AP1000TM Nuclear Power Plant Passive Safety System Actuation using Explosively Opening “Squib Valves”

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Abstract. In the last decades the world demand for energy was growing rapidly and despite the economic crisis no basic change in this development can be expected for the future. Especially the developing countries with fast growing populations and economies will have an increasing need for energy in all forms while available resources are decreasing. The extreme volatility of energy prices in the last years has shown how dependent on cheap and reliable energy we are and how dangerous it is to focus only on few sources. On the other hand the excessive use of fossil fuel in the last century has led to a man made climate change by emission of greenhouse gases. The renaissance of nuclear power is one of the answers to these issues. Global warming cannot be avoided on a short but carbon free nuclear technology can help limiting the effects of climate change and provide billions of people with cheap and reliable energy at the same time.

However, a worldwide “nuclear renaissance” has some prerequisites. Beside economic competitiveness advanced nuclear safety based on proven, evolutionary technologies is the most important condition for the acceptance of new nuclear power plants. Half of the world’s nuclear reactors are based on proven Westinghouse design. These plants have more than 10,000 years of operating experience. The AP1000™ plant is the result of an evolutionary development process where advanced, passive safety features have been combined with proven components from operating plants. Significant design simplifications together with the reduction of piping, cabling, pumps, valves and seismic grade building size have led to reduced investment costs. A consequent modularization enables the plant to be constructed within three years. Passive safety functions relying only on natural forces make the plant safer than any existing reactor. Because active decay heat removal systems do not have to be safety grade classified any more, construction, inspection and maintenance are less expensive as for competing designs. Extensive testing programs were performed for the new passive safety functions ensuring their reliability.

The AP1000™ plant is the only design which received the NRC design certification for the new “one-step” licensing process according to 10 CFR 52. Up to now four orders have been placed in China and the AP1000™ plant will be the standard design for the ambitious Chinese nuclear energy program. Construction of the first plant was started in March 2009 at the Sanmen site for which two AP1000™ plants were ordered and four more are planned in the future. At the Haiyang site construction will start in autumn 2009. Two AP1000™ plants were ordered for this site and six more are in planning. Additionally six contracts have been signed in the US and several utilities are applying for Combined Construction and Operating License based on the AP1000™ plant design. The AP1000™ plant also will be the workhorse for future new builds in Europe and other countries (2), (3).

1. Introduction

The safety systems of the AP1000™ plant rely on passive principles such as gravitation, pressurized gas and natural circulation. However, actuation of the passive safety systems for decay heat removal and safety injection requires one-time alignment of valves. Such active measures are acceptable if they are extremely reliable and do not significantly influence the failure probability of the passive safety systems. Where ever possible fail-open valves are used, which actuate the safety function upon loss of electrical power, loss of operating media or after receiving a control signal.

In some cases reliable opening of valves is absolutely necessary for the function of the safety systems but unintended opening of a safety valve during normal operation has to be avoided. In addition leakage under normal operation conditions is not acceptable if the valve represents the only barrier between the primary circuit and the containment atmosphere. The solution to this issue was found by using explosively opening valves - the so called squib valves. These valves are leak tight, stay closed with high reliability during normal operation and fulfill the leak-before-break criteria so that plant shutdown can be performed before rupture. On the other hand Probabilistic Analysis has shown a very high probability of opening on demand and safety functions will be available when needed. In combination with other types of valves the squib valves guarantee diversity and provide protection against common cause failure.

2. Passive Core Cooling System

The Passive Core Cooling System (PXS) of the AP1000^{TM} plant provides emergency core cooling following postulated design basis events (1). To accomplish this primary function, the passive core cooling system is designed to perform the following functions:

- Emergency core decay heat removal
- Reactor coolant system emergency makeup and boration
- Safety injection
- Containment pH control

Emergency core decay heat removal is provided by the Passive Residual Heat Removal Heat Exchanger (PRHR HX). The heat exchanger consists of a bank of C-tubes in the In-containment Refueling Water Storage Tank (IRWST) which is a large water reservoir inside the containment. The heat exchanger connects to the reactor coolant system through an inlet line from one reactor coolant system hot leg and an outlet line to the associated steam generator cold leg plenum. The inlet line is normally open and the outlet line is normally closed with fail-open air-operated valves. Upon actuation these valves open and a natural circulation establishes from the core to the PRHR HX and back. The decay heat is removed to the IRWST and from there via evaporation to the containment. Condensation occurs on the containment walls and the condensed water flows back into the IRWST. Long-term cooling is provided by the containment cooling system which removes the heat to the atmosphere.

Reactor coolant system emergency makeup and boration is provided by two Core Makeup Tanks (CMTs) which contain approximately 70 m^3 of borated water. Each CMT connects via a open line to the cold leg of the primary circuit and via a direct injection line to the reactor pressure vessel. The direct injection line is normally closed with two parallel fail-open air-operated valves. Upon actuation the valves open and by gravity reactor coolant makeup is provided directly into the reactor pressure vessel. Natural circulation starts and at the beginning hot water from the cold leg replaces the cold water in the CMTs. In a later stage steam replaces the water in the CMTs until they are completely filled with steam and direct injection from the IRWST into the reactor core is initiated.

2.1. Safety Injection

The passive core cooling system (see Fig. 1) provides sufficient water to the reactor coolant system to mitigate the effects of a loss of coolant accident (LOCA). In the event of a large LOCA, up to and including the rupture of a hot or cold leg pipe, where essentially all of the reactor coolant volume is initially displaced, the passive core cooling system rapidly refills the reactor vessel, refloods the core, and continuously removes the core decay heat.

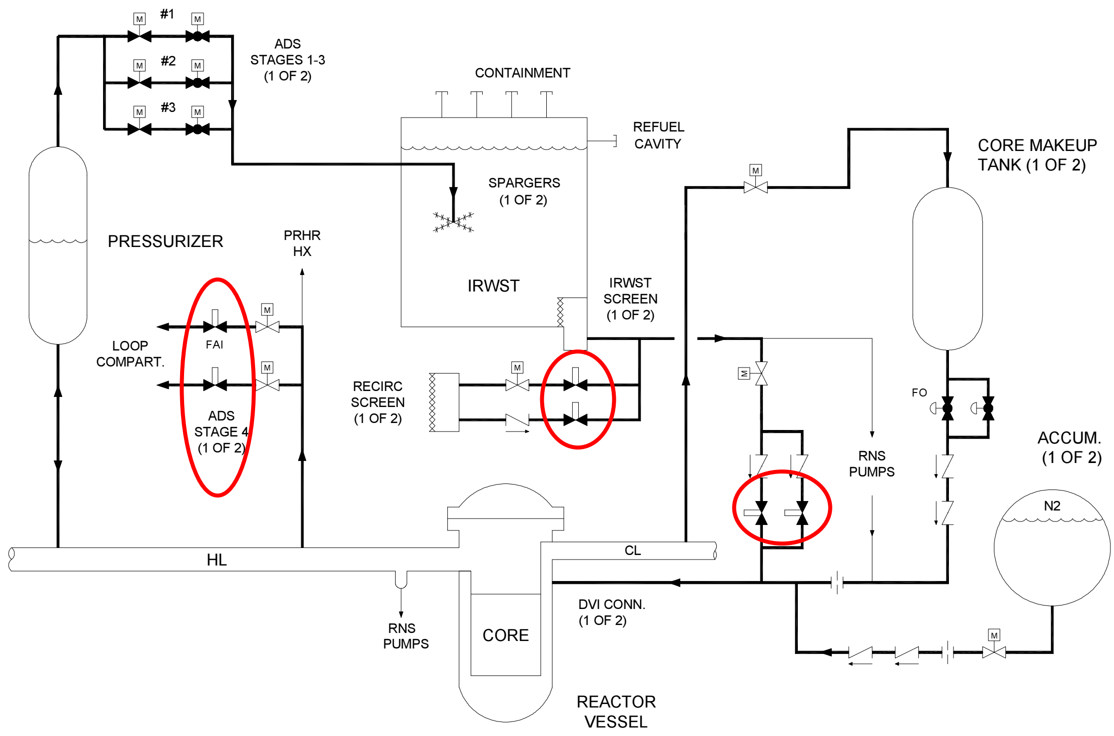

FIG. 1: Passive Safety Injection with Squib Valves (marked by red circles)

In the event of a small LOCA the passive core cooling system depressurizes the reactor coolant system and provides long-term safety injection. The passive core cooling system provides depressurization using the four stages of the Automatic Depressurization System (ADS) to permit a relatively slow, controlled reactor coolant system pressure reduction. After the pressure in the reactor coolant system is released parallel squib valves in the In-containment Refueling Water Storage Tank injection lines open automatically. Check valves, arranged in series with the squib valves, open when the reactor pressure decreases to below the in-containment refueling water storage tank gravitational head. Finally water from the IRWST is directly injected by gravity into the reactor pressure vessel and provides cooling to the core.

After a longer period the IRWST drains and water fills the containment sump. Two recirculation screens in the containment sump are connected to the direct vessel injection lines. Each connection has two parallel lines and each line is isolated by a squib valve. If the IRWST water level is low the squib valves open and long-term recirculation from the containment sump into the reactor coolant system starts.

The passive core cooling system uses four different sources of passive injection during loss of coolant accidents.

- Accumulators provide a very high flow for a limited duration of several minutes.

- The core makeup tanks provide a relatively high flow for a longer duration.
- The in-containment refueling water storage tank provides a lower flow, but for a much longer time.
- The containment sump is the final long-term source of water. It becomes available following the injection of the other three sources and flood-up of the containment.

2.2. Automatic Depressurization System

The Automatic Depressurization System (ADS) releases the pressure from the reactor coolant system and enables safety injection from low pressure systems into the reactor coolant system for long-term cooling. Especially for small break LOCAs depressurization of the primary circuit is important. Without depressurization safety injection into the core could not be guaranteed due to the large pressure difference. As a consequence a steam bubble might form in the reactor pressure vessel and the fuel elements might not be covered with water anymore.

In order to release pressure in a controlled manner the ADS has four stages. The first three stages (ADS-1,2,3) are connected to the pressurizer. Each stage has two parallel lines with two motor operated valves in series which are normally closed. If loss of coolant occurs and the water level in the CMTs drops below a certain setpoint the first stage of the ADS is initiated, the motor operated valves open and release pressure via spargers into the IRWST. The second and third stages of the ADS open with a programmed time delay. They also release pressure via spargers into the IRWST.

The fourth stage of the ADS (ADS-4) is the ultimate safety feature to depressurize the reactor coolant system. The ADS-4 has four parallel lines connected to the hot legs of the reactor coolant system. It is activated when the water level in the CMT drops to 20 %. Unlike the first three stages of the ADS the fourth stage releases the pressure directly into the containment atmosphere until equilibrium is reached. Each line has an explosively opening valve (Squib Valve) and an open motor operated valve in series. In addition to their high reliability the squib valves provide diversity to the motor operated valves in the ADS-1,2,3. Once opened the squib valves can not be closed again and stay open. Since each line is separated from the containment atmosphere only by the respective squib valve unintended opening would directly lead to the loss of primary coolant with all its unwanted consequences.

If the final stage of depressurization (ADS-4) is needed three independent actuation systems supply the signal to open. During normal operation a sophisticated “arm” and “fire” logic prevents spurious opening.

3. Squib Valves

A squib valve consists of housing, actuator subassembly, nipple and nipple shear cap (see Fig. 2). Nipple and nipple shear cap are manufactured as one piece and close the valve leak tight during normal operation. The actuator subassembly consists of a piston, a tension bolt and a booster assembly with the explosive charge. In closed position the tension bolt holds the piston. On actuation the charge explodes, the tension bolt breaks and the blast moves the piston against the nipple shear cap with high speed. As a consequence the shear cap is removed from the nipple and the valve opens. Once the mechanism was activated the squib valve can not be closed again.

The actuation of the squib valves is provided by three independent igniters. Two actuation circuits of the Protection and Safety Monitoring System (PMS) and one actuation circuit of the Diverse Actuation System (DAS) are available to send the open signal on demand. This configuration results in a high reliability of actuation

The AP1000™ plant design includes explosively opening squib valves because of their high reliability and suitability to a function where there is a one-time need for the valve to open (4). This reputation is supported by the use of explosive valves in many designs where the valve cannot fail to perform its function. Examples of these designs include weapons systems and space systems. The explosive valve design is simple and there are few ways for the valve to fail to actuate. This type of design contrasts with the designs of air-operated or motor-operated valves, which have more moving parts that can fail and prevent the valve from actuating.

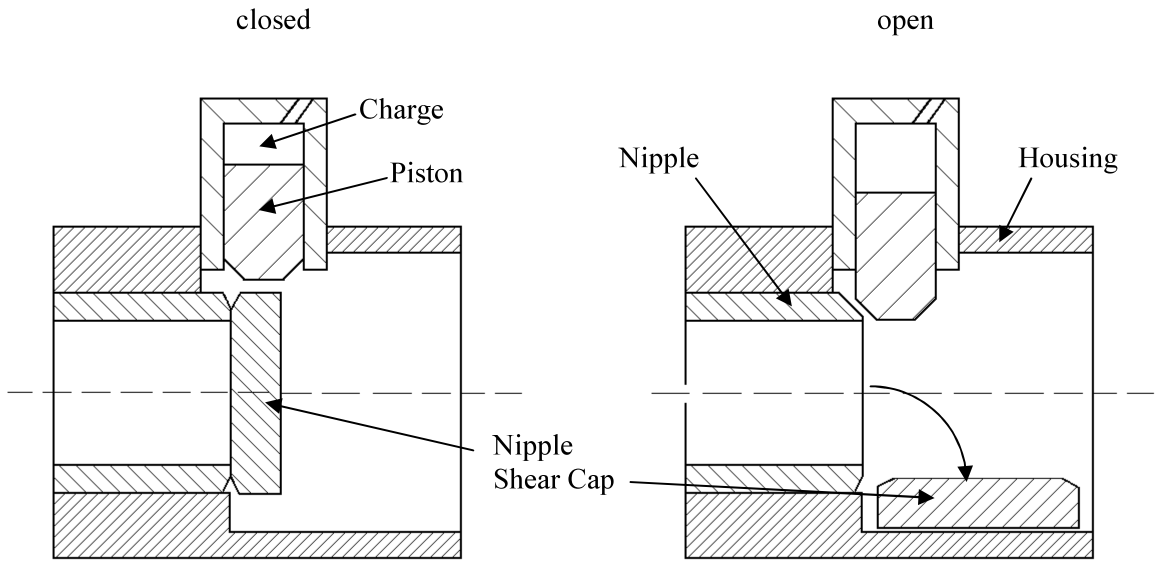

FIG. 2: Explosively Opening Squib Valve (principle sketch)

Reference 5 indicates a failure probability (failure to operate) for explosive valves of 3E-03 per demand. This failure rate does not indicate a valve design with extremely high reliability, as would be expected. This may be because the basis for the value is a small population of valves and extrapolation from older, less relevant data. Sandia Laboratories have worked on designs of weapons systems and space systems where explosive valves are commonly used. They were consulted to verify the failure probability of 3E-03 per demand. Two sources at Sandia produced failure data based on a large population of explosive valves. The data produced failure probabilities of 2.0E-04 per demand and 3.2E-04 per demand. Each of these values is relevant to the AP1000™ plant explosive valve failures. A geometric mean of all three values produces a failure probability of 5.8E-04 per demand (4).

$$\left(3\cdot 10^{-3}\cdot 2\cdot 10^{-4}\cdot 3.2\cdot 10^{-4}\right)^{1/3} = 5.8\cdot 10^{-4}$$

The squib valves of the AP1000™ plant have been evaluated for mechanical rupture. The shear cap was designed according to ASME rules and is manufactured from the excellent material Incoloy 690. Leak-before-break analysis has shown that a leak would occur before potential rupture. Therefore, a potential leak will be identified timely before rupture could occur and the plant can be shutdown safely.

Squib valves are used for different functions in the passive core cooling system (see Fig. 1). Beside the ADS-4 squib valves are placed in the IRWST injection lines and in the sump recirculation lines. In all three cases the squib valves represent the only barrier between the primary circuit and the containment atmosphere or the IRWST water inventory which is open to the containment atmosphere. Therefore, many steps have been taken to reduce the probability of spurious actuation.

(1) A two out of four actuation logic prevents actuation unless it is really required. For instance two out of four detectors in the CMT need to indicate a low water level (20 %) before the actuation sequence of the ADS-4 is initiated.
(2) If manual actuation is needed two switches have to be activated.
(3) A sophisticated two stage “arm” and “fire” actuation circuit prevents spurious opening.

4. Conclusions

The passive core cooling system of AP1000^{TM} plant needs one-time alignment of valves to actuate. In systems where high reliability to open one-time in combination with leak-tightness and high reliability against spurious actuation is needed, explosively opening squib valves are used. These valves represent proven technology. Extensiv testing and analysis have shown a low value of non-opening on demand of 5.8E-4. If the squib valves are used in a redundant configuration the failure probability of the passive safety functions due to failure of the squib valves becomes insignificant. In addition and due to their diverse working principle explosively opening squib valves provide protection against common cause failure. Spurious actuation is prevented by the actuation logic and analysis has shown that the leak-before-break criteria are fulfilled for the squib valves of AP1000^{TM} plant.

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