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NATURAL CIRCULATION AND PASSIVE SAFETY SYSTEMS

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NATURAL CIRCULATION AND PASSIVE SAFETY SYSTEMS

Presented by

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OBJECTIVES

Providing general overview on:

- Working principles of natural circulation
- Some typical examples of passive safety systems used in the design of advanced water cooled reactors
- Identification of natural circulation phenomena

OVERVIEW

- Introduction
- Natural circulation and its working principle
- Natural circulation loops
- Passive safety systems and examples
- Passive safety principles and integration of passive safety systems into Advanced Water Cooled Reactors (AWCRs) for:
  - Heat removal from intact primary system
  - Heat removal from the primary system of the reactor in case of accidents
  - Passive removal of heat from containment
- Identification and characterization of phenomena for passive safety systems for AWCRs
- Concluding remarks

INTRODUCTION (I)

- Advance plant design: A design of current interest for which improvement over its predecessors and /or existing designs is expected
- Two groups of advanced designs:

  - Evolutionary design

  - Innovative design
- Evolutionary design: achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. E.g., ABWR, EPR. Designs, which are developed with a great emphasis on **utilization of passive safety systems and inherent safety features,** belong to this category. E.g., AP 600, AP 1000, ESBWR, SWR 1000, HPLWR (SCWR), etc.

INTRODUCTION (II)

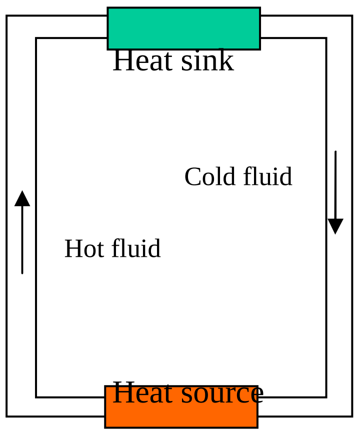
- Innovative design: An advanced design which incorporates radical conceptual changes in design approaches or system configuration with existing practice. E.g., PIRUS, IRIS, CAREM, etc.
- Increased safety requirements, the aim to introducing effective and transparent safety functions, expanded considerations of severe accidents lead to **growing consideration of passive safety systems for AWCRs** (See lecture slides SC03 of IAEA SCWR Training Course)
- To reduce the complexity of the emergency core cooling and of the long-term decay heat removal systems by increased use of **passive systems**

DEFINITIONS

- **A Passive component** is a component which does not need any external input to operate
- **A passive system** is either a system which is composed entirely of passive components or a system which uses active ones in a very limited way to initiate subsequent passive operation
- Passive safety systems are characterized by their full reliance upon natural forces, such as natural circulation, gravity, to accomplish their designated safety functions.

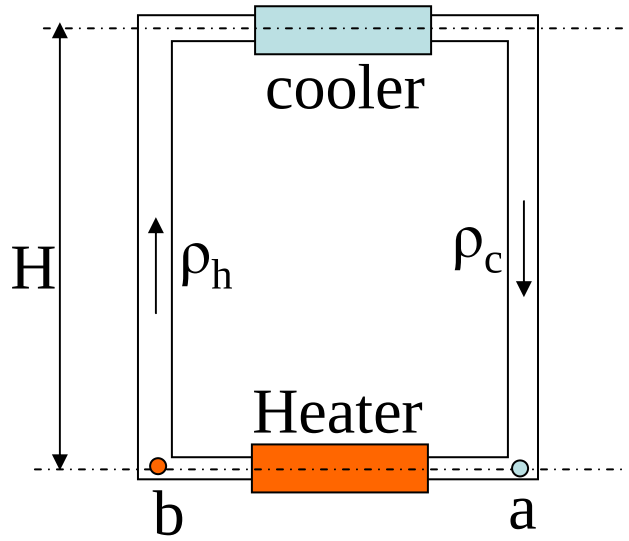
INTRODUCTION TO NATURAL CIRCULATION

- **NATURAL CIRCULATION** is a process by which fluid motion is driven by a **density difference** and **no external source of energy** is required.
- A heat source, a heat sink, and the pipes connecting them form the essential hardware of a natural circulation system
- The pipes to the heat source (heater) and heat sink (cooler) in such a way that they form a continuous circulation path
- When the flow path is filled with working fluid, circulation can set automatically following the activation of the heat source under the influence of a body field such as gravity
- With both the source and sink conditions maintained constant, a steady condition is expected to be achieved, which can continue indefinitely, if the integrity of the closed loop is maintained.



WORKING PRINCIPLE OF NC

- **Due to the difference in densities between the vertical legs, a pressure difference is created between stations 'a' and 'b' which is the cause of the flow.**
- **At steady state the driving buoyancy force is balanced by the retarding frictional force thus providing a basis for the estimation of the flow rate**.
- The flow rate through the loop is limited by the sum of the resistances in the components and interconnecting piping.



$$gH\left(\rho_c - \rho_h\right) = \frac{RW^2}{2\bar{\rho}}$$

Where g – acceleration due to gravity, m/s^2
R - hydraulic resistance, m^{-4}
W – mass flow rate, kg/s

Natural circulation flow is enhanced by the loop height and the difference in densities

NATURAL CIRCULATION LOOPS (I)

• Because of its simplicity, natural circulation loops are widely used in energy conversion systems.

• To take advantage of natural movement of warm and cool fluids, the heat source and heat sink must be at the proper elevations.

• Usually, the heat sink is located above the source to promote natural circulation.

• Such loops in which the fluid circulation is caused by the thermally induced buoyancy force are also known as natural circulation loops, thermo-syphon loops or natural convection loops.

NATURAL CIRCULATION LOOPS (II)

- The primary function of a natural circulation loop is to transport heat from a heat source to a heat sink.
- The main advantage of the natural circulation system is that the heat transport function is achieved without the aid of any fluid moving machinery, e.g., pumps.
- The absence of moving/rotating parts to generate the motive quantity of force (motive force) for flow makes it less prone to failures reducing the maintenance and operating costs.
- The motive force for the flow is generated within the loop simply because of the presence of the heat source and heat sink.
- Due to this natural circulation loops find several engineering applications in conventional as well as nuclear industries. Notable among these applications are solar water heaters, transformer cooling, geothermal power extraction, cooling of internal combustion engines, gas turbine blades, computer cooling, and nuclear rector cores. In addition to these industrial applications, it is also observed as weather systems, ocean currents, and household ventilation.

PASSIVE SAFETY SYSTEMS

- An important feature of several advanced reactors designs is the incorporation of passive safety systems. The International Atomic Energy Agency (IAEA) conference on *"The safety of Nuclear Power: Strategy for the Future",* convened in 1991, recommended that for new plants "**the use of passive safety features is a desirable method of achieving simplification and increasing the reliability of the performance of essential safety functions and should be used wherever appropriate".**
- In addition to IAEA, Europe, the USA and other countries have established some basic goals and requirements for future nuclear power plants. As an example, in Europe, the major utilities have worked together to propose a common set of nuclear safety requirements known as the European Utility Requirements (EUR). One of the common requirements for the new nuclear plants is the use of forgiving design characterized by simplicity and passive safety features where appropriate.
- Consequently, nuclear plant designers select active safety systems, passive safety systems, or combinations considering fulfilment of required safety functions with sufficient reliability, and the impact on plant operation and cost.
- **A number of passive systems incorporated in advanced reactors employ natural circulation as the mode of energy removal underlining the importance of natural circulation in nuclear reactor design.**

Considerations of Passive Safety Systems in AWCRs(I)

• The expanded considerations of severe accidents after the Three-Mile Island-2 (TMI-2) accident in 1979, increased safety requirements and the aim at introducing effective and transparent safety functions lead to growing consideration of passive safety systems for Advanced Water Cooled Reactors (AWCRs).

• In the advanced designs, attempts have been made to reduce the complexity of the emergency core cooling and of the long-term decay heat removal systems by increased use of passive systems.

• Following the IAEA definitions (as in one of the previous slide),

- a passive component is a component which does not need any external input to operate
- a passive system is either a system which is composed entirely of passive components or a system which uses active ones in a very limited way to initiate subsequent passive operation.

• Passive safety systems are characterized by their full reliance upon natural forces, such as natural circulation, gravity, to accomplish their designated safety functions. They are also making safety functions less dependent on active systems and components, like pumps, diesel generators, electromotor-driven valves, etc.

• AWCR design incorporates passive safety features to perform safety-related functions.

Considerations of Passive Safety Systems in AWCRs(II)

- Design features proposed for the passive AWCRs include the use of passive, gravity-fed water supplies for emergency core cooling and natural circulation decay heat removal, and natural circulation cooling within the core for all conditions.
- These types of nuclear plants also employ automatic depressurization systems (ADSs), the operation of which are essential during a range of accidents to allow adequate emergency core coolant injection from the lower pressure passive safety systems.
- The low flow regimes associated with these designs will involve natural circulation flow paths not typical of current operational Light Water Reactors.
- These passive AWCR designs emphasize enhanced safety by means of improved safety system reliability and performance.
- These objectives are achieved by means of improved safety system simplification and reliance on immutable natural forces for system operation.

Examples of Passive Safety Systems

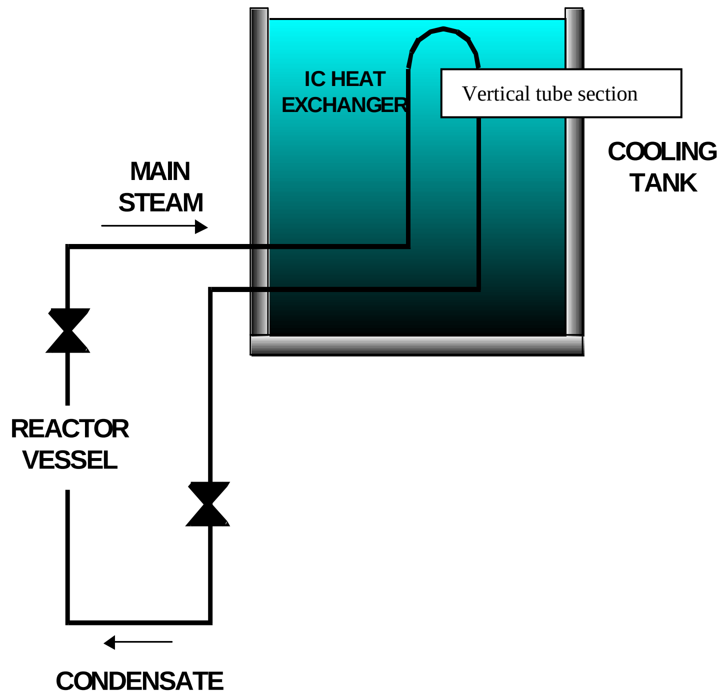
There are number of passive safety systems considered in different plant designs. Here, to enhance understanding of these systems, four different typical examples will be given and their operation will be explained in short:

- Isolation condenser cooling (IC) system
- Pre-pressurized core flooding tanks (accumulators)
- Elevated gravity driven tank
- Containment passive heat removal/pressure suppression systems

(Note: Further passive safety systems are described in IAEA-TECDOC-1624)

Isolation condenser (IC) cooling system

- Passively cooled core isolation condensers are designed to provide cooling to a Boiling Water Reactor (BWR) core subsequent to its isolation from the primary heat sink, the turbine/condenser set.
- During power operations, the reactor is normally isolated from the Isolation Condenser (IC) heat exchanger by closed valves. In the event that the core must be isolated from its primary heat sink, the valves are opened and main steam is diverted to the IC heat exchanger where it is condensed in the vertical tube section of the IC heat exchanger.
- Heat is transferred to the atmosphere through the heat exchanger and Isolation Condenser System/ Passive Containment Cooling System (ICS/PCCS) pool (cooling tank).
- The condensate returns to the core by gravity draining inside the tubes.



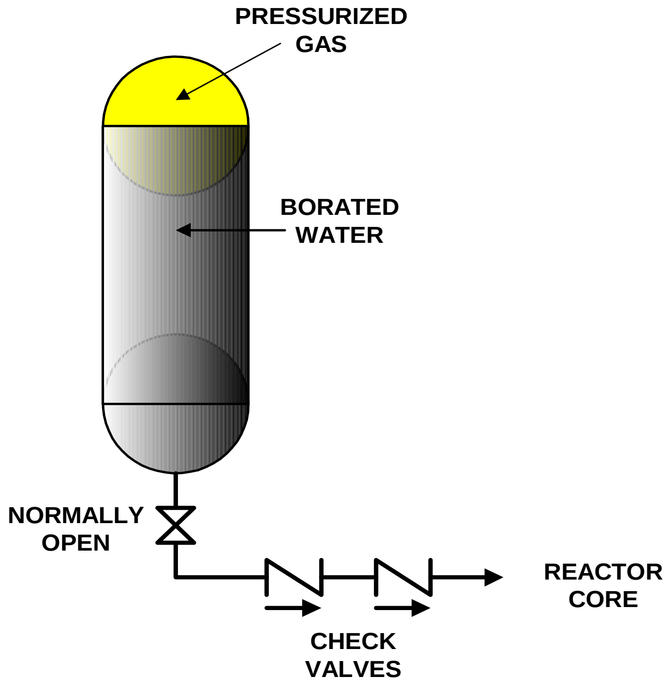
Pre-pressurized core flooding tanks (Accumulators)

• Pre-pressurized core flooding tanks, or accumulators, are used in existing nuclear power plants and they constitute part of the emergency core cooling systems.

• They typically consist of large tanks having about 75% of the volume filled with cold borated water and the remaining volume filled with pressurized nitrogen or an inert gas.

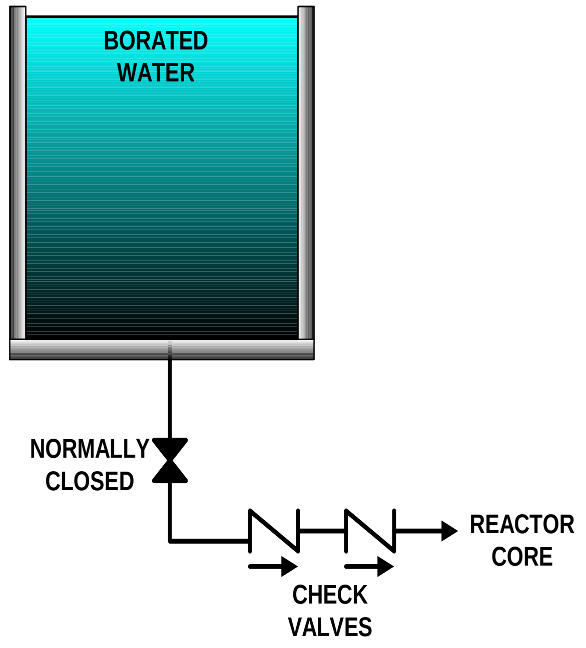
• The contents of the tank are isolated from the Reactor Coolant System (RCS) by a series of check valves that are normally held shut by the pressure difference between the RCS and the fill gas in the tank.

• In the event of a Loss-of-Coolant Accident (LOCA), the core pressure will drop below the fill gas pressure. This results in opening the check valves and discharging the borated water into the reactor vessel.



Elevated Gravity Drain Tank (Gravity Driven Cooling System)

- Under low pressure conditions, elevated tanks filled with cold borated water can be used to flood the core by the force of gravity.
- In some designs, the volume of water in the tank is capable of injecting large volumes of water into the depressurized reactor pressure vessel to keep the reactor core covered at least 72 hours following loss-of-coolant accident. And it has a capacity sufficiently large to flood the entire reactor cavity.
- Operation of the system requires that the isolation valve be open and that the driving head of the fluid exceed the system pressure plus a small amount to overcome the cracking (opening) pressure of the check valves.
- The performance of the gravity driven cooling tank may be limited, for a very short time period, under core uncovery conditions due to steam production in the core region.

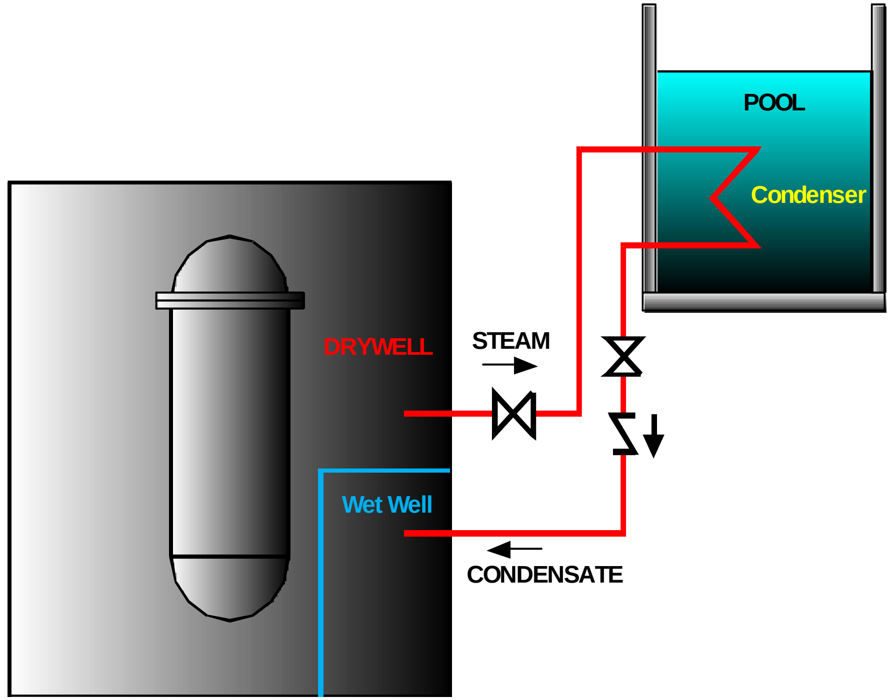


Containment passive heat removal/pressure suppression systems (I)

- Containment passive heat removal/pressure suppression systems use an elevated pool as a heat sink.
- Steam vented in the containment will condense on the containment condenser tube surfaces to provide pressure suppression and containment cooling.
- Two different zones of the containment, typically characterized by different pressures in case of accident (pressure is the same during normal operation), are connected with the rising and the descending side of a pool-type steam condenser heat exchanger. In this case, the steam-air mixture is the working fluid with condensate in the descending leg. The containment pressure is low (slightly above atmospheric pressure), driving forces may be low and working condition may not be stable over certain limited range of conditions.
- Positive driving forces may be low in this case and careful system engineering is needed.

Containment passive heat removal/pressure suppression systems (II)

- Containment pressure reduction and heat removal following a loss-of-coolant accident (LOCA) using an external steam condenser heat exchanger.



PASSIVE SAFETY PRINCIPLES OF NEXT GENERATION ALWR DESIGNS

- Low volumetric heat generation rates,
- Reliance solely on natural forces, such as gravity and gas pressurization, for safety system operation
- Dependence on natural phenomena, such as natural convection and condensation, for safety system performance.

HEAT REMOVAL FROM INTACT PRIMARY SYSTEM (I)

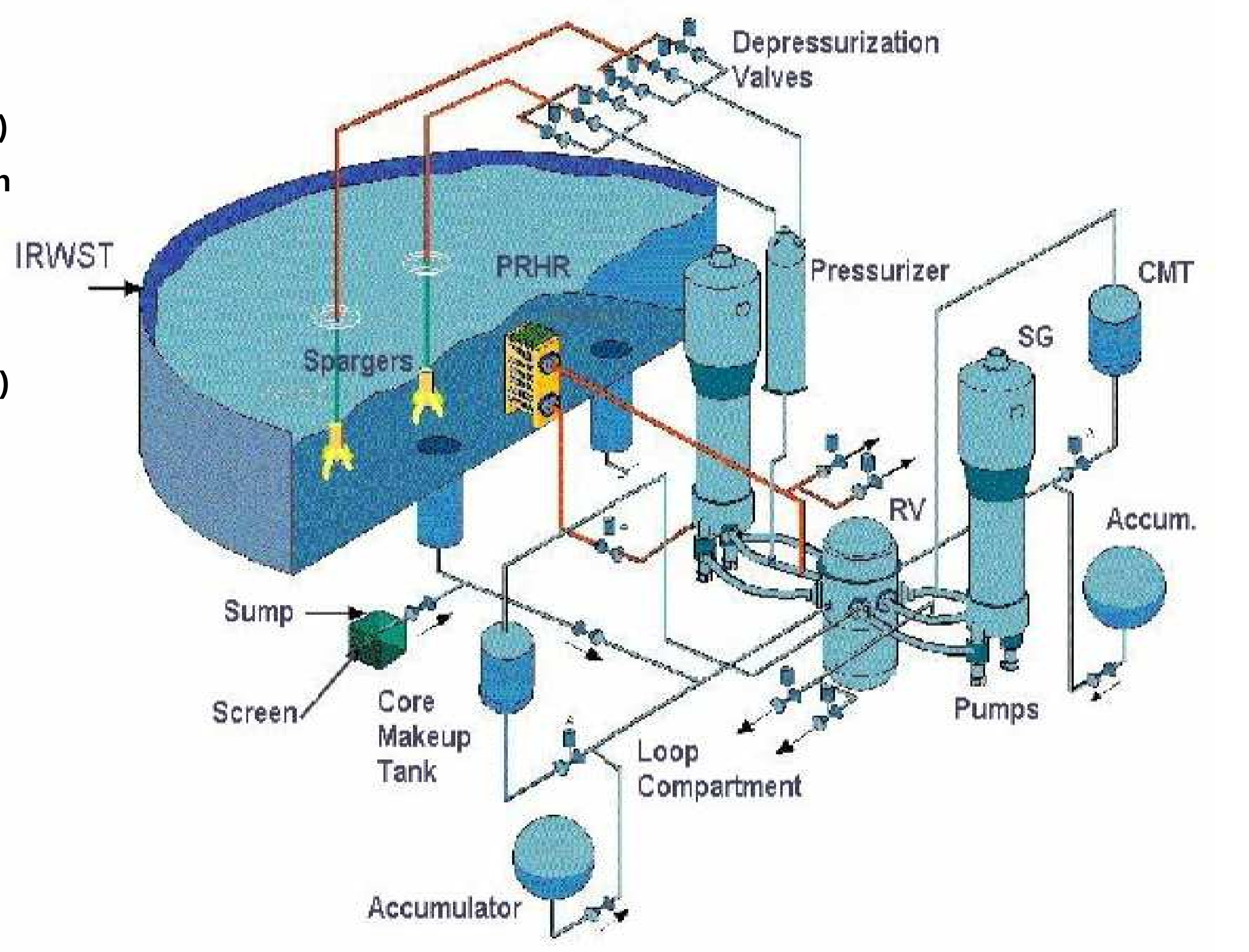
- The engineered safety features, which incorporate these passive safety principles, achieve increased reliability by means of system redundancy, minimization of system components, non-reliance on external power sources, and integral long term decay heat removal and containment cooling systems.
- Decay heat can be removed by circulating the primary coolant in heat exchangers or condensers typically immersed in pools inside the containment

HEAT REMOVAL FROM INTACT PRIMARY SYSTEM (II)

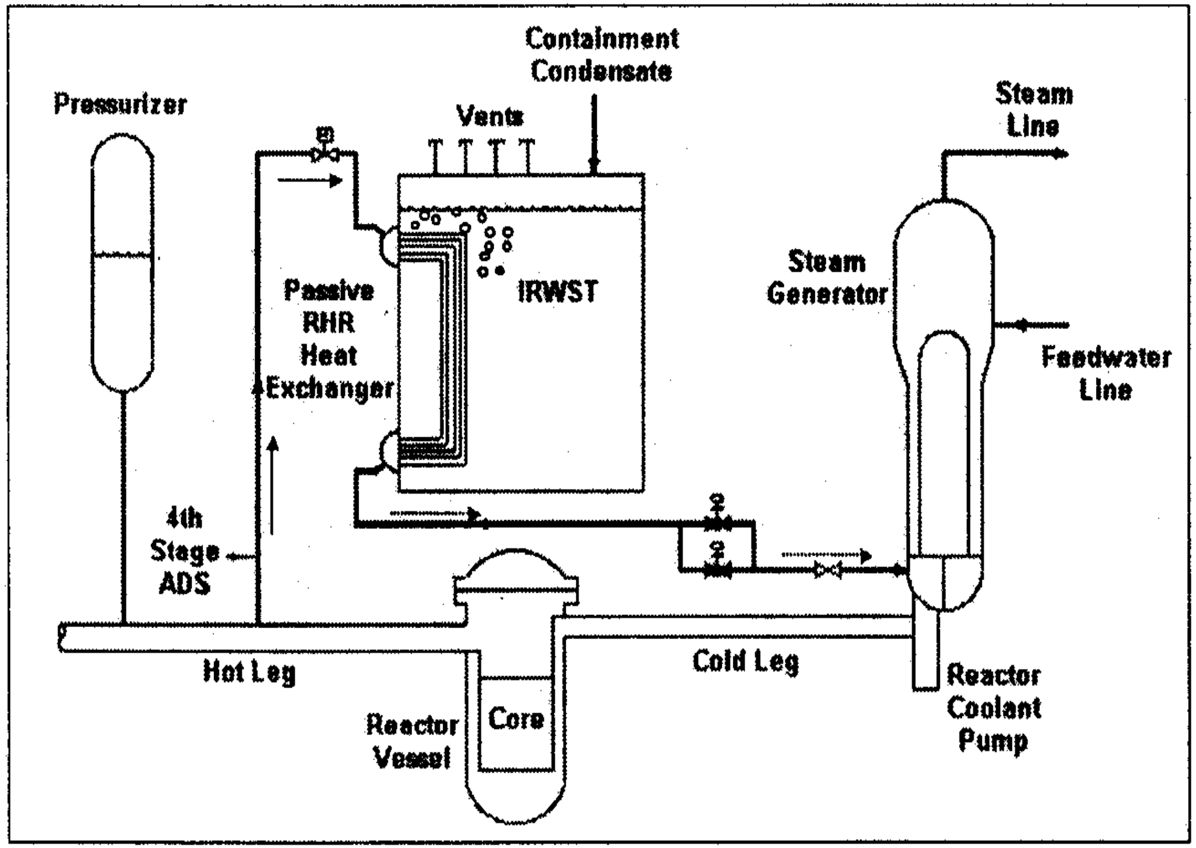
- Heat exchangers connected to the primary system and immersed in a water pool inside the containment, e.g., AP600/AP1000 where Passive Residual Heat Removal (PRHR) heat exchanger is immersed in IRWST, SWR 1000 has emergency condensers permanently connected to the core and located in Core Flooding Pool
- Another solution is the use of Isolation Condensers connected to the Reactor Pressure Vessel and immersed in external pools, as in ESBWR

AP600 Passive Core Cooling System

- **Passive Residual Heat Removal (PRHR) System**
- **Core Make-up Tanks(CMTs)**
- **Automatic Depressurization System (ADS)**
- **Accumulator Tanks**
- **In-containment Refueling Water Storage Tank, (IRWST)**
- **Lower Containment Sump**

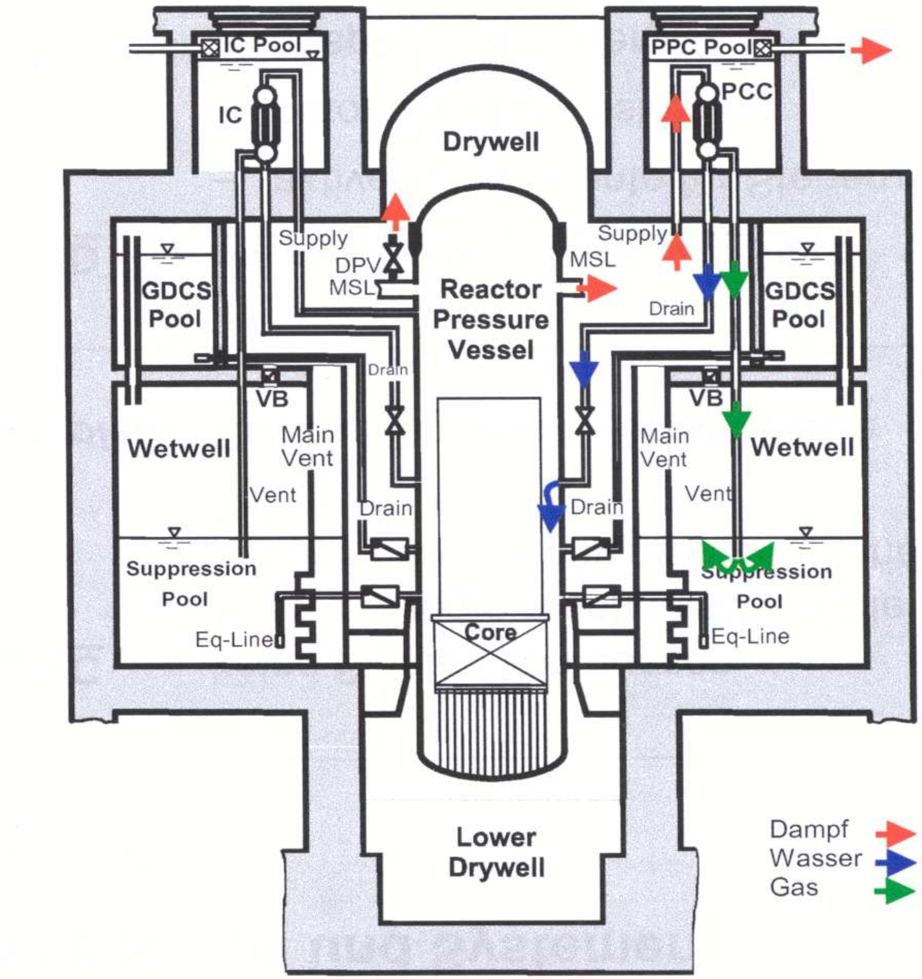


AP-600/ AP 1000 Passive Residual Heat Removal

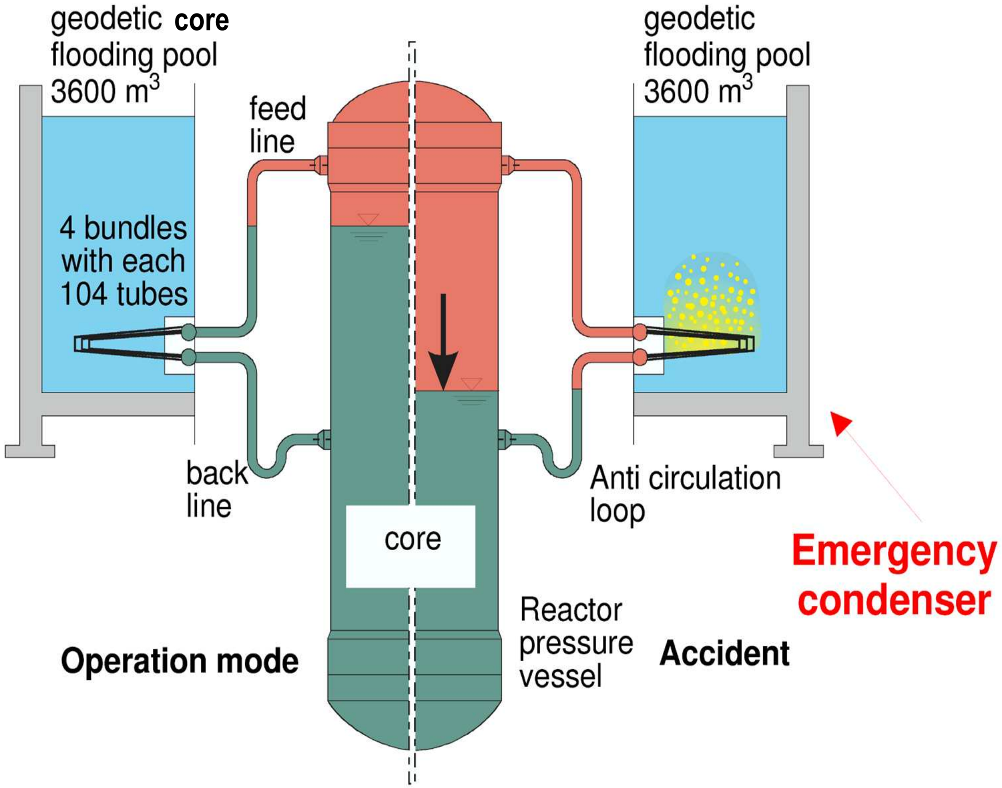


- HX connected to the primary system and immersed in the IRWST
- Actuates on low pressurizer pressure or level
- Station Blackout

ESBWR PASSIVE SAFETY SYSTEMS



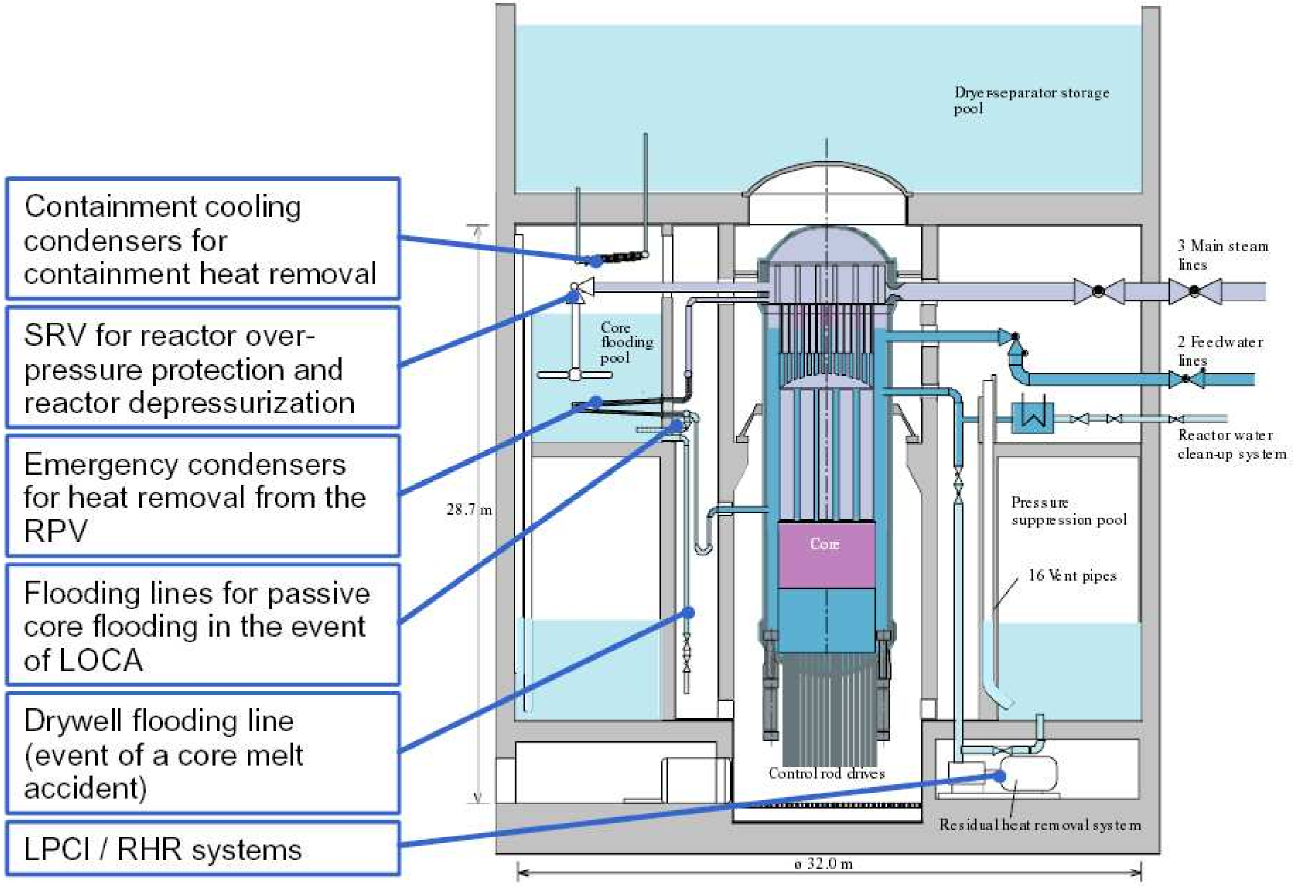
KARENA (SWR-1000) Emergency Condenser for removing heat from the primary system



- Loop seal: Hot water does not rise and start boiling

- Collapse of the voids in and above the core region leads to automatic activation of the Emergency Condenser (connected to the RPV without valves and immersed in the Core Flooding Pool)
- Two-step cooling
- Needs some pressure in primary system

PASSIVE HEAT REMOVAL IN KARENA (SWR 1000)



HEAT REMOVAL FROM INTACT PRIMARY SYSTEM OF THE REACTOR IN CASE OF ACCIDENTS (I)

- In case of LOCA, passive solutions for decay heat removal from the core rely on:

  - High-pressure gravity driven water tanks connected at their top to the primary system, e.g., Core make-up tanks (CMT) at any pressure, High-pressure accumulators at about 50 bar,

  - Flooding of the core after depressurization of the primary system by ADS operation, e.g., lower-pressure Core reflood tanks (CRT) at about 15 bar, In-Containment Refueling Water Storage Tank (IRWST),Gravity driven cooling system (GDCS)

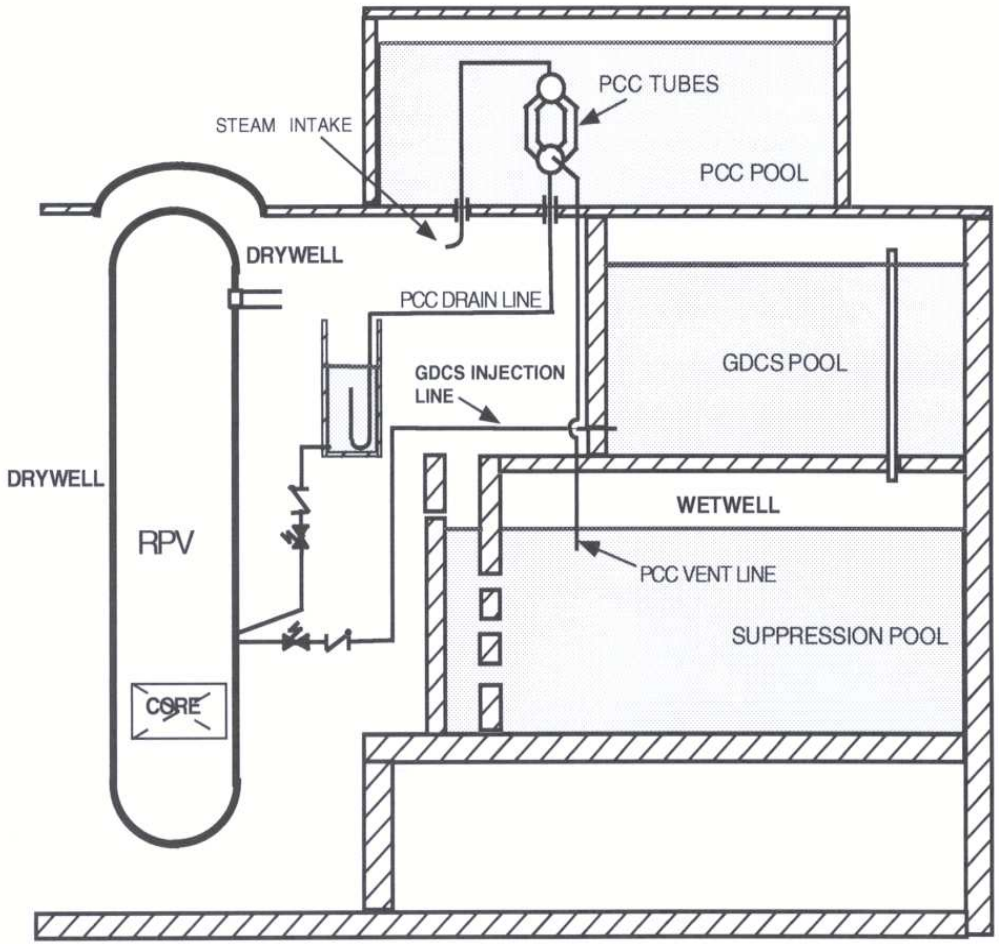
HEAT REMOVAL FROM INTACT PRIMARY SYSTEM OF THE REACTOR IN CASE OF ACCIDENTS (II)

- The primary system of ALWRs is designed such that the core can be kept covered in spite of breaches in the primary system
- In addition, elimination of primary system piping contributes to the elimination of certain LOCA scenarios, e.g. large break LOCA as in PWRs or BWRs
- Passive plants rely on **automatic depressurization** of the primary system and actuation of low-pressure gravity driven core make-up tanks.

PASSIVE REMOVAL OF HEAT FROM CONTAINMENT

- All containment systems profit from the **passive heat sink** provided by the **structures** inside the containment and containment building
- By the time structures get saturated, decay heat levels are lower and the containment cooling systems can fully cope with the decay heat removal
- Thus, capacity needed for containment cooling is reduced.
- Other solution for decay heat removal from containment is the use of condensers
- Condensers immersed in pools can be located either inside the containment, near the roof, or outside the containment.
- In all cases the heat removal rates are enhanced by phase change, e.g., condensation, wetting of the containment walls

ESBWR Passive Containment Cooling System



Identification and characterization of phenomena for passive safety systems for advanced water cooled NPPs

- As it can be observed from the examples given, natural circulation phenomena are very much coupled with the type of passive systems, their combinations, and also the type of the nuclear plant considered.
- Thermal-hydraulic phenomena and related parameter ranges that characterize the performance of passive systems do not differ, in general, from phenomena that characterize the performance of systems equipped with active components.
- This is specifically true for transient conditions occurring during safety relevant scenarios. For example friction pressure drops or heat transfer coefficients are affected by local velocity and void fraction and not by the driving force that establishes those conditions, e.g. gravity head or centrifugal pump.
- The same can be repeated for more complex phenomena like two phase critical flow or counter-current flow limiting.
- A large number of thermal-hydraulic phenomena that are expected to occur in passive systems during accident are classified in the OECD/Nuclear Energy Agency (OECD/NEA) documents.
- The OECD/NEA list of phenomena for passive systems was up-graded and modified in IAEA Coordinated Research Program on "Natural Circulation Phenomena, Modeling and Reliability of Passive Safety Systems that Utilize Natural Circulation," considering the recently proposed passive systems by the industry.
- Twelve phenomena influencing natural circulation were identified and characterized for passive systems based upon the key layout of the nuclear plant designs considered.

Identification and characterization of phenomena for passive safety systems for advanced water cooled NPPs (Table 1 in Choi, Cleveland and Aksan (NED-2011))

Phenomena identification		Characterizing thermal-hydraulic aspect
1	Behaviour in large pools of liquid	Thermal stratification Natural/forced convection and circulation Steam condensation (e.g. chugging, etc.) Heat and mass transfer at the upper interface (e.g. vaporization) Liquid draining from small openings (steam and gas transport)
2	Effects of non-condensable gases on condensation heat transfer	Effect on mixture to wall heat transfer coefficient Mixing with liquid phase Mixing with steam phase Stratification in large volumes at very low velocities
3	Condensation on containment structures	Coupling with conduction in larger structures
4	Behaviour of containment emergency systems	Interaction with primary cooling loops
5	Thermo-fluid dynamics and pressure drops in various geometrical configurations	3-D large flow paths e.g. around open doors and stair wells, connection of big pipes with pools, etc. Gas liquid phase separation at low Re and in laminar flow Local pressure drops
6	Natural circulation in closed loop	Interaction among parallel circulation loops inside and outside the vessel Influence of non-condensable gases Stability Reflux condensation
7	Steam liquid interaction	Direct condensation Pressure waves due to condensation
8	Gravity driven cooling and accumulator behaviour	Core cooling and core flooding
9	Liquid temperature stratification	Lower plenum of vessel Down-comer of vessel Horizontal/vertical piping
10	Behaviour of emergency heat exchangers and isolation condensers	Low pressure phenomena
11	Stratification and mixing of boron	Interaction between chemical and thermo-hydraulic problems Time delay for the boron to become effective in the core
12	Core make-up tank behaviour	Thermal stratification Natural circulation

Modified from the table provided in Aksan and D'Auria (1996).

CONCLUDING REMARKS (I)

• The use of passive safety systems such as accumulators, condensation and evaporative heat exchangers, and gravity driven safety injection systems eliminate the costs associated with the installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies.

• However, considering the weak driving forces of passive systems based on natural circulation, careful design and analysis methods must be employed to assure that the systems perform their intended functions, in addition to the experimental elaborations.

• As a result, passive safety systems are being considered for numerous reactor concepts and may potentially find applications in the future reactor concepts, as identified by the Generation IV International Forum (GIF), e.g. in SCWR designs.

• Another motivation for the use of passive safety systems is the potential for enhanced safety through increased safety system reliability.

CONCLUDING REMARKS (II)

- These objectives are achieved by means of improved safety system simplification and reliance on immutable natural forces for system operation.
- Most systems rely on boiling or condensation to obtain sufficiently high heat transfer rates under natural circulation conditions
- Simulating the performance of these safety systems is central to analytical safety evaluation of reactor designs (which are utilizing passive safety systems)
- Since the new passive ALWR designs incorporate significant changes from the familiar current LWR designs and place higher reliance on individual systems, a thorough understanding of these designs is needed with respect to system interactions.
- In addition, there is a close coupling in both plant designs between the reactor coolant system and the containment during an accident.
- As seen from the list of identified phenomena, natural circulation phenomena in nuclear plants is much broader field and related to other groups of phenomena which needs to be considered in combination.

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