

USE OF PASSIVE COOLING SYSTEMS IN GENERATION IV NUCLEAR REACTORS FOR CORE DECAY HEAT REMOVAL AND CONTAINMENT COOLING

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Abstract

The Pebble Bed Modular Reactor (PBMR) concept evolved from a German high temperature helium-cooled reactor design with ceramic spherical fuel pebbles. The removal of parasitic heat between the reactor core and concrete citadel is facilitated through the Reactor Cavity Cooling System (RCCS). The RCCS primary function is to passively maintain the cavity temperature within a required range. This is in order to provide protection to the concrete structures surrounding the reactor and also, during loss of coolant accident operating conditions, to transport parasitic heat from the reactor to the environment.

Several Generation IV reactor designs incorporate passive safety systems. The main objective of this study is to familiarise the reader with specific "innovative" nuclear reactor designs and discuss the different passive safety systems employed in these designs for core decay heat removal and containment cooling systems. A table is given comparing the type, thermal efficiency, fuel, coolant and passive safety systems employed by each reactor to those of the PBMR.

Keywords: Pebble Bed Modular Reactor, PBMR, passive safety, core decay heat removal, parasitic heat removal, containment cooling, accumulator, core make-up tank, gravity drain tank, heat exchanger, isolation condenser, natural circulation, containment spray

1. Introduction

The International Atomic Energy Agency (IAEA) defines a passive system as "*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*". This has allowed for passive safety systems to be divided into three broad categories.

Category A is characterised by no "intelligence" input. In other words: no signal inputs, parametric changes or operator decision inputs are necessary to initiate action. In addition, a Category A passive safety system cannot incorporate external power sources or forces, moving mechanical parts or moving working fluids. Category B differs as it allows for moving working fluids. The motion

of the fluid can only be caused by a change in thermal-hydraulic conditions due to activation of the safety system (as with natural circulation). Category C passive safety systems may contain moving mechanical parts, regardless of whether a working fluid is also present. This category includes all safety systems that require check or relief valves, trip mechanisms, rupture disks or any other mechanical parts required to activate the safety system.

Passive safety systems and components are mainly incorporated into nuclear reactors to improve reliability and simplify safety systems. The IAEA note that passive safety systems should be used wherever possible keeping in mind that passivity should: reduce the number of components (reducing safety actions); eliminate short-term operator input during an accident; minimise dependence on external power sources, moving mechanical parts and control systems and finally reduce lifetime-associated costs of the reactor.

The Generation III+ and Generation IV nuclear reactor concepts currently under development across the globe all incorporate passive safety systems, whether it be as a primary coolant, decay heat removal, containment cooling, loss of coolant accident or emergency core cooling system. Extensive literature is available on each of the reactors mentioned in this study therefore their design and operating characteristics will not be discussed in detail.

Note that since the AP1000 is (to date) the only reactor design that has been approved for production, the system characteristics of the reactors are liable to change.

2. Reactors

2.1 AP 1000

The Westinghouse AP1000 is a two-loop pressurized light water reactor (PWR) designed to yield 1154MWe. The AP1000 and its predecessor AP600 were the first nuclear reactor designs using passive safety technology licensed anywhere in the world. The AP1000 is the first Generation III+ reactor to receive Design Certification from the United States Nuclear Regulatory Commission (USNRC)

The reactor core is designed for both Uranium Oxide (UO₂) and Mixed Oxide (MOX) fuel assemblies and utilizes 69 control rods in order to control reactivity. The basic functioning of the AP1000 (and all PWR in general) is as follows: Nuclear fission in the reactor fuel generates heat which is transferred to the primary coolant through

forced convection. The hot primary fluid is then passed through a heat exchanger inside the steam generator and heat is transferred to the secondary coolant fluid by means of forced convection, conduction through the heat exchanger tube walls and boiling on the outer surfaces of the tubes. It is important to note that no mixture of the primary and secondary coolant fluids occurs which reduces risk of radioactive particle transmittance. The pressurized steam generated in the secondary coolant passes through a steam turbine which generates electricity. The secondary coolant is then cooled and condensed prior to being pumped back into the steam generator. The cooled primary coolant is then pumped back into the reactor vessel, where the process is repeated.

2.2 AHWR

The Advanced Heavy Water Reactor (AHWR) is a 300MWe (500m³/day of desalinated water) boiling light water cooled, heavy water moderated, vertical pressure tube type reactor currently being designed in Bhabha Atomic Research Centre (BARC) in India.

The reactor core is fuelled with clusters consisting of concentric rings of (Th-²³³U)O₂ pins and (Th-Pu)O₂ pins. The Uranium and Plutonium included in these pins enrich the Thorium, which in its natural state does not contain any fissile isotope, allowing for the onset of fission.. The core is submerged in borated heavy water which acts as both moderator and reflector and aids the 12 control rods in controlling reactor reactivity.

The basic functioning of the AHWR is as follows: Heat from nuclear fission in the fuel assemblies is transferred to the primary coolant fluid through natural convection. Natural circulation drives the hot coolant to the steam drums, where steam is separated and fed to the turbine. Excess steam is utilized by the desalination plant, fed through a condenser and then ultimately pumped back to the steam tank and then gravity fed into the core.

2.3 SMART

The Small Modular Advanced Reactor Technology (SMART) is a small, modular PWR which is continuously studied by the Korea Atomic Energy Research Institute (KAERI) in Daejeon, South Korea for the dual purpose applications of seawater desalination (40,000m³/day) and small scale power generation (90 MWe). The SMART uses water as the moderator as well as primary coolant, has a rated thermal power of 330 MWt and a construction period of less than 36 months.

The core of the SMART is designed to be fuelled with either low-enrichment Uranium or a Uranium and Thorium mixture. With advancement in material technology, the core can run for a maximum of 15 years before refuelling is required. Reactivity in the reactor is controlled by means of a control drum surrounding the core made of either Cadmium or a Boron Carbide and a Beryllium reflector.

The basic functioning of the SMART is as detailed in section 2.1.

2.4 APWR+

The Advanced Pressurized Water Reactor (APWR+) is a four-loop 1500 MWe PWR currently under development in a joint venture between five Japanese utility companies (Hokkaido, Kansai, Shikoku, Kyushu, and Japan Atomic Power), Mitsubishi Heavy Industries Ltd and Westinghouse Electric Corporation.

The core of the APWR+ consists of 257 fuel assemblies designed to contain 121 tonnes of Uranium Oxide or MOX fuel. Reactivity is controlled through 69 control rod clusters inserted axially into the core and a unique radial reflector design.

The basic functioning of the APWR+ is as detailed in section 2.1.

2.5 KERENA

KERENA is a 1250 MWe Boiling Water Reactor (BWR) design (previously known as SWR-1000) developed by the French nuclear power conglomerate AREVA. The design is based on the Gundremmingen nuclear power plant but utilizes extensive German input yielding a reactor design with a 60 year operating life, that only needs refuelling every second year and can be built in less than 48 months.

The KERENA core consists of 664 fuel assemblies containing 136.3 Mg of 3.54% enriched ²³⁵U. Reactivity is controlled by means of 157 fine-motion control rod drives as successfully used in German BWR designs since 1968. The basic design of the reactor is identical to established BWR designs barring dimensional changes and the incorporation of passive safety systems.

The basic function of the KERENA reactor (and all BWR in general) is as follows:

Heat from nuclear fission in the fuel assemblies is transferred to the primary coolant fluid through natural convection. Steam is formed in the reactor core and fed to steam turbines through the main steam lines at the top of the reactor through natural circulation. The steam and condensate mixture exiting the turbine is fed through a condenser and ultimately pumped back into the reactor core through feedwater lines and the cycle is repeated.

2.6 ESBWR

The Economic Simplified Boiling Water Reactor (ESBWR) is 1560 MWe modular reactor developed by General Electric Hitachi, based on their previous successes with advanced BWR's. The preliminary design was approved by the NRC and is currently awaiting Referred Combined Construction and Operating License (COL) approval.

The ESBWR is a light water moderated and cooled reactor whose core consists of 1132 fuel assemblies containing 4.2% enriched UO_2 and supports a fuel cycle of 1-2 years (General Electric Hitachi Nuclear Energy, 2008). 269 control rod blades utilizing fine motion control rod drives controls the reactivity within the core and reportedly has the best-in-class core damage probability of 3×10^{-8} core damage events per reactor-year.

The basic functioning of the ESBWR is as detailed in Section 2.5.

2.7 PBMR

The Pebble Bed Modular Reactor (PBMR) is a 110 MWe gas cooled high temperature reactor currently under development by Pebble Bed Modular Reactor (Pty) Limited in conjunction with several South African universities. What differentiates this design is its intrinsic safety: the reactivity diminishes as the fuel temperature rises. This has been demonstrated with the Arbeitsgemeinschaft Versuchsreaktor (AVR) built in Germany in 1960.

The reactor employs enriched UO_2 particles coated in silicon carbide and pyrolytic carbon (TRISO particles). Approximately 15000 of these particles are encased in a graphite sphere which forms the fuel pebble of 60 cm in diameter. When fully loaded, the reactor core will contain approximately 360 000 of these pebbles.

The basic functioning of the PBMR is as follows: Helium gas (primary coolant) is fed into the top of the reactor core through a blower. Heat from nuclear fission in the fuel pebbles is transferred to the primary coolant fluid through natural convection. The hot primary fluid is then used to heat a secondary coolant fluid (light water) through a steam generator heat exchanger to ensure no radioactive particle transmittance. The pressurized steam generated in the secondary coolant passes through a steam turbine which generates electricity. This secondary coolant loop can also be coupled to a process plant to generate process heat as well as for cogeneration. The secondary coolant is then cooled and condensed prior to being pumped back into the steam generator. The primary coolant is circulated through a recuperator, pre-intercooler, intercooler and compressors before re-entering the reactor core.

2.8 IHTR-H

The Indian High Temperature Reactor (IHTR-H) is an 80000 Nm^3/h hydrogen producing reactor concept currently being developed by the Bhabha Atomic Research Centre (BARC) in India, capable of producing process heat around 1273 K. The design is based on the Compact HTR, which is essentially a 100kWe technology demonstration module using the same base fuel particles as the PBMR yielding a negative reactivity.

The IHTR-H core is made up of 19 prismatic beryllium oxide (BeO) moderator blocks containing TRISO particles

imbedded in a graphite fuel tube. The moderator blocks are surrounded by 18 BeO reflectors which in turn are surrounded by graphite reflectors. The primary coolant is a lead-bismuth (Pb-Bi) eutectic alloy and 7 tungsten shut-off rods are incorporated to shut down the reactor.

The basic functioning of the IHTR-H is as follows: The cold primary coolant is gravity fed into the reactor core where heat from nuclear fission in the fuel assemblies is transferred to the fluid through natural convection. A heated fluid then rises through the top of the core and passes through a turbine which generates electricity. The fluid is then fed through a recuperator, pre-cooler, compressor, inter-cooler, another compressor and then through the recuperator before re-entering the core and establishing natural circulation.

2.9 MASLWR

The Multi-Application Small Light Water Reactor (MASLWR) is a modular 35 – 50 MWe PWR developed by the Idaho National Engineering and Environmental Laboratory (INEEL), Nexant Inc. and the Oregon State University (OSU). The reactor was designed as a low cost, early implementation electricity generation unit with the flexibility of process heat applications as well.

The reactor core is designed for 24 fuel assemblies containing 8% enriched UO_2 fuel pellets. At current developmental stage, it is assumed that core and fuel design is similar to that of established PWRs. The basic functioning of the MASLWR is as follows:

The primary coolant enters the reactor core where heat from nuclear fission in the fuel assemblies is transferred to the fluid through natural convection causing the fluid to rise. The hot primary coolant transfers heat through convection to the helical coil steam generator surrounding the core annulus causing the secondary coolant fluid to boil. The cooled primary fluid returns to the bottom of the reactor pressure vessel establishing natural circulation. The secondary coolant leaves the pressure vessel as superheated steam and is fed to the turbine which generates electricity. The cooled fluid is then fed through a condenser and then pumped back into the steam generator, completing the circuit.

3 Passive Safety Systems

This section describes passive safety systems employed in several generation IV reactor designs for core decay heat removal and reactor containment cooling only as these are the major functions of the RCCS of the PBMR.

3.1 Core Decay Heat Removal Systems

3.1.1. Accumulators

Pre-pressurized core flooding tanks, or accumulators, are designed to cool the core when system pressure drops

rapidly such as loss of coolant accident (LOCA) conditions. An accumulator as a rule consists of a large tank 75% of which is filled with cold borated water, the rest with pressurized nitrogen to ensure tank pressure equals normal operating system pressure. As can be seen from Figure 1, the accumulator is isolated from the reactor core through a series of check valves. During LOCA conditions, system pressure will drop below accumulator pressure, opening the valves and flooding the core with the borated water. In doing so accumulators aid core decay heat removal during plant shut down as well as injecting boron which acts as a neutron poison, ensuring cessation of the fission reaction. Accumulators are a category C passive safety system due to their reliance on valves for actuation.

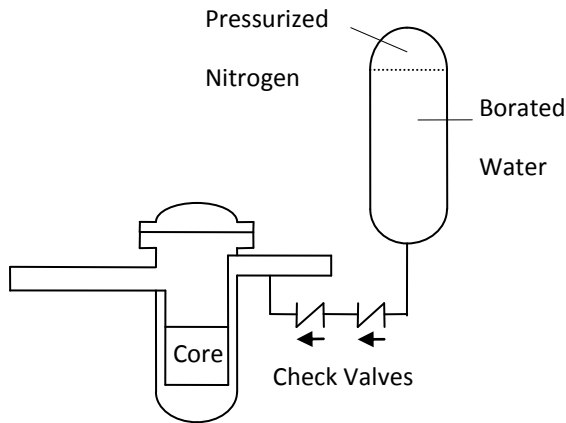


Figure 1: Schematic Layout of Accumulator (IAEA, 2006)

3.1.2 Core Make-up Tanks

Elevated tank natural circulation loops, or core make-up tanks are designed to supplement the primary coolant system during accident conditions when system pressure remains relatively high (like small breaks in the primary coolant system, steam break accidents and leaks of primary coolant through to secondary coolant). As can be seen from Figure 2, the core make-up tank is isolated from the reactor core through a combination of a normally closed valve and a series of check valves. A normally open valve before the tank inlet ensures the tank contents are at system pressure. During accident conditions the valves open, allowing the cold borated water to be gravity fed into the core and forcing the hot primary coolant into the top of the tank establishing natural circulation. Core make-up tanks are another category C passive safety system due to their dependence on valves for activation.

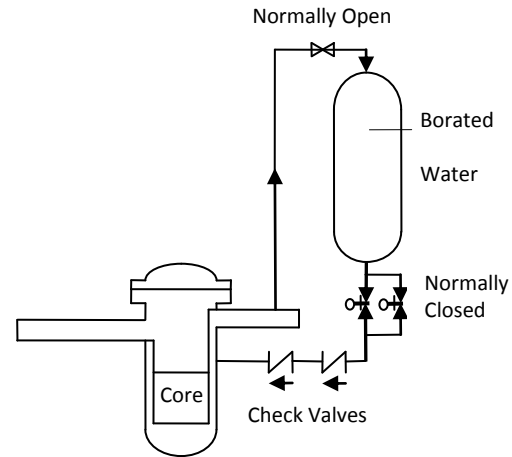


Figure 2: Schematic Layout of Core Make-up Tank (IAEA, 2006)

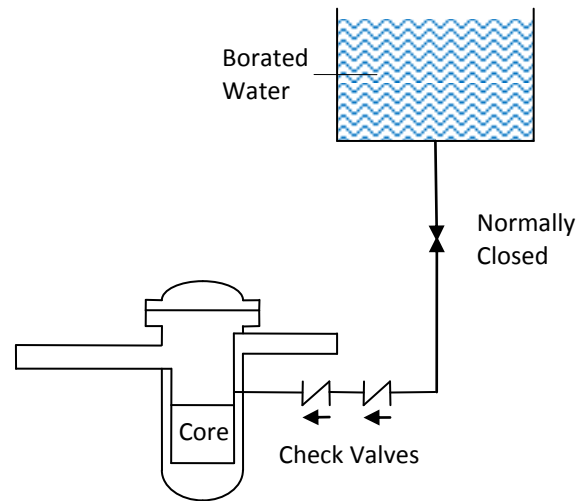


Figure 3: Schematic Layout of Gravity Drain Tank (IAEA, 2006)

3.1.3 Gravity Drain Tanks

Gravity drain tanks are designed to flood the core during LOCA or forced shutdown accident conditions in low pressure reactors. This ensures that fuel integrity is maintained and that core decay heat is removed to maintain reactor vessel structural integrity for a specified period of time. As can be seen in Figure 3, the tank is isolated from the reactor core through a normally closed valve or rupture disk and a series of check valves. During accident conditions, the valves are opened and the cold borated water is gravity driven into the core. Gravity drain tanks are category C passive safety systems due to their reliance on mechanical components for activation.

3.1.4 Passive Residual Heat Removal Heat Exchangers

The passive residual heat removal heat exchanger is a single phase natural circulation loop that removes residual heat from the reactor core. As can be seen from Figure 4, a C-tube type heat exchanger is immersed in the gravity drain tank (as detailed in section 3.1.3). During LOCA conditions, the normally closed isolation valve is opened; hot water rises through the line attached to the hot leg of the reactor and enters the heat exchanger at full system pressure and temperature. Heat is removed through boiling on the outside surface of the heat exchanger tubes. The cold coolant is gravity fed to the primary loop through the outline line attached to the steam generator and natural circulation is established. Passive residual heat exchangers are a category C passive safety system due to their reliance on valves for activation.

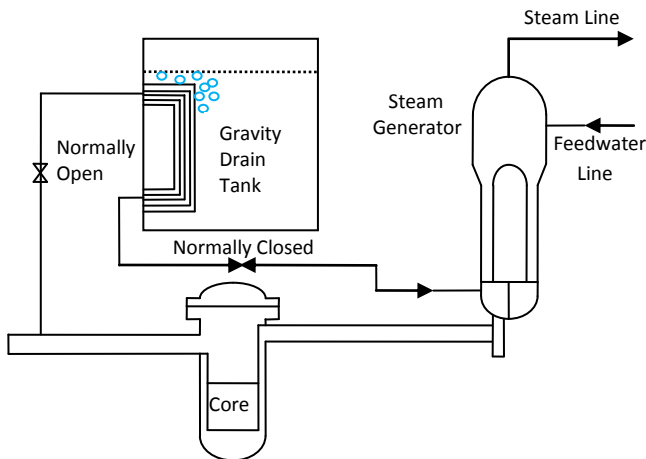


Figure 4: Schematic Layout of Passive Residual Heat Exchanger (IAEA, 2006)

3.1.5 Passively Cooled Core Isolation Condensers

The passively cooled core isolation condenser serves the same purpose as the passive residual heat exchanger (as detailed in section 3.1.4) and is a two phase natural circulation loop. As can be seen from Figure 5, an isolation condenser is immersed in the gravity drain tank (as detailed in section 3.1.3). The condenser is isolated from the core through normally closed isolation valves. During LOCA conditions, the isolation valves are opened and steam from the core in BWRs or the steam generator in PWRs enters the condenser at full system pressure and temperature. Heat is removed through boiling on the outside surface of the heat exchanger tubes and the steam is condensed. The cold coolant is gravity fed to the core or steam generator and natural circulation is established. Passively cooled core isolation condensers are another category C passive safety system due to their reliance on mechanical valves for activation.

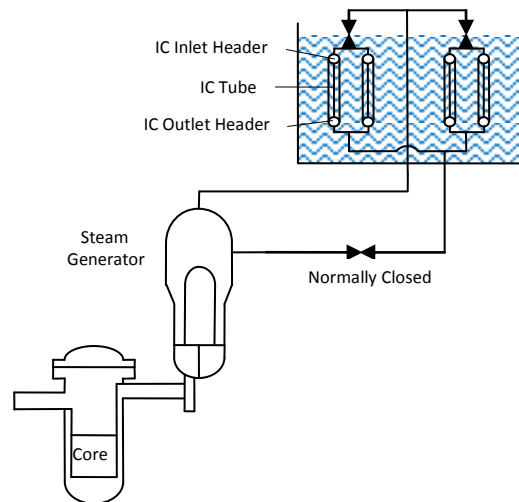


Figure 5: Schematic Layout of a Passively Cooled Core Isolation Condenser (IAEA, 2006)

3.1.6 Sump Natural Circulation

In the event of severe LOCA conditions or ex-vessel severe accidents, the operator can act to flood the reactor cavity with the gravity drain tank. Once the reactor vessel is submerged, the sump valves are opened to establish a natural circulation path. Decay heat is removed through natural convection resulting in boiling and the generated steam is vented into the containment. Cooler water is then drawn in through the sump screens completing the loop. Sump natural circulation is designed to vessel structural integrity. Figure 6 shows a schematic layout of sump natural circulation which is a category C passive safety system due to its reliance on valves for activation.

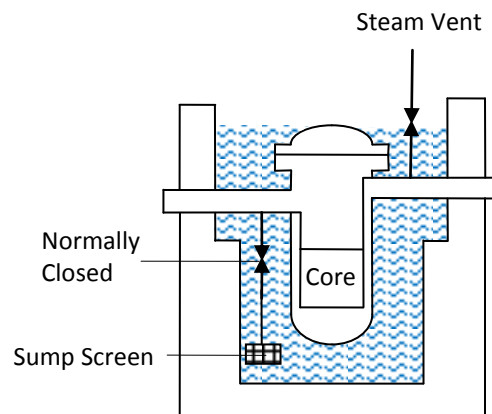


Figure 6: Schematic Layout of Sump Natural Circulation (IAEA, 2006)

3.2 Containment Cooling Systems

3.2.1 Containment Passive Heat Removal Systems

The passive containment cooling systems are designed to protect the concrete structure of the reactor located in the high-temperature zone. As can be seen from Figure 7, the system consists of an elevated storage pool (usually the gravity drain tank) which acts as a heat sink. Connecting the pool to the containment is a natural circulation loop ending in containment cooling condensers situated between the concrete structure and the reactor pressure vessel. If steam should be released into the drywell atmosphere, the resulting heat is removed through condensation of the steam on the condenser pipes, heating the coolant and establishing natural circulation. Though they do not rely on mechanical parts for actuation, containment passive heat removal systems require a moving working fluid thus they are a category B passive safety system.

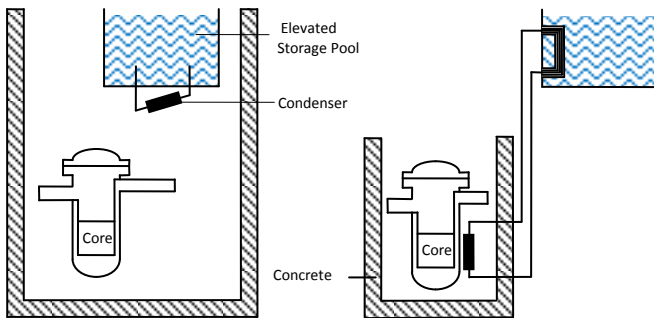


Figure 7: Schematic Layout of Containment Passive Heat Removal Systems (IAEA, 2006)

3.2.2 Passive Containment Spray Systems

Passive containment spray systems require the reactor and all of the passive safety injection systems to be housed in a large steel vessel which in turn resides inside a concrete structure. This concrete structure has ducts that allows cool outside air to come into contact with the outside surface of the containment vessel. When steam is vented into containment vessel, it rises until it comes into contact with the containment dome where it is cooled by liquid spray and condensed into liquid. Through conduction and natural convection, the energy of the steam is transferred to the air on the outside of containment. As the air is heated, it rises and creates 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. Figure 8 shows a schematic layout of a passive containment spray system. Due to its reliance on spray mechanisms, this is a category C passive safety system.

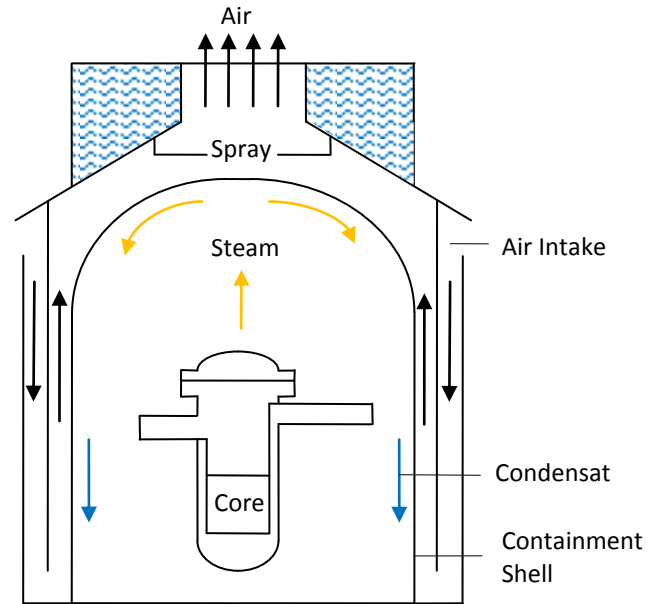


Figure 8: Schematic Layout of Passive Containment Spray System (IAEA, 2006)

4. Comparison

Table 1 shows a summary comparison between the current generation IV reactor designs discussed in section 2. The main focuses are on type of nuclear power reactor, rated or expected thermal power and efficiency, type of fuel used, coolant used and the passive safety systems (as discussed in section 3).

The table clearly shows nuclear reactors dependant on conventional fuel pins and assemblies, though capable of much higher thermal power output, are less efficient and require the implementation of more passive safety systems than PBMR, IHTR-H and MASLWR reactors. The TRISO fuel particles clearly enhance the safety of the reactors whilst the differences in thermal power output are due to the modular design of the smaller reactors.

When looking at the passive safety systems incorporated in the designs, it is important to note that all the reactors implement a passive containment heat removal system. It is also interesting to note that the reactors designs using conventional fuel all make use of gravity drain tanks as well as isolation condensers to maintain core and fuel integrity during LOCA conditions. The nature of the TRISO particle allows very high temperature operation without loss in fuel integrity and the passive containment heat removal system aids in the removal of core decay heat from the cavity between the reactor pressure vessel and the reactor containment. This eliminates the need for the gravity drain tanks and associated passive safety systems.

5. Conclusions

Having identified a number of so-called innovative reactors and the various core decay heat removal and containment cooling systems it is concluded that natural circulation not only plays an important role in present-day reactor systems but is certain to play an ever increasing role in the quest for inherently safe, or often called “walk away and forget”, designed systems.

Table 1: Reactor Technology Comparison

	Type	Thermal Power	Efficiency	Fuel	Coolant	Passive Safety Systems
AP1000	PWR	3400 MW	35.1 %	< 4.95% UO ₂	Light water	Accumulators Core Make-Up Tanks Gravity Drain Tanks Passive Residual Heat Exchangers Sump Natural Circulation Passive Containment Spray System
AHWR	HWR	920 MW	Unknown	Th-Pu)O ₂ :20 pins (Th-U ²³³)O ₂ : 32 pins	Light water	Accumulators Gravity Drain Tanks Passively Cooled Core Isolation Condensers Containment Passive Heat Removal System
SMART	BWR	330 MW	± 30%	U ²³⁵ or a mixture (35% UO ₂ – 65% ThO ₂)	Light water	Accumulators Gravity Drain Tanks Passively Cooled Core Isolation Condensers Sump Natural Circulation Containment Passive Heat Removal System
APWR+	PWR	4451 MW	39%	UO ₂	Light water	Accumulators Gravity Drain Tanks Passive Containment Spray System
KERENA	BWR	3370 MW	37.2 %	3.54% U ²³⁵	Light water	Gravity Drain Tanks Passively Cooled Core Isolation Condensers Sump Natural Circulation Containment Passive Heat Removal System
ESBWR	BWR	4500 MW	34.7 %	4.2% UO ₂	Light water	Gravity Drain Tanks Passively Cooled Core Isolation Condensers Containment Passive Heat Removal System
PBMR	HTR	400 MW	41%	U ²³⁵ or a mixture (35% UO ₂ – 65% ThO ₂) TRISO coated particles in graphite spheres	Helium	Containment Passive Heat Removal System
IHTR-H	HTR	600 MW	40-57%	²³³ UO ₂ and ThO ₂ based TRISO coated particles in graphite spheres	Pb Salt	Containment Passive Heat Removal System
MASLWR	PWR	150 MW	Unknown	8% UO ₂ pellets	Light water	Sump Natural Circulation Containment Passive Heat Removal System

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