ADVANCES IN TECHNOLOGIES FOR DECAY HEAT REMOVAL

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Abstract

The various decay heat removal concepts that have been used for the evolutionary water reactor plant designs developed worldwide are examined and common features identified. Although interesting new features of the "classical" plants are mentioned, the emphasis is on passive core and containment decay heat removal systems. The various systems are classified according to the function they have to accomplish; they often share common characteristics and similar equipment.

1 INTRODUCTION

Various water-cooled reactor concepts are at different R&D and design phases today. These include plant designs that incorporate well proven active safety systems, as well as plants where certain safety functions, and in particular long-term decay heat removal from the core and/or the containment, are achieved by passive systems. Examples of these evolutionary plants (evolutionary Light Water Reactors, LWR or Heavy Water Reactors, HWR) are listed below, in three categories: Pressurized Water Reactors (PWR) of Western and Eastern design, Boiling Water Reactors (BWR) and Heavy Water Reactors (HWR):

LWR/PWR:	EPR, System 80+, KNGR, APWR, EP 1000, AC-600, AP-600, MS-600, etc. Evolutionary VVER-1000, VVER-640, etc.
LWR/BWR:	ABWR, BWR 90, ESBWR (SBWR), SWR-1000, etc.
HWR:	CANDU-9, CANDU-6, AHWR, etc.

Design information on these systems can be found in recent IAEA-TECDOCs [1]-[4] and in the proceedings of this conference. The *phenomena* that are relevant for decay heat removal and their importance are discussed in [5].

1.1 Core and containment cooling

In water reactors, the fuel bundles must be kept covered with water to ensure their coolability. During the first phase of Loss of Coolant Accidents (LOCA), the primary coolant systems undergo complex transients. The main concerns during this phase are the evacuation of the heat *stored* in the fuel rods during normal operation and retention of sufficient water in the Reactor Pressure Vessel (RPV). This is achieved by keeping adequate thermal-hydraulic conditions in the core and replenishing the coolant lost during the blowdown process. In this respect, the presence of larger water inventories in the RPV during normal operation are beneficial. At the end of this first phase, the state of the primary system is stabilized; the main concern then becomes the evacuation of the decay heat. The decay heat must be removed first from the core in the RPV and from the primary system, and then from the containment where typically it is finally dumped.

This evacuation of the decay heat has been assured in most "classical" water reactor systems by redundant and diverse *active* Emergency Core Cooling Systems (ECCS) and containment cooling systems. The most recent ALWR and AHWR designs take advantage of accumulated experience and combine the best characteristics of existing reactor systems in an optimal way to achieve even higher reliability and safety in active core and containment heat removal. Examples are the EPR, ABWR, BWR 90, System 80+, KNGR, etc. [1], as well as evolutionary CANDU and VVER designs. High degrees of reliability and safety can be achieved by increasing system redundancy, separation, diversity, etc. Since active systems need fairly large power supplies to operate, the availability of the sources of electricity must also be improved. Such improvements bring, however, added complexity to the systems.

1.2 The passive plants

In certain other new-generation evolutionary plants designed worldwide, attempts have been made to reduce the complexity of the long-term decay heat removal systems; one approach adopted in several designs has been to achieve this safety function via increased use of *passive* systems.

The passive plants require no operator actions to mitigate Design-Basis Accidents (DBA). Passive systems use only "natural" forces such as gravity, natural circulation and compressed gas to operate. Containment structures, water pools or the atmosphere provides the heat sinks needed to dispose of the decay heat. There are no *active* components such as pumps, fans, diesels, water chillers, etc. Passive systems may require, however, the alignment and actuation of a few valves; passive valve actuators have also been proposed, but they may not be indispensable, given the relative simplicity and the high degree of reliability that simple valve alignments can achieve. Thus, passive systems do not require redundant, *safety-grade*, active ECCS and containment cooling systems and the corresponding redundant safety-grade emergency power supplies. The ambient air is most often the ultimate heat sink; this results in the elimination of the safety-grade service water system. The elimination of safety-grade systems should result in considerable simplification of the plants and capital cost reductions. In addition, typical unattended operation periods of the order of days (typically 72 hours) can be achieved.

The classical ECCS and containment cooling systems are typically replaced by:

- Natural-circulation cooling of the core (when the primary system is intact)
- Gravity Driven Cooling Systems (GDCS) (with the primary system breached)
- Passive Containment Cooling Systems (PCCS)

Since the pressure and temperature differences driving passive cooling are usually small, the corresponding single-phase heat transfer rates are relatively weak and evaporation or condensation of the coolant is usually necessary to get reasonable heat transfer areas and heat exchanger sizes.

This paper reviews design approaches taken to improve the safety of long-term heat removal from the core and the containment in the new generation of evolutionary plants, in particular the plants described in [1]. Certain advances achieved by further improving *active* systems and their configurations are mentioned, but the main emphasis is on reviewing the various *passive* approaches proposed and in identifying common features and trends. The paper does not consider the so-called *innovative* plants where the design deviates significantly from that of existing plants and where more radical approaches have been proposed [1].

The various systems are classified in terms of the *function* that they have to accomplish. In this light, one finds out that although there are many combinations of possible passive systems and their variations, they most often share common characteristics.

2 DECAY HEAT REMOVAL FROM THE CORE AND THE CONTAINMENT

After certain incidents or accidents, avoidance of further degradation of the system requires:

a) Management of the condition of the *primary system:* the core must be kept covered, *and* the decay heat removed from the primary system. Keeping the core covered requires refilling of the RPV, classically via the ECCS. If the decay heat is not fully removed from the primary system via the break (case of small primary-system breaches), the primary system must either be forcefully depressurized (the classical solution in BWRs) or the Steam Generators (SG) must also be engaged in the decay heat removal process (PWRs).

b) Evacuation of the decay heat from the *containment.*

In the **"classical" new evolutionary plants,** improved decay heat removal capability and safety are achieved by *active* systems having:

- even better system design: greater redundancy, independence, separation, etc. (typically four separate trains according to the n+2 redundancy concept)
- other improved characteristics such as:
    - a larger water inventory in the RPV (or in the SG secondary side): this results in later core uncovery (or SG dryout) [GY3]
    - larger pressurizer volume [GY4]
    - elimination of primary system piping (to decrease the probability of a LOCA [GY5])
    - Direct Vessel Injection (DVI) of emergency coolant [GY6]
    - relocation of emergency cooling water sources inside the containment:[GY7] e.g., relocation of the Refuelling Water Storage Tank (RWST, that provides emergency coolant) inside the containment: the In-Containment RWST (IRWST) solution
    - flooding of the reactor cavity (to a level above the top of the fuel [GY8])
    - automatic depressurization of the primary system followed by low-pressure safety injection
    - use of fire water system for cooling, e.g., as containment spray, etc.

The ***passive* plants** incorporate novel technologies; these are *the focal point in this review.* Passive plant features will be discussed according to system function or according to the different accidental plant conditions and corresponding passive approaches for decay heat removal. The states or cases considered below are:

- Primary System intact but loss of the heat sink (SG or turbine)
- Primary System breached at high or medium pressure
- Primary System breached and depressurized
- removal of decay heat from the Containment.

3 REMOVAL OF THE DECAY HEAT FROM AN INTACT PRIMARY SYSTEM

If the Primary System is intact but the normal heat sink (secondary side of SG or turbine) has been lost, the decay heat must still be removed from either the RPV (BWR) or the SG (PWR). The following solutions, all based on the *passive connection of the primary system to a Heat Exchanger (HX)* (or condenser) have been proposed:

- *Heat exchangers connected to the primary system and immersed in a water pool inside the containment.* Examples are the AP-600 or the EP 1000, Figure 1, where a Passive Residual Heat Removal (PRHR) HX is immersed in the IRWST. A similar, but limited-capacity solution for PWRs is also considered in [6]. The SWR-1000 has Emergency Condensers permanently connected to the core and located in the Core Flooding Pool, Figure 2. Residual heat removal in these cases is a *two-step process*, since the pools eventually saturate and vaporize and the steam must be condensed by another system.
- An alternative is the *cooling of the secondary-side of the SGs* using a condenser. Such immersed emergency condenser solutions have been adopted for the KNGR [7], for CANDU systems (Figure 3), and by Siemens. The VVER-1000 and the AC-600 use natural-circulation air-cooled condensers located outside the containment. The air-cooled solutions provide an unlimited heat sink at the likely expense of a very large heat transfer area.
- A solution involving *Isolation Condensers connected to RPV* and immersed in external pools has been adopted for the ESBWR, Figure 4, and is also used for the Indian, heavy-water-moderated, light boiling-water-cooled AHWR.
- A similar solution has been adopted for the passive cooling of the moderator in CANDUs, Figure 3.

4 DECAY HEAT REJECTION IN CASE OF A LOCA

Several new designs have been improved by placing emergency cooling water sources *inside* the containment. For example, in the APWR the refuelling water storage tank has been moved inside the containment, as noted above. The AP-600 and the EPP have several water sources located inside the containment: Core Make-Up Tanks (CMT), high-pressure accumulators, lower-pressure Core Reflood Tanks (CRT) and also an In-Containment Refuelling Water Storage Tank (IRWST).

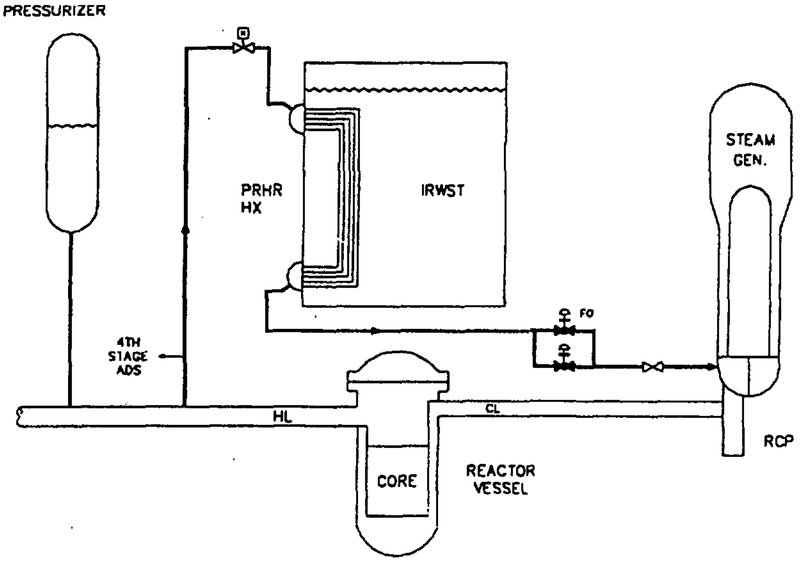

FIG. 1. The AP-600 Passive Residual Heat Removal (PRHR) system using a HX connected to the primary system and immersed in the IRWST.

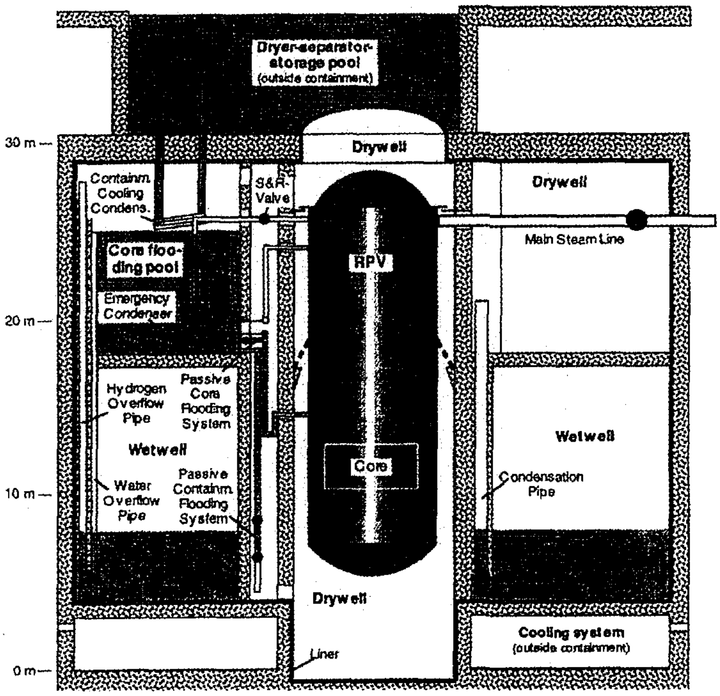

FIG. 2. The SWR-1000. Scramming of the reactor leads to collapse of the voids in and above the core region; this leads to automatic activation of the Emergency Condenser connected to the RPV without valves and immersed in the Core Flooding Pool. After depressurization, the Core Flooding Pool provides gravity cooling to the primary system. The Containment Cooling Condensers condense steam in the containment; light non-condensibles that may accumulate near the roof of the containment are vented to the Suppression Pool.

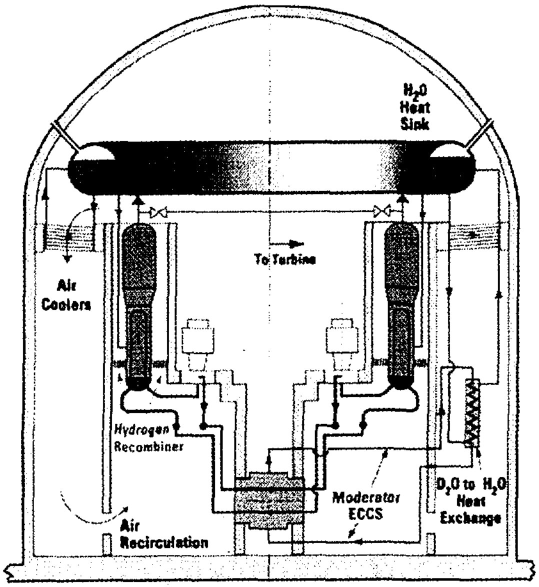

FIG. 3. Evolutionary CANDU 6 passive heat-rejection systems. The Steam Generator Heat Rejection system condenses steam from the SG in a condenser located inside the large toroidal Passive Emergency Water System (PEWS) tank. The Moderator Heat Rejection System has an intermediate HX also rejecting heat to the PEWS. The containment is cooled by air coolers fed by water from the PEWS that promote natural circulation inside the containment. The PEWS acts as the heat sink for all these systems.

To eliminate the need for long-term continuous pumped addition of coolant to the vessel, in several new designs there are provisions for flooding the reactor cavity to a level above the top of the fuel. Examples are the BWR 90 and most of the passive plants.

The primary system of LWRs is designed so that the core can be kept covered in spite of breaches in the primary system. Elimination of primary system piping contributes, however, also to the elimination of certain LOCA scenarios. Examples are the elimination of the recirculation piping in the ABWR by use of Reactor Internal Pumps. A somewhat similar trend can be observed in the AP-600 and the EPP where the primary system recirculation pumps were directly attached to the SGs.

Considering the continuum of breaches ranging from "intact primary system" to large-break LOCA, one realizes that decay heat removal from the primary system under high pressure can partly be performed by the systems for removal of the decay heat from an intact primary system discussed above. Thus, only additional solutions proposed for make up of the primary inventory and for medium and low pressure emergency injection are mentioned below.

The AP-600 uses a *Core Make-up Tank (CMT):* The pressure on top of this tank is equalized with primary system pressure, Figure 5. Thus, the CMT can provide make-up water to the core by gravity at any pressure. A CMT is also used in the AC-600.

For intermediate pressure levels in PWRs, injection of water from *accumulators* (at about 5,0 MPa (50 bar)) or core reflood tanks (at about 1,5 MPa (15 bar)) is used.

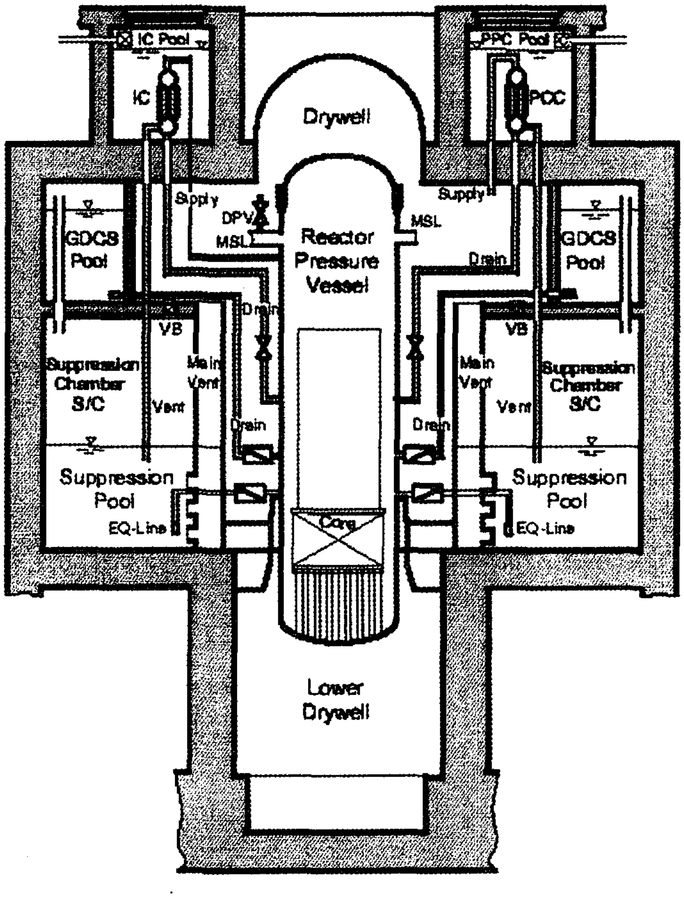

FIG. 4. The ESBWR passive core and containment cooling systems. The Isolation Condensers (IC) condense steam from the RPV. The Gravity Driven Cooling System (GDCS) pool floods the core after depressurization of the primary system. The Passive Containment Cooling System (PCCS) condenses containment steam and vents the non-condensibles to the Suppression Pool.

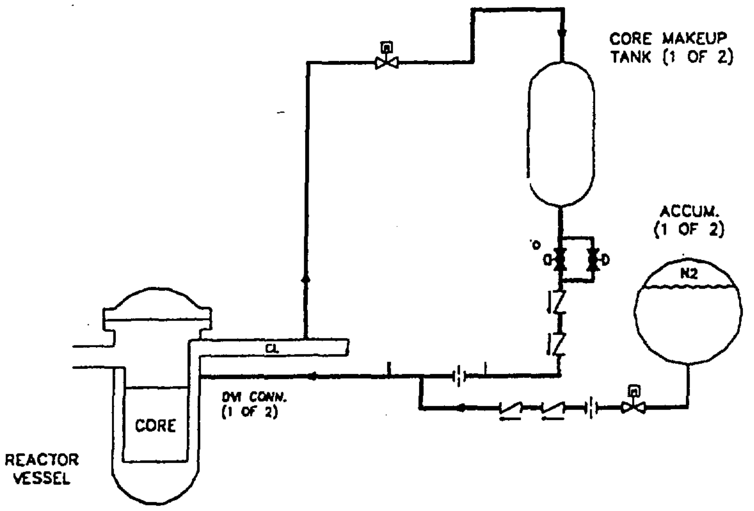

FIG. 5. The principle of the Core Makeup Tank, as used in the AP-600: the top of the tank is connected to the primary system by a pressure equalization line; thus, gravity injection of coolant into the RPV at any pressure is made possible.

To better cope with the pressurized LOCA scenarios, two approaches have generally being used:

a) intentional automatic depressurization of the primary system (similar to the Automatic Depressurization System, ADS, of the classical BWRs) and subsequent use of low-pressure safety injection (LPCI) systems, or

b) increase of the capacity of the high-pressure coolant injection (HPCI) system.

ADS systems have been incorporated in the AP-600 and the EPP. Other designers have opted, however, for higher-capacity LPCIs; for example, the ABWR has a reinforced HPCI relieving reliance on its ADS.

In the passive plants, one relies on *automatic depressurization* of the primary system and actuation of low-pressure gravity-driven core make-up systems. This solution is retained for the ESBWR (Figure 4) and the SWR-1000 (Figure 2). Both passive BWRs provide for gravity-driven, low-pressure core flooding. The AP-600, after depressurization, uses the IRWST inventory to reflood the RPV by gravity.

5 REMOVAL OF THE DECAY HEAT FROM THE 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 other containment cooling systems take over the decay heat removal function. Thus, the needed capacity of containment cooling systems is reduced.

Novel solutions that have been proposed for containment cooling include:

- Cooling of the containment building in the AP 600 from the outside by natural draft enhanced by a water film on the wall, Figure 6. Such solutions are possible with metallic containment walls only.

- An Italian alternative solution [8] for the EP 1000 proposes a finned condenser installed near the roof, inside the containment building, an intermediate sealed thermosiphon loop penetrating through the double concrete containment walls, and an external hybrid (initially immersed, water-cooled and later air-cooled) HX, Figure 7. Cooling of the containment atmosphere by *containment condensers* installed near the roof is also proposed for both the SWR-1000 and for CANDU systems: the SWR-1000 has a containment-cooling condenser with its secondary system connected to an external pool, Figure 2. The CANDU 6 containment coolers have their secondary sides connected to the PEWS tank, Figure 3.

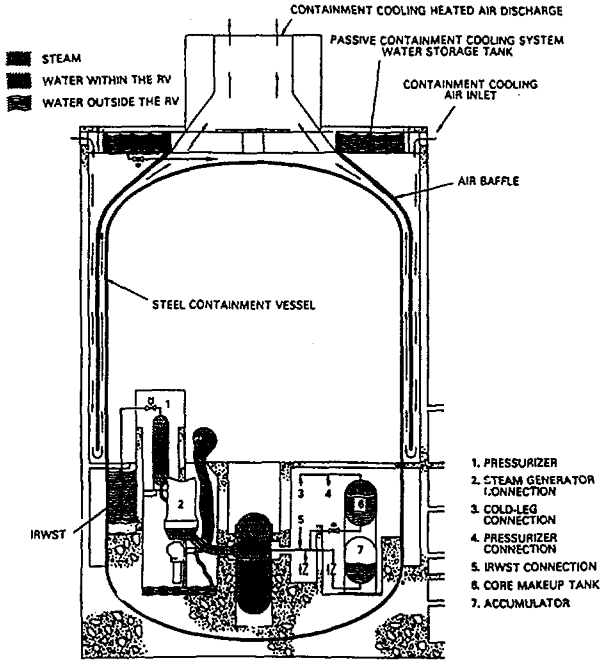

FIG. 6. Passive containment cooling for the AP-600. Air circulates by natural draft in the space created between the metallic containment wall and the outside concrete wall. The water storage tank at the top of the building wets the containment surface with a water film, needed to enhance the process after shutdown, when the decay heat is still high.

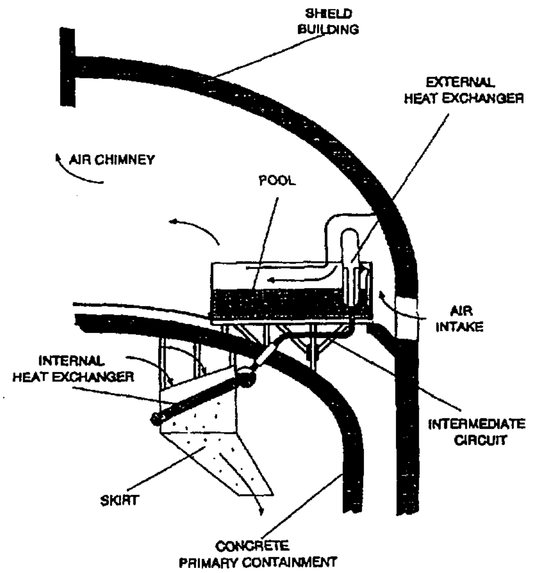

FIG. 7. Passive containment cooling solution proposed as an alternative to the AP-600 external-wall cooling concept.

- Finally, the ESBWR proposes a novel Passive Containment Cooling System (PCCS): Condensation of containment steam takes place in a *condenser immersed in an external pool.* The condenser tubes are always connected to the drywell. The noncondensibles are discharged to the Suppression Pool by an ingenious venting system, Figure 4.

6 CONCLUSIONS

A large number of evolutionary LWRs and HWRs with improved primary-system and containment decay heat removal concepts have been proposed. These have been categorized and presented summarily in this paper, according to their intended function. Although there is a diversity of designs stemming from all countries developing evolutionary water reactors, there is a relatively small number of optimal technical solutions that have been retained. Several novel passive cooling solutions have been proposed and constitute the main emphasis in this review.

Most systems rely on boiling and condensation to obtain sufficiently high heat transfer rates under natural circulation conditions. With the primary system intact, decay heat is removed by circulating the primary coolant in heat exchangers or condensers, typically immersed in pools. Novel solutions for decay heat removal from the core rely on depressurization of the primary system followed by flooding of the core by gravity or with high-pressure gravity-driven core make-up tanks connected at their top to the primary system. Novel solutions for decay heat removal from the containment are based either on cooling of the (metallic) containment wall from the outside, or on use of condensers; these can be located either inside the containment near the roof (the containment steam condensing on the outside of the tubes) or outside the containment, immersed in pools (the containment steam condenses inside the tubes).

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