 3-D large flow paths e.g. around open doors and stair wells, connection of big pipes with pools, etc.&lt;br&gt;• Gas liquid phase separation at low Re and in laminar flow&lt;br&gt;• Local pressure drops</td>
</tr>
<tr>
<td></td>
<td>Gravity driven cooling and accumulator behaviour</td>
<td>• Core cooling and core flooding</td>
</tr>
<tr>
<td>Emergency Boron Injection Tank</td>
<td>Gravity driven cooling and accumulator behaviour</td>
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<td>Core make-up tank behaviour</td>
<td>• Thermal stratification&lt;br&gt;• Natural Circulation</td>
</tr>
<tr>
<td></td>
<td>Liquid temperature stratification</td>
<td>• Lower plenum of vessel&lt;br&gt;• Down-comer of vessel&lt;br&gt;• Horizontal/vertical piping</td>
</tr>
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<td>Natural circulation</td>
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Thermal hydraulic challenges, related to the simulation of passive systems

Thermal hydraulic challenges:
1. Condensation of steam or steam mixed with non-condensables
2. External natural convection of water around the external surface
3. Temperature fields (stratification) in water pools

Based on the proposals for HORIZON 2020 Call: NFRP-2016-2017 (Euratom fission 2016-2017):
• Proposal number: 754343, NUSMoR_plus (NUgenia Small Modular Reactor with infinite passive containment cooling)
• Proposal number: 755494, NONCOND (Noncondensable Gases Effects on Reactor Coolant System and their Improved Modelling and Analysis)
Thermal hydraulic challenges, related to the simulation of passive systems

1. Effect of non-condensables on the processes in Reactor Cooling System

Potential sources of non-condensable gases for the reactor coolant system:

1. NCG’s dissolved normally in primary coolant and their release after pressure decrease in LOCA
2. Hydrogen or other gases released and accumulated in PRZ top due to continuous spraying and electrical heater operation
3. Nitrogen dissolved in ACCUM water and its release after injection into depressurized RCS during LOCA
4. Release of NCG gases dissolved in non-deaerated water in ECCS tanks and injected into RCS during LOCA
5. Radiolysis of water due to gamma rays continuing after reactor SCRAM
6. Incidental direct inflow of gaseous nitrogen from one or more ACCUM’s into RCS due to failure in ACCUM isolation in LOCA
7. Reverse flow at break in LBLOCA if RCS pressure drops under containment pressure
8. Production of hydrogen in case of core overheating and clad-water reaction
9. Number of other potential NCG sources relevant to SHUTDOWN conditions (free reactor level in contact with containment atmosphere, penetration of gas to RCS over not tight lines of deaeration system, etc.)
Thermal hydraulic challenges, related to the simulation of passive systems

1. Effect of non-condensables on the processes in Reactor Cooling System

Possible consequences of presence of non-condensable gases in RCS:
1. Degradation of heat transfer at SG (especially in condensation mode)
2. Full blocking of heat transfer surfaces (SG’s or other heat exchangers)
3. Higher primary pressure in some transients and accidents
4. Blocking of flow paths due to cumulation of NCG’s in upper parts of RCS
5. Effect of dissolved gases on the onset of subcooled boiling and critical heat flux
6. Lower spraying efficiency
7. Dissolved gases affects pressure waves
8. Effects on passive safety systems performance
9. Creation of explosive mixture of gases in upper parts of RCS or in containment
Thermal hydraulic challenges, related to the simulation of passive systems

1. Effect of non-condensables on the processes in Containment structures

Infinite passive decay heat removal in case of Flexblue design
1. Effect of non-condensables on the processes in Containment structures

Specific (comparing with RCS):

• Condensation of steam or steam and non-condensables on containment structures at near vacuum, atmospheric and slightly overpressures conditions, at different types of condensation (droplets, film condensation or transitional forms).
• Large concentrations of non-condensables and relatively small driving temperature differences
• The experimental investigation of condensation of steam or steam mixed with non-condensables on containment structures and the setting of representative boundary conditions is extremely difficult

Conclusion

• The simulation of the condensation phenomena and effect of non-condensables requires the experimental investigation and improvements in the system codes or CFD tools.
Thermal hydraulic challenges, related to the simulation of passive systems

2. External natural convection of water around the external surface

Infinite passive decay heat removal in case of Flexblue design
Thermal hydraulic challenges, related to the simulation of passive systems

2. External natural convection of water around the external surface

- Currently, no validated models are available for the simulation of the free convection flow around horizontal cylinders for the Rayleigh number (Ra), which is the product of the Grashof number (Gr) and the Prandtl number (Pr) larger than $10^{12}$. The working points of the subsea-based containments are in the order of magnitude for Ra of $10^{15}$.
- In literature, several correlations describing natural convection heat transfer at horizontal cylinders are available. Here, the average Nusselt number (Nu) is determined by $Nu = C \cdot Ra^a$. C and a are experimentally determined constants. Correlations for the calculation of heat transfer coefficients (HTC) exist for $Ra \leq 10^{12}$ (e.g. Mc Adams, Churchill and Chu, Morgan, Sedahmed and Schmilt, Heo and Chung).
Thermal hydraulic challenges, related to the simulation of passive systems

2. External natural convection of water around the external surface


Nusselt number versus Rayleigh number of existing correlations
Thermal hydraulic challenges, related to the simulation of passive systems

2. External natural convection of water around the external surface

- As long as the thickness of the boundary layers is less than the gap width between containment and transport shell, the heat transfer at the outer side of the containment is not influenced. This is e.g. the case for a clean surface.
- In case of biological fouling and / or mussel growth, the roughness of the surface and the boundary layer thickness will increase.

**Conclusion**
- The influence on the heat transfer around the external surface and the gap mass flow has to be investigated.
Thermal hydraulic challenges, related to the simulation of passive systems

3. Temperature fields (stratification) in water pools


Simulation of the temperature fields in one sector of the Gravitational Driven Water Pool

Simulation of the temperature stratification in the vessels, which simulates the geodetic core flooding pool fields in the NOKO test facility
Thermal hydraulic challenges, related to the simulation of passive systems

3. Temperature fields (stratification) in water pools

- Experiments on temperature fields (stratification) in water pools were performed in the test facilities NOKO (Forschungszentrum Jülich), PANDA (Paul Scherrer Institut), TOPFLOW and the Side Wall Heated Tank (Helmholtz-Zentrum Dresden-Rossendorf), in the Glass Tank and ITL of the Bhabha Atomic Research Centre.

- Analyses of Thermal Stratification Phenomena could be divided into:
  - basic studies (such as the Glass Tank tests of BARC)
  - integral tests (such as the Integral Test Loop (ITL) or the NOKO tests).

- The ILT was constructed at BARC for the investigation of the overall heat transfer behaviour of the main heat transport system of the Advanced Heavy Water Reactor especially the Isolation Condensers (ICs) and the Gravitational Driven Water Pools (GDWPs).

- The NOKO facility (Forschungszentrum Jülich) simulates the flooding pool of the KERENA by a horizontal tank with an 8 tube test bundle section of the emergency condenser of the SWR-1000.

- Both, measurements and post-test calculations show that, during IC operation, strong temperature stratifications occur in the first 6 h. Similar finding were obtained by 2D simulations of the flooding pool heat up of the NOKO facility.
Thermal hydraulic challenges, related to the simulation of passive systems

3. Temperature fields (stratification) in water pools

- The behaviour of large water pools is of particular importance for two applications:
  - Various SMR concepts provide water pools partially bounded by containment structures as a heat sink for selected transients or LOCA. The temperature distributions in the water pools at the inner side of the containment walls influence decisively the local heat transfer.
  - Some SMR concepts use a water pool in which the containments or a part of the containments (e.g. NuScale) are immersed. Also here, temperature and velocity fields establish during containment cooling.

- The challenge of this issue is to develop and validate course mesh 2D/3D pool models for the computer tools to simulate the behaviour of water pools inside and outside the containment.

Conclusion

- In the computer simulation it is necessary to improve the understanding of the physical phenomena inside the water pools.
- To check whether the 2D/3D models of the computer tools can reach the required space resolution and accuracy with acceptable CPU time.
Computer codes and modelling gaps for the simulation of passive systems
The thermal hydraulic code ATHLET (Analysis of the Thermal Hydraulics of leaks and Transients) originally developed by GRS GmbH for the analysis of the whole spectrum of transients and LOCAs in western types of LWRs. Currently ATHLET can be applied as well for Russian reactors (VVER, RBMK) and advanced gas, liquid or molten salt cooled fast reactors.

ATHLET consists of several modules, each addressing one special issue, such as thermal hydraulics (TFD), heat transport and heat conduction (HECU), neutron kinetics (NEUKIN) and simulation of balance and control systems (GCSM). Further modules and codes such as a 3D neutron kinetic or CFD can be coupled via interfaces.

Currently national research projects are ongoing for the further development and validation of ATHLET for ALWR, SMR and Gen IV reactors. One selected example is the development of 2D/3D module to enhance the capabilities of ATHLET in simulating complex, multidimensional flow phenomena.
Computer codes and modelling gaps for the simulation of passive systems

COCOSYS

- The Containment Code System COCOSYS (developed by GRS GmbH) is used for comprehensive simulations of phenomena occurring during (severe) accidents in LWR containments.
- COCOSYS applies as far as possible mechanistic models.
- In the past, various passive safety features (such as containment cooling condensers) have been simulated.
- The challenge is the modelling of mixing respectively separation of steam / gas mixtures in the vicinity of the building condenser or of structures (such as walls, floor, ceiling, other internals).
- COCOSYS is successfully validated for a large spectrum of condensation experiments of HDR, BMC and ThAI. Because the code models are developed on the basis of the aforementioned experiments, the computational results are in good agreement with the measurements.
MELCOR

• MELCOR (Methods for Estimation of Leakages and Consequences of Releases) is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants.
• MELCOR is being developed at Sandia National Laboratories for the US NRC as a second-generation plant risk assessment tool and the successor to the Source Term Code Package.
• A broad spectrum of severe accident phenomena in both, boiling and pressurised water reactors, is treated in MELCOR in a unified framework. These include thermalhydraulic response in the reactor coolant system, reactor cavity, containment and confinement buildings; core heat-up, degradation, and relocation; core-concrete attack; hydrogen production, transport, and combustion; fission product release and transport behaviour.
• Current uses of MELCOR include the estimation of severe accident source terms and their sensitivities and uncertainties in a variety of applications.
Computer codes and modelling gaps for the simulation of passive systems

ASTEC

- ASTEC (Accident Source Term Evaluation Code) has been developed jointly over a number of years by the IRSN and GRS.
- In 2015 both parties decide to abandon the joint development and to continue independently with individual development priorities.
- The general purpose of the ASTEC is to simulate all the phenomena occurring during a severe accident in a water-cooled nuclear reactor, from the initiating event to the possible release of radioactive products (source term) outside the containment.
- Although the main purpose of ASTEC is the modelling of phenomena during severe accidents, this modular structure code has special module CESAR for the modelling of thermal-hydraulic processes.
- The CESAR module is meant for the two-phase thermal-hydraulics of coolant flows in the reactor coolant primary and secondary systems using a numerical approach based on five equations.
Computer codes and modelling gaps for the simulation of passive systems

**ANSYS CFX**

- ANSYS CFX (Analysis of Systems – Common Field eXercise) is a commercial Computational Fluid Dynamics (CFD) software tool for simulation of fluid flows in a virtual environment and is developed by ANSYS, Inc.
- ANSYS CFX is an engineering method for simulating the behaviour of systems, processes and equipment involving flow of gases and liquids, heat and mass transfer, chemical reactions and related physical phenomena.
- It is e.g. applied to simulate containment phenomena such as condensation at structures, loads associated with the presence of hydrogen during a hypothetical severe accident or the behaviour of passive autocatalytic recombiners.
- ANSYS CFX was successfully validated against relevant test (such as PHEBUS, PANDA, TOSQAN, MISTRA and THAI) within the OECD International Standard Problem 47.
Computer codes and modelling gaps for the simulation of passive systems

OpenFOAM

- OpenFOAM (Open Source Field Operation and Manipulation) is a free, open source CFD software toolbox with an extensive range of features to solve a wide range of applications from complex fluid flows involving turbulence and heat transfer to solid mechanics.
- The application range of Open FOAM is comparable to that of ANSYS CFX.
Conclusion

• In the long term, Computational Fluid Dynamic (CFD) codes would be suitable for the simulation of the 3D velocity and temperature fields of large water pools.
• Until now, the suitability of the CFD codes was only demonstrated for single-phase issues. Additionally, multiscale approaches in which system codes are coupled to CFD codes were developed and applied for selected applications.
• The application of CFD codes for two-phase flow simulations requires further extensive model development and validation.
• The computer capacity will probably no longer be a limiting factor for two-phase flow simulations.
• In the long term, also methods required for the determination of uncertainties will be available.
Example of simulation of natural convection flow with conjugate heat transfer using 1-D and 3-D codes
Example of simulation of natural convection flow with conjugate heat transfer

The experimental facility (rectangular vessel) is 1/910 the size of the Passive Condensate Cooling Tank in the Condensing Heat Removal Assessment Loop (PASCAL test facility), which represents the passive auxiliary feedwater system.

Example of simulation of natural convection flow with conjugate heat transfer


- In the pool of water were inserted five (TF-01 ÷ TF-05) thermocouples to monitor and record the thermal changes during the experiment.
- These thermocouples were placed in the center of the pool, except the TF-02 thermocouple, which were placed 2 mm away from the heater rod surface.
- Thermal power of heater rod is 600 W. Heat losses – 310 W.

Temperature of water

Temperature of walls
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using one-dimensional code RELAP5

Model nodalization
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using one-dimensional code RELAP5

Results of calculation
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using one-dimensional code RELAP5

The energy loss coefficients in nodes close to the heater 10102, 10103 and 10302, 10303 are significantly increased (EXP-51e.r)

Assumed, that all heat is transferred only to the node, which is placed above heater (EXP-9.r)
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using 3-D code ANSYS Fluent

Mesh of computational model:

Mesh size 433948 cells
The smallest cell size 0.9 mm
The biggest cell size 9.0 mm

Initial density
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using 3-D code ANSYS Fluent

Results of calculation
Example of simulation of natural convection flow with conjugate heat transfer

Simulation using 3-D code ANSYS Fluent

Comparison of measures and calculated temperatures of water
Conclusion

• The heat losses through the walls should be greater than mentioned in the experimental description (> 300 W).
• The modelling of temperature fields (stratification) in the water pool is complicated using 1-D codes.
• In the 1-D simulation the nodes below the heater should be smaller. The 1-D code does not allow to model the circulation of water around the surface of the heater, which interferes with the circulation of water in adjacent nodes.
• Due to limitation of 1-D codes, it is recommended to use CFD codes for the modelling of such water temperature stratification in pools effect.
Summary

• The main challenge, related to the SMR based on LWR technology in the post-Fukushima world is the development of simple, robust and efficient infinite passive cooling systems.

• The main problems, related to the passive cooling approaches, are:
  1. Needs for the harmonization of nuclear rules and regulations;
  2. Thermal hydraulic challenges, related to the availability of experiments for computer models validation;
  3. Availability of computer codes and modelling gaps for the simulation of passive systems.

• As the thermal hydraulic challenges the following problems are discussed:
  – condensation of steam or steam mixed with non-condensables,
  – external natural convection of water around the external surface,
  – temperature fields (stratification) in water pools.

• In presentation the problems of harmonization of the definitions for passive safety systems is discussed and the capacity of tools developed and validated in Europe such as ATHLET, COCOSYS, ASTEC, CFD and others are analyzed.

• The example of simulation of natural convection flow with conjugate heat transfer using 1-D and 3-D codes is presented.
Thank you for the attention

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