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Open Issues Associated with Passive Safety Systems Reliability Assessment

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Outline

- **Introduction**
  - **Passive Systems**
  - **Passive Systems Reliability and Safety**
  - **Applications to advanced reactors**
  - **Thermal-hydraulic (t-h) Passive Systems**
- **Reliability Assessment Approaches**
- **Open Issues and Implementation**
  - **Uncertainties**
  - **Dependencies**
  - **Integration into accident sequences within a psa framework**
  - **Passive vs active systems**
- **Summary**
- **Outlook**

Generics

- Innovative reactors largely implement passive safety systems
- Reactivity control, decay heat removal, fission product containment
- Applications of passive systems for innovative reactors demand high availability and reliability
- PSA analysis
- Accident sequence definition and assessment
  - Event Tree and Fault Tree model
- Introduction of a passive system within an accident scenario in the fashion of a front-line system and in combination with active systems and human actions

Recalls

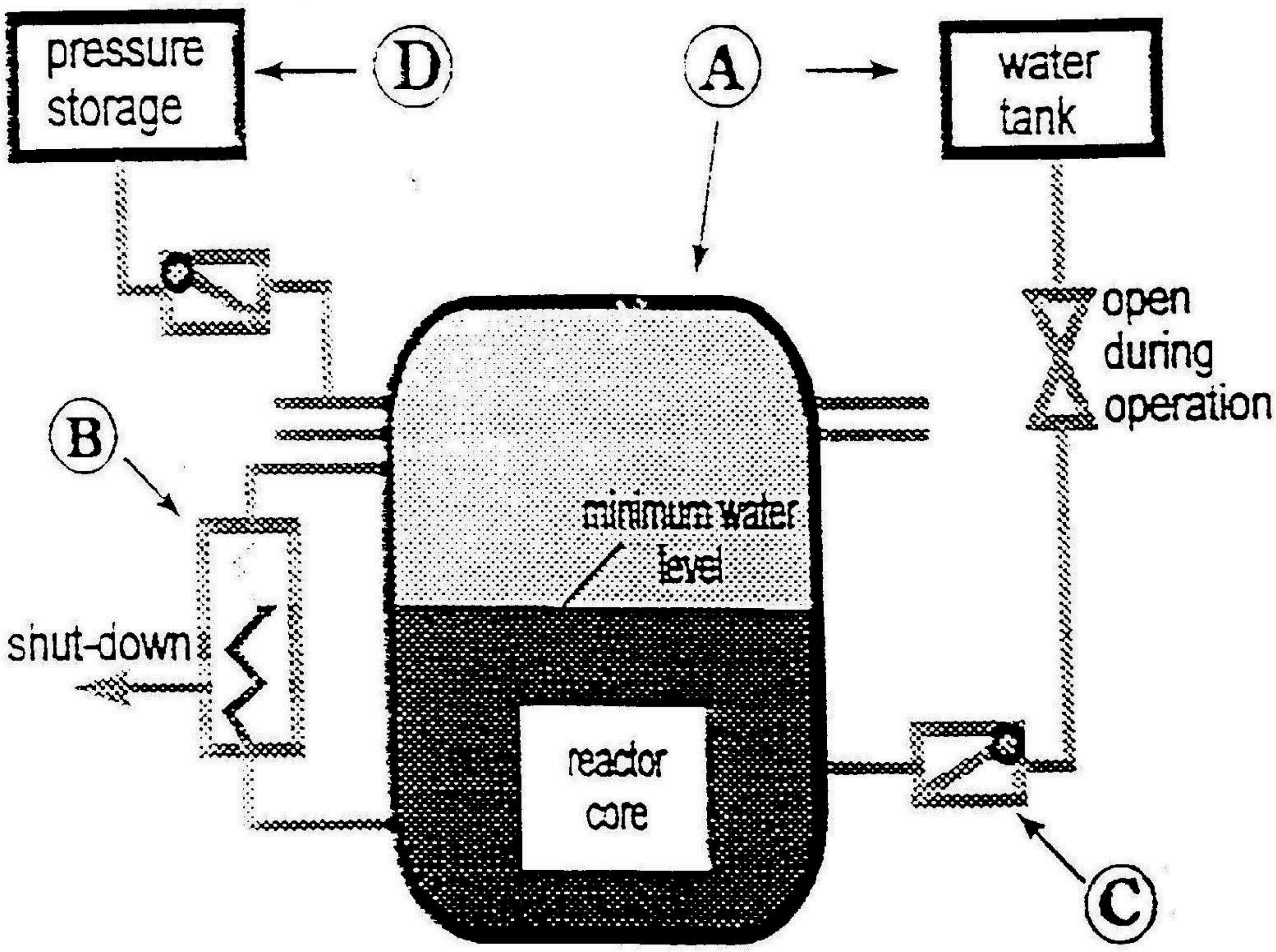
- **IAEA (*IAEA-TECDOC-626*) definitions:**
  - ***Passive Component*: a component which does not need any external input to operate**
  - ***Passive System*: either a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation**

- **Passive System Categorization:**
  - **A: physical barriers and static structures,**
  - **B: moving working fluids,**
  - **C: moving mechanical parts,**
  - **D: external signals and stored energy (passive execution/active initiation)**

Classification of Passive Systems

	Category-A	Category-B	Category-C	Category-D
Input Signal, External Power Sources, Forces	No	No	No	Yes
Moving Mechanical Parts	No	No	Yes	Yes
Moving Working Fluid	No	Yes	Yes/No	Yes/No
Some examples	▪ Core cooling system relying only on radiation/ conduction ▪ Physical barriers against release of fission products	▪ Reactor cooling based on natural circulation	▪ Systems consisting of accumulators or storage tanks and discharge lines equipped with check valves. ▪ Mechanical actuators such as check valves and spring loaded relief valves	▪ Emergency core cooling systems based on gravity/compress -ed Nitrogen driven flow of water activated by battery-powered valves. ▪ Mechanical Shut-Off rods

Examples



pressure storage
D
A
water tank
open during operation
B
minimum water level
shut-down
reactor core
C

Passive Systems Reliability

- **Probabilistic reliability methods for passive A safety functions have been extensively developed and applied in fracture mechanics**
- **For several passive C and D systems reliability figures may be derived from operating experience**
- **For passive B type systems basing on physical principle (natural circulation) denoted as t-h (thermal-hydraulic) passive systems, there is no agreed approach towards their reliability assessment yet**
  - **Deviations of natural forces or physical principles from the expected conditions, rather than classical component mechanical and electrical faults**
  - **System/component reliability (piping, valves, etc.)**
    - **mechanical component reliability**
  - **Physical phenomena "stability" (natural circulation)**
    - **factors impairing the performance/stability of the physical principle (buoyancy and density difference) upon which passive system operation is relying**

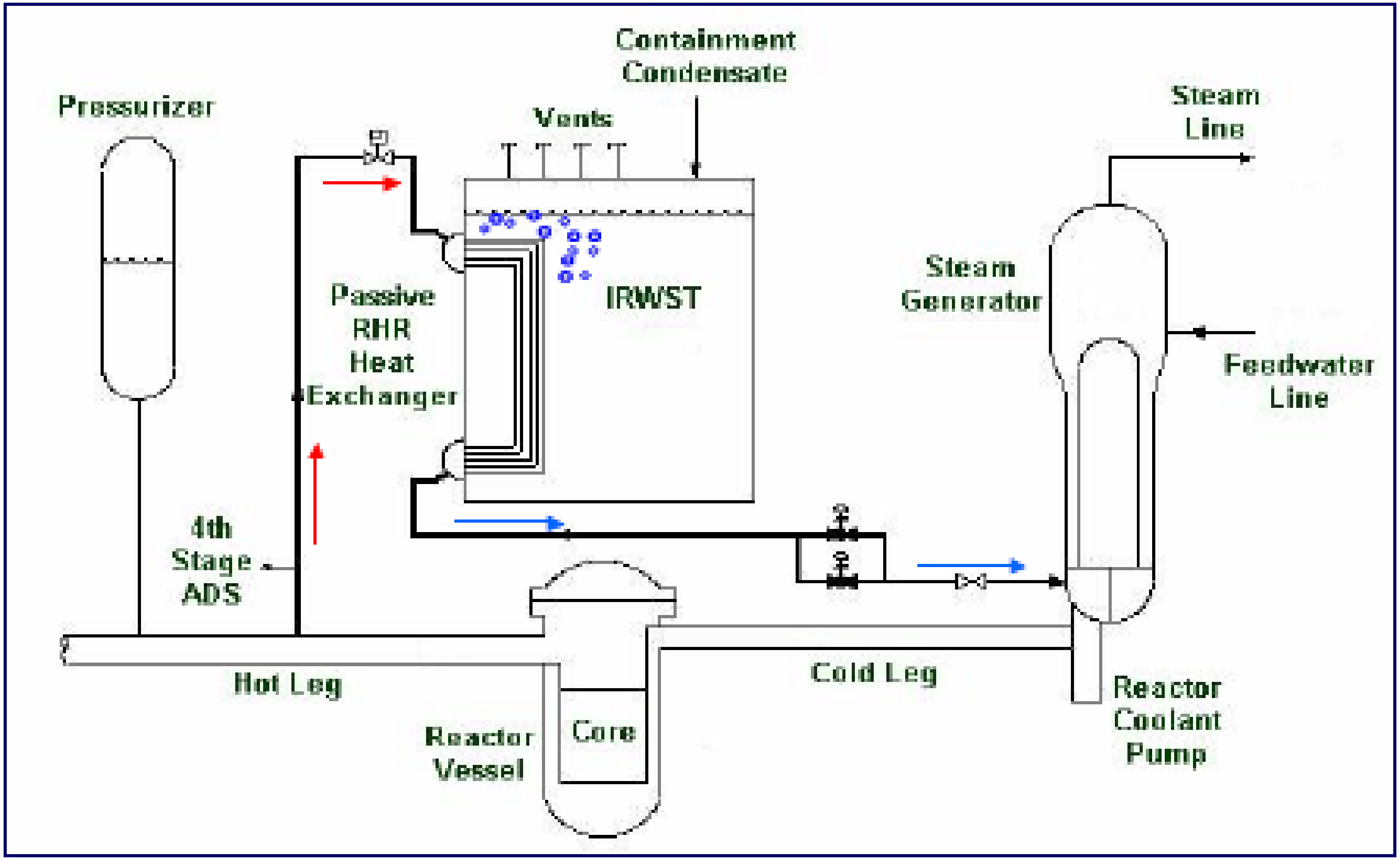
- **NEA CSNI/WGRISK Workshop on *Passive Systems Reliability—A Challenge to Reliability, Engineering and Licensing of Advanced Nuclear Power Plants*, Cadarache, (F), 4-6/03/'02, NEA/CSNI/R(2002)10**
- **IAEA-TECDOC-1474, *Natural circulation in water cooled nuclear power plants. Phenomena, models, and methodology for system reliability assessments*, 2005**

Thermal-hydraulic Passive Systems

- **Natural circulation: small engaged driving forces and thermal-hydraulic factors affecting the passive system performance (e.g. non condensable fraction, heat losses)**
- **System from the predictable nominal performance to the state of degradation of the physical principle in varying degrees up to the failure**
- **Occurrence of physical phenomena leading to pertinent failure modes**
- **Physical principle deterioration dependency on the boundary conditions and mechanisms needed for start-up and maintain the intrinsic principle**
- **Passive Systems for decay heat removal implementing in-pool heat exchangers and foreseeing the free convection (e.g. PRHR for AP 600 and AP 1000, Isolation Condenser for SBWR and ESBWR)**

T-h Passive Systems in Advanced reactors

AP600/AP1000 Passive Residual Heat Removal (PRHR) System



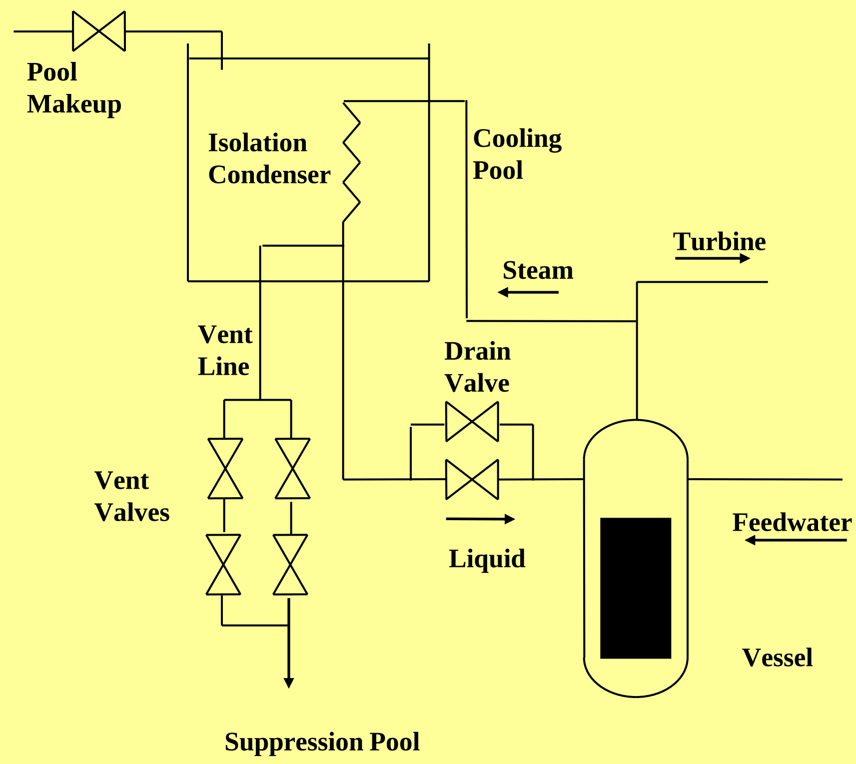
T-h Passive Systems in Advanced reactors

Isolation Condenser (SBWR, ESBWR)

- Core Decay Heat removal from the reactor, by natural circulation following an isolation transient, including a heat source and a heat sink where condensation occurs via a heat exchanger

- Limit the overpressure in the reactor system at a value below the set-point of the safety relief valves, preventing unnecessary reactor depressurization

- Isolation Condenser actuation on MSIV position, high reactor pressure and low reactor level



Scheme of the Isolation Condenser

Reliability Assessment Approaches (basics)

- **To provide essentials for passive system reliability assessment (ENEA)**
- **Approach based on independent failure modes**
  - **Burgazzi L., *Evaluation of Uncertainties Related to Passive Systems Performance*, Nuclear Engineering and Design, Volume 230, May 2004, pp-93-106**
  - **Burgazzi L., *Addressing the Uncertainties Related to Passive System Reliability*, Progress in Nuclear Energy, Vol. 49, pp. 93-102, January 2007**
- **Approach based on failure modes of passive system hardware components**
  - **Burgazzi L., *Passive System Reliability Analysis: a Study on the Isolation Condenser*, Nuclear Technology, Vol. 139, pp. 3-9, July 2002**
  - **Burgazzi L., *Failure Mode and Effect Analysis for the Safety and Reliability Analysis of a Passive System*, Nuclear Technology, Vol. 156, pp.150-158, November 2006**
- **Functional reliability or load-capacity approach**
  - **Burgazzi L., *Reliability Evaluation of Passive System through Functional Reliability Assessment* , Nuclear Technology, Volume 144, pp. 145-151, November 2003**
  - **Burgazzi L., *Thermal-hydraulic Passive System Reliability-Based Approach*, Reliability Engineering and System Safety, Vol. 92, pp. 1250-1257, September 2007**

Reliability Assessment Approches (integrated methods)

- **To achieve a more consistent methodology,**
  - **to include t-h code simulations**
  - **to capture all the phenomena involved and their interactions**
  - **to merge probabilistic and physical, i.e. t-h, aspects**

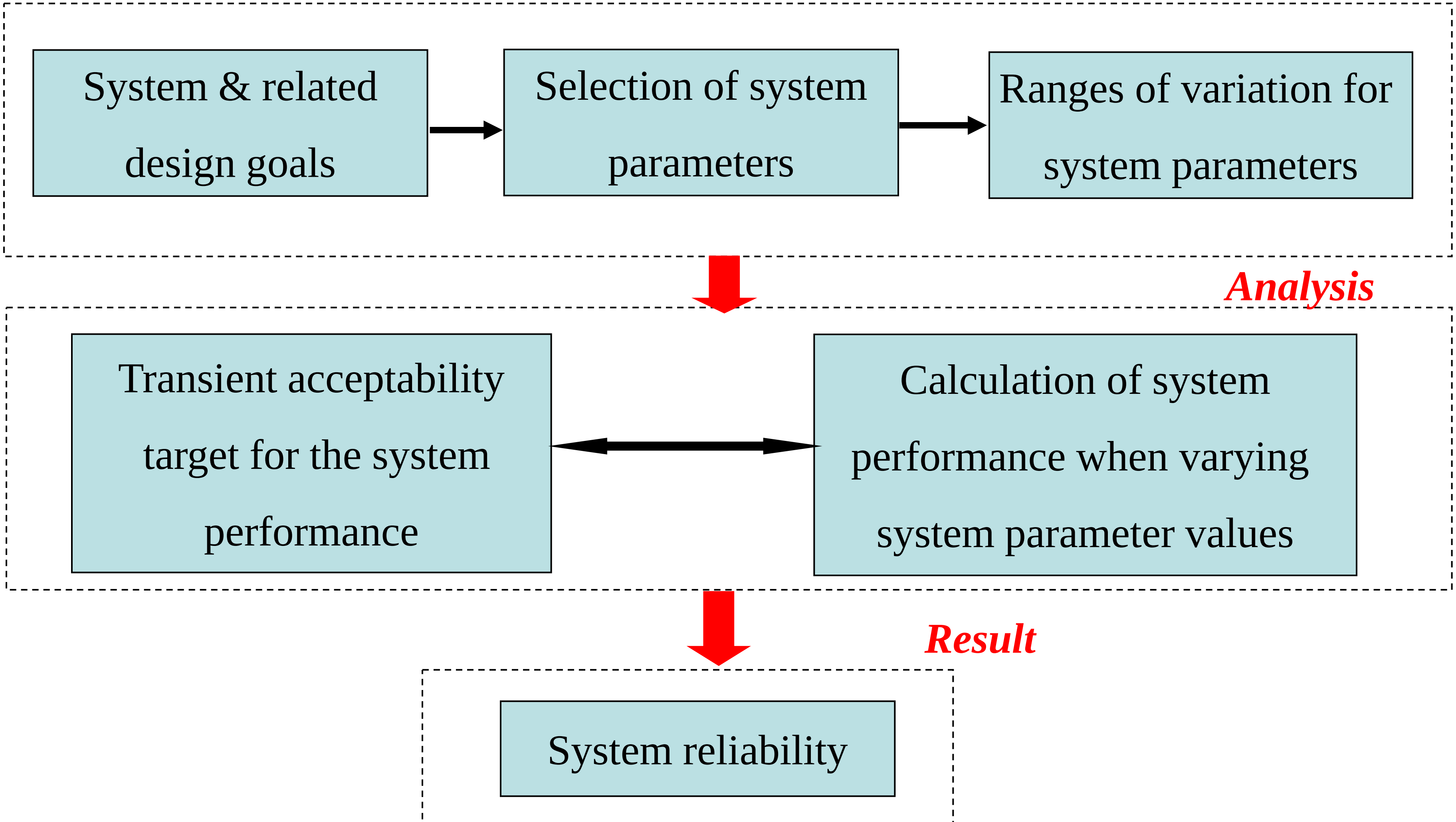
- **REPAS (REliability of PAssive Systems)**
  - **ENEA, University of Pisa, Polytechnic of Milano, University of Rome**
    - **J. Jafari, F.D'Auria, H. Kazeminejd, H. Davilu, *Reliability evaluation of a natural circulation system*, *Nuclear Engineering and Design 224 (2003) 79–104***

- **RMPS (Reliability Methods for Passive Safety Functions)**
  - **Fifth European Union Framework Programme project (2001-2004)**
    - **Marques M., et al., *Methodology for the reliability evaluation of a passive system and its integration into a Probabilistic Safety Assessment,* Nuclear Engineering and Design 235 (2005) 2612–2631**

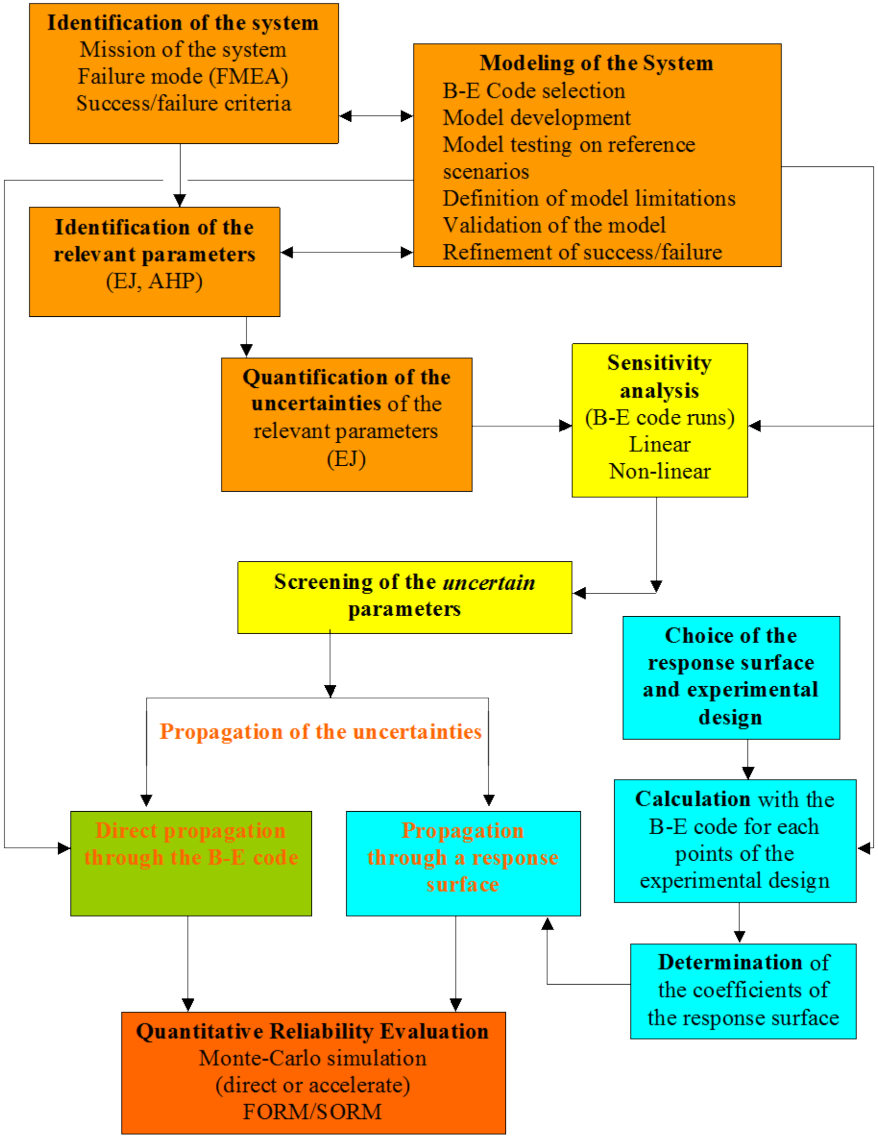
- **APSRA (Assessment of Passive System ReliAbility)**
  - **Bhabha Atomic Research Centre (India)**
    - **Nayak A. K., et al., *Passive system reliability analysis using the APSRA methodology,* Nuclear Engineering and Design, Volume: 238, Issue: 6, June, 2008, pp. 1430-1440**
    - **Nayak A.K et al., *Reliability assessment of passive isolation condenser system of AHWR using APSRA methodology,* Reliability Engineering and System Safety, Volume: 94, Issue: 6, June, 2009, pp. 1064-1075**

REPAS Method

Simplified diagram of the REPAS methodology



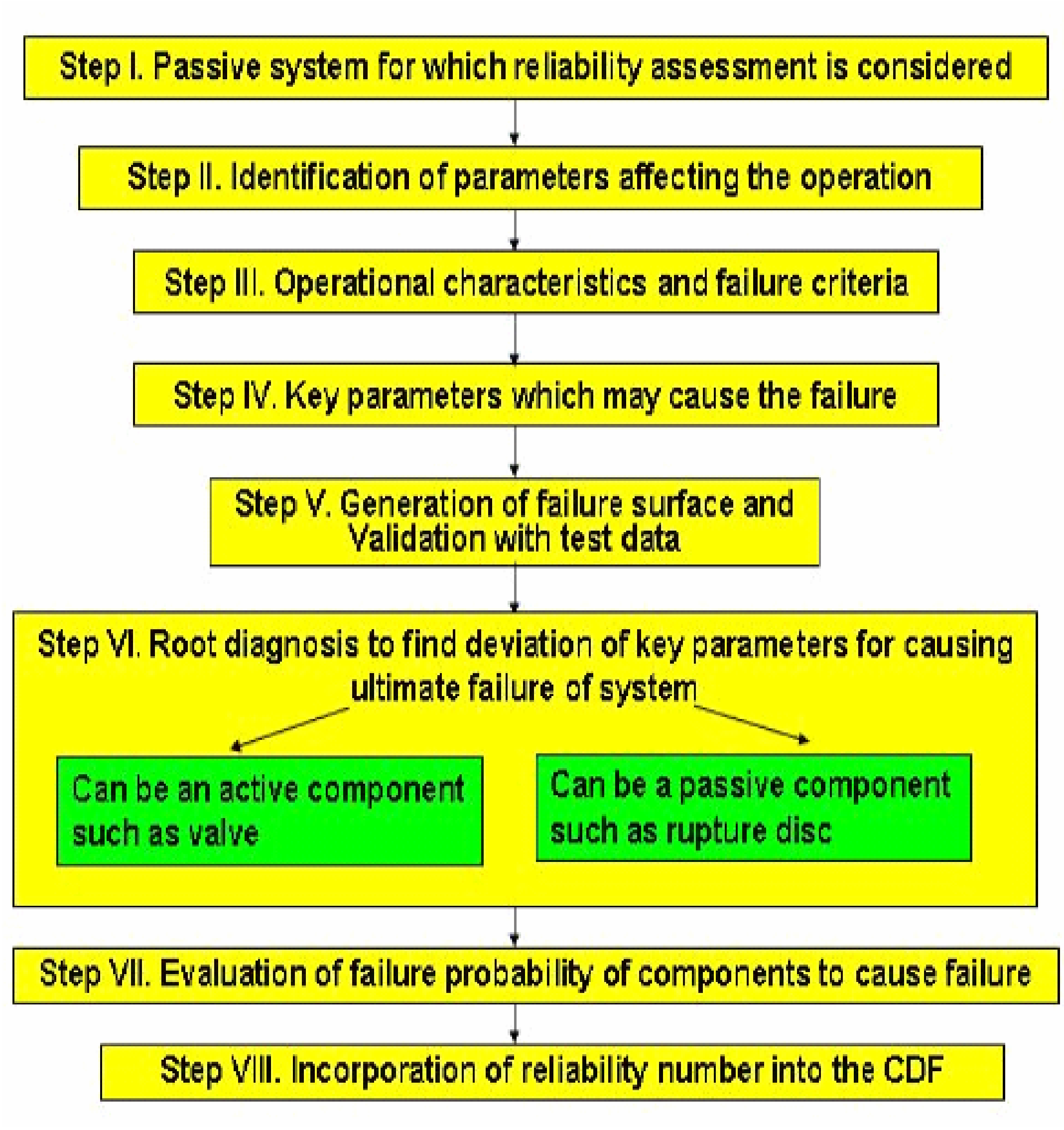
RMPS Methodology: roadmap



RMPS Methodology: Objectives

- To propose a specific methodology to evaluate the reliability of passive systems
- Identification and quantification of the sources of uncertainties and determination of the important variables
- Propagation of the uncertainties through a T-H model and reliability evaluation of the T-H passive system
- Integration of the T-H passive system in an accident sequence, as a basic event
- www.rmps.info

APSRA Methodology



Assessment of Passive Systems ReliAbility (APSRA)

- **Failure surface**
- **Deviations of all critical parameters influencing the system performance**
- **Causes of deviation through root diagnosis**
- **Mechanical components (as valves, control systems, etc.)**
- **Failure probability through classical PSA (fault tree)**
- **Comparison of test data with t-h code prediction to reduce uncertainties**

Open issues related to t-h passive systems reliability

- **Analysis of the different methodologies proposed so far**
- **Uncertainties**
  - **Passive system performance**
  - **T-h code**
- **Dependencies**
  - **Relevant variables**
- **Integration of passive systems into an accident sequence within a psa framework**
- **Passive vs active systems**

Sources of uncertainties related to passive system performance

- **Uncertainties related to natural circulation system behaviour prediction**
  - **Deviations of the natural forces or physical principles from the expected conditions**
  - **Phenomenological uncertainties, due to scarcity of operational and experimental data**
  - **Epistemic Uncertainties, i.e. related to the state of knowledge**
- **Difficulties in performing meaningful reliability analysis and deriving credible reliability figures**
  - **Expert judgment elicitation and engineering/subjective judgment**
- **Burgazzi L., *Evaluation of Uncertainties Related to Passive Systems Performance*, Nuclear Engineering and DesignVolume 230, May 2004, pp 93-106**

Aleatory
Geometrical properties
Material properties
Initial/boundary conditions (design parameters)
Epistemic
T-H analysis
Model (correlations)
Parameters
System failure analysis
Failure criteria
Failure modes (critical parameters)

Categories of uncertainties associated withT-H passive systems reliability assessment

Zio, E., Pedroni, N., *Building confidence in the reliability assessment of thermal hydraulic passive systems.* Reliability Engineering and System Safety, 94 (2009), 268-281

Sources of uncertainties related to t-h code

- **Uncertainties in the best estimate codes can arise due to e.g.,**
  - **Inadequate physical models built in the codes to represent a specific phenomena;**
  - **Absence of models to represent a particular phenomena;**
  - **Approximation in simulating system geometry;**
  - **Deviations of the input parameters in respect of initial and boundary conditions;**
  - **Uncertainties in thermophysical properties and thermohydraulic relationships.**

- **The uncertainty analysis (<u>of a code prediction</u>) implies a procedure to evaluate the precision (or the error) that characterizes the application of a best-estimate code**

- **The reliability analysis (<u>of a system</u>) aims at characterizing the ability of a system '*to operate satisfactorily*', following assigned specifications, over a period of time**

- **Therefore the uncertainty of the code can affect the prediction of the system**

Uncertainty and sensitivity qualitative analysis

Grade Rank for Uncertainty and Sensitivity

	Grade	Definition
Uncertainty	H M L	The phenomenon is not represented in the computer modelling or the model is too complex or inappropriate which indicates that the calculation results will have a high degree of uncertainty. The phenomenon is represented by simple modelling based on experimental observations or results. The phenomenon is modelled in a detailed way with adequate validation.
Sensitivity	H M L	The phenomenon is expected to have a significant impact on the system failure The phenomenon is expected to have a moderate impact on the system failure The phenomenon is expected to have only a small impact on the system failure

Failure Modes related Uncertainty and Sensitivity

TOPIC	UNCERTAINTY	SENSITIVITY
Envelope failure	L	H
Cracking	L	L
Non-condensable gas	H	H
Thermal stratification	H	H
Surface modification	M	L

Burgazzi L., *Evaluation of Uncertainties Related to Passive Systems Performance*, Nuclear Engineering and DesignVolume 230, May 2004, pp 93-106

Expert judgment elicitation process

Open Issues: Dependencies

- **Assumption of independence among relevant parameters adopted in the analysis (zero covariance)**
  - **safety variables**
    - **e.g. flow rate, exchanged heat**
  - **critical parameters driving the modes of failure**
    - **e.g. non-condensable gas**

- **In case of dependence (e.g. degradation measures), parameters can not be combined freely and independently**

- **Joint pdfs, e.g. multivariate distributions**
- **Conditional subjective probability distributions**
- **Covariance matrix**
- **Functional relationships between the parameters**

- **Burgazzi L., *Reliability Prediction of Passive Systems based on Bivariate Probability Distributions*, Nuclear Technology, Volume 161, pp. 1-7, January 2008**
- **Burgazzi, L., *Evaluation of the Dependencies Related to Passive System Failure*, accepted for publication in Nuclear Engineering and Design, DOI information: http://dx.doi.org/10.1016/j.nucengdes.2009.08.019**

Open Issues: Integration of passive systems within an accident sequence

- **Limitations of PSA (event tree development)**
  - **Binary representation (success or failure, intermediate states are usually not treated)**
  - **Time treatment (chronology of events instead of actual timing)**

- **Need for the development of dynamic event tree in order to evaluate the interaction between the parameter evolution during the accident and the system state**

- **Evaluation for 72 hours grace period, compared to 24 hrs in classical PSA**

- **Time-variant stochastic process**
  - **the evolution of physical parameters over time, in terms of probability distributions**
- **Burgazzi, L., *About Time-variant Reliability Analysis with reference to Passive Systems Assessment*, Reliability Engineering and System Safety, Vol. 93, pp.1682-1688, 2008**

Open Issues: Active vs Passive

- **Functional and economic comparison of active vs passive safety systems, required to accomplish the same mission**

- **Passive**
  - **Advantages e.g.,**
    - **No external power supply: no loss of power accident**
    - **No human factor**
    - **Better impact on pubblic acceptance, due to the presence of “natural forces”**
    - **Less complex system than active and therefore economic competitiveness**
  - **Drawbacks e.g.,**
    - **Reliance on “low driving forces”, as a source of uncertainty**
    - **Licensing requirement (open issue)**
    - **Reliability assessemnt in any case (lack of data)**

Conclusions and Path forward (1/3)

- **As the future reactor concept makes use of passive safety features in combination with active safety systems, the question of Natural Circulation Decay Heat Removal (NCDHR) reliability and performance assessment into the ongoing PSA constitutes a challenge**

- **Development of a consistent methodology for the evaluation of the reliability of the passive systems**

- **Future needs**

➢ ***Clear rules for identification and quantification of uncertainties.***
  - ➢ ***Formal expert judgment (EJ) protocol to estimate distributions for parameters whose values are either sparse or not available***
  - ➢ ***Sensitivity analysis techniques to estimate the impact of changes in the input parameter distributions on the reliability estimates***

➢ ***Clear distinction between the prediction of the thermal hydraulic code and the true behaviour of the passive system under consideration.***
  - ➢ ***Problem of model uncertainties***

➢ ***The time dependence of the passive system reliability***
  - ➢ ***Dynamic event trees***

Conclusions and Path forward (2/3)

Future needs (following):

- ***Evaluation of the dependencies among relevant system parameters***
- ***Comparison of different methodologies***
- ***Merge elements of different methodologies : RMPS, APSRA/BARC, REPAS and ENEA methodologies, since high dependency of results upon the assumptions underlying the models***
- ***Establish guidelines and criteria for the comparison of active and passive systems***

Conclusions and Path forward (3/3)

International efforts in progress

- **IAEA Coordinated research project (CRP) on *"Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"* (2008-2011)**
  - **the objective is to determine a common analysis-and-test method for reliability assessment of passive safety system performance**

- **IAEA CRP on "*Natural Circulation Phenomena, Modelling and Reliability of Passive Systems*" (2004-2008)**
  - **TECDOC-1474, "Natural Circulation in Water Cooled Nuclear Power Plants", November 2005**
  - **TECDOC-XXXX, "Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants", ready for publication**
  - **TECDOC-XXXX, "Natural Circulation in Water-Cooled Nuclear Power Plants: Phenomena, Modelling, and Reliability of Passive Systems that Utilize Natural Circulation", under preparation**