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APPLICATION OF NATURAL CIRCULATION SYSTEMS: ADVANTAGES AND CHALLENGES II

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KEY WORDS

Natural circulation, Advanced reactor designs, Passive cooling systems, decay heat removal.

ABSTRACT

Applications of natural circulation systems are provided for advanced light water reactor designs. Design features proposed for the passive advanced light water reactors include the use of passive, gravity-fed water supplies for emergency core cooling and natural circulation decay heat removal from the primary system and the containment, and natural circulation cooling within the core for all conditions. Examples are given from different types of advanced reactor designs for the use of passive safety systems under the operational, transient, and accident conditions. Challenges encountered in the design of passive safety systems for HPLWR are discussed in short, as an example case.

LECTURE OBJECTIVES

Lecture on this subject will provide an idea about the use of the natural circulation systems for the future reactor designs. Some examples will be provided for the passive cooling of these reactor designs. Challenges to be overcome for the use of natural circulation in the design of passive safety systems are provided with an example case.

1. INTRODUCTION

Advanced Light Water Reactor (ALWR) designs have been under development for the last fifteen years worldwide. Different aspects of these new plant designs are described fairly extensively and systematically in references [1] to [6]. Further information can be found in specialized international conferences [7] to [12].

New designs –designs that have not yet been built or operated- are generally, called advanced designs [3]. In general, an advanced plant design is a design of current interest for which improvement over its predecessors and/or existing designs is expected. Advanced designs can be categorized into two groups:

- Evolutionary design: An evolutionary design is an advanced design that achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. An evolutionary design requires at most engineering or confirmatory testing before commercial deployment. As examples for advanced LWRs are ABWR, EPR, etc. In this category, there are also designs, which are developed with a great emphasis on utilization of passive safety systems and inherent safety features. Typical examples are Advanced Passive PWR AP 600, AP1000, and the simplified BWR (SBWR), ESBWR, SWR 1000, HPLWR, etc.
- Innovative design: An innovative design is an advanced design, which incorporates radical conceptual changes in design approaches or system configuration with existing practice, e.g., PIRUS, IRIS, etc. This design category will most likely require a prototype or demonstration plant.

All ALWRs incorporate significant design simplifications, increased design margins, and various technical and operational procedure improvements, including better fuel performance and higher burnup, a better man-machine interface using computers and improved information displays, greater plant standardization, improved constructability and maintainability, and better operator qualification and simulator training.

The expanded considerations of severe accidents, increased safety requirements and the aim at introducing effective and transparent safety functions lead to growing consideration of passive safety systems for ALWRs. In the evolutionary 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 [3], a passive component is a component which does not need any external input to operate and 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. ALWR design incorporates passive safety features to perform safety-related functions.

Design features proposed for the passive ALWRs include the use of passive, gravity-fed water supplies for emergency core cooling and natural circulation decay heat removal, e.g., for AP600, AP1000, SBWR and ESBWR, and natural circulation cooling within the core for all conditions, e.g., SBWR and ESBWR. Both types of 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 LWRs. These passive ALWR 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. Simulating the performance of these safety systems is central to analytical safety evaluation of advanced passive reactor designs.

Specially, the passive safety principles of the next generation ALWR designs include:

- 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.

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. In the design of the current generation of operating reactors, redundancy and independence have been designed in the protection systems so that no single failure results in loss of the protection function. Since the new passive ALWR designs incorporate significant changes from the familiar current LWR designs and place higher reliance on individual systems, a through understanding of these designs is needed with respect to system interactions. These interactions may occur between the passive safety systems, e.g., the core make-up tanks and accumulators in the AP1000, and the ADS system and isolation condensers in the ESBWR. In addition, there is a close coupling in both plant designs between the reactor coolant system and the containment during an accident.

It can also be noted that in order fully profit from the safety benefits due to the introduction of the passive safety systems, the behavior of plants in which engineering safety features involving active components have been replaced with completely passive devices must be carefully studied to ensure the adequacy of the new design concepts for a wide spectrum of accident conditions. In fact, choice of passivity is an advantage in reducing the probability of the wrong operator interventions, especially in the short-term period after an accident, although passive systems require more sophisticated modelling techniques to ascertain that the natural driving forces that come into play can adequately accomplish the intended safety functions. Hence there is also the need for an in-depth study of the basic phenomena [1] concerning the design of ALWRs, which make use of passive safety features.

2. HEAT REMOVAL FROM INTACT PRIMARY SYSTEM

In the cases when the primary system is intact but the normal heat sink (e.g., secondary side of steam generator or turbine) has been lost, the decay heat is not transferred to the containment with the blowdown flow and must still be removed from either the reactor pressure vessel (for BWRs) or steam generator (for PWR). The solutions are proposed using the passive connection of the primary system to a heat exchanger (or condenser). Heat exchangers connected to the primary system and immersed in a water pool inside the containment are used. As one of the examples, the AP600/AP1000 designs ([6] and [7]) where passive residual heat removal (PRHR) heat exchanger is immersed in the in-containment refueling water storage tank (IRWST) as shown in figures 1 and 2. The PRHR provides primary coolant heat removal via a natural circulation loop. Hot water rises through the PRHR inlet line attached to one of the hot legs. The hot water enters the tube sheet in the top header of the PRHR heat exchanger at full system pressure and temperature. The IRWST is filled with cold borated water and is open to containment. Heat removal from the PRHR heat exchanger occurs by boiling on the outside surface of the tubes. The cold primary coolant returns to the primary loop via the PRHR outlet line that is connected to the steam generator lower head.

Another example is the SWR-1000 ([5] and [6]), which has emergency condensers permanently connected to the core and located in the core reflooding pool, as in figure 3. The emergency condensers are connected to the RPV without isolating elements, and thus actually form part of RPV. Each emergency condenser consists of a steam line leading from the RPV nozzle to a heat exchanger tube bundle. This tube bundle is located in the core flooding pool at a low elevation. The outlet on the heat exchanger primary side is the reflooding line with integrated anti-circulation loop. The working principle of the emergency condenser design is illustrated in figure 3. Given the normal water level inside the RPV, there prevails a stratified condition inside the emergency condenser. The upper part of the steam line is filled with steam while the lower part is filled with water. The water remains cold (except for a small layer below the RPV water level), as the anti-circulation loop prevents hot water from the RPV to enter the reflooding line from below. No convection occurs and thus thermal losses are negligible as long as the water level in the RPV remains normal. The water level in the steam line of the emergency condenser is several meters lower because the density of the water inside the RPV is lower than that of the water in the emergency condenser. This stratified condition changes to natural circulation if the water level inside the RPV drops by more than 0.7 m. Consequently, when the water level in the emergency condenser then drops by more than 0.5 m, steam enters the heat exchanger bundle. The steam then condenses inside the heat exchanger tubes and the resultant condensate flows via the reflooding line back into the RPV. If the water level inside the RPV is lower than the inlet nozzle of the reflooding line, the maximum driving pressure differential will be reached at a pressure of about 0.5 bar. This pressure differential is used to overcome the flow resistances in the steam line, heat exchanger tube bundle and reflooding line. The emergency condenser continues to function as long as the water level inside the RPV remains lower than 0.7 m below the normal RPV water level, as experimentally determined. On the secondary side, natural circulation also occurs once the emergency condenser begins to work. At low heat transfer rates, there is single-phase flow, while at higher rates two-phase flow occurs due to water evaporation. Normally, the water inventory of the flooding pool below the heat exchanger bundle could not be used as a heat sink due to stratification. To overcome this problem, the heat exchanger is enclosed in a chimney. Water enters the chimney at the bottom of the pool and exits at the top several meters above the heat exchanger.

Another solution is the use of isolation condensers connected to the reactor pressure vessel and immersed in external pools as in ESBWR design (figure 4). The ESBWR uses isolation condensers for high-pressure inventory control and decay heat removal under isolated conditions ([8] and [9]). The isolation condenser system consists of four totally independent high-pressure loops, each containing a heat exchanger that condenses steam on the tube side and transfers the heat to water in large pool, outside the containment, which is vented to atmosphere. The isolation condenser (IC) is connected by piping to the RPV, and is placed at an elevation above the source of steam in the RPV and when steam is condensed, the condensate is returned to the vessel via a condensate return line. The steam line connected to the vessel is normally open and the condensate return line is normally closed. This allows the IC and drain piping to fill with condensate, which is maintained at a cooler temperature by the IC/PCC pool water during normal operation. The ICs are designed to handle the stored energy in the RPV and the core decay heat. In this way, there is no energy discharged to the suppression pool, there is no safety relief valve operation and there is no loss of reactor inventory. This makes a high-pressure make-up system unnecessary for ESBWR.

3. HEAT REMOVAL FROM THE PRIMARY SYSTEM OF THE REACTOR IN CASE OF ACCIDENTS

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 bars, In-containment Refueling Water Storage Tank (IRWST), Gravity Driven Cooling System (GDCS).

Several new designs have been improved by moving emergency cooling water sources inside the containment. As examples, the AP-600/AP-1000 have several water sources located inside the containment such as CMTs, high-pressure accumulators, lower pressure CRT and also IRWST (see figure 1); ESBWR have the GDCS inside the containment (see figure 4). In case of the AP-600/AP-1000 using CMT, the pressure on top of this tank is equalized with primary system pressure. Thus the

CMT can provide make-up water to the core by gravity at any pressure. For intermediate pressure levels in advanced PWRs, injection of water from accumulators (at about 50 bar) or core refold tanks (at about 15 bar) is used.

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, however, also to elimination of certain LOCA scenarios, e.g., elimination of large break LOCA as in PWRs and BWRs. Examples are the elimination of the recirculation piping in the ABWR by use of reactor internal pumps [6] and similar trend can be observed in the AP600/AP1000 where the primary system recirculation pumps are directly attached to the steam generators.

Two approaches have generally being used in order to better cope with the pressurized LOCA scenarios:

1. Intentional automatic depressurization of the primary system and subsequent use of low-pressure safety injection (LPCI) systems,
2. Increase of the capacity of the high-pressure coolant injection (HPCI) system.

In the passive plants, one relies on automatic depressurization of the primary system and, consequently, actuation of low-pressure gravity driven core make-up systems. This solution is chosen for the ESBWR and the SWR1000. Both of these passive BWRs provide gravity driven, low-pressure core flooding. It is the GDCS pool that floods the ESBWR. The core reflooding pool provides the same function for the SWR1000 (see figures 3 and 5). The ADS system is also incorporated in the AP-600/AP-1000. After depressurization, the AP-600/AP-1000 uses the IRWST inventory to reflood the RPV with gravity. On the other hand, the ABWR has a higher capacity HPCI relieving reliance on the ADS.

4. PASSIVE REMOVAL OF HEAT FROM CONTAINMENT

All containment systems profit from the passive heat sink provided by the structures inside the containment and the containment walls. The structures are usually needed to absorb the higher level of decay heat generation immediately after shutdown and limit the initial containment pressure. By the time these heat sinks get saturated (reach equilibrium temperatures with the containment atmosphere), the decay heat levels are lower and the containment systems can fully cope with the decay heat removal function. Thus, capacity needed for containment cooling is reduced.

A schematic of the AP600/AP1000 containment is presented in figure 6, which shows the cooling of the containment building from the outside by natural draft enhanced by a water film on the thin metallic containment wall. It consists of a large steel vessel that houses the Nuclear Steam Supply System (NSSS) and all of the passive safety injection systems. The steel containment vessel resides inside of a concrete structure with ducts that allows cool outside air to come in contact with the outside surface of the containment vessel. The wetted surface of the containment shell is coated with a well-wetting paint to promote even distribution of water. When steam is vented into containment via a primary system break or ADS-4 valve actuation, it rises to the containment dome where it is condensed into liquid. The energy of the steam is transferred to the air on the outside of containment via conduction through the containment wall and natural convection to the air. As the air is heated, it rises through the ducts creating a natural circulation flow path that draws cool air in from the inlet duct and vents hot air out the top of the concrete structure. The condensate inside containment is directed back into the IRWST and the containment sump where it becomes a source of cool water in the sump recirculation process. Early in a LOCA transient, cold water is sprayed by gravity draining onto the containment vessel head to enhance containment cooling. A large tank of water, located at the top of the containment structure, serves as the source of water for this operation and is released in a programmed way producing a thin water film on the containment wall surface. By the time the water supply is exhausted, the decay heat removal needs are reduced and dry cooling of the wall suffices.

AP600/AP1000 containment cooling design is possible with metallic containment walls only. An alternative solution has been proposed for EP1000, which is a similar design to AP600 [10]. This design has two thick, concrete containment walls. It consists of finned condenser installed near the roof, inside the containment building, an intermediate sealed thermo-siphon loop penetrating through the double concrete containment walls, and an external hybrid (initially immersed, water-cooled and later air-cooled) heat exchanger, as in figure 7. When the water inventory in the external pool is lowered, a passage for the air opens and the non-immersed part of the tubes acts as an air-cooled condenser.

The cooling of the containment atmosphere by containment condensers installed near the roof is also proposed for the SWR1000 reactor design. The SWR1000 has a containment-cooling condenser (CCC) with its secondary system connected to an external pool, as in figure 5. In the event of failure of the active residual heat removal systems, four CCCs are designed to remove residual heat from the containment to the dryer-separator storage pool located above the containment. The CCCs are actuated by rising temperatures in the containment. They use natural circulation both on the primary and on the secondary sides. The working principle of the CCC is shown in figure 8. It comprises a simple heat exchanger mounted about 1 m above the water level of the core reflooding pool. If the temperature in the drywell atmosphere increases over that in the dryer-separator storage pool, the water inside the heat exchanger tubes heats up. It flows to the outlet line due to the slope of the exchanger tubes. The outlet line ends at a higher elevation level than the inlet line; consequently the lifting forces are increased for the whole system. Depending on the heat transfer rate and cooling water temperature, secondary-side flow can be single-phase, intermittent, or two-phase. In the hypothetical case of a core melt accident, a hydrogen-steam mixture would also be possible. Given nitrogen, steam and mixture thereof, primary flow is downwards due to the densities of pure gases an a nitrogen-steam mixture increase with decreasing temperature. This results in the expected downward flow. Condensed steam drops into the core flooding pool. However, the opposite is true for a hydrogen-steam mixture, as the density of this mixture decreases with decreasing temperature, resulting in an upward flow through the heat exchanger tube bundle. But this does not pose any problem for the SWR1000 because both directions of flow on the primary side are equivalent.

The PCCS is the preferred means of decay heat removal following a LOCA for ESBWR (figures 4 and 9). The system is a unique ESBWR engineered safety feature (similar to the SBWR PCCS). Containment heat removal is provided by the PCC system, consisting of four low-pressure loops, which is a safety related system ([8] and [9]). Each loop consists of a heat exchanger, which opens to the containment, a condensate drain line that returns the PCCS condensate to a PCCS condensate tank, which is connected to the RPV via its own nozzle, and a vent discharge line submerged in the suppression pool. The four heat exchangers, similar to the ICs, are located in cooling pools external to the containment. Once PCCS operation is initiated following RPV depressurization, the condensate return line to the vessel is opened permanently. The PCCS uses natural convection to passively provide long-term containment cooling capability. The PCCS pool is sized to remove post-LOCA decay heat at least 72 hours without requiring the addition of pool inventory.

The PCCS heat exchangers are extensions of containment. The lines entering and leaving the PCCS from the drywell do not have containment isolation valves. No sensing, control, logic or power operated devices are required for the PCCS to initiate. Flow through the PCCS loop is driven by the pressure difference created between the containment drywell and the suppression pool that exists following a LOCA and the pressure drop through the PCCS tubes. The PCCS condensate is returned to the RPV under the force of gravity.

One key feature of the ESBWR allows an economical scale up of the reactor design. It effectively allows larger wetwell-to-drywell volume ratio, without significantly enlarging the containment. The

GDCS pool region and the wetwell are connected by pressure equalization lines. As a result of this connection, the additional air space volume created by the GDCS pool draining, which is now available for the wetwell gases to expand keeping the containment pressure low, following an accident. This change improves the long-term containment pressure response.

5. AN EXAMPLE CASE: SAFETY FUNCTIONS, IN CASE OF TRANSIENTS AND IN THE EVENT OF ACCIDENTS FOR HPLWR DESIGN

It is the aim of the development of the High Performance Light Water Reactor (HPLWR) to use both passive and active safety systems ([11], and [12]) for performing safety-related functions in the event of transients or accidents (see figure 10). The most frequent events requiring system function for prevention of intolerable fuel rod temperatures comprise anomalies in plant operation, or so-called transients. As a result of the specific properties of supercritical water, the water inventory within a HPLWR RPV is about 1/10th of that of a BWR or a PWR. This means that in case of incidents and accidents, the heat storage capacity of the existing water inventory in the primary circuit is low. Concerning the control of incidents and accidents this fact has to be considered appropriately. In general this means that as fast as possible, flow, which is able to cool the core has to be maintained. Later on the core has to be flooded with water from all sources, including water reservoirs external to the primary circuit.

From the comparison of analyses for a hot line break and a loss of feed-water flow accident, it is recognized that a reduction of temperature occurs in the first case, while in the second case under assumption of a fast HP water injection into the RPV a considerable larger temperature increase occurs [11]. As a consequence of these results, it is expected that the core cooling is more effective in case of loss of flow accidents, if the ADS is activated and followed by a low pressure water injection from the suppression pool, compared to an HP injection. Although this has to be substantiated by further analyses, this procedure seems to be the appropriate mode to control these kinds of accidents. Therefore in case of incidents with loss of feed-water flow it is proposed to apply the principle of ADS following by low-pressure coolant injection. Whether accumulators can be used in addition or even instead of the pumps need to be investigated in some detail. This mode should result in the lowest temperature loads of the fuel rods and in reliable systems for accident control. It should be pointed out that the same design philosophy has also been adopted in the design of Advanced Light Water Reactors (ALWR).

The HPLWR is being evaluated with particular emphasis on improved economics while maintaining the safety and reliability level achieved by advanced LWR. As mentioned above, it will rely on passive safety features to flood the core when necessary and to cool the containment. As the design of the HPLWR progresses and matures, additional evaluations will also be performed to assess the potential for new passive safety systems in the HPLWR design. In addition, the HPLWR design relies in part on existing proven technologies (e.g. supercritical fossil power plants).

6. CONCLUDING REMARKS

Passive ALWR 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. Most of the passive safety 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 advanced reactor designs.

For the intact primary system conditions, the decay heat can be removed by circulating the primary coolant in heat exchangers or condensers typically immersed in pools inside the containment. In case of LOCA, passive solutions for decay heat removal from the core rely either on high-pressure gravity driven core make-up tanks connected at their top to the primary system, or upon depressurization of the primary system followed by flooding of the core by gravity. Further, solutions for decay heat removal from the containment are based either on cooling of the metallic containment from the outside or on use of condensers. The condensers can be located either inside the containment, near the roof, or outside the containment, immersed in pools.

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 interaction.

NOMENCLATURE

ABWR	Advanced Boiling Water Reactor
ADS	Automatic Depressurization System
ADS-4	Four stage ADS for AP600/AP1000
CMT	Core Make-up Tanks
CRT	Core Reflood Tanks
AP600	Advanced Pressurized Reactor, 600MWe
AP1000	Advanced Pressurized Reactor, 1000MWe
BWR	Boiling Water Reactor
CCC	Containment Cooling Condenser
ECCS	Emergency Core Cooling System
EP1000	European AP1000
EPR	European Pressurized Reactor
ESBWR	European Simplified Boiling Water Reactor
GDCS	Gravity Driven Cooling System
HP	High Pressure
HPIS	High Pressure Injection System
HPLWR	High Performance Light Water Reactor
IAEA	International Atomic Energy Agency
IC	Isolation Condenser
IRIS	The International Reactor Innovative and Secure (Westinghouse with International co-operation)
IRWST	In-containment Refueling Water Storage Tank
LOCA	Loss Of Coolant Accident
LPIS	Low Pressure Injection System
LWR	Light Water Reactor
NSSS	Nuclear Steam Supply System
PCC	Passive Containment Cooling
PCCS	Passive Containment Cooling System
PIRUS	ABB Atom, Sweden, Passive Design Reactor
PRHR	Passive Residual Heat Removal
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SBWR	Simplified Boiling Water Reactor
SWR1000	Siede Wasser Reaktor, 1000MWe

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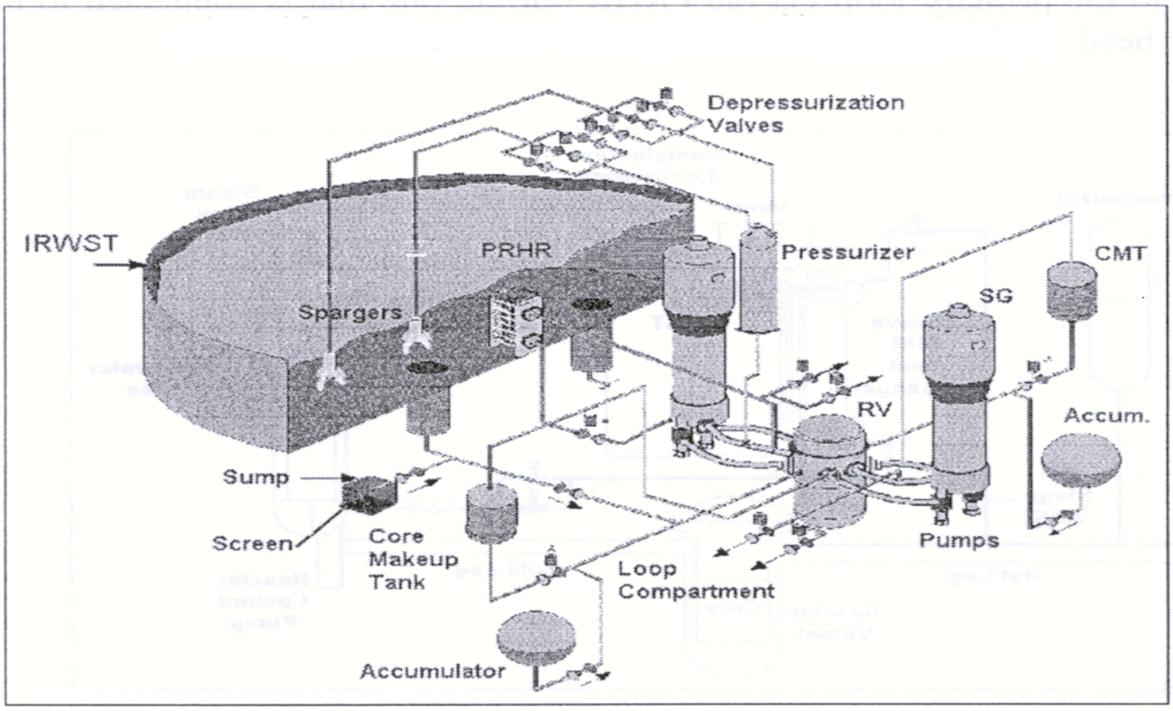

Figure 1: Schematic of the passive safety systems used for the AP600/AP1000 designs

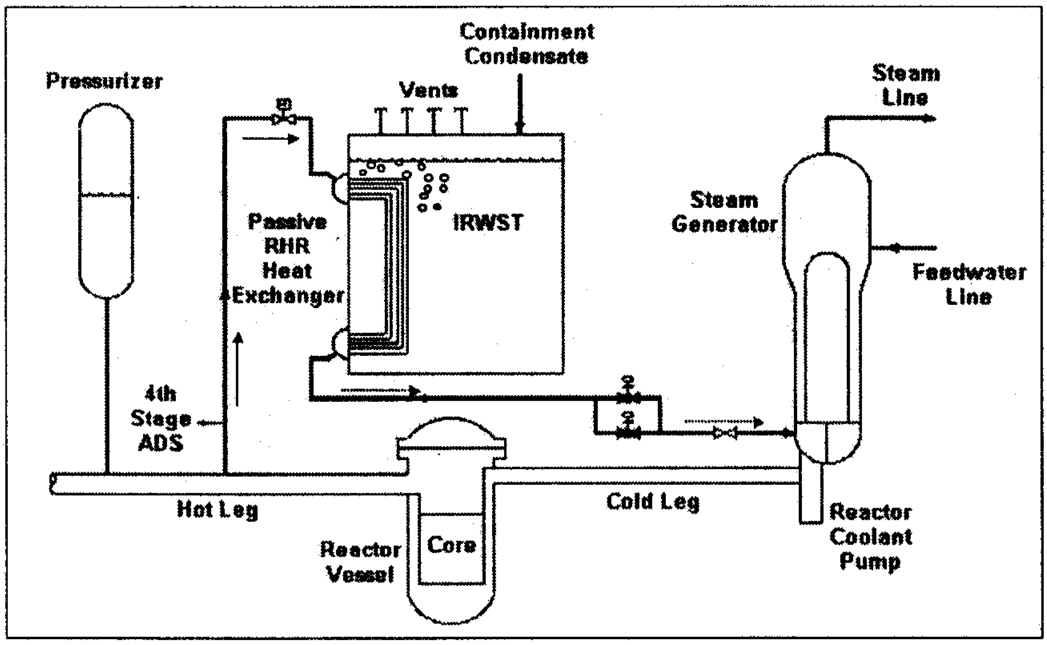

Figure 2: The AP600/1000 Passive residual heat removal system (PRHR) using a heat exchanger connected to the primary system and immersed in the IRWST

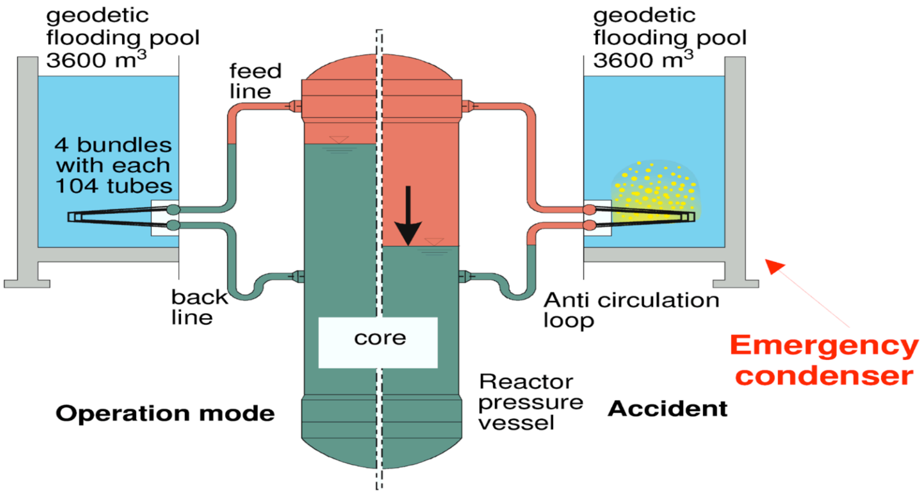

Figure 3: The SWR1000 Emergency condenser for removing heat from the primary system by gravity flow

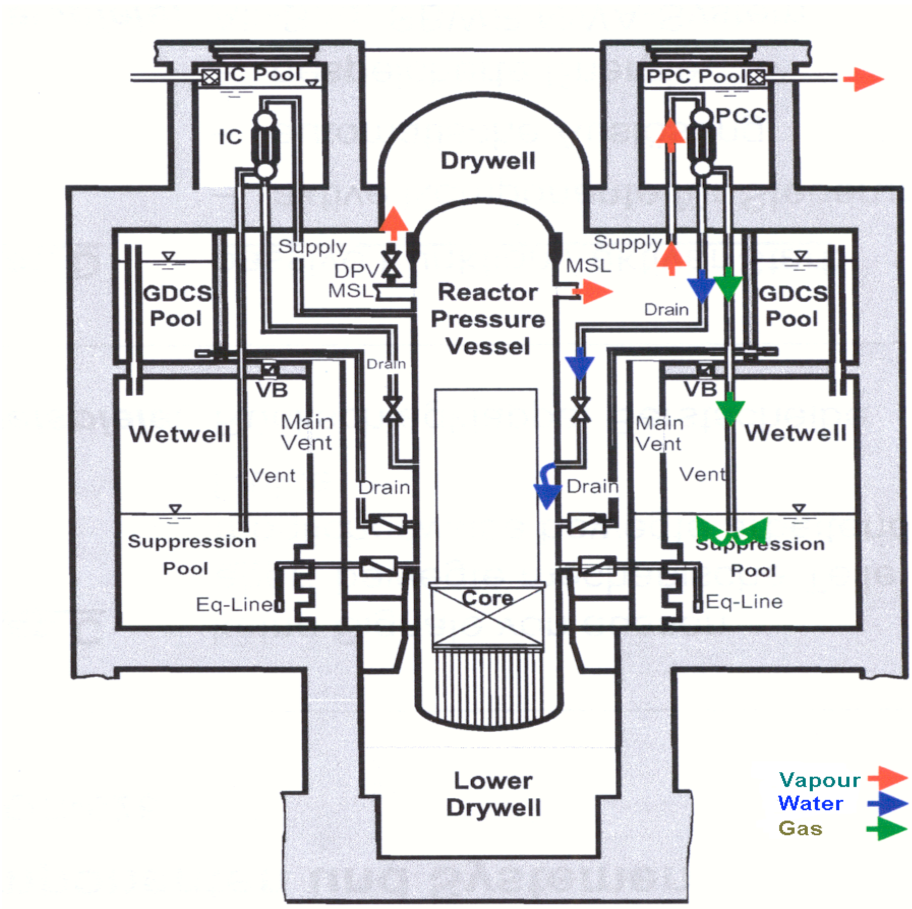

Figure 4: The ESBWR design and passive safety systems

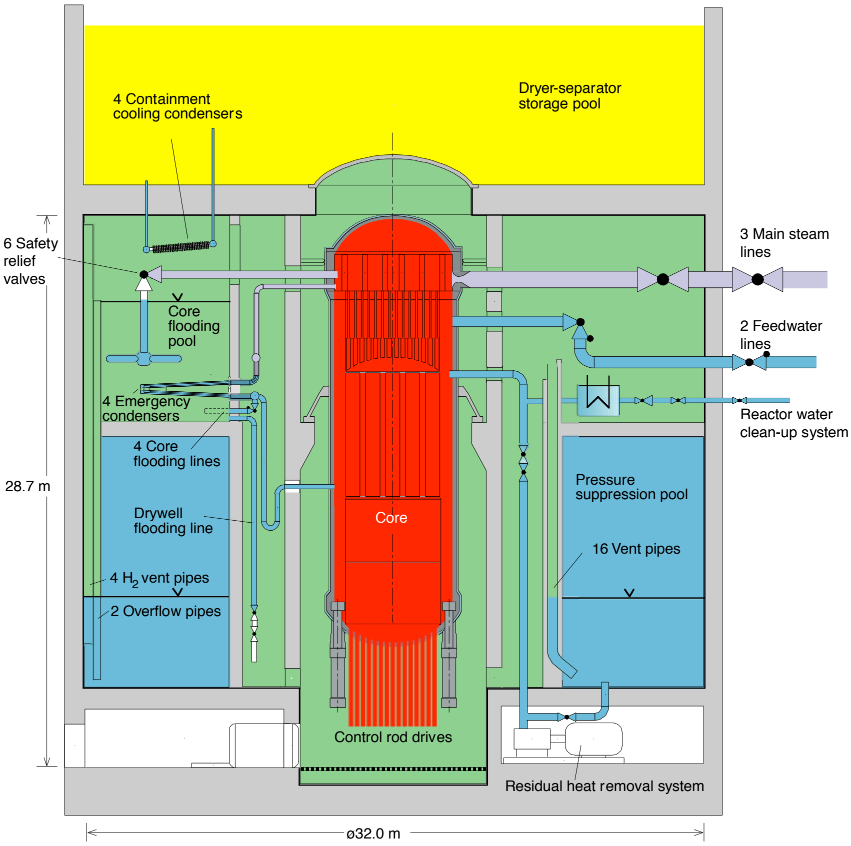

Figure 5: Conceptual arrangement of the SWR1000 Containment and passive safety cooling systems

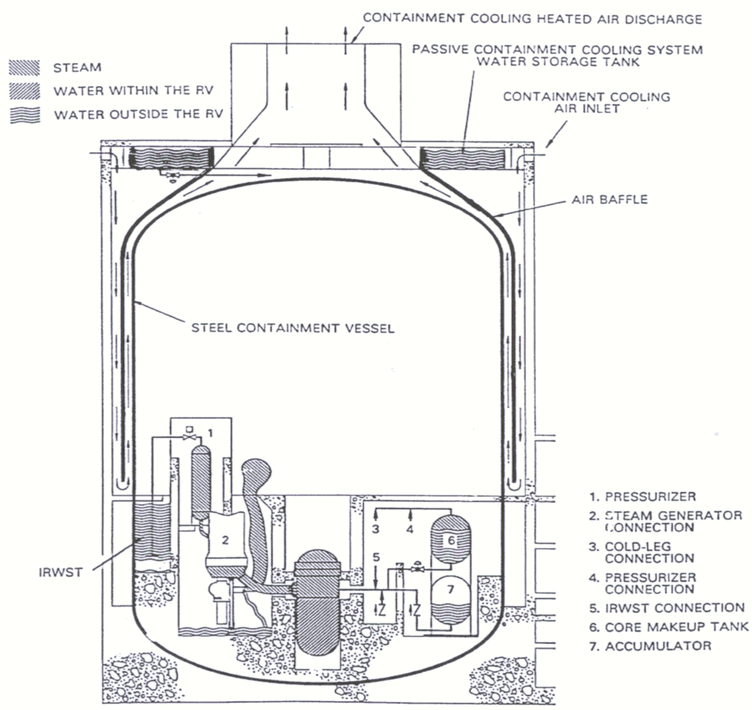

Figure 6: Passive containment cooling for the AP600/AP1000 design

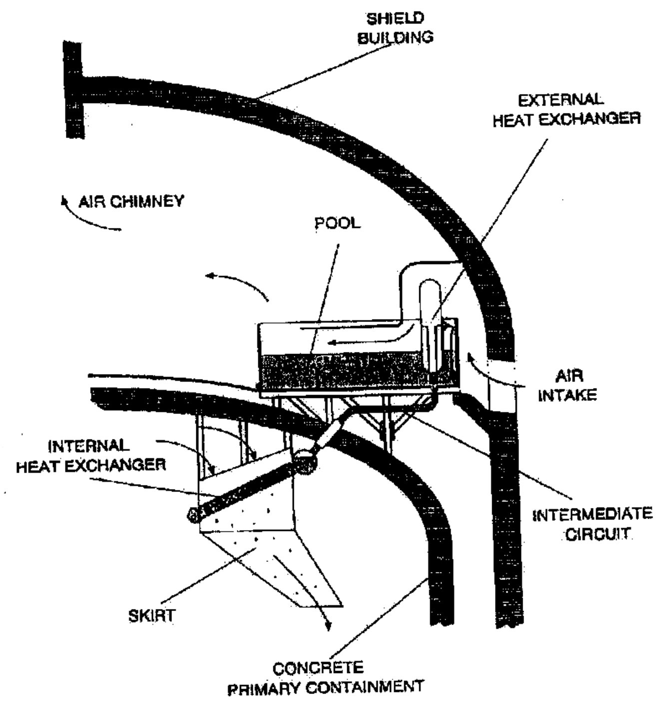

Figure 7: Double concrete containment passive cooling system proposed as an alternative to the AP600 external wall-cooling concept

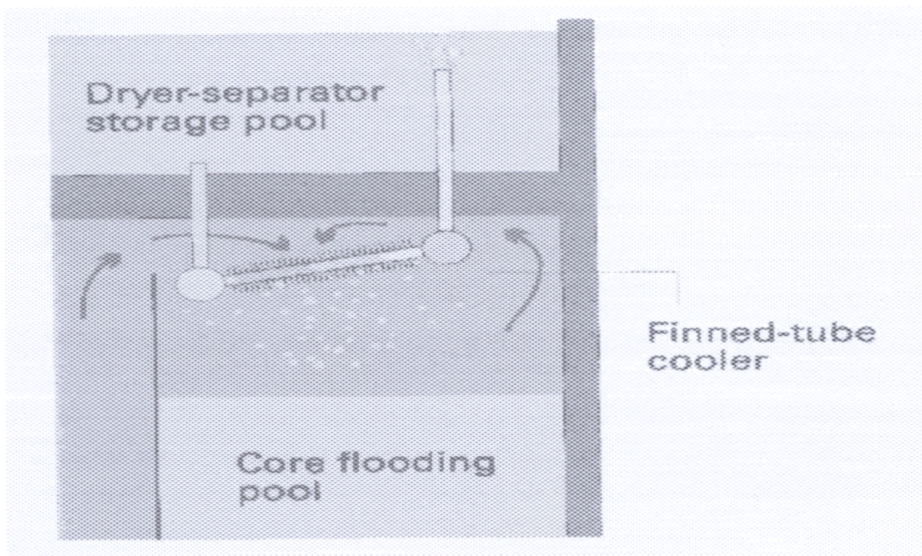

Figure 8: Containment Cooling Condenser for SWR1000

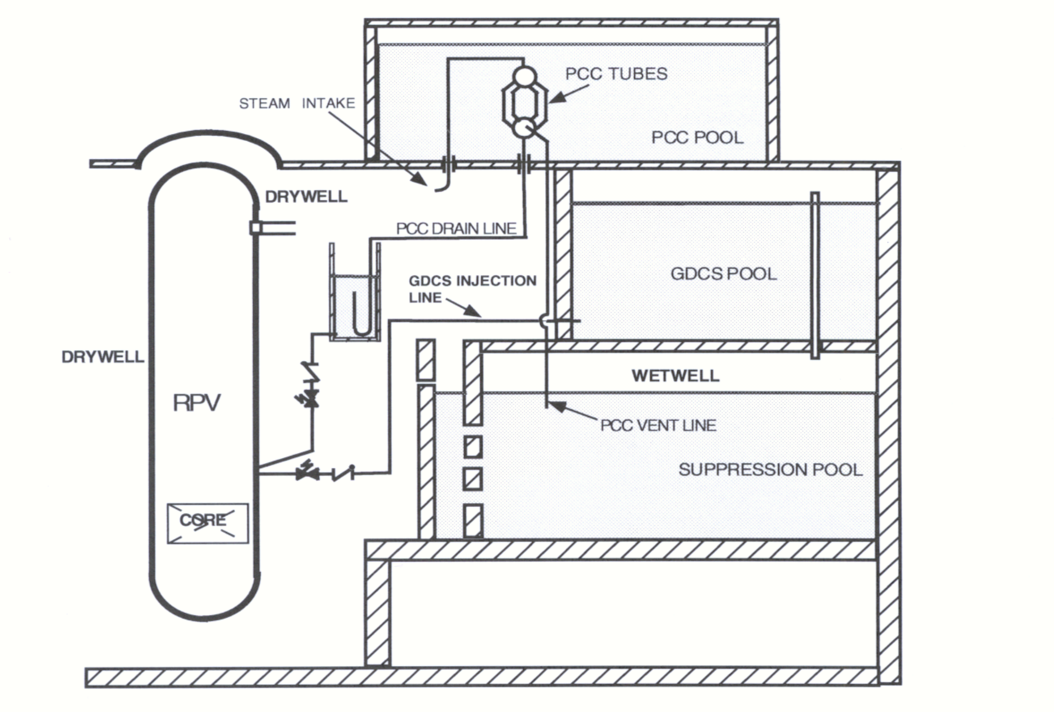

Figure 9: The ESBWR Passive Containment Cooling System condenses containment steam and vents the non-condensable to the suppression pool

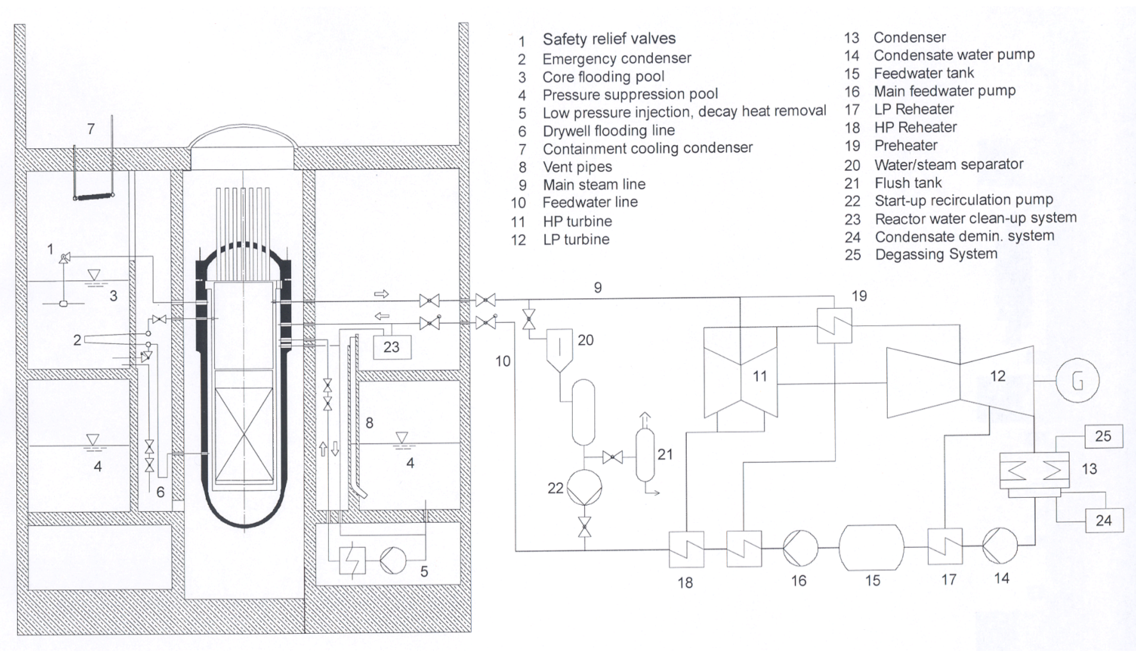

Figure 10: Schematics of the HPLWR primary circuit, safety systems and containment concept