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Advanced Water Cooled Reactors

Bilbao Y Leon S.

IAEA
Vienna
AUSTRIA

Natural Circulation Phenomena for Passive Safety Systems of Advanced Water Cooled Reactors

Sama BILBAO Y LEON
S.Bilbao@iaea.org

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Passive Safety Systems (1)

- **Classification of Passivity (IAEA-TECDOC-626)**

	Category A	Category B	Category C	Category D
Signal inputs of intelligence	No	No	No	Yes
External power sources or forces	No	No	No	No
Moving mechanical parts	No	No	Yes	Limited
Moving working fluid	No	Yes	Yes	Limited

Passive Safety Systems (2)

- **Advantages of Passive Safety Systems**
  - **Eliminate the cost associated with the installation, maintenance and operation of active safety systems that require multiple components with independent and redundant electric power supplies**
  - **Enhance safety by increasing the reliability**
- **Challenges of Passive Safety Systems**
  - **Weak driving force**
  - **Careful design and analysis methods are required**

⇨ **IAEA conducted a CRP on Natural Circulation Phenomena, Modelling and Reliability of Passive Systems**

CRP on Natural Circulation Phenomena, Modelling and Reliability of Passive Systems (1)

- **Specific Objectives**
  - **establish the status of knowledge: reactor start-up & operation; passive system initiation & operation; flow stability, 3-D effects and scaling laws**
  - **investigate phenomena influencing reliability of passive NC systems**
  - **review experimental databases for the phenomena**
  - **examine the ability of computer codes to predict NC and related phenomena**
  - **apply methodologies for examining the reliability of passive systems**
- **Participants (16)**
  - **CNEA, Bariloche, Argentina**
  - **CEA, France**
  - **FZ Dresden, Germany**
  - **BARC, India**
  - **Univ. of Pisa, Italy**
  - **ENEA, Italy**
  - **IVS, Slovakia**
  - **JAEA, Japan**
  - **KAERI, Rep. of Korea**
  - **Gidropress, Russian Federation**
  - **University of Valencia, Spain**
  - **PSI, Switzerland**
  - **Idaho State University, USA**
  - **Oregon State University, USA**
  - **Purdue University, USA**
  - **European Commission, JRC - Petten**

Outcomes of CRP on Natural Circulation Phenomena, Modelling and Reliability of Passive Systems (2)

- **Document Publication**
  - **TECDOC-1474, "Natural Circulation in Water Cooled Nuclear Power Plants", November 2005**
  - **TECDOC-1624, "Passive Safety Systems in Water Cooled Nuclear Power Plants: The Use of Natural Circulation", November 2009**
  - **TECDOC-XXXX, "Natural Circulation in Water-Cooled Nuclear Power Plants: Phenomena, Modelling, and Reliability of Passive Systems that Utilize Natural Circulation", under preparation**
- **Training Course on Natural Circulation Phenomena and Modeling in Water Cooled NPPs**
- **Last RCM: November 2008**

CRP on Natural Circulation Phenomena, Modelling and Reliability of Passive Systems

- **2nd TECDOC: "Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants"**
  - **20 reference designs (evolutionary and innovative)**
  - **PASSIVE SAFETY SYSTEMS FOR CORE DECAY HEAT REMOVAL**
    - **Pre-Pressurized Core Flooding Tanks (Accumulators)**
    - **Elevated Tank Natural Circulation Loops (Core Make-up Tanks)**
    - **Gravity Drain Tanks**
    - **Passively Cooled SG Natural Circulation**
    - **Passive Residual Heat Removal Heat Exchangers (Single-Phase Liquid)**
    - **Passively Cooled Core Isolation Condensers (Steam)**
    - **Sump Natural Circulation**
  - **PASSIVE SAFETY SYSTEMS FOR CONTAINMENT COOLING**
    - **Containment Pressure Suppression Pools**
    - **Containment Passive Heat Removal/Pressure Suppression Systems**
    - **Passive Containment Spray Systems**

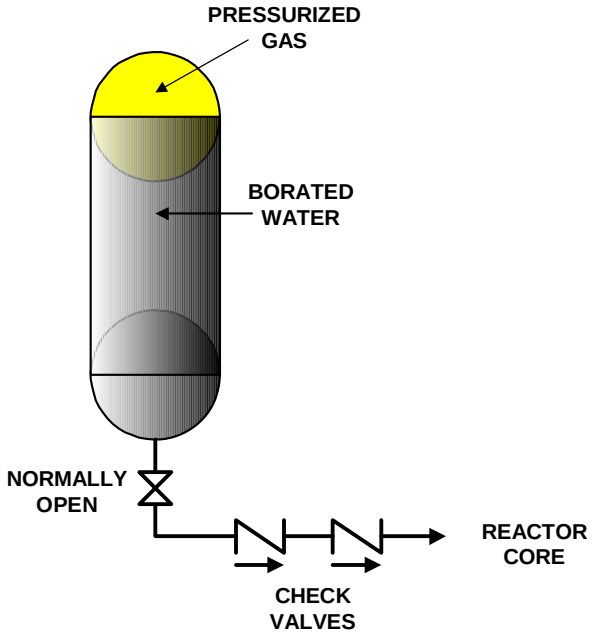
20 Reference Advanced Designs Considered to Survey the Passive Safety Systems

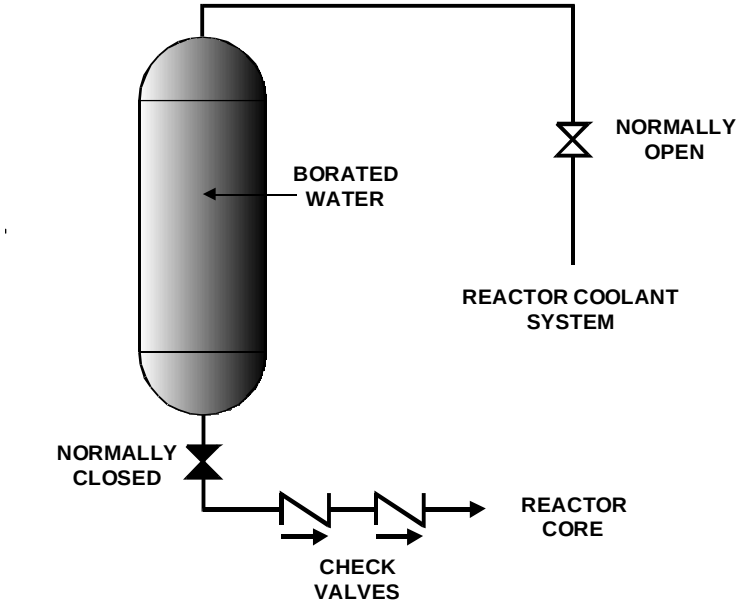
- **Evolutionary and Innovative Designs**

- **BWRs**
  - SWR 1000
  - SBWR
  - ESBWR
  - ABWR-II
  - RMWR
  - LSBWR
- **Loop-type PWRs**
  - AP 600; AP 1000
  - WWER 640
  - WWER 1000
  - APWR+
- **Integral PWRs**
  - SMART
  - CAREM
  - IRIS
  - NuScale
  - PSRD
  - IMR
  - SCOR
- **HWRs**
  - AHWR
  - ACR
- **Super-critical WCRs**
  - SCWR-CANDU

Type of Passive Safety Systems (1)

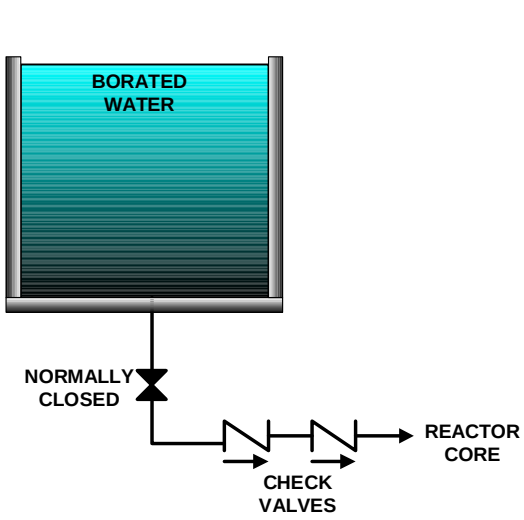
- **Passive Safety Systems For Core Decay Heat Removal**
  - **(1) Pre-Pressurized Core Flooding Tanks (Accumulators)**
  - **(2) Elevated Tank Natural Circulation Loops (Core Make-up Tanks)**

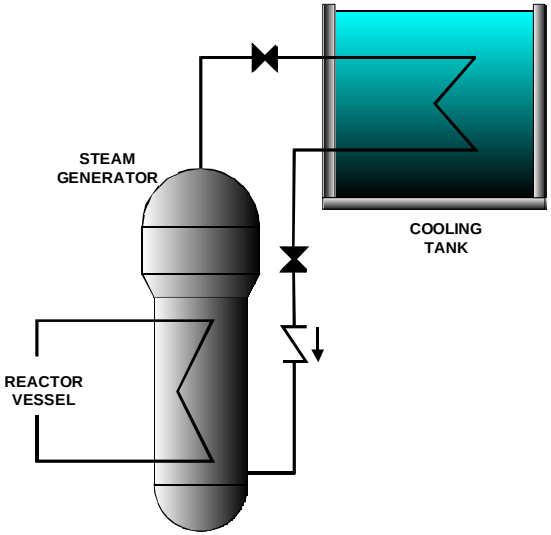


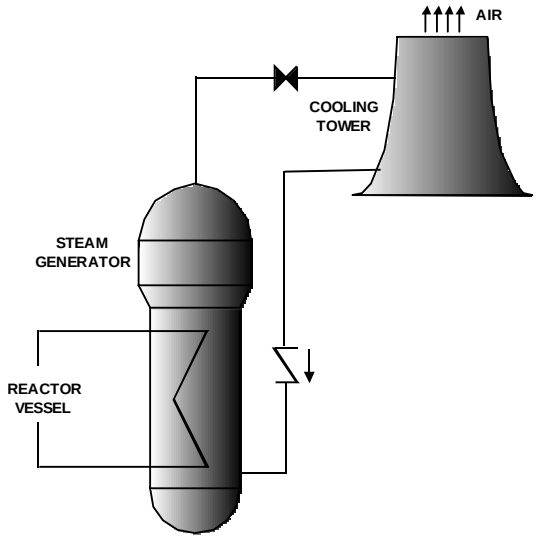


Type of Passive Safety Systems (2)

- **Passive Safety Systems For Core Decay Heat Removal**
  - **(3) Gravity Drain Tanks**
  - **(4) Passively Cooled SG Natural Circulation**

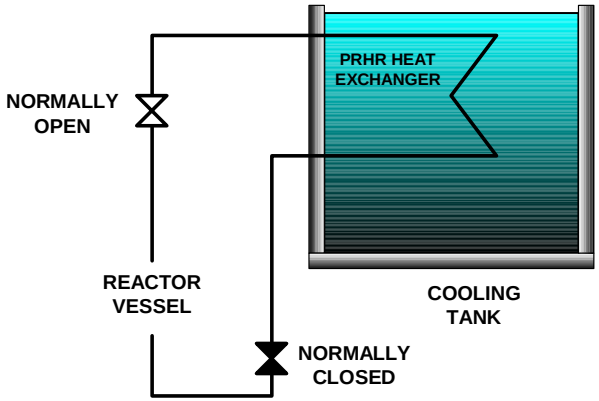


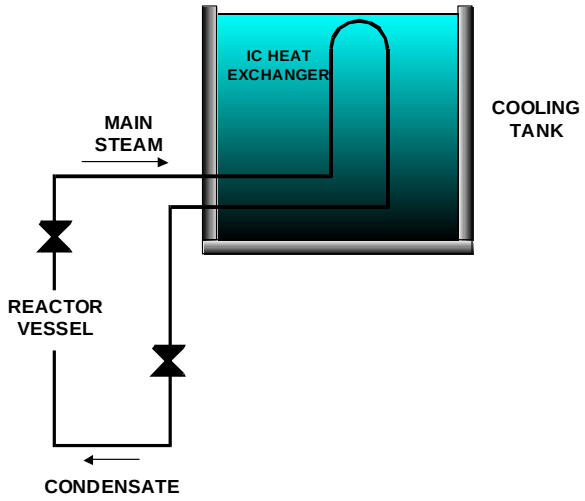


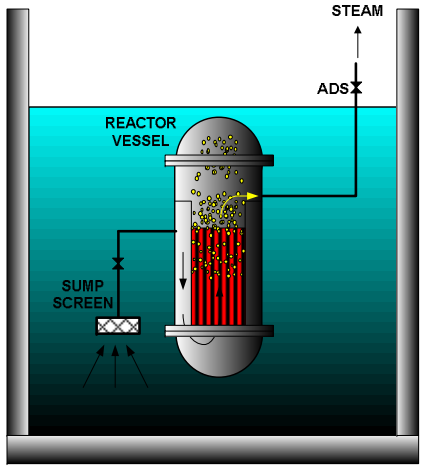


Type of Passive Safety Systems (3)

- **Passive Safety Systems For Core Decay Heat Removal**
  - **(5) Passive Residual Heat Removal Heat Exchangers (Single-Phase Liquid)**
  - **(6) Passively Cooled Core Isolation Condensers (Steam)**
  - **(7) Sump Natural Circulation**

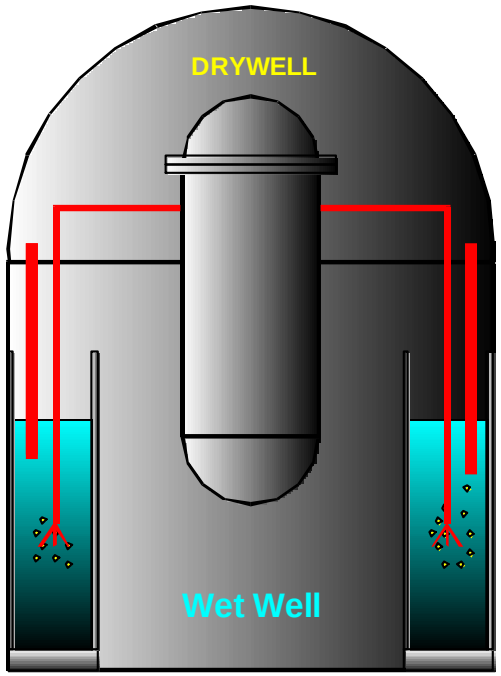




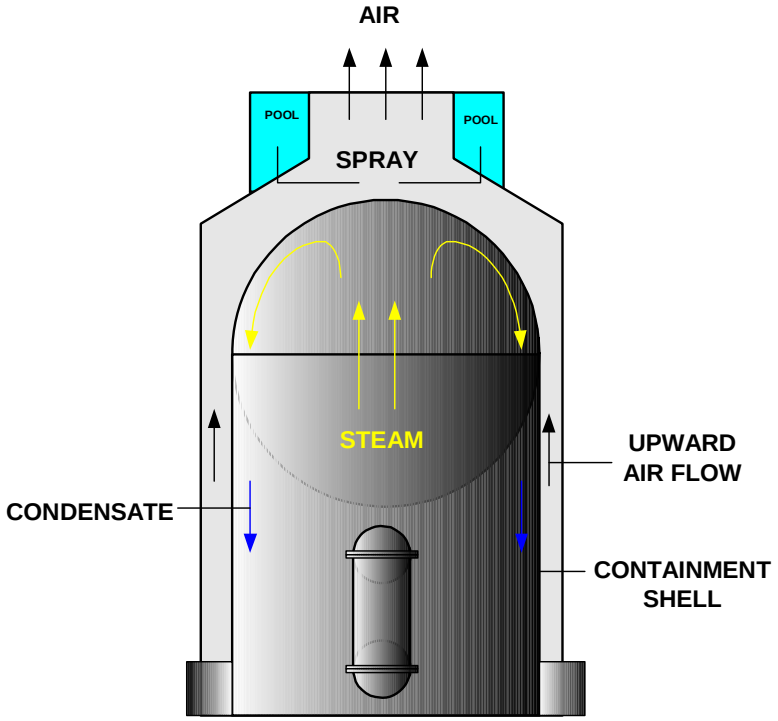


Type of Passive Safety Systems (4)

- **Passive Safety Systems For Containment Cooling**
  - **(1)Containment Pressure Suppression Pools**
  - **(2)Passive Containment Spray Systems**

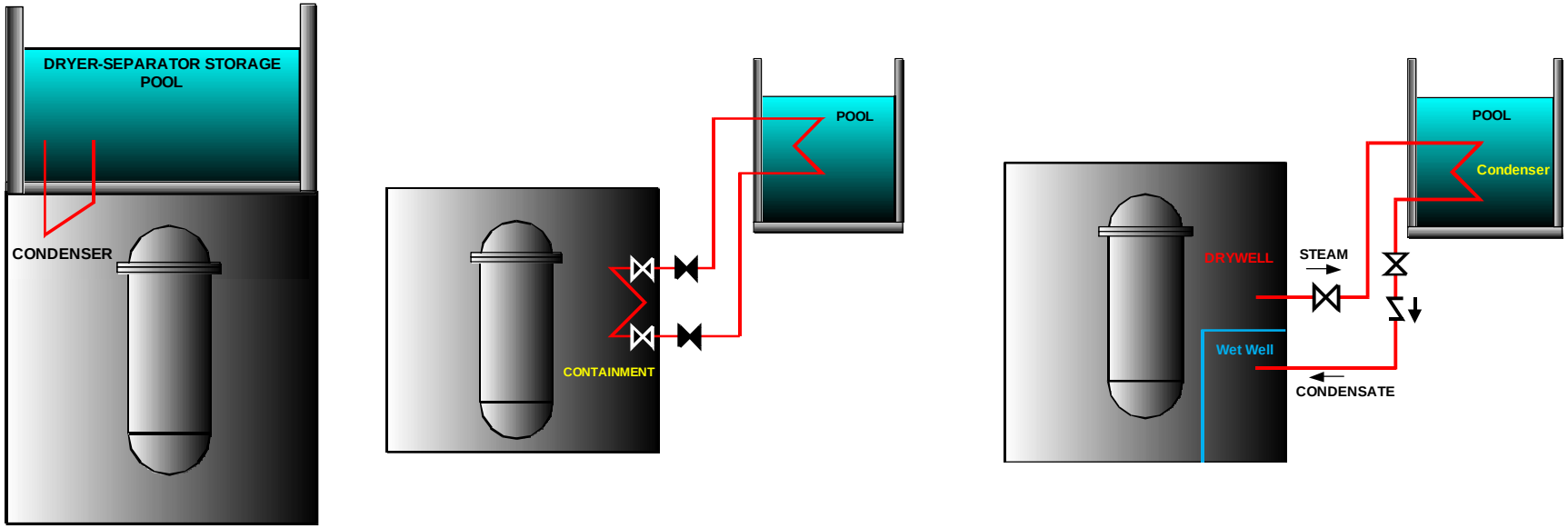


SUPPRESSION POOL



Type of Passive Safety Systems (5)

- **Passive Safety Systems For Containment Cooling**
  (3) Containment Passive Heat Removal/Pressure Suppression Systems



Phenomena Identification

- Behaviour in Large Pools of Liquid
- Effect of Non-condensable Gasses on Condensation Heat Transfer
- Condensation on the Containment Structures
- Behaviour of Containment Emergency Systems
- Thermo-fluid Dynamics and Pressure Drops in Various Geometrical Configurations
- Natural Circulation in Closed Loop
- Steam Liquid Interaction
- Gravity Driven Cooling and Accumulator Behaviour
- Liquid Temperature Stratification
- Behaviour of Emergency Heat Exchangers and Isolation Condensers
- Stratification and Mixing of Boron
- Core Make-up Tank Behaviour

Cross Listing of Passive Safety Systems with Phenomena (1)

Type of Passive Safety System	Passive Safety Systems of Advanced Designs	Related Phenomena
Pre-pressurized Core Flooding Tanks (Accumulators)	Accumulators (AP-1000) ECCS accumulator subsystem (WWER 640/V-407) First stage hydro-accumulators (WWER 1000/V-392) Advanced accumulators (APWR+) Standby liquid control system (ESBWR) Accumulator (AHWR)	Gravity driven cooling and accumulator behaviour Effects of non-condensable gases on condensation heat transfer Thermo-fluid dynamics and pressure drops in various geometrical configurations
Elevated Tank Natural Circulation Loops (Core Make-up Tanks)	Core make-up tanks (AP-1000) Second stage hydro-accumulators (WWER 1000/V-392) Core make-up tanks (ACR-1000) Core make-up tanks (SCWR-CANDU)	Gravity driven cooling and accumulator behaviour Natural circulation Liquid temperature stratification Thermo-fluid dynamics and pressure drops in various geometrical configurations Core Make-up Tank Behaviour
Elevated Gravity Drain Tanks	Core flooding system (SWR 1000) IRWST injection (AP-1000) ECCS tank subsystem – Elevated hydro-accumulators open to the containment (WWER 640/V-407) Gravity-driven cooling system (SBWR and ESBWR) Suppression pool injection (SBWR and ESBWR) Gravity-driven core cooling system (LSBWR) Gravity-driven water pool (GDWP) injection (AHWR) Reserve water system (ACR-1000) Reserve water system (SCWR-CANDU)	Gravity driven cooling and accumulator behaviour Thermo-fluid dynamics and pressure drops in various geometrical configurations

Cross Listing of Passive Safety Systems with Phenomena (2)

Type of Passive Safety System	Passive Safety Systems of Advanced Designs	Related Phenomena
Passively Cooled Steam Generator Natural Circulation (water cooled)	SG passive heat removal system (WWER 640/V-407) Passive residual heat removal system (SMART) Passive emergency heat removal system (IRIS)	Behaviour of emergency heat exchangers and isolation condensers Behaviour in large pools of liquid Natural circulation
Passively Cooled Steam Generator Natural Circulation (air cooled)	Passive residual heat removal system via SG (WWER 1000/V-392) Passive core cooling system using SG - open loop (APWR+)	Natural circulation Behaviour of containment emergency systems (PCCS, external air cooling, etc.)
Passive Residual Heat Removal Heat Exchangers	Passive residual heat removal system (AP-1000) Passive moderator cooling system – inside insulated PT without CT (SCWR-CANDU)	Behaviour of emergency heat exchangers and isolation condensers Natural circulation Effects of non-condensable gases on condensation heat transfer Behaviour in large pools of liquid
Passively Cooled Core Isolation Condensers	Emergency condensers (SWR 1000) Isolation condenser system (SBWR and ESBWR) Passive reactor cooling system (ABWR-II) Isolation condenser (RMWR) Isolation condenser (AHWR)	Behaviour of emergency heat exchangers and isolation condensers Natural circulation Behaviour in large pools of liquid
Sump Natural Circulation	Lower containment sump recirculation (AP-1000) Primary circuit un-tightening subsystem (WWER 640/V-407)	Natural circulation Behaviour in large pools of liquid

Cross Listing of Passive Safety Systems with Phenomena (3)

Type of Passive Safety System	Passive Safety Systems of Advanced Designs	Related Phenomena
Containment Pressure Suppression Pools	ADS 1-3 steam vent into IRWST (AP-1000) Automatic depressurization through safety relief valves – vent into suppression pool (SBWR and ESBWR) Steam vent into suppression pool through safety valves (CAREM) Steam vent into suppression pool through ADS (IRIS)	Behaviour in large pools of liquid Steam liquid interaction Condensation on containment structures
Containment Passive Heat Removal/Pressure Suppression Systems (Steam Condensation on Condenser Tubes)	Containment cooling condensers (SWR 1000) Passive containment cooling system (AHWR)	Behaviour of containment emergency systems Behaviour in large pools of liquid Effects of non-condensable gases on condensation heat transfer Condensation on containment structures
Passive Containment Spray Systems	Passive containment cooling system (AP-1000) Containment cooling spray (ACR-1000) Containment cooling spray (SCWR-CANDU)	Condensation on containment structures Effects of non-condensable gases on condensation heat transfer Behaviour of containment emergency systems

Conclusions

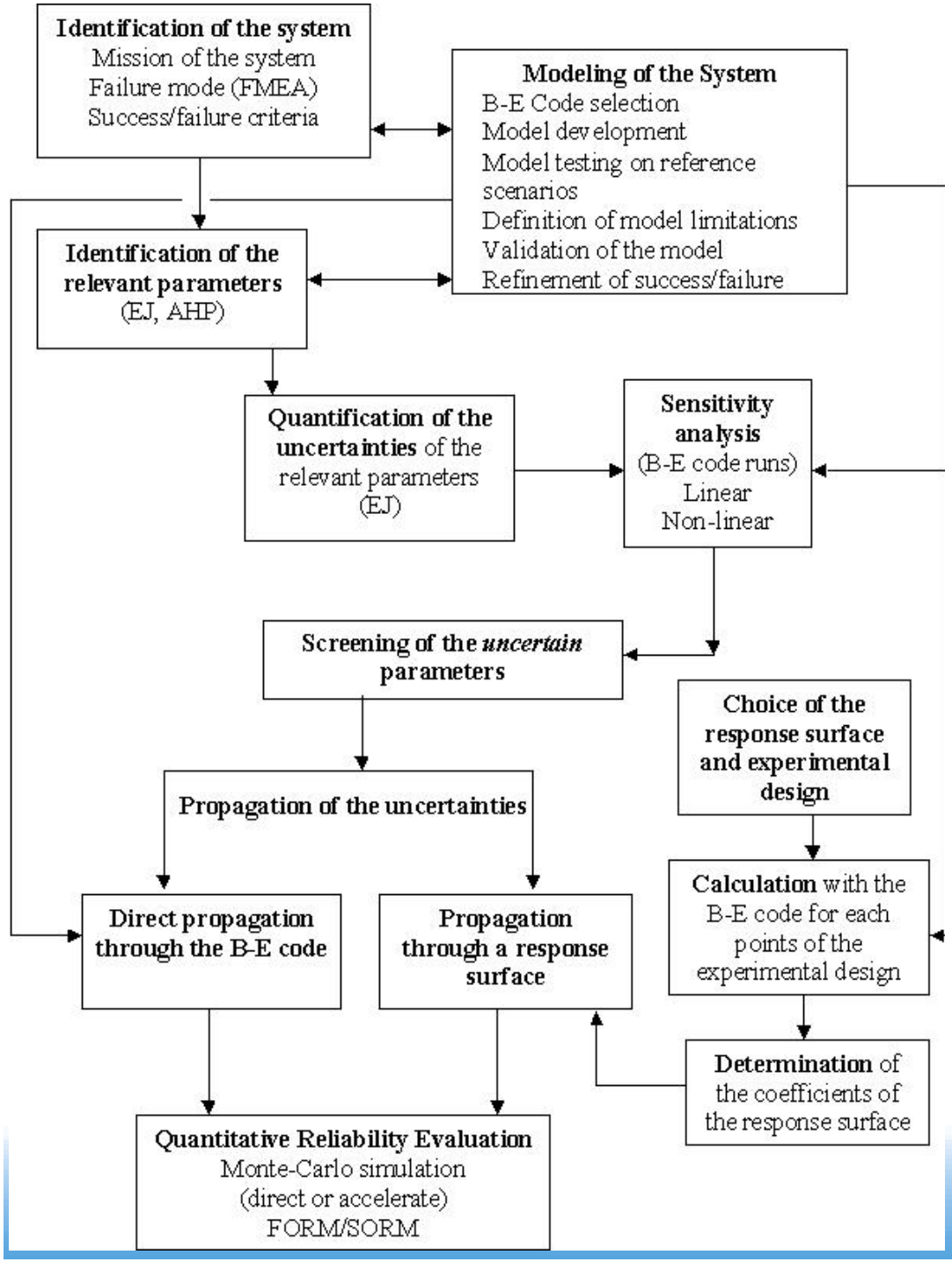
- **Passive systems are widely considered in advanced nuclear reactor designs and are adopted for coping with critical safety functions**
- **A dozen different passive system types, having a few tens of reactor specific configurations, suitable to address safety functions in primary loop or in containment have been distinguished**
- **The thermal-hydraulic performance of the passive systems has been characterized by less than a dozen key phenomena considering relevant thermal-hydraulic aspects. Cross correlations between key thermal-hydraulic phenomena and reactor specific safety systems have also been established**
- **The levels of development, or even the actual deployment of the concerned reactor designs (i.e. equipped with passive systems) for electricity production are very different**

CRP on Natural Circulation Phenomena, Modelling and Reliability of Passive Systems

- **3rd TECDOC: "Natural Circulation in Water-Cooled Nuclear Power Plants: Phenomena, Modelling, and Reliability of Passive Systems that Utilize Natural Circulation"**
  1. **INTRODUCTION**
  2. **IDENTIFICATION AND DEFINITION OF PHENOMENA**
  3. **CHARACTERIZATION OF PHENOMENA**
     - **3.1 Behaviour in Large Pools of Liquid**
     - **3.2 Effect of Non-condensable Gasses on Condensation Heat Transfer**
     - **3.3 Condensation on the Containment Structures**
     - **3.4 Behaviour of Containment Emergency Systems**
     - **3.5 Thermo-fluid Dynamics and Pressure Drops in Various Geometrical Configurations**
     - **3.6 Natural Circulation in Closed Loop**
     - **3.7 Steam Liquid Interaction**
     - **3.8 Gravity Driven Cooling and Accumulator Behaviour**
     - **3.9 Liquid Temperature Stratification**
     - **3.10 Behaviour of Emergency Heat Exchangers and Isolation Condensers**
     - **3.11 Stratification and Mixing of Boron**
     - **3.12 Core Make-up Tank Behaviour**
  4. **INTEGRAL TESTS AND PLANT ANALYSES, EXAMPLE CASES**
  5. **METHODOLOGY FOR EXAMINING PASSIVE SYSTEM RELIABILITY AND EXAMPLE APPLICATION**
  6. **CONCLUSIONS AND RECOMMENDATIONS**

CHAPTER 5: METHODOLOGY FOR EXAMINING PASSIVE SYSTEM RELIABILITY AND EXAMPLE APPLICATION

1. Description of the RMPS Methodology (CEA)
2. Methodology Improvements
    1. Expert Judgement Techniques
    2. Distribution Sensitivity Analysis
3. Alternative Methodologies
    1. ENEA Methodologies
    2. APSRA Methodology (BARC)
    3. Comparison RMPS, ENEA & APSRA
4. Reliability Analysis of CAREM-like Passive Residual Heat Removal System with RMPS Methodology



RMPS Methodology

Conclusions

- Reliability values associated with system AND scenario → Need to incorporate all reliability data into a single characteristic value for a given system under all scenarios
- Human Factors should be considered
- When choosing active vs passive system, consider
  - Reliability
  - Efficiency
  - Simplicity
  - Robustness
  - Human Factors
  - Economic Evaluations


Thank you!