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Comparison of Advanced Mid-Sized Reactors Regarding Passive Features, Core Damage Frequencies and Core Melt Retention Features

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ABSTRACT

New Light Water Reactors, whose regular safety systems are complemented by passive safety systems, are ready for the market. The special aspect of passive safety features is their actuation and functioning independent of the operator. They add significantly to reduce the core damage frequency (CDF) since the operator continues to play its independent role in actuating the regular safety devices based on modern instrumentation and control (I&C). The latter also has passive features regarding the prevention of accidents. Two reactors with significant passive features that are presently offered on the market are the AP1000 PWR and the SWR 1000 BWR. Their passive features are compared and also their core damage frequencies (CDF). The latter are also compared with those of a VVER-1000. A further discussion about the two passive plants concerns their mitigating features for severe accidents. Regarding core-melt retention both rely on in-vessel cooling of the melt. The new VVER-1000 reactor, on the other hand features a validated ex-vessel concept.

1 INTRODUCTION

The larger-sized European Pressurized Reactor (1600MWe) is the first new accepted reactor in Western Europe. The large experience with similar PWRs, redundancy and reliability of safety systems, a modern I&C, an ex-vessel core-catcher and its design against commercial airline crashes are its main selling points (Esteve, 2005). However, mid-size reactor designs such as SWR 1000 (1290-1330 MWe) or AP1000 (1090 MWe) and also the new VVER-1000 with ex-vessel core catcher will have lower initial cost due to their smaller size and the highly passive new plants should additionally profit from their low Core Damage Frequencies (CDFs) and the lower cost of these simplified plants. The latter is no contradiction since e.g. for the SWR 1000 the simplifications in system and components reduce the capital cost by 30% compared to existing BWRs of the same power (Brettschuh, 2001).

The Westinghouse AP-1000 is based on 35 years of experience with PWRs and the earlier AP-600 design that was already developed in the 80's as a safer, simpler and more economical alternative to LWRs at the time after the Three-Mile Island accident. AP600 was already submitted for licensing in 1992 and in 1999 the USNRC granted Design Certification to the AP600 (Cummins, 2005). The AP1000 uses the same design and safety approaches. In many regards it is an up-rated AP600 aimed at producing electrical energy at rates that are competitive in the US market. The AP1000 received Final Design Approval from the USNRC in September 2004 and it is expected to receive Design Certification by the USNRC later in 2005. This means that the AP1000 and its predecessor the AP600 are the only fully licensed highly passive plants today. (Cummins, ICAPP'05)

The Framatome-ANP SWR 1000 development was started in 1992 and is based on earlier German Boiling Water reactors such the Lingen Plant (1968) that featured the worlds first fine-motion control rod drive, the Brunsbűttel reactor that was the first BWR in the world with internal water recirculation pumps and the twin-unit plant Gundremmingen B and C starting commercial operation 20 years ago featuring additionally a three-train, full-range residual heat removal system and a pre-stressed concrete containment with a steel liner. These innovations set examples for BWR development worldwide. The new SWR 1000 design fulfills international nuclear regulatory requirements and has been offered to TVO for the fifth nuclear unit in Finland. (Brettschuh, 2005)

2 THE AP1000 PASSIVE SAFETY FEATURES

2.1 Emergency Coolant System

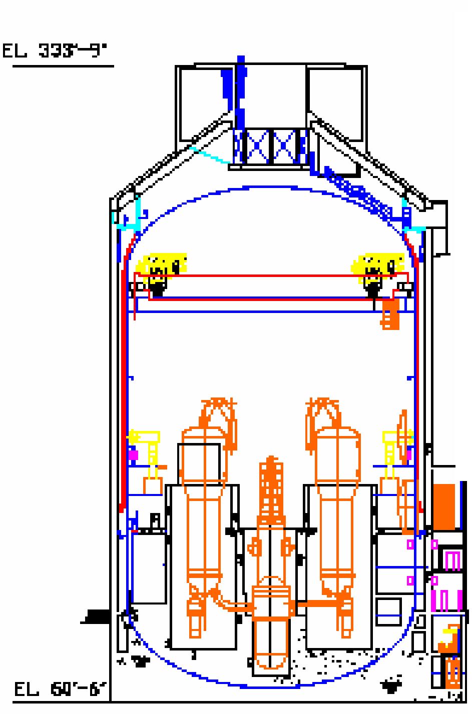
The passive emergency core cooling system shown in Fig 1-3 protects the plant against reactor coolant system leaks of various sizes and locations. It provides core residual heat removal, safety injection and depressurization. Safety analyses (using NRC-approved codes) show the effectiveness of the passive core cooling system following various reactor coolant system break events. Even for a double-ended rupture of a main coolant pipe, this emergency coolant system cools the reactor with ample margin to a peak cladding temperature limit (less than 870°C are reached), (Cummins, ICAPP'05).

2.2 Passive Safety Injection and Depressurization

The passive emergency cooling system uses three sources of water to maintain core cooling through safety injection - see Fig.3. These are the two core makeup tanks (CMT – 70 m^3 each), the accumulators, and the in-containment water storage tank (IRWST – 2334 m^3). Long-term injection is provided by gravity from the IRWST. The reactor coolant system must have depressurized below one bar, before the IRWST starts providing cooling water. The automatic depressurization system uses four stages to permit a slow, controlled pressure reduction (Schulz, 2005; Cummins, 2005).

2.3 Passive Residual Heat Removal

The passive residual heat removal system contains one passive residual heat removal heat exchanger (PRHRHX) that is connected with the inlet and outlet of one reactor coolant loop. It satisfies the safety criteria for loss-of-feedwater, feedwater line breaks, and steam line breaks. The IRWST provides the heat sink. After more than an hour boiling starts and the steam passes to the containment. It condenses on the inside of the steel containment and, after collection, drains back into the IRWST. This passive residual heat removal system can of course also be important in a Station Blackout accident. The passive containment cooling (see below) is equally important for this type of accident if the active heat removal systems don't work.



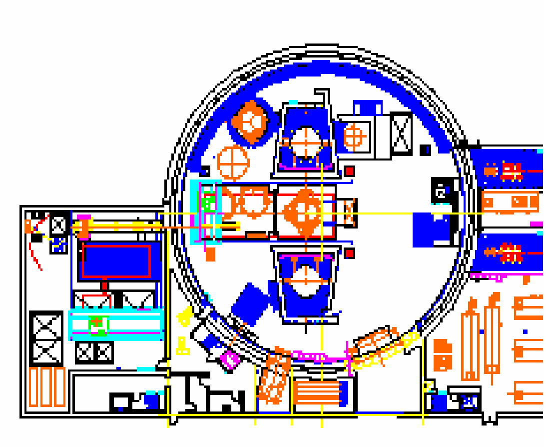


Fig. 1 AP1000 Plan showing semi-circular In–Containment Refueling Water Storage Tank (IRWST)

Fig. 2 AP1000 Axial Section (RCS) and Passive Cooling System (PCRS) - Schematic

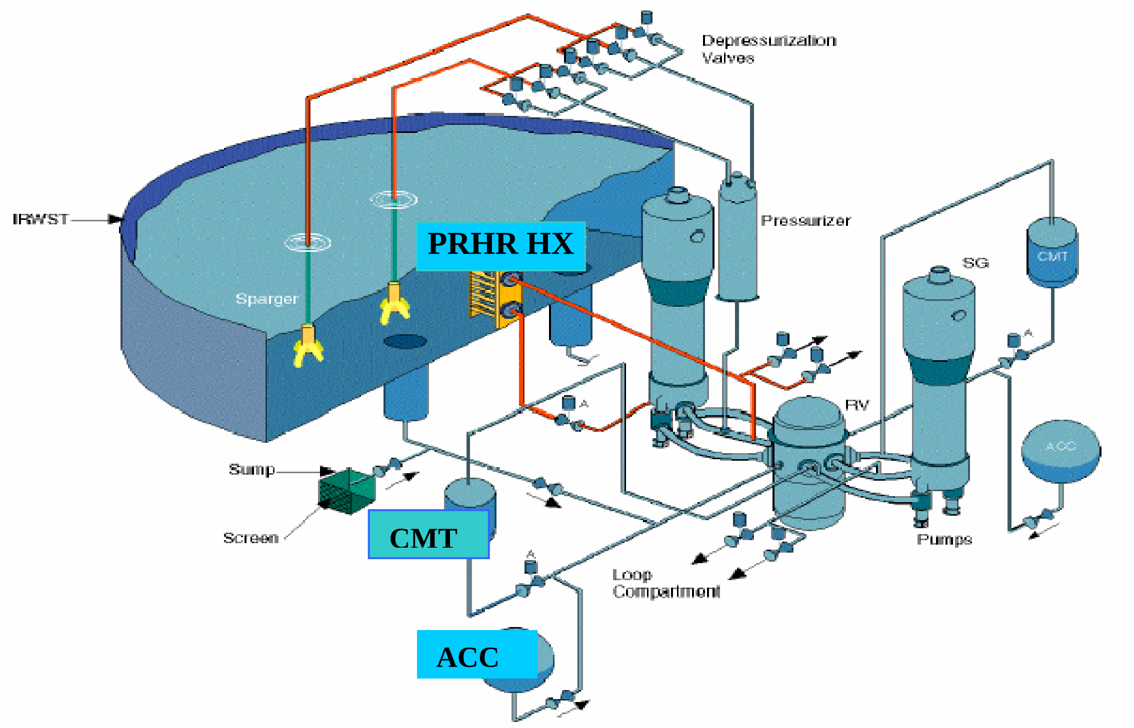


Fig. 3 AP1000 Reactor Cooling System

2.4 Passive Containment Cooling System

A concrete shield building surrounds the steel containment and provides protection from external hazard such as missiles (Schulz, 2005). During an accident the air-cooling through the gap is supplemented by water evaporation. The water drains by gravity from a tank located at the top of the containment shield building The accident sequences that are covered by the passive core cooling system include Loss-of-Flow accidents, feed line break accidents, steam generator tube ruptures, small and large-break LOCA accidents and anticipated transients without scram (ATWS).

3 PASSIVE SAFETY FEATURES OF THE SWR-1000

3.1 Safety Relief Valve System

The safety relief valves provide two safety functions: “pressure relief” in case of overpressure, e.g. after a turbine trip and “depressurization” in case of a LOCA. The depressurization is also relevant for severe accident mitigation to prevent a high-pressure melt ejection. Four of the relief valves are designed according to the pressurization principle. For diversity reasons the four other ones are based on the de-pressurization principle. The relief lines feed into steam quenchers in the core flooding pools and not to pressure suppression chamber (see Fig. 4). Fig. 5 shows that the relief valves are equipped with different pilot valves. The pressure relief function is activated by the reactor protection system (RPS) via solenoid pilot valves and by passive spring loaded pilot valves. The depressurization function on the other hand is again activated by the RPS and solenoid pilot valves and in a diverse manner by the Passive Pressure Puls Transmitter (PPPT) system via diaphragm pilot valves. (Meseth, 2004).

3.2 Emergency Condensers

These are completely passive devices for residual heat removal from the RPV to the flooding pools (see Figs.4 and 6). As a result, the need for high-pressure injection systems is eliminated. The emergency condensers also function in part as a diverse means of depressurization. The emergency condenser system consists of four separate sub-systems remove the residual heat when the water level in the downcomer drops. In order to limit the break mass flow in case of a total break of a condensate line of an emergency condenser, the RPV nozzle is equipped with an outflow reducer. The efficiency of these emergency condensers was verified at the NOKO facility at the German Research Centre at Jűlich (Meseth, 2004).

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3.3 Core Flooding Pools

As mentioned above, the four core flooding pools (3200 m^3) act as a heat sink for the emergency condensers and the safety relief valve system (see Figs. 4 and 6). In addition they are used to flood the core following RPV depressurization in case of a LOCA. To actuate the flooding, spring check valves open automatically after depressurization of the RPV in case of a LOCA. In the event of a serious core melt, the water from the flooding pools is used to cool the RPV from the outside. This flooding is activated actively since an accidental and unnecessary opening could lead to a thermal shock in the vessel head.

3.4 Containment Cooling Condensers

The 4 containment-cooling condensers (CCCs) remove residual heat passively from the containment and transfer it to the large storage/shielding pool (2800 m^3 - see Fig. 4). The rising temperature in the containment actuates them. There are four CCCs, one above each core flooding pool. The heat exchanger tubes are mounted in a slight angle to horizontal for a clearly directed natural circulation within the tubes. The experimental validation of this new component has been achieved at the Panda facility at the PSI in Switzerland. In order to remove non-condensable gases from the condenser H_2 vent pipes are provided (Meseth, 2004).

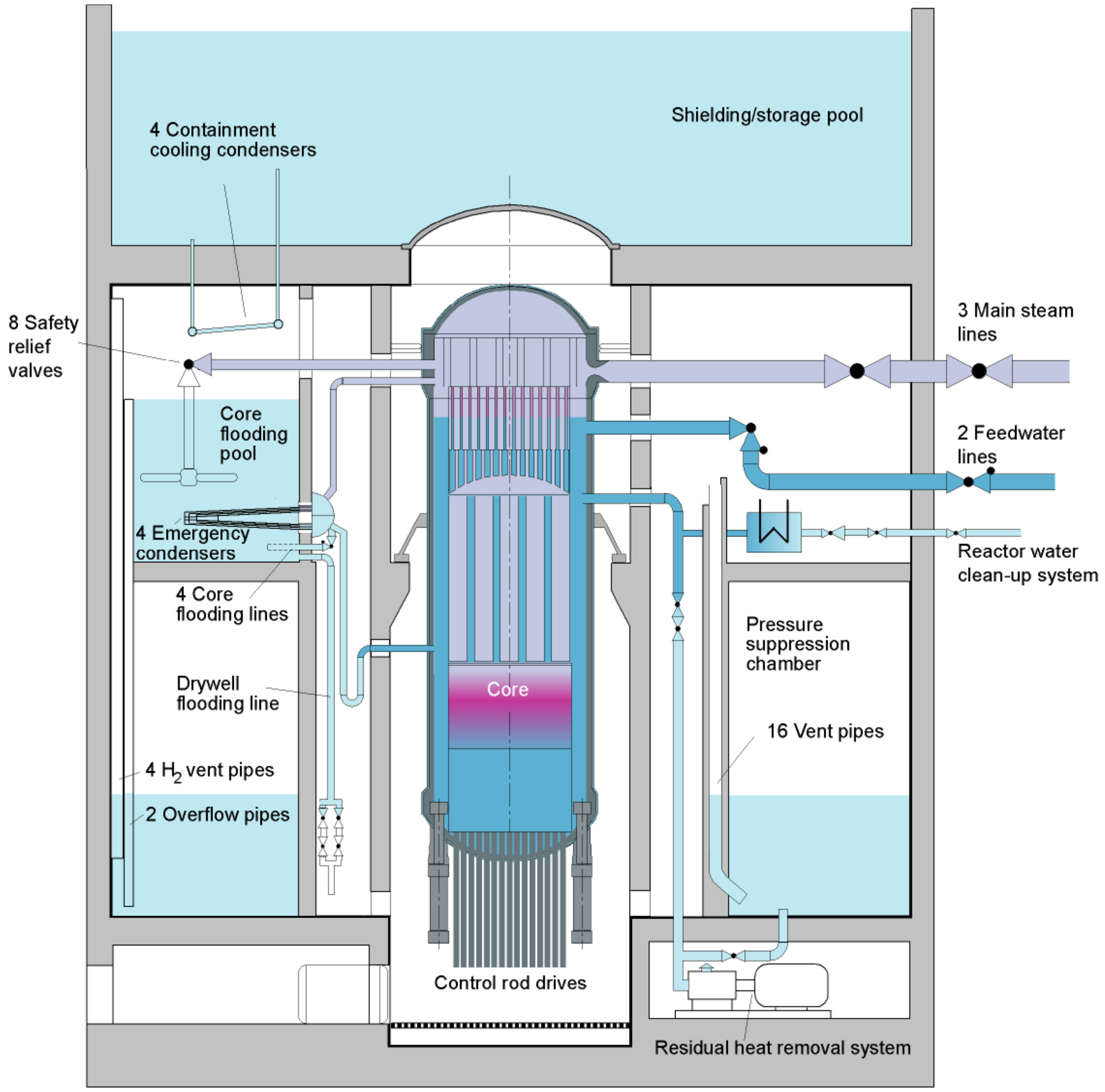
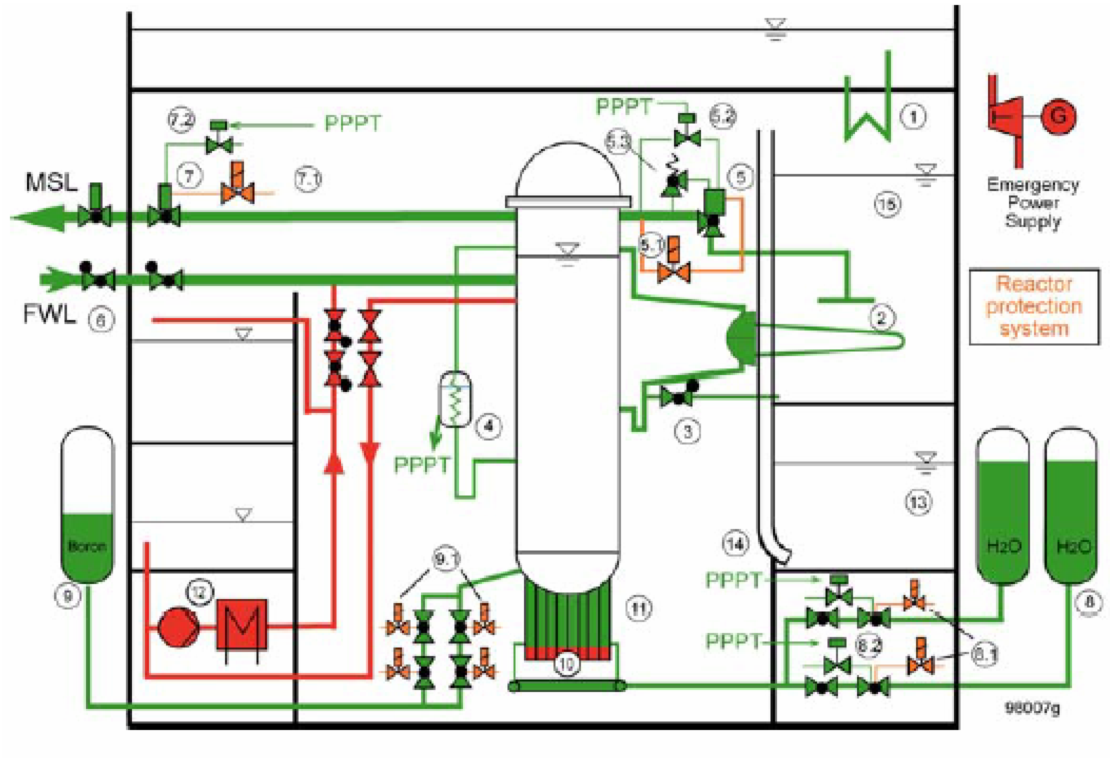
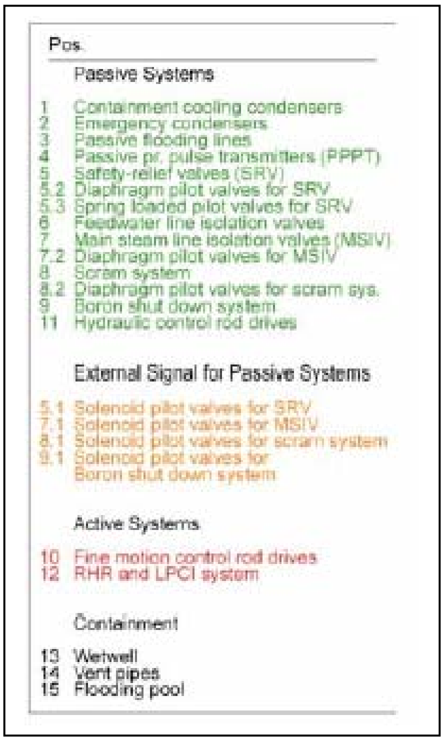


Figure 4 SWR 1000 Reactor layout with passive devices





Pos.	
	Passive Systems
1	Containment cooling condensers
2	Emergency condensers
3	Passive flooding lines
4	Passive pr. pulse transmitters (PPPT)
5	Safety-relief valves (SRV)
5.2	Diaphragm pilot valves for SRV
5.3	Spring loaded pilot valves for SRV
6	Feedwater line isolation valves
7	Main steam line isolation valves (MSIV)
7.2	Diaphragm pilot valves for MSIV
8	Scram system
8.2	Diaphragm pilot valves for scram sys.
9	Boron shut down system
11	Hydraulic control rod drives
	External Signal for Passive Systems
5.1	Solenoid pilot valves for SRV
7.1	Solenoid pilot valves for MSIV
8.1	Solenoid pilot valves for scram system
9.1	Solenoid pilot valves for Boron shut down system
	Active Systems
10	Fine motion control rod drives
12	RHR and LPCI system
	Containment
13	Wetwell
14	Vent pipes
15	Flooding pool

Figs 5 and Table 1 SWR 1000
Passive and Active Safety Features

The complementarity of the passive and active safety systems is shown in both Fig.5 and Table 1. For example the passive and redundant fast hydraulic scram system that is driven by pressurized tanks (8) is passively actuated (8.2) by a Pressure Pulse Transmitter (PPPT – see Fig.7) but can also be activated actively (8.1). In (11) the hydraulic control rod drives are indicated. Another fast and passive shutdown system is the pressure–driven boron injection. However, the actuation of this system is active via the reactor protection system. The only purely active shutdown system is the system of fine motion control rod drives (10). The passive containment condensers (1) and passive emergency condensers (2) are complementary to the active emergency Reactor Heat Removal (RHR) system. The two types of passive safety relieve valves (5.2 and 5.3) and the passive main steam line isolation valves (7) can also be activated actively. The activation of the passive core flooding lines (3) and passive feed water isolation valves (6) is purely passive. The flooding of the dry well (i.e. the reactor cavity) (14) for containing a core melt in the vessel bottom is activated passively (13, 15) - see below.

3.5 Passive Emergency Condenser

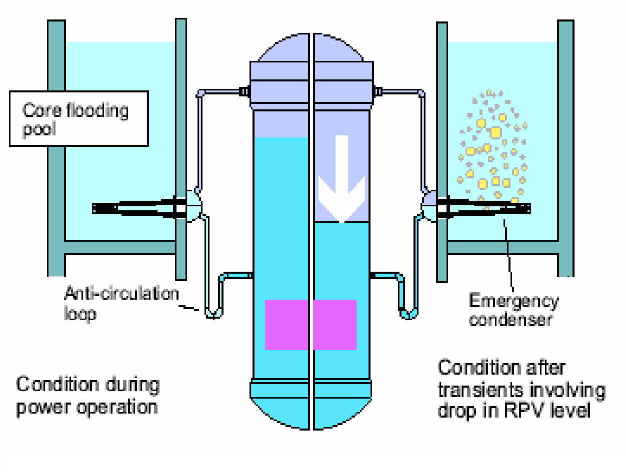


Figure 6 Passive emergency Condensors

Both the emergency condenser in Fig. 6 and the Passive Pressure Pulse Transmitter (PPPT – Fig.7) work on the same principle. Their working depends on the well-defined water level in the downcomer. When this level is normal (left side of Figs. 6 and 7) these devices don't work. When the water level drops, the corresponding water level in the vertical pipe also drops. Once steam gets to the emergency condenser (Fig.6) the condensation heat transfer too the core flooding pools removes a great deal of heat and a natural circulation starts (Meseth, 2004).

3.6 Passive Pressure Pulse Transmitters

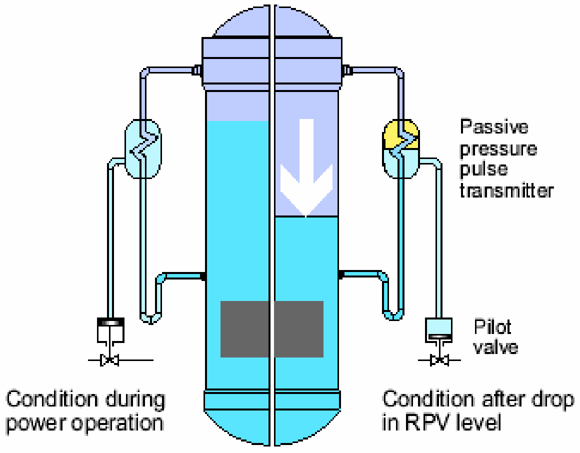


Fig. 7 Passive Pressure Pulse

When the condensation heat transfer in the small heat exchangers starts, the fluid on the secondary side expands and actuates a pilot valve. The passive pressure pulse transmitters serve to initiate reactor scram, vessel depressurization and containment isolation by closing the main steam lines. They function without electrical power supply, external media, or actuation via I&C signals. The actual valve operation is accomplished using system fluids and valves with stored actuation energy. There are 2 x 4 safety-relevant PPPTs that are located at two different elevations. The PPPTs at the highest elevation initiate reactor scram (a hydraulic injection of the control rods), the ones at the lower level initiate depressurization and containment isolation (Meseth, 2004).

4 CONCLUSION ON PASSIVE SYSTEMS IN BOTH AP1000 AND SWR 1000

First a few thoughts about the different behavior of PWRs and BWRs in accident conditions may be useful. The BWR has only one circuit – therefore one is not concerned about problems in a second circuit. Also since the BWR is at a lower pressure and already boiling before an accident starts, it is easier to depressurize it gently and then flood it passively – in the PWR four different stages are required for a controlled de-pressurization – see above. A disadvantage of the direct cycle in the BWR is its direct coupling with the turbine regarding a trip or load shedding. But the 8 passive and diverse relieve valves will counteract these effects

In the BWR the lowering of the water level in the downcomer is highly useful for the activation and functioning of two important passive devices, the emergency condenser and the

PPPTs in Figs. 6 and 7. More generally the number and variety of passive systems in the SWR 1000 is larger – 4 emergency condensers, 4 passively opening flooding lines, 2 × 4 relieve valves, passive containment isolation and a passively activated and also passively driven fast shutdown system. A special passive aspect of the AP-1000 is the use of the entire inner steel containment, cooled by air-draft, as a long-term passive heat removal system. The containment recirculation and the boration of the core are sufficient to last for at least 30 days (Cummins, 2005). But another aspect of the use of the whole containment as heat sink as in AP1000 is the impact of a larger aircraft, which is a severe accident aspect – see in the last part of this paper.

4.1 Comparison of Core Damage Frequencies of AP1000, SWR 1000 and the VVER-1000

The main advantage of the more passive plants is their lower probability to get into a core-melt as expressed by the core damage frequency (CDF). For the SWR 1000 a CDF that is somewhat lower than 10-7 per reactor year is given (for initiating events occurring during power operation and plant shutdown, Brettschuh, 2004). For AP1000 a corresponding number which is somewhat higher than 10-7 was recently published (Cummins, 05). These CDFs that are about 2 orders of magnitude lower than those for reactors with mostly active safety systems. E.g. for the VVER-1000 at Temelin a CDF value of about 10-5 is estimated (DEFRA/RAS/01.001, 2001).

In the recent paper on AP1000 from which the above CDF value was quoted (Cummins, 05), another value of about 10-5 is given for no reactor operator action. This indicates the importance of the new passive approach. However, the same AP1000 paper claims that currently operating reactors have a CDF of ~ 4×10-5 and a CDF value for no operator action of ~ 2×10-3. This implies that current LWRs already have significant passive and some inherent safety aspects (Wider, 2003).

The PSA results of SWR 1000 are essentially determined by the failure rates of the components of the active and the passive systems. For new passive components no operational experience is available. A failure mode and effects analysis was performed for all new components. This estimation also served to determine the failure rates. Three essential modes of the new passive components were investigated (Brettschuh-2, 2005):

- Leakage of the system
- Accumulation of inert gases
- Clogging of the tubes

The modeling of the passive systems was developed from comparable known components such as heat exchangers. TVO and VTT of Finland provided the common cause failures probabilities (CCF). Due to the conservative CCF probabilities the unavailability of the containment cooling condensers and the emergency condensers (4 trains) is in the same range as that of the active heat removal system (2 trains). Therefore, and due to the experimental validation of the passive systems, the low CDF value for the SWR 1000 appears credible.

For the AP1000 the PRA has been used interactively as part of the design process since the beginning of the AP600 program in 1985. Seven major design quantifications have been performed on AP600 and one on AP1000. During each of these, the PRA results were reviewed for potential modifications. Many design and operation changes have been made based on these PRA insights (Cummins, 2005). Therefore and because there has also been an international cooperation on validating the passive approaches, the low CDF value quoted above is also credible.

5 SEVERE ACCIDENT ASPECTS

5.1 In -Vessel Core Melt Retention

Both the SWR 1000 and the AP1000 rely on in-vessel core melt retention in the highly unlikely case of a large core melt. For the SWR 1000 a relatively convincing large paper (Kolev, 2004) is available as well as a large-scale experimental verification of the vessel cooling through ex-vessel natural water circulation and nucleate boiling (Schmid, 2004). For the heat fluxes from the molten pool, more conservative heat fluxes (twice as high) as found in the IVA calculations of Kolev (Kolev, 2004) were used. The maximum local heat flux calculated by Kolev is 300 kW/m^2.

The paper of Kolev gives some general conclusions:

- If the maximum heat flux to the lower vessel head is from the metal layer on top of the molten pool, there is no strong effect from a change in vessel radius
- Increasing the vessel radius reduces the maximum heat flux in the lower head and therefore influences the process positively
- Increasing the delay time of the melt relocation reduces the maximum heat flux into the coolant
- Internal structures penetrating the debris or being closely above them (a) consume decay heat and (b) rapidly increase the metallic layer above them, and thus, reduce the maximum heat flux into the coolant
- A large external water level reduces the forces on the vessel at the oxide level due to the larger buoyancy force – this reduces axial stresses in the vessel
- A large external water level hinders melt release for a predominant part of the lower head

The above arguments 2-6 all give a larger vessel BWR (SWR 1000: RPV inner diameter 7.1m, AP1000: 4m) with a large steel structures both in the SWR 1000 lower head and above and also a high collapsed water level of 12 m in the flooded reactor cavity (see Fig. 8) an advantage regarding in-vessel cooling. The core melt phase in the SWR 1000 is about 8 hrs according to MELCOR analyses vs. 2 hours as e.g. in TMI-2. When the water level in the downcomer of the SWR 1000 decreases to the top of the core the flooding of the reactor cavity is actively initiated. Using the heated-up water from the core flooding pools will not lead to a thermal shock of vessel bottom. When molten fuel gets into the lower head, the housing tubes of the control rod drives at the bottom of the vessel could cause problems in case of a melt attack. This has been considered in the design of SWR 1000. A 70-ton support plate below the vessel bottom anchors the control drive housings and instrumentation assemblies so that they will not be ejected if the welds between housing tubes and vessel bottom melted.

A recent ICAPP'05 paper on AP1000 (McLaughin, 2005) states that analyses with MAAP, detailed calculations of the in-vessel core melting and relocations and also MELCOR analyses by the NRC conclude that sufficient oxide core debris will relocate to the lower plenum before achieving a fully molten, naturally circulating pool. There is no strong basis to assume that the AP1000 vessel will fail from a transient intermediate state with a thin metal layer.

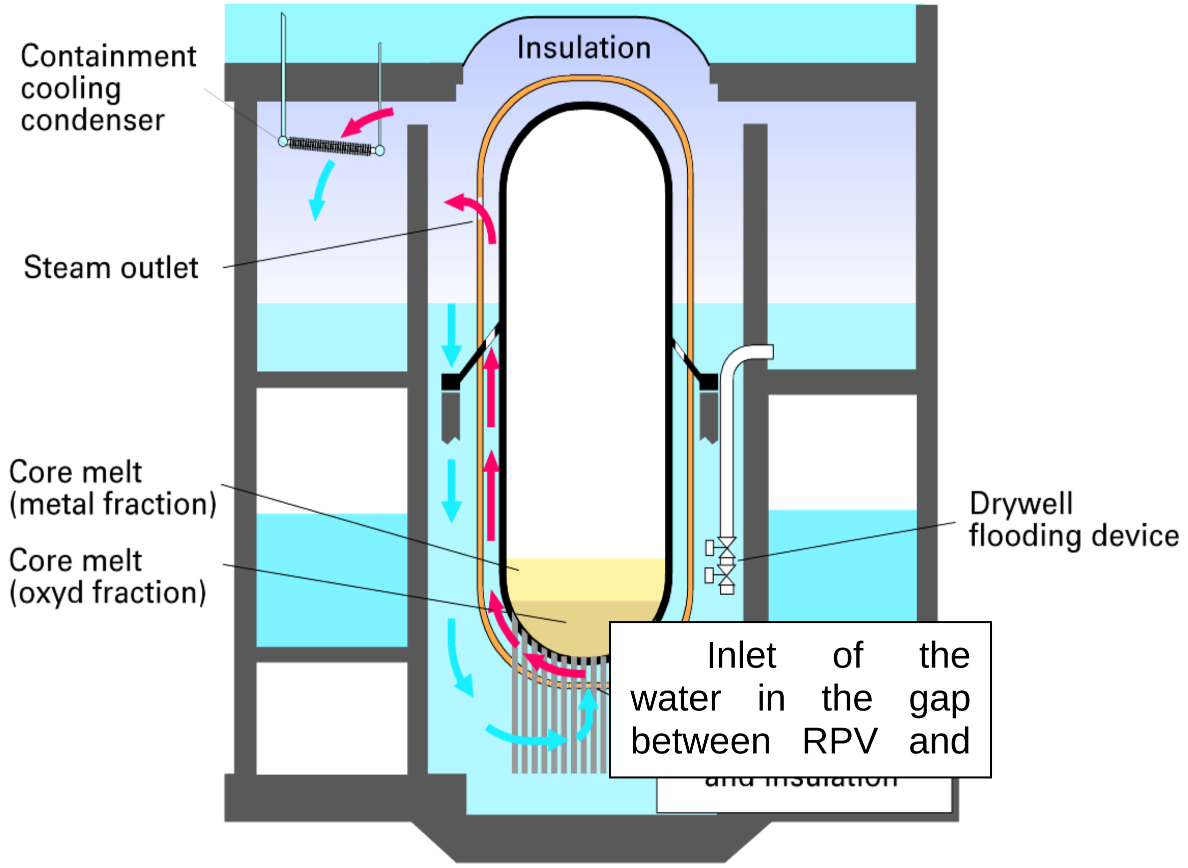


Figure 8 Ex-Vessel Core Cooling of SWR 1000

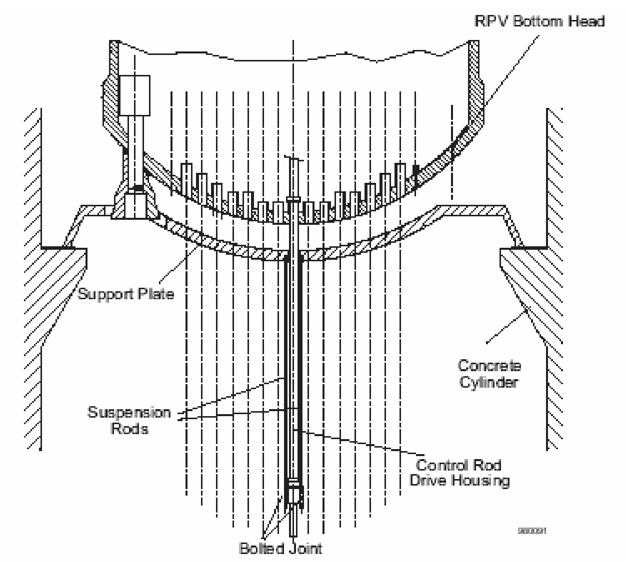


Figure 9 SWR 1000 Design for retention of control rod drive housing and instrumentation assemblies by 70 t support plate below the vessel – there are large enough gaps to let cooling water through

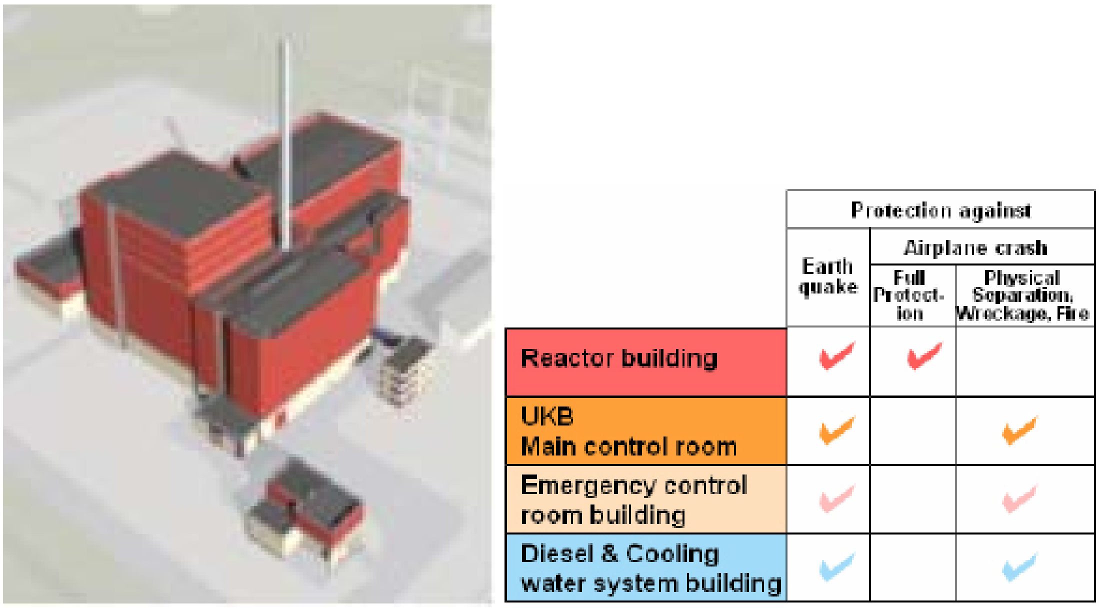
5.2 Prevention of Hydrogen Explosions

In SWR 1000 the containment is inerted with nitrogen to prevent pressure and temperature-raising hydrogen- oxygen reactions (deflagration or detonation), (Brettschuh, 2004)

In the AP1000, hydrogen igniters and passive autocatalytic recombiners prevent hydrogen explosions (Cummins, 2005)

5.3 Physical Protection against External Events

For the SWR 1000 the reactor building is the only building protected against all three major external hazards – seismic events, aircraft crash (military or commercial) and explosion pressure waves. The buildings containing the emergency diesels and safety related cooling water systems are protected against aircraft crash through physical separation (diesel buildings 120 m away) and are also designed to accommodate loads from seismic events and explosion pressure waves. The emergency control room building is protected in the same way and physically separated from the main control room located in the supporting systems building. Since none of the other buildings contain safety related equipment or components with a high radioactive inventory, they are only designed to withstand seismic loadings according to standard industrial practices.



	Protection against		
	Earth quake	Airplane crash	
		Full Protect-ion	Physical Separation, Wreckage, Fire
Reactor building	✓	✓	
UKB Main control room	✓		✓
Emergency control room building	✓		✓
Diesel & Cooling water system building	✓		✓

Fig. 10 SWR 1000 Protection against external events

The AP1000 has to comply with the USNRC regulations. The latter requires considering the impact of a business jet onto the reactor containment. In EU countries such as Germany and France this would not be sufficient.

5.4 Conclusions

Both new mid-sized plants with extensive passive features represent a major progress regarding safety and probably also economics because of the simplified designs. The SWR 1000 has probably a somewhat lower core damage frequency due to a more diverse and redundant passive safety system including passive shutdown and containment isolation.

Regarding severe accident aspects the larger vessel of the SWR 1000 with considerable more internal steel structures in the lower part of the vessel and a large external water level improve the likelihood of in-vessel core melt retention. The SWR 1000 reactor building design against military and commercial aircraft crash loads is required in some countries.

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