PWR Prague 2026

Design and Thermal-Hydraulic Characteristics of a Passive Auxiliary Feedwater System for Advanced Power Reactors

Jan Hruškovič

2026 / 10 / 21



FNC TECHNOLOGY CO., LTD.

CONTENTS

1 Introduction

2 PAFS Design and Operating Principle

3 Thermal-Hydraulic Characteristics

4 Validation, Analysis, and Applications

5 Conclusions

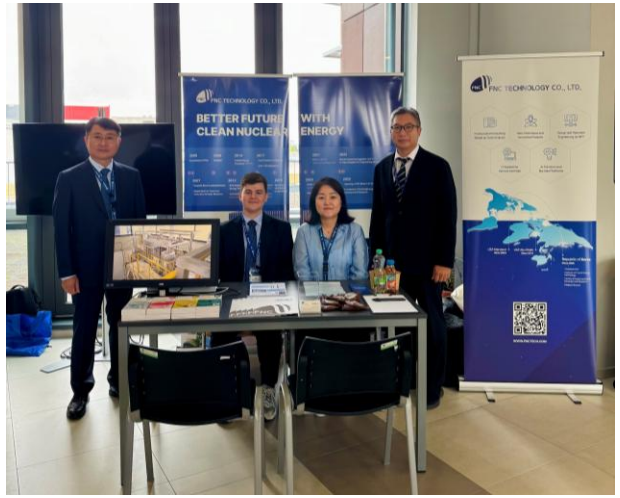
Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

0 About FNC

FNC Technology

- **FNC Technology** – largest **private** nuclear engineering company in Korea
- Provide **engineering services** in various areas of nuclear industry and R&D
- Participated in **joint R&D with Czech** and **APR1000 EUR certification**
- Overseas offices in **Abu Dhabi** (UAE), **Maryland** (USA), **Prague** (CZ)
- Well-established **partnership** with Czech institutions and companies

FNC
㈜미래와도전
FNC Technology Co., Ltd.





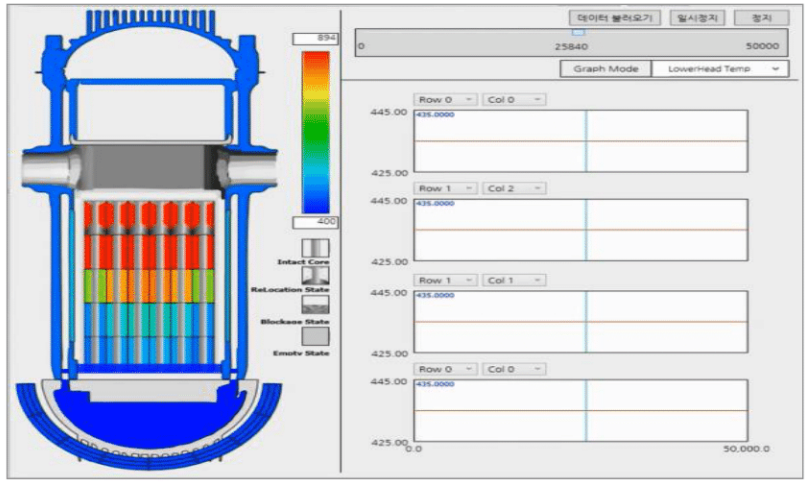


Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

COMPETENCE

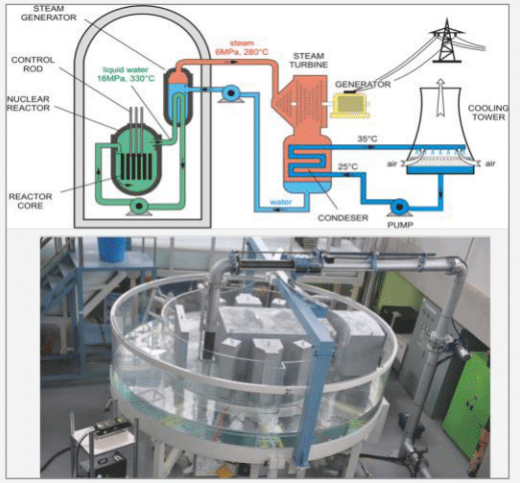
Future & Challenge with FNC Technology Co., Ltd.

Safety Analyses



- DBA Analysis
  - Development of S-Hybrid SIT and PECCS(Passive ECCS)
  - Technology Development for Safety Improvement of Advanced Power Plant(APR+) Design
- DEC(Design Extension Condition) Analysis
  - Development of Severe Accident Management Guidance(SAMG) for BNPP 1,2,3&4
  - Safety Analysis for Hydrogen Explosion in Severe Accident

Fluid System Engineering

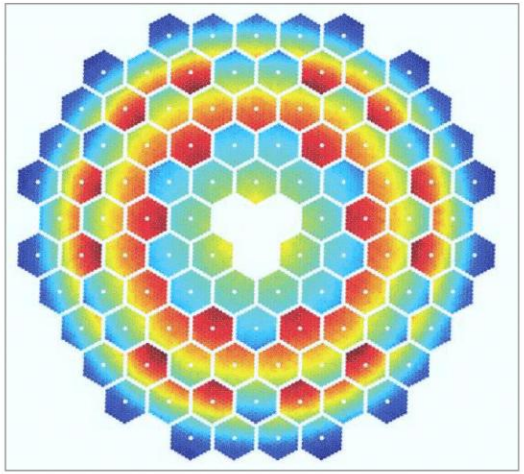


- ECCS Strainer Performance Test
- Downstream Effect Test of Sump Strainer for Long-Term Core Cooling Test
- ECCS Gas Accumulation Assessment
- Flow Accelerated Corrosion Assessment

COMPETENCE

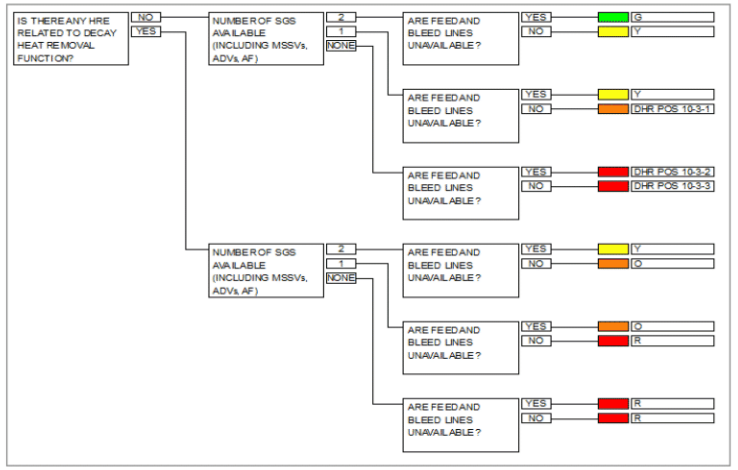
Future & Challenge with FNC Technology Co., Ltd.

Nuclear Core and T-H Design Analyses



- Core Design and Neutronics Analysis
- Core Criticality Analysis
- Core Thermal-Hydraulic Analysis
- Core Cooling Verifying Test
- Reactor Internal Structure Assessment

Risk Assessment

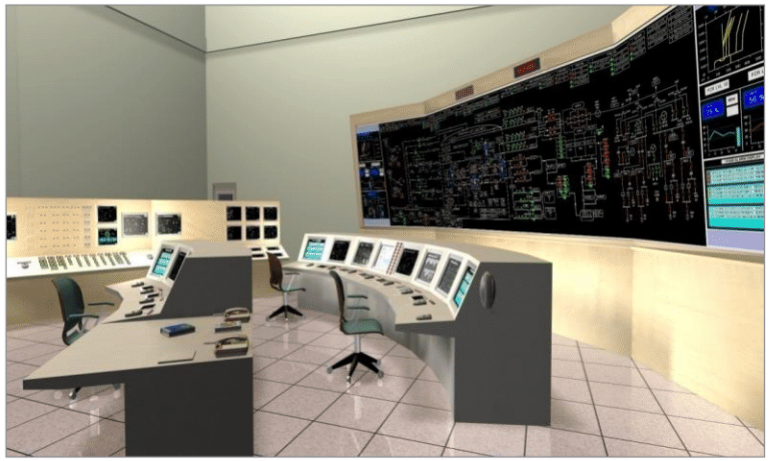


- Development of PSA Model in Low-power & Shutdown Mode
- Development of PSA Model for Multi-Units
- Risk Informed Application
  - Development of Outage Risk Monitoring (ORION) Model for APR1400

COMPETENCE

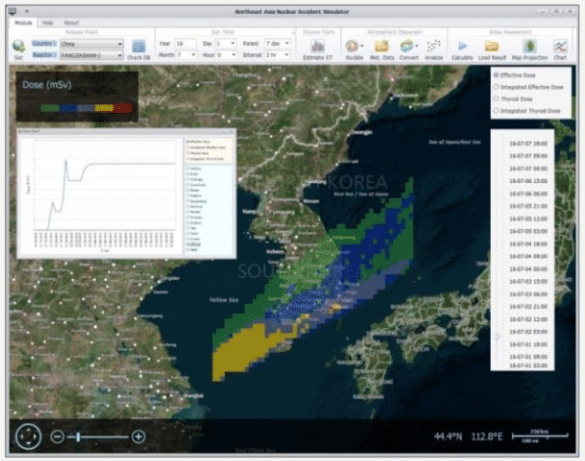
Future & Challenge with FNC Technology Co., Ltd.

Instrumentation & Control



- MCR Display Sharing Technology for APR1400
- Improvement of Simulator for APR1400 using Virtual Distributed Control system(DCS)
- Development of Software
  - SW for PMAS(Plant Monitoring Annunciation System)

Radiation & Environment

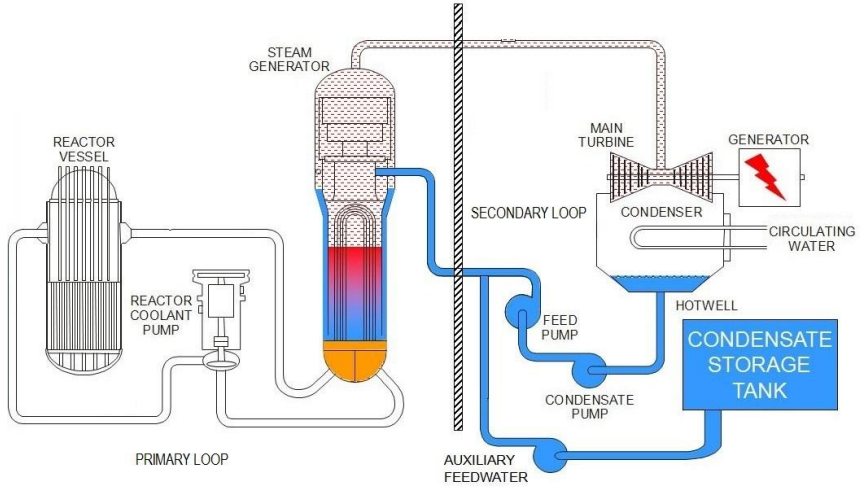


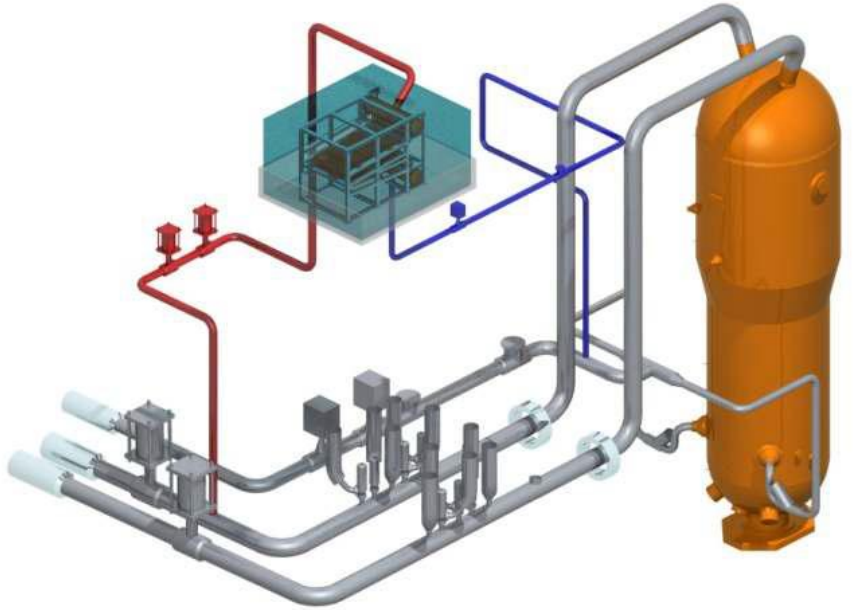
- Shielding Analysis for Nuclear Facility
- Atmospheric Dispersion Modeling
- Development of Radiation Detection System
- Dose Assessment for Safety Analysis Report & Environmental Report

1 Introduction

Why Passive Auxiliary Feedwater System?

- **Long-term decay heat removal** after reactor shutdown is required
- In traditional PWRs, RCS cooling is provided via SG secondary side
  - **Conventional auxiliary feedwater systems** rely on pumps requiring **continuous supply of electricity** and may require operator actions
- **PAFS** provides cooling function by **passive mechanisms**
  - **Natural circulation** is established in **closed-loop system**
  - Boiling (SG), condensation (PCHX), gravity, cooling-water inventory
  - **Reduction of dependence on active pumps** and supply of electricity
  - Relatively **simple design** and reduction of plant components
  - Continued steam-generator cooling during accident conditions
- The PAFS concept has been developed for several Korean advanced reactor designs, including APR+, iPOWER, APR1000, and i-SMR
- **PAFS operation was confirmed experimentally** (ATLAS test facility)



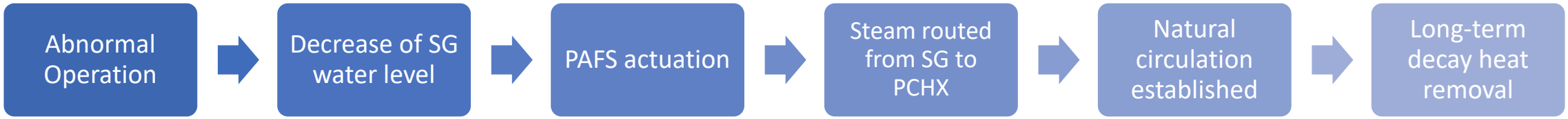


Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

1 Introduction

PAFS Safety Function and Actuation Conditions

- PAFS is **normally isolated** during plant **normal power operation**
- **Low steam-generator water-level** (~25 %) **actuates PAFS** by opening of actuation (isolation) valves
- **Opening of the actuation valve** establishes the closed-loop heat-removal path
- Steam generated in the SG subsequently enters the PAFS steam-supply line and condenses in PCHX
- **PAFS** can support **heat removal** following any scenario involving **loss of normal feedwater**
- **Integral testing** confirmed heat-removal capability under different system boundary conditions
- PAFS is designed for **long-term operation**, heat removal is available without any action required

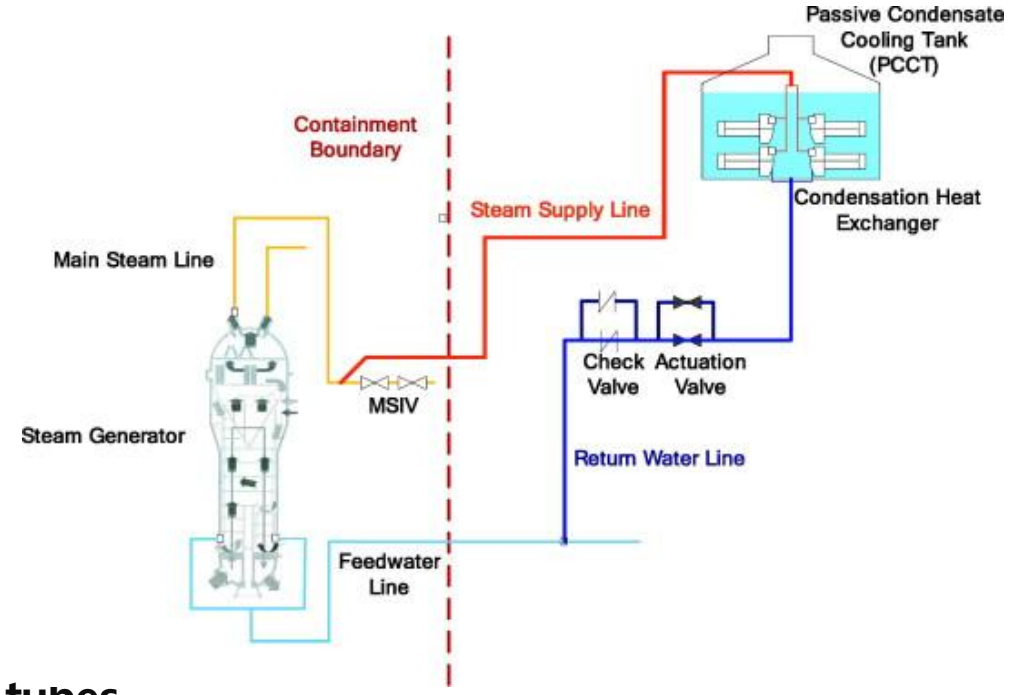


Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

2 PAFS Design and Operating Principle

PAFS System Configuration

- Main components
  - Steam Generator (SG)
  - Steam-supply line (connected to main steam line)
  - **Passive condensation heat exchanger (PCHX)**
  - **Passive condensation cooling tank (PCCT)**
  - Condensate-return line
  - PAFS actuation and isolation valves



- Steam generator as the heat source / PCHX as the heat sink
- **PCCT** has **large water inventory** and provides **cooling to PCHX tubes**
- **PCHX/PCCT** are located at a **higher elevation relative to the SG**, condensate is returned to the SG by gravity
  - This arrangement forms a **closed natural-circulation loop**
  - PAFS is arranged in **two independent trains** to provide required heat-removal capacity and redundancy

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

2 PAFS Design and Operating Principle

Natural-Circulation Mechanism

- **Steam** generated in SG has high-temperature and **relatively low-density**
- Condensation in the PCHX tubes produces **higher-density condensate / water**
- **Gravity returns condensate to the steam generator**, no circulation pump is required
- **Density difference**, together with the **elevation difference** (SG vs. PCHX), establishes **natural circulation**
- Stable PAFS operation requires **sufficient natural-circulation driving head** to overcome hydraulic resistance
  - Major resistance contributors – steam-supply line, valves and fittings, PCHX header and tubes, return-line
  - Both **single-phase** and **two-phase pressure losses** affect the natural-circulation flow rate
- **System pressure**, **flow resistance**, and **component elevation** strongly influence the resulting circulation flow and heat-removal capability of PAFS (hydrostatic driving force must exceed total loop flow resistance)
- PAFS provides **reliable operation** over relevant accident conditions and **wide range of system parameters**

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

2 PAFS Design and Operating Principle

Key PAFS Design Parameters

Main parameters to be considered

- **System pressure** – affects saturation conditions, steam properties and condensation (~7.5 MPa)
- **Elevation difference** – provides the hydrostatic head for natural circulation
- Steam-supply and return-line diameter/length – determine hydraulic resistance
- **Local loss coefficients** – valves, bends, junctions and headers
- **PCHX heat-transfer area** – related to the required heat-removal capability
- PCHX tube diameter and length – affect both pressure loss and condensation
- PCHX inclination – influences condensate drainage and internal flow regime (~3° in the reference design)
- PCCT initial temperature/subcooling – controls the initial pool-side heat-transfer behavior
- PCCT inventory and PCHX submergence – determine passive cooling capability and duration

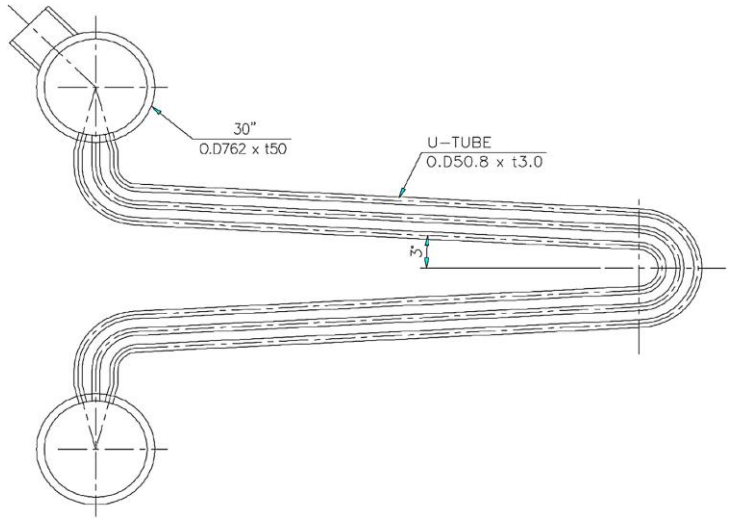
The final **PAFS design** is therefore a **coupled thermal-hydraulic optimization** considering all components **as a whole system**, rather than independent sizing of individual components

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

3 Thermal-Hydraulic Characteristics

PCHX Design Characteristics

- PCHX is a **submerged**, nearly horizontal **U-shaped condensation heat exchanger**
  - High-pressure (saturated) steam enters the PCHX from the SG
  - Heat is transferred through the tube wall to the PCCT water pool
  - **Condensed water** must **drain continuously** toward the outlet/return line
- Selected a small tube inclination (3°) to enhance condensate drainage
- Tube number and dimensions were selected considering both
  - Required heat-removal capability, including redundancy
  - Internal flow-regime/two-phase flow phenomena considerations



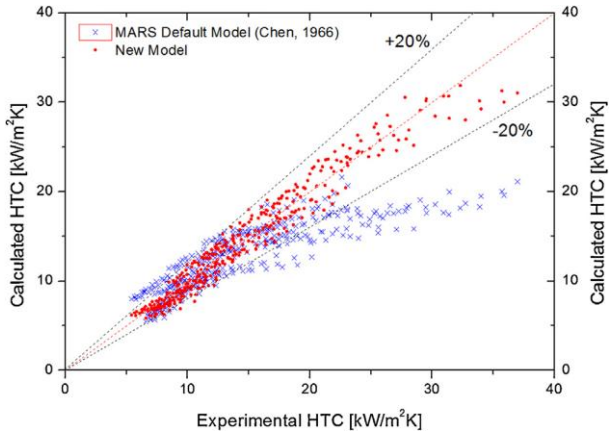
- The **PCHX inlet steam condition is plant-specific**; **saturated or superheated** inlet conditions can result in different flow and heat-transfer behavior and **may require different design considerations**
- In principle, PCHX behavior is similar for iPower, APR+, APR1000 (saturated steam)
- However, in case of integral SMRs, phenomena and design considerations can be different (superheated steam)

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

3 Thermal-Hydraulic Characteristics

Condensation and Flow Characteristics in the PCHX

- **Steam enters the PCHX** at high pressure and progressively **condenses along the tube**
  - Local steam quality and mass flux decrease toward the outlet, as condensation progresses
  - Condensate accumulates predominantly in the lower region of the nearly horizontal tube
  - Depending on local conditions, annular / stratified / stratified-wavy two-phase flow may occur
  - Under gravity-dominated conditions, separated/stratified flow becomes particularly important



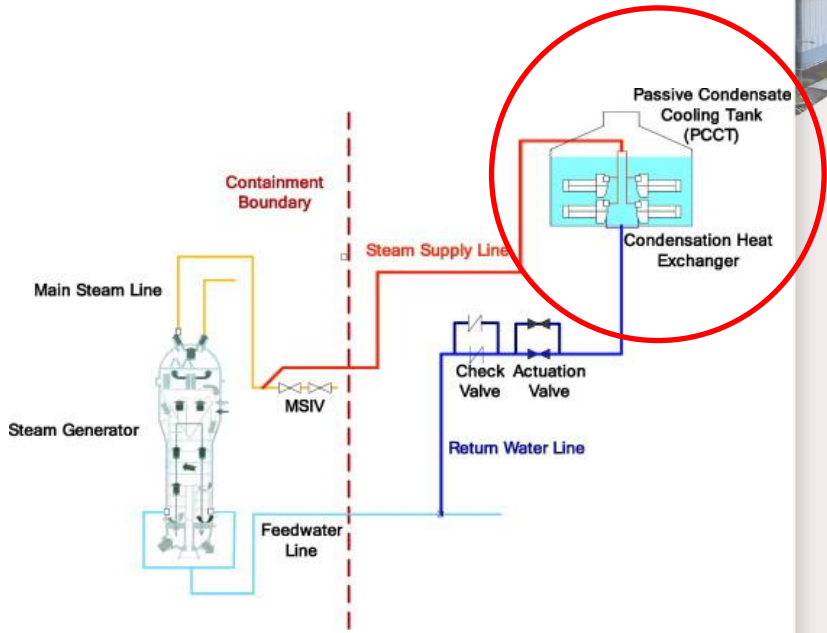
- **Heat-transfer coefficients** are therefore **not uniform** around the tube circumference
  - Upper tube region may experience direct steam-film condensation while the lower region has a deeper condensate layer
  - Local **heat transfer coefficient** and **heat flux** generally **change along the tube** as condensation progresses
- **Condensation heat-transfer modeling** strongly influences **predicted PCHX heat-removal capacity**
  - Accurate representation of flow regime is important for realistic safety/system-code prediction
  - Condensate film thickness and distribution affect the local thermal resistance and condensation heat-transfer coefficient

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

3 Thermal-Hydraulic Characteristics

PCCT Thermal-Hydraulic Characteristics

- PCCT initially contains a large inventory of relatively cool water
- PCHX transfers condensation heat to the surrounding pool through the tube walls
- Early response is characterized by pool heating and natural convection
  - Local heating around PCHX establishes **buoyancy-driven circulation within the tank**
  - With **continued heat transfer**, water near the PCHX **approaches saturation**
  - **Nucleate boiling** develops on the **external PCHX wall surface**
  - **Boiling and evaporation** progressively **reduce PCCT inventory**
  - Pool hydrostatic pressure and local subcooling change as water level decreases



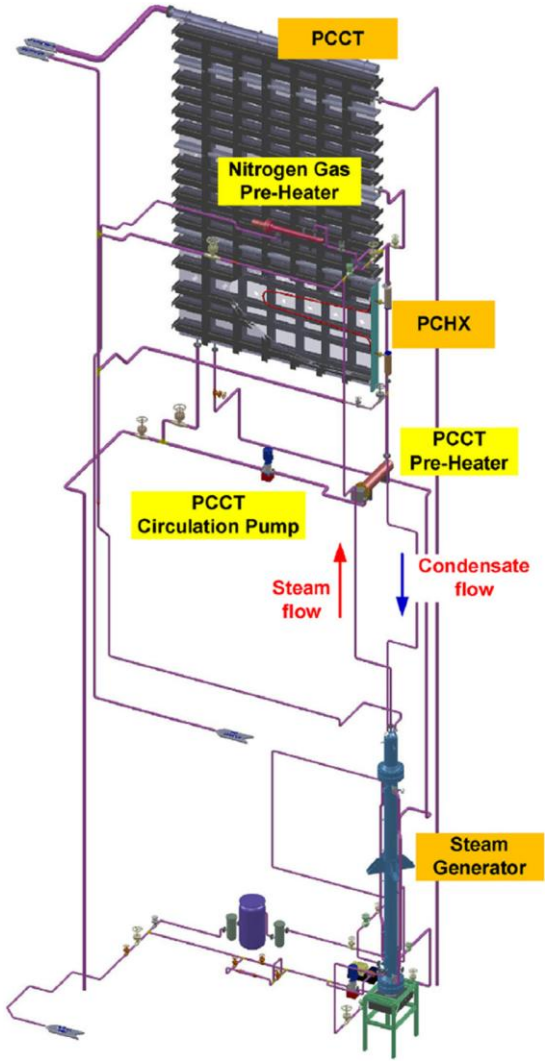
- **PASCAL** tests confirmed **tube-level** two-phase flow and heat transfer **characteristics**
- **ATLAS-PAFS** demonstrated integral **PAFS performance** under representative accident conditions
- PCCT thermal-hydraulic conditions act as external boundary and influence the overall PAFS performance
  - Ultimately, inventory depletion becomes the limiting consideration for long-term cooling capability

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

4 Validation, Analysis, and Applications

Experimental Validation: PASCAL and ATLAS-PAFS

- Passive-system development **requires experimental confirmation**
- Two complementary experimental facilities were established by KAERI
- **PASCAL – Separate Effect Test**
  - Prototypic single PCHX tube to investigate condensation heat transfer and flow behavior
  - Measurement of local and overall heat-transfer characteristics
  - Investigation of PCCT natural convection, boiling, water-level and subcooling effects
  - Database for assessment of condensation and pool-side heat-transfer models
  - Suitable for improvements of system code prediction capability for pressure drop and heat transfer
- **ATLAS-PAFS – Integral Effect Test**
  - PAFS coupled to main components of primary and secondary systems
  - Investigation of PAFS actuation, startup and natural-circulation behavior
  - Evaluation of interaction between PAFS, steam generator and reactor coolant system
  - Investigation of PAFS performance under representative accident conditions
  - Integral database for system-code assessment and validation for overall plant response



Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

4 Validation, Analysis, and Applications

PAFS Performance and Long-Term Cooling Characteristics

- **Integral tests** demonstrated **successful PAFS operation** under various accident and system boundary conditions
  - Following PAFS actuation, steam generated in the SG is condensed in the PCHX and condensate is returned by gravity
  - PAFS was **tested for various accident scenarios** (loss of feedwater, steam generator tube rupture, station blackout, etc.)
- Natural circulation provides **continued** secondary-side **heat removal** and supports RCS cooldown **without active pumps**
  - The **fundamental PAFS heat-removal** mechanism **remains the same** even though plant conditions and responses may change
- **Long-term cooling capability** is strongly related to the available **PCCT water inventory** and PCHX submergence
  - During extended operation, PCCT water is heated to saturation and gradually depleted by boiling and evaporation
  - As PCCT water level decreases, submerged PCHX heat-transfer area is reduced and heat-removal performance can decrease
  - However, **PAFS is designed for long-term cooling capability**, with sufficient capacity for several hours of operation
- Experiments **confirm** the **PAFS design** for **sustained passive cooling capability** under various plant condition
  - The experimental database provides a technical basis for assessment of PAFS applications in advanced power reactors

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

4 Validation, Analysis, and Applications

System Analysis and Modeling of PAFS

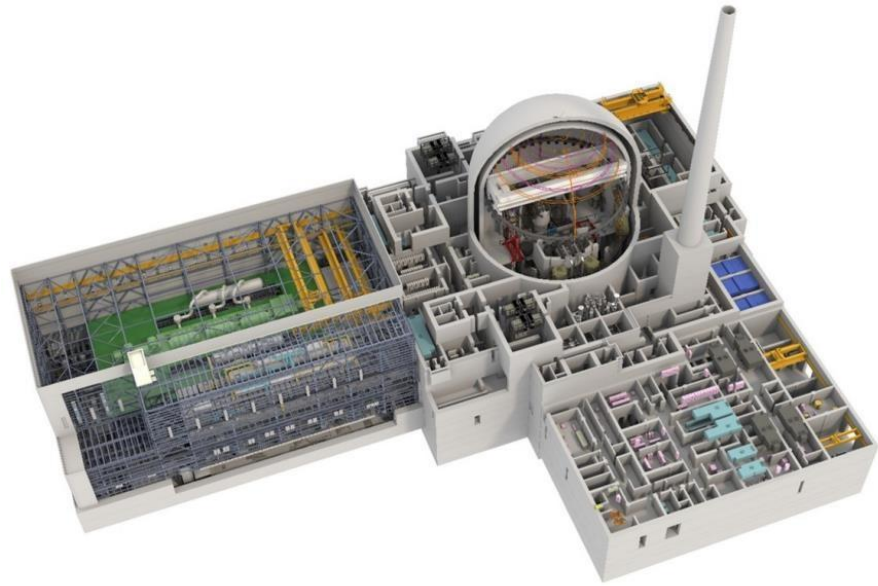
- **System thermal-hydraulic codes** are used for PAFS design evaluation, transient analysis, and **safety assessment**
- Accurate PAFS analysis requires **careful modeling** of the complete closed-loop system, including the steam generator, steam-supply line, PCHX, return-water line, and PCCT, and **suitable two-phase flow and heat transfer models**
- Important modeling considerations include
  - **Steam condensation** inside nearly-horizontal PCHX tubes
  - **Single- and two-phase pressure losses** in piping, valves, fittings and PCHX
  - Water **pool-side natural convection** and nucleate boiling
  - Heat structures and **thermal interaction between the PCHX and PCCT**
- Separate- and integral-effect experimental results provide the basis for assessment and validation of the relevant models
- **Sensitivity study** of natural-circulation performance to hydraulic resistance, condensation models should be considered
- The validated analysis methodology can be used to evaluate PAFS performance under various accident conditions

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

4 Validation, Analysis, and Applications

Application to Advanced Power Reactors

- PAFS can be applied to both advanced **large reactors** and **small modular reactors**
- The fundamental operating principle is based on **steam condensation**, and **natural circulation**
- Plant-specific PAFS design should consider
  - Required **decay-heat-removal capacity** based on time
  - Steam-generator **operating pressure** and transient conditions
  - **Elevation difference** between the steam generator and PCHX
  - Steam-supply and condensate-return **piping configuration**
  - **PCHX geometry** and total heat-transfer area
  - Total **hydraulic resistance** of the natural-circulation loop
  - **PCCT capacity**, water inventory and required cooling duration



- Application to different reactor designs requires same passive heat-removal principles but **system-specific optimization**
- Experimental validation and system-code analysis provide technical basis for adapting PAFS to advanced reactor designs

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

5 Conclusions

Summary and Conclusions

- PAFS provides reliable passive secondary-side heat removal by condensation of steam generated in SG
- **System configuration is fundamental** to the PAFS operation – elevation, hydraulic resistance, PCHX geometry and system pressure determine **natural-circulation performance**
- **PCHX and PCCT** thermal hydraulics characteristics are **strongly coupled** – tube-inside condensation and pool boiling influence natural convection, boiling and water inventory inside the PCCT
- Separate- and integral-effect **experiments provide a strong validation basis** for understanding the detailed phenomena and **support system-code prediction capability** for simulation of plant response
- PAFS provides a **mature technical basis for passive heat removal** in advanced power reactors, while plant-specific application requires appropriate sizing and assessment of the complete closed-loop system
- PAFS can be **applicable to both large reactors**, as well as **small modular reactors**

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

ABOUT

FNC TECHNOLOGY CO., LTD.

Republic of Korea

Headquarters

Heungdeok IT Valley Bldg. 32F, 13, Heungdeok 1-ro,
Giheung-gu , Yongin-si , Gyeonggi-do, 16954, Korea
+82-31-8065-5114

Daejeon Branch

Daeduk Tech Business Center, 1004-2, 593,
Daeduk-daero, Yusung-gu, Daejeon, 34112, Korea
+82-42-867-5114

Institute of Future Energy Technology

46, Tapsil-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 17084, Korea
+82-31-8005-5618

Facility & Equipment Development Research

46, Tapsil-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 17084, Korea
+82-31-8065-5114

Overseas

UAE Abu Dhabi Branch

Office 904, Capital Tower, Al Rawhah, PO Box 95133, Abu Dhabi, UAE
+971-2-643-5144

USA Maryland Branch

11140 Rockville Pike, Suite 380A, Rockville, MD 20852, USA
+1-202-577-5537

Czech Republic Prague Branch

FLEKSI Filadelfie (3A.15), Želetavská 1525/1, 140 00 Praha 4 -
Michle, Czech Republic

Copyright 2026. FNC Technology Co., Ltd. all rights reserved.

THANK YOU

FNC TECHNOLOGY CO., LTD.

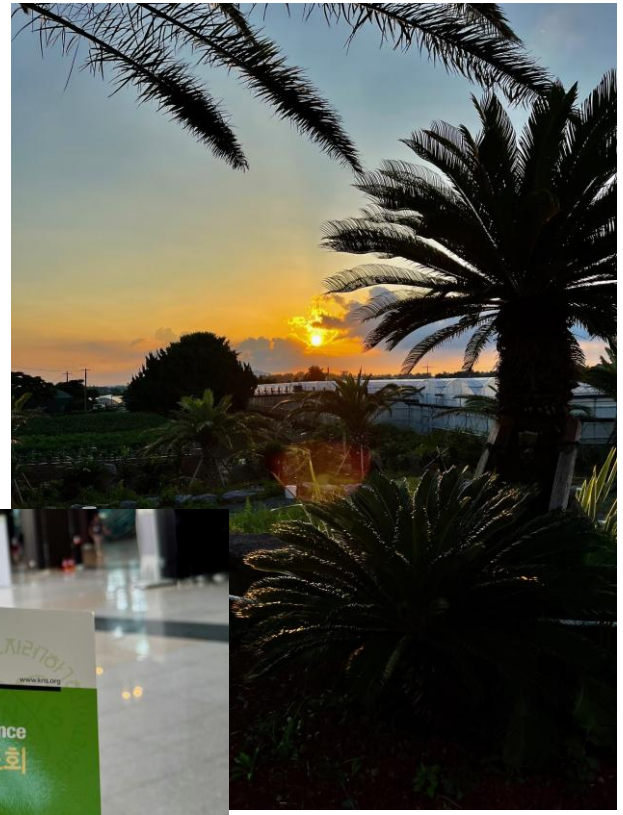


One more thing…

Korean Nuclear Society Conference













Copyright 2026. FNC Technology Co., Ltd. all rights reserved.